

AFO AND THE OXYGEN COST OF WALKING IN CEREBRAL PALSY

THE EFFECT OF HINGED ANKLE FOOT ORTHOSES ON THE
OXYGEN COST OF WALKING IN CHILDREN WITH SPASTIC
DIPLEGIC CEREBRAL PALSY

BY

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ABSTRACT

Children with cerebral palsy (CP) have a higher than normal $\dot{V}O_2$ uptake during walking. While various interventions are used to improve locomotion, little is known about their effect on the metabolic and cardiopulmonary cost of walking. We therefore assessed the effects of one popular intervention, hinged ankle foot orthoses (AFO), on cardiopulmonary and metabolic variables during 2 min of steady state treadmill walking at three speeds: 3 kph, comfortable walking speed (CWS) and fast walking speed (FWS). We also assessed the effect of these braces on comfortable and maximum ground walking speed and on gross motor abilities using the Gross Motor Function Measure. Ten children with spastic diplegic CP ($9.01 \text{ years} \pm 2.10$) who habitually used hinged AFO participated. Not all children could walk at all speeds on the treadmill however, and some cardiopulmonary and metabolic data on three children were missing due to equipment failure. We performed an ANOVA on data for children who walked at 3 kph and CWS ($n=8$ for heart rate (HR); $n=9$ for pulmonary ventilation and metabolic variables) and a t-test on data at FWS ($n=9$ for HR, $n=8$ for pulmonary ventilation and metabolic variables). When children wore AFO, absolute $\dot{V}O_2$ was reduced by 4.6% at 3 kph and by 4.1% at FWS, and absolute $\dot{V}O_2$ per metre walked by 4.6% and 4.4% at the same speeds, respectively. Adjusting $\dot{V}O_2$ for body mass, or for resting $\dot{V}O_2$ or calculating energy expenditure in kJ, revealed the same pattern. Pulmonary ventilation was lower with AFO on by 7.17%, but only at 3 kph. AFO did not affect gross motor abilities. Nor did it affect HR, or the respiratory exchange ratio at any speed, nor any physiologic variable at CWS. We suggest the lower O_2 cost may reflect an increase in stability and a corresponding decrease in coactivation of lower limb antagonistic muscles.

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TABLE OF CONTENTS

Page

REVIEW OF THE LITERATURE.....	1
Introduction.....	1
Measures of Gross Motor Ability in Cerebral Palsy.....	1
Gross Motor Behaviour Tests.....	2
Gross Motor Field Tests.....	6
Definitions Commonly used in Studies of Energy Expenditure During Walking.....	7
Selected Issues in Energy Expenditure During Walking in Children: Emphasis on Those Relevant to Children with Cerebral Palsy.....	10
The Oxygen Cost of Walking.....	10
Walking Economy and Endurance.....	11
The Influence of Age on Work Capacity and Mechanical Efficiency in Cerebral Palsy.....	11
Habituation to the Treadmill.....	12
Generalisability to the Field of Responses to Treadmill Testing.....	14
The Effect on Cardiovascular and Metabolic Variables of Interventions Designed to Improve Walking in Children with Cerebral Palsy.....	14
The Use of Ankle Foot Orthoses in Cerebral Palsy.....	17
Hypothesis.....	19
Objectives.....	19
METHODS.....	20
Subjects.....	20
Design and Protocols.....	22
Calculations and Data Reduction.....	28
Statistical Analysis.....	30
RESULTS.....	32
Ground Walking Speed.....	32
Gross Motor Function (GMFM).....	33
Cardiopulmonary Variables.....	33
Heart Rate.....	33
Pulmonary ventilation.....	33
Metabolic Variables.....	34
Absolute Oxygen Uptake.....	34
Ventilatory Equivalent for Oxygen.....	34
Mass Adjusted Oxygen Uptake.....	34
Net Oxygen Uptake.....	35
Absolute Oxygen Uptake per metre walked.....	35
Mass Adjusted Oxygen Uptake per Metre Walked.....	36
Respiratory Exchange Ratio.....	36
Energy Expenditure.....	37
Gross Energy Expenditure.....	37
Net Energy Expenditure.....	37
Summary of Results.....	37
DISCUSSION.....	39
Ground Walking Speed.....	39
Gross Motor Function (GMFM).....	40

Cardiopulmonary Variables	41
Heart Rate	41
Pulmonary Ventilation	43
Metabolic Variables	45
Absolute Oxygen Uptake	45
Ventilatory Equivalent for Oxygen.....	46
Mass Adjusted Oxygen Uptake.....	47
Net Oxygen Uptake.....	50
Absolute Oxygen Uptake per metre walked.....	51
Mass Adjusted Oxygen Uptake per Metre Walked.....	52
Respiratory Exchange Ratio	53
Energy Expenditure	55
Statistical Power.....	55
Study Strengths and Limitations.....	58
Strengths.....	58
Limitations	59
Coactivation in Spastic Cerebral Palsy.....	64
 CONCLUSIONS AND RECOMMENDATIONS	 69
Conclusions.....	69
Recommendations for Further Research.....	70
 BIBLIOGRAPHY	 75
 APPENDICES.....	 125
Appendix A: Information Form.....	125
Appendix B: Consent Form	126
Appendix C: Visit 1 Parent Questionnaire	127
Appendix D: Physical Activity Questionnaire.....	128
Appendix E: Visit 2 Parent Information Sheet	132
Appendix F: Visit 2/3 Parent Questionnaire.....	133

LIST OF TABLES

- Table 1: Gender, age, anthropometric data and relative body adiposity of individual subjects with comparisons to norms.
- Table 2: Details of AFO use.
- Table 3: Intended and actual belt speeds for individual subjects.
- Table 4: Sample group means, standard error data and ANOVA results for ground walking speed (n=10).
- Table 5: Sample group means, standard error data and ANOVA results for Gross Motor Function Measure dimension scores (n=10).
- Table 6: Group means, standard error data and ANOVA results for heart rate (HR).
- Table 7: Group means, standard error data and ANOVA results for pulmonary ventilation ($\dot{V}E$).
- Table 8: Group means, standard error data and ANOVA results for absolute oxygen uptake ($\dot{V}O_{2abs}$).
- Table 9: Group means, standard error data and ANOVA results for the ventilatory equivalent for oxygen ($\dot{V}E/\dot{V}O_2$).
- Table 10: Group means, standard error data and ANOVA results for mass adjusted oxygen uptake ($\dot{V}O_{2mass}$).
- Table 11: Group means, standard error data and ANOVA results for net oxygen uptake ($\dot{V}O_{2net}$).
- Table 12: Group means, standard error data and ANOVA results for absolute oxygen uptake per metre walked ($\dot{V}O_{2mw}$).
- Table 13: Group means, standard error data and ANOVA results for mass adjusted oxygen uptake per metre walked ($\dot{V}O_{2mmw}$).
- Table 14: Group means, standard error data and ANOVA results for respiratory exchange ratio (RER).
- Table 15: Group means, standard error data and ANOVA results for gross energy expenditure (EE_{gross}).
- Table 16: Groups means, standard error data and ANOVA results for net energy expenditure (EE_{net}).
- Table 17: Summary of results

LIST OF FIGURES

- Figure 1: Effect of AFO on ground walking speed at comfortable walking speed (CWS) and maximum walking speed (MWS) conditions. Error bars denote SEM (n=10).
- Figure 2: Individual ground walking speed responses to AFO at comfortable walking speed (CWS) and maximum walking speed (MWS) conditions (n=10).
- Figure 3: Effect of AFO on the Standing and Walking, Running & Jumping (WRJ) dimensions of the Gross Motor Function Measure. Error bars denote SEM (n=10).
- Figure 4: Individual dimension score responses to AFO at Standing and Walking, Running & Jumping (WRJ) dimensions of the Gross Motor Function Measure (n=10).
- Figure 5: Effect of AFO on heart rate (HR).
- Figure 6: Individual heart rate (HR) responses to AFO.
- Figure 7: Effect of AFO on pulmonary ventilation ($\dot{V}E$).
- Figure 8: Individual pulmonary ventilation ($\dot{V}E$) responses to AFO.
- Figure 9: Effect of AFO on absolute oxygen uptake ($\dot{V}O_{2abs}$).
- Figure 10: Individual absolute oxygen uptake ($\dot{V}O_{2abs}$) responses to AFO.
- Figure 11: Effect of AFO on the ventilatory equivalent oxygen ($\dot{V}E/\dot{V}O_2$).
- Figure 12: Individual ventilatory equivalent for oxygen ($\dot{V}E/\dot{V}O_2$) responses to AFO.
- Figure 13: Individual mass adjusted oxygen uptake ($\dot{V}O_{2mass}$) responses to AFO.
- Figure 14: Effect of AFO on net oxygen uptake ($\dot{V}O_{2net}$).
- Figure 15: Individual net oxygen uptake ($\dot{V}O_{2net}$) responses to AFO.
- Figure 16: Effect of AFO on absolute oxygen uptake per metre walked ($\dot{V}O_{2mw}$).
- Figure 17: Individual absolute oxygen uptake per metre walked ($\dot{V}O_{2mw}$) responses to AFO.
- Figure 18: Individual mass adjusted oxygen uptake per metre walked ($\dot{V}O_{2mw}$) responses to AFO.
- Figure 19: Effect of AFO on the respiratory exchange ratio (RER).
- Figure 20: Individual respiratory exchange (RER) responses to AFO.
- Figure 21: Effect of AFO on gross energy expenditure (EE_{gross}).

Figure 22: Individual gross energy expenditure (EE_{gross}) responses to AFO.

Figure 23: Effect of AFO on net energy expenditure (EE_{net}).

Figure 24: Individual net energy expenditure (EE_{net}) responses to AFO.

REVIEW OF THE LITERATURE

Introduction

Cerebral palsy (CP) is the most common paediatric motor disorder (Pharoah, 1985), affecting between 1.4 and 6.5 per 1000 school-aged children (Nelson and Ellenburg, 1978; Paneth and Kiely, 1985) depending on the reporting criteria used. A prevalence of 2.0 per 1000 school-aged children is generally accepted as the most reasonable estimation (Paneth and Kiely, 1985). Cerebral palsy is considered by many to be the most common paediatric physical disability treated by rehabilitation professionals (Wilson, 1991). Spastic diplegia, where legs are more involved than arms, affects about 32% of these children, and is the most frequent subtype of CP (Nelson and Ellenburg, 1978). One of the main physical disabilities caused by spastic diplegia is a decrease in walking proficiency, which is accompanied by a higher than normal oxygen uptake ($\dot{V}O_2$) during walking (Campbell and Ball, 1978; Duffy et al., 1996; Unnithan et al., 1996a). This high $\dot{V}O_2$ may be one cause of the early fatigability (Bar-Or, 1983a; 1996a) that is reported in CP (Berg, 1970; Dahlbäck and Norlin, 1985). Interventions which decrease $\dot{V}O_2$ during locomotion could therefore potentially benefit a large proportion of physically disabled children.

Measures of Gross Motor Ability in Cerebral Palsy

The measurement of gross motor ability in CP remains of great interest and a challenge to professionals who serve and study this population (Boyce et al., 1991; Campbell, 1992; Goldberg, 1991; Palisano et al., 1997). In the following review, gross motor ability measures are classified under two broad categories: 1) gross motor behaviour tests and 2) gross motor field tests. Gross motor behaviour tests are defined as standardised, observational tests of gross motor behaviour that do not involve sophisticated laboratory equipment. The assessor asks the child to hold a particular posture or perform a particular movement, or otherwise attempts to invoke the desired behaviour, and scores the resulting posture or movement based on specific

criteria as set down by the test developers. Gross motor field tests are defined as measures of gross motor skill that relate more to the child's routine performance in everyday life. This system of describing tests reflects the opinions of this author and is presented here strictly for purposes of clarification in describing the measures. These classifications and definitions are arbitrary and in some cases tests or parts of tests may belong to both categories. Tests discussed below are examples of those commonly considered for use with school aged children who have CP, according to two fairly recent reviews (Boyce et al., 1991; Campbell, 1992). Assessments that involve parent or child recall on how the child performs will not be discussed.

Gross Motor Behaviour Tests

Boyce et al. (1991) suggest three broad criteria be considered when selecting a gross motor behaviour test: 1) validity; *i.e.*, the test actually measures what it purports to measure; 2) reliability, where test scores remain consistent in the absence of a change in what is being measured; and 3) responsiveness, where test scores reflect change in what is being measured when such change occurs.

The Bruininks-Oseretsky Test of Motor Proficiency (Bruininks, 1978) has both gross and fine motor components which can be scored separately. Its normative sample was a large ($n=765$) group of healthy North American children between 5 and 14 years old. The test is reported to be reliable, both between assessors (interrater) and between tests (test-retest). The specific reliability statistics were not identified in the manual but were given as .87 for test-retest reliability and .90 to .98 for interrater reliability (Bruininks, 1978). The test developers also claim the test is valid. To the best of this author's knowledge, no data attesting to these claims have been published in peer-reviewed journals. The test's responsiveness to change in gross motor ability is unknown. Several of the gross motor components of the test, such as walking on a balance beam, would however, be challenging or impossible for many children with spastic diplegia. Boyce et al. (1991) suggest that the test is more suitable for discriminating healthy children from those with clumsiness or general developmental delay.

The Peabody Developmental Motor Scales also contain both fine and gross motor sections which can be considered separately (Folio and Dubose, 1983). Normative data for the test came from a sample of 617 new born to 7 year old children, 107 of whom had known motor abnormalities. The test has good interrater ($r=.99$) and test-retest ($r=.88$) reliability (Hinderer et al., 1989). Criterion validity ($r=.63-.93$) has been shown with reference to the Bayley Motor Scale (Palisano, 1986).

The Gross Motor Function Measure (GMFM) is different from the above tests in that it is specifically designed to assess change in children with movement abnormalities such as CP (Russell et al., 1989). The test was constructed in consultation with professionals who treat and study these children. The specific motor behaviours assessed are those believed by these professionals and the test developers to reflect the motor abilities and deficits of children with cerebral palsy, from mild to severe (Russell et al., 1993). The validation and reliability study (Russell et al., 1989) was done on a group of 170 children, 111 of whom had CP, 34 of whom had no known disability and 25 of whom had acute head injury. In the absence of a "gold standard" to use for validation, the authors used several indirect methods. They assumed that healthy children under 3 years develop at a faster rate than older children. They therefore compared changes in scores of younger (< 3 years old) and older children (> 3 to < 20 years old) over a 4 to 6 month period. The change scores were significantly ($p<.0001$) higher in the younger children, supporting their hypothesis. This group of researchers also felt that for children with CP, severity not age, would determine change scores. In other words, irrespective of age, children clinically considered less severe would have greater change scores than more severe children. There was a trend to support this hypothesis ($p=.07$) for children under 3 years of age. The authors attribute this lack of significance to low statistical power due to small sample size in each of the age by severity group. Overall however, there was a significant interaction between age and severity. The extent to which children's severity level affected change scores varied depending on the age of the group. No specific rationale however is given for using age three years as the cut off age between fast and slow gross motor development. For the CP group, Russell and colleagues mention that

their sample purposefully had a large number of younger children, both under 3 and 3-5 years old as these age groups, they felt, would be expected to show functional changes (improvements) more than older children. No references are given to support this statement. It appears that Russell et al. hypothesised that maturation of the nervous system and the rate of acquisition of gross motor skills slows down with age, especially after age 3 years. Since these authors wanted to see if the GMFM would be sensitive to change, they compared healthy children and those with CP who they thought were more likely to change (those under 3 years) and to those they thought were less likely to change (those over 3 years). It is generally felt that the rate of central nervous system maturation (Connolly and Prechtl, 1981) and correspondingly gross motor skill acquisition, (Bayley, 1969; Folio and Dubose, 1983; Frankenburg and Dodds, 1967) markedly decreases in healthy children after age 2 years, at least with respect to the types of skills tested on the GMFM. One can only assume that age 3 was used to compensate for the delayed development of children with CP. To the best of this author's knowledge, no studies have reported on the actual rate of gross motor skill acquisition in a large group of children with CP. It may be indeed be that change in CP is dependent both on age and severity, as these results of Russell and colleagues suggest.

The GMFM change scores of children classified as mild, moderate, and severe by their treating therapist were also compared. There was no significant difference in these scores. In addition, Russell and co-workers compared 4-6 month change scores in children recovering from head injury to those with CP; the assumption being that, as head injury is an acute condition and CP is not, a valid test would show greater change in the head injury group. This was the case ($p < .05$). One other method used to validate the test was to compare perceived 4-6 month change in children with CP to change scores on the GMFM. Perceived change between the first and second visits was assessed using a 14 point Likert scale (-7 a great deal less function to +7 a great deal more function). A structured questionnaire about the child's function was administered to parents and therapist at both visits. After completing the second questionnaire, the parents and therapists had access to the first and used the two questionnaires to assist themselves in rating the child's

change. Two groups of therapists were used, those who treated the child and those who did not know the child. The later group assessed the child by watching videotapes of him or her performing various physical activities. Video based judgements of change correlated moderately well ($r=.82$) with change scores. Treating therapists' and parents' ratings of change were lower ($r=.65$ and $r=.54$, respectively). Notwithstanding the lower correlations with subjective assessments of behaviour, the authors consider the GMFM to be a valid indicator of gross motor behaviour which is sensitive to gross motor change in children with CP. Reliability scores showed excellent interrater ($r=.99$) and intrarater ($r=.99$) reliability. The GMFM, especially the Walking, Running, Jumping dimension, has also been shown to correlate with other physical performance measures used in CP, such as walking speed (Damiano and Abel, 1996; Drouin et al., 1996). and peak and mean lower limb anaerobic power (Parker et al., 1993). Gains in knee flexor and extensor muscle strength are also reflected in the increases in the Standing and Walking, Running and Jumping dimension scores, especially in children with spastic diplegia (MacPhail and Kramer, 1995).

Similar to the GMFM, the Gross Motor Performance Measure is specifically designed to assess motor behaviour in CP. The test uses a subset of the motor behaviours rated in the GMFM and assigns a score based on the child's ability to realign or maintain alignment of body segments and coordinate or control the movement of body segments as they perform the required motor act (Boyce et al., 1995). The interrater and intrarater reliability is acceptable ($ICC=.92$, $ICC=.96$) according to the authors (Gowland et al., 1995). Validity and responsiveness (Boyce et al., 1995) were assessed in a manner similar to that for the GMFM. The 4-6 month change scores (similar sample size and population mix as GMFM validation study) were significantly greater ($p<.05$) for head injured children compared to those with CP. Scores for mild, moderate and severe CP were significantly different from each other ($p<.05$). Validity was questioned by the authors themselves because there was no difference in scores among the age groups and change scores were not different in the different age groups. Boyce and colleagues suggest the use of the test is limited at this point due to both the difficulty administering it, which

requires familiarity with the GMFM and a 1 day workshop, and the unclear results of the validation study.

In summary, of the four gross motor behaviour tests reviewed, only one test, the GMFM, has been designed specifically for use with the CP population. It is also the only test shown to correlate with other measures of physical performance or be otherwise responsive to changes in physical performance. The test also has the desirable properties of being reliable, and at least somewhat valid.

Gross Motor Field Tests

The gross motor field tests described here are those that have been used in previous studies of physical capacity in CP. Two tests, speed of walking up and walking down a 5 m ramp with a 15% incline, are unique to one training study (Spira and Bar-Or, 1975). These authors found a significant increase in walking speed going up and down the ramp in a group of adolescents with spastic CP following one year of enhanced physical activities such as twice weekly swimming and adapted ball sports.

Two other field tests, comfortable and maximum walking speed, have been used in studies assessing differences in energy expenditure during walking between healthy children and those with CP (Campbell and Ball, 1978; Duffy et al., 1996; Hoofwijk et al., 1995; Rose et al., 1990). These measures have also been used by researchers interested in the effects of interventions such as ankle foot orthoses (AFO) (Middleton et al., 1988; Mossberg et al., 1990; Radtka et al., 1997), strength training (MacPhail and Kramer, 1995), enhanced physical activity (Spira and Bar-Or, 1975), use of hand-held assistive devices (crutches, canes, walker) (Rose et al., 1985), and orthopaedic surgery (Dahlbäck and Norlin, 1985).

Unlike the tests of gross motor behaviour, gross motor field tests with the CP population are not standardised across studies and have not undergone validity or reliability assessments. Walking speed on level ground seems to be somewhat discriminative in terms of gross motor ability, in that children with CP walk slower than healthy children at comfortable (Campbell and

Ball, 1978; Duffy et al., 1996; Unnithan et al., 1996a), and maximum (Hoofwijk et al., 1995) walking speeds. The responsiveness of walking speed tests to changes in physical ability is less clear. There is a trend for AFO use to increase comfortable walking speed, although results are not significant (Middleton et al., 1988; Radtka et al., 1997). Comfortable and maximum speed do increase with enhanced physical activity and there is a significant positive correlation between maximum walking speed and maximum aerobic power (Spira and Bar-Or, 1975). Comfortable and maximum walking speed however, do not change with changes in knee extensor and flexor muscle strength (MacPhail and Kramer, 1995). Based on data from Rose and colleagues (Rose et al., 1985), it is difficult to assess the relationship between walking speed and physical ability as measured by the need for greater (walker) or less (canes) support when walking. There appears to be a trend for the average walking speed of children who use walkers to be lower (1.56 kph, ± 88) than that of children who habitually ambulate with canes (1.73 kph, ± 54). Since the group sizes were small and unequal (n=5 for walkers; n=7 for canes), one can not make firm conclusions based on this study. Increases in maximum walking speed as the result of various lower limb orthopaedic surgeries were reported anecdotally (Dahlbäck and Norlin, 1985), but not measured.

Although the relationship between walking speed and physical performance or ability is undoubtedly complex, walking speed does appear to vary with physical ability to some extent.

Definitions Commonly used in Studies of Energy Expenditure During Walking

It is assumed that for steady state, submaximal exercise such as walking, the body derives its energy through aerobic metabolism and thus $\dot{V}O_2$ reflects biochemical energy expenditure (EE) (Rowland, 1996b). Researchers interested in EE during walking express this variable in many different ways, depending on the questions being asked and the resulting factors that need to be accounted for in the measure. Body (or body segment) mass, limb length, speed of locomotion, fuel source and mechanical energy produced are just a few of the myriad of factors

that can be accounted for in a measure or index of locomotion related EE. The following definitions are those commonly used in studies measuring the O₂ cost of walking or walking economy or efficiency. These will be the definitions used throughout this paper.

The O₂ cost of walking is the $\dot{V}O_2$ during a period of steady state walking. Oxygen uptake can be expressed as the total or absolute $\dot{V}O_2$ ($\dot{V}O_{2abs}$) which is measured in L·min⁻¹. In order to compare persons of different sizes, especially important in paediatric research, $\dot{V}O_2$ can also be expressed relative to body mass; i.e., a mass adjusted $\dot{V}O_2$ ($\dot{V}O_{2mass}$) and expressed in ml·kg⁻¹·min⁻¹. It should be noted that there is some controversy in paediatric exercise physiology as to the appropriate scaling factor when normalising for body mass, or if indeed it is to mass that one should be normalising (Rowland, 1996a). The controversy stems from the fact that it may not simply be the absolute mass of the child that determines how much O₂ he or she will consume during exercise and that $\dot{V}O_2$ may not increase to the same degree throughout development. These matters are less relevant in research on EE during walking or other weight bearing activities because in these instances it is the body mass that is being moved (Rowland, 1996a). One other way to express $\dot{V}O_2$ is as net $\dot{V}O_2$ ($\dot{V}O_{2net}$), namely the difference between resting and steady state exercise values. Calculating $\dot{V}O_{2net}$ allows the investigator to determine EE during walking, independent of resting levels. The caveats for this measurement are outlined below (see Discussion, Net Oxygen Uptake).

Energy expenditure during walking is the biochemical energy required by the body to do the work of walking. In paediatric exercise physiology research, EE is usually estimated using $\dot{V}O_2$ (with a correction for differences in $\dot{V}O_2$ with different fuel sources) and converted to units of energy, kJ. Gross EE (EE_{gross}) is the total or absolute EE during the period of walking being assessed. Net EE (EE_{net}) is the EE above that required to maintain homeostasis at rest. Specific methods of calculating EE_{gross} and EE_{net} are found in the Methods section, below.

Walking efficiency, is the ratio between mechanical work (energy) produced by the body during walking and the steady state EE required to perform that work. If calculated per unit of time, the units in the numerator and denominator are those for power, W. While a discussion of

mechanical power calculations is beyond the scope of this review, suffice to say, it is extremely difficult to estimate mechanical power during walking and hence difficult to determine walking efficiency. Sophisticated biomechanical analysis techniques must be employed. Depending on the approach used, internal work (moving body segments), transfers of energy within and between segments, differences in the work performed by eccentric and concentric muscle contraction may be accounted for to greater or lesser degrees, thus influencing the overall mechanical power estimate and the overall estimate of efficiency (Frost et al., 1997a). Calculating *mechanical muscular efficiency* is more frequently done as it can be easily determined using arm or leg ergometry. Energy expenditure is calculated in the manner described above using $\dot{V}O_{2net}$. Mechanical power is calculated as the force on the ergometer flywheel multiplied by the distance travelled by the perimeter of the fly wheel per unit of time (Leger, 1996). The resulting ratio value is thought to be an estimate of the muscle contraction efficiency (Rowland, 1996b). In studies in exercise physiology, mechanical muscular efficiency is usually referred to as mechanical efficiency. We will keep this convention here.

Due to the complexity of calculating walking efficiency, *walking economy* is frequently determined instead. Economy of walking is the O_2 cost or $\dot{V}O_{2abs}$ per unit of distance walked ($\dot{V}O_{2mw}$), and is usually measured in $L \cdot m$. When comparing individuals of different sizes, $\dot{V}O_{2mass}$ per unit of distance walked ($\dot{V}O_{2mmw}$) is used and is usually expressed in $ml \cdot kg^{-1} \cdot m^{-1}$.

The need for specialised equipment and the difficulties encountered in measuring $\dot{V}O_2$ in young children with cerebral palsy are probably responsible for the paucity of studies assessing EE during gait. These children for example, may accept neither the mouth piece nor mask. They may also drool excessively and have poor lip closure (Berg and Bjure, 1970). Researchers interested in the physiologic responses to walking in CP have therefore frequently calculated the *cardiovascular cost of walking*, either as walking HR in beats per metre (Mossberg et al., 1990; Rose et al., 1985), or as net HR (HR above rest) per metre walked (Jeng et al., 1996; MacPhail and Kramer, 1995; Mossberg et al., 1990; Rose et al., 1985; 1989; 1990).

Selected Issues in Energy Expenditure During Walking in Children: Emphasis on Those Relevant to Children with Cerebral Palsy

The Oxygen Cost of Walking

Whether measured on a level treadmill (Frost et al., 1997a, 1997b), an inclined treadmill (Forster et al., 1994; Kanaley et al., 1989) or on the ground (Waters et al., 1983), the O₂ cost of walking expressed per kg body mass, decreases in healthy children as they age. The higher O₂ cost in younger children is associated with an increase in coactivation (simultaneous activity of antagonistic muscles) at the thigh and leg (Frost et al., 1997b). Frost et al. suggest that this increase may reflect the greater need for stability in younger children.

There are no specific studies investigating the effect of age on the O₂ cost of walking in children with CP. Campbell and Ball (1978) however, did note the tendency for the O₂ cost of walking per kg body mass to increase with age in children with spastic diplegia. Compared to healthy children, however, the O₂ cost is higher in CP, whether children walk on the ground at a comfortable pace (Campbell and Ball, 1978; Duffy et al., 1996) or on the treadmill at the same absolute speed (Unnithan et al., 1996a). Walking economy in CP is lower, with $\dot{V}O_2$ in ml·kg⁻¹·m⁻¹ being 1.5 to 2.5 times greater in cerebral-palsied children (Campbell and Ball, 1978; Duffy et al., 1996). Unnithan et al. found that the increased $\dot{V}O_2$ in CP during gait is related to an increase in thigh and leg coactivation. They suggested possible causes such as delayed maturation of the locomotor system, compensation due to altered lower limb muscle mechanics and a lack of appropriate inhibition due to the original brain damage (see Discussion, Coactivation in Cerebral Palsy for further details on this topic).

There is another body of research that compares the O₂ and cardiovascular cost of treadmill or floor walking between healthy children and those with CP (Rose et al., 1985; 1989; 1990). Although these investigators also found children with CP to incur a higher O₂ and cardiovascular cost during walking, their values may not be accurate due to their methodology. The investigators did not indicate if or how they determined steady state exercise. Thus it is unknown if, or to what degree, HR or $\dot{V}O_2$ reflected EE during walking. More importantly, children

were allowed to hold on to the treadmill handrails without measurement of the degree or frequency of holding on, both of which are known to reduce $\dot{V}O_2$ (Green and Foster, 1991).

Walking Economy and Endurance

It has been suggested (Bar-Or, 1983a; Unnithan et al., 1996a) that poor walking economy in CP may be related to the complaints of fatigue during walking at low intensities noted in these children (Berg, 1970; Dahlbäck and Norlin, 1985). Since they walk at a greater percentage of their maximum $\dot{V}O_2$ than healthy children (Unnithan et al., 1996a), Unnithan et al. suggest that in prolonged physical activity, these children may fatigue sooner than their able-bodied peers. With healthy children, the relationship between running economy and endurance (walking economy and walking endurance relationships apparently not being of interest to researchers) is complex. For children of the same age, there appears to be no clear relationship between submaximal running economy and endurance performance as measured by time to complete a distance run (Krahenbuhl and Pangrazi, 1983). This does not imply that no relationship exists between economy of locomotion and endurance, but rather that factors other than running economy probably play a role in determining performance times. Such factors may obscure an economy-endurance relationship. Longitudinal studies on the other hand (Daniels et al., 1978; Krahenbuhl et al., 1989), have shown that as children age, maximum $\dot{V}O_2$ remains essentially unchanged, yet the O_2 cost of running is less per kg body mass and time on endurance tests improves.

The Influence of Age on Work Capacity and Mechanical Efficiency in Cerebral Palsy

Although the precise influence of age on the O_2 cost of walking in CP is unknown, like Campbell and Ball (1978), Spira and Bar-Or (1975) have commented on the tendency over time for adolescents with CP to progressively walk less and use assistive devices more. Spira and Bar-Or attribute this decrease in walking to a decrease in work capacity as muscle strength does not appear to increase sufficiently to meet the demands of increased body mass, resulting in less physical activity and detraining. A 1-2 year longitudinal study by Lundberg (1973), illustrates the

deterioration in the cardiovascular response to exercise: HR at a given work load on the cycle ergometer increased by 10 bpm per year. A second 4-5 year follow-up on the same children (Lundberg, 1984), however, did not show a continued pattern of decrease in metabolic or cardiovascular responses to exercise, although, mechanical efficiency (cycle ergometry) did decrease from an average of 13.4 % to 11.6% during the total 6 years of this study.

Decreased mechanical efficiency in itself may therefore be a factor contributing to both the higher O_2 cost of walking in CP and the tendency to walk less with age. Children with CP have lower than normal mechanical efficiency whether measured by cycle (Emons and Van Baak, 1993; Jones and McLaughlin, 1993; Lundberg, 1984) or arm ergometry (Bar-Or et al., 1976). Values range between 11.6% to 15.6%. Values are higher for arm (15.1%) compared to leg ergometry. The highest value, 15.6% is unique in that it is a calculation of gross mechanical efficiency, using $\dot{V}O_{2abs}$ rather than $\dot{V}O_{2net}$ to estimate biochemical EE (Jones and McLaughlin, 1993). Mechanical efficiency in healthy children and adults, who do not differ from each other, is on average 25% (Bar-Or, 1983a). Bar-Or suggests that the low efficiency in children with CP is a result of "wasteful" movement. Children show increased coactivation and have difficulty completing smooth revolutions on the ergometer. Thus, some of the work of muscular contraction is not as directly applied to the pedals as with healthy children. Poor mechanical efficiency, he goes on to say, may be related to inefficient or uneconomical gait, which worsens as children age. Training programs of an aerobic nature have not been successful in improving mechanical efficiency in CP (Bar-Or et al., 1976; Emons and Van Baak, 1993; Lundberg, 1984).

Habituation to the Treadmill

Little information exists on the extent to which familiarity with the treadmill influences the cardiovascular and O_2 cost of walking. Frost et al. (1995) assessed between trial (same day) and between day changes in metabolic ($\dot{V}O_2$) respiratory exchange ratio (RER) and cardiovascular (HR) variables as well as kinematic variables (stride rate, stride length, hip amplitude), at various running or walking speeds. They assumed that as the child became more familiar with the

treadmill, they would “habituate to it”. In other words, steady state metabolic and cardiovascular values would decrease (children would become more economical) and improved economy would be reflected by a decreased stride rate, an increased hip amplitude (children would no longer try to increase stability by lowering their centre of gravity) and an increased stride length. In addition, a more stable pattern would be seen and reflected in decreased variability of these measures. These changes would be seen between trials within the same day and between days. In actual fact however, there was great variability in responses. Some subjects did show the expected changes, while others did not. As a group, children did not show any clear pattern to allow the authors to make recommendations to ensure habituation. Their results point to the need to individually monitor children. Frost et al. (1995) however, felt that accommodation to the treadmill, where the gait is “fairly” normal and stable, could occur in one session, although accommodation per se, was not examined in this study. Other researchers looking at variability in running economy in children have suggested that more than one testing session may improve reliability of results (Rogers et al., 1994).

There is no consistent accommodation protocol in treadmill studies of walking economy in children with CP. Unnithan and co-workers (1996a) gave children a standardised 15 minute treadmill training session. Their accommodation criterion appeared to be that the child was able to walk several minutes on the treadmill without holding on to the handrails. They do not specifically define accommodation or habituation. Jeng et al. (1996) gave a 15-20 minute practice trial, but do not state any standard procedure or criteria for accommodation. Several other studies state neither criteria for accommodation nor procedures for the practice trial (Dahlbäck and Norlin, 1985; Rose et al., 1989; 1990). No data are available for treadmill habituation in CP. It therefore appears that increased variability could have been introduced into the results of these studies by a failure to control for children’s treadmill accommodation and habituation patterns.

Generalisability to the Field of Responses to Treadmill Testing

Since the majority of children, and especially children with CP, do not usually walk on a moving treadmill belt, it would seem important to know how generalisable results are from treadmill studies to the field. Jeng and colleagues (1996) found that both healthy children and those with CP have a slower preferred walking speed on the treadmill compared to walking on level ground (see Discussion, Absolute Oxygen Uptake per Metre Walked).

The O₂ cost of walking on the treadmill compared to the floor is significantly less for older (age 55-66 years) and younger (age 19-29 years) men (Pearce et al., 1983). This finding is true for a variety of self-selected speeds: comfortable (average decrease of 7.3%), fast (average decrease of 8%) and as fast as possible (average decrease of 4.1%). The authors attribute their findings to the assistance in forward propulsion that the body receives from the treadmill belt motor.

The Effect on Cardiovascular and Metabolic Variables of Interventions Designed to Improve Walking in Children with Cerebral Palsy

There are few studies that have examined the effect of various therapeutic interventions on physiological responses during walking in the child with CP. MacPhail and Kramer (1995) assessed the effects of a lower limb strength training program for adolescents with CP. Seventeen subjects trained knee flexors and extensors with an isokinetic dynamometer three times per week for 8 weeks. Strength changes (peak torque and work) were the same for knee flexors and extensors. Although the group as a whole showed strength increases between 12% and 28%, which were similar in magnitude to healthy adults, the adolescents with spastic diplegia showed gains in peak torque (40%) that were almost 3 times that of the children with spastic hemiplegia and gains in work (31%) that were twice as great. Three month follow-up testing showed that significant strength gains were maintained and the losses (32% peak torque and 25% work) were similar to those of healthy people. No change however, was found in comfortable or maximum ground walking speed following training or at the follow up visit. Likewise, no

changes in the cardiovascular cost of walking were found. Changes in gross motor ability were significant for 9 of their 17 subjects. The authors conclude that, although walking function may not have improved, a short period of strength training one to two times per year would still be of benefit to this population given the increases in strength found. The measures of the cardiovascular cost of walking used by McPhail and Kramer however, may not be optimum. Their cardiovascular index of heart beats per metre walked, was calculated by using the ratio of walking heart rate above rest to walking velocity. The investigators however, did not describe if or how they determined steady state during rest and exercise. Since heart rate is sensitive to several other environmental factors besides exercise (see Discussion, Heart Rate) it would seem crucial to determine if values were stable. Also, MacPhail and Kramer did not discuss whether the resting values were similar for the three testing sessions. This too could obviously have affected results.

Mossberg et al. (1990) used the same measure as MacPhail and Kramer to investigate the effect of AFO on the cardiovascular cost of walking in 18 children (mean age 8.3 years) with spastic diplegia. Resting HR was determined during a 5 min rest period. Children walked twice, once with AFO and once without, for 5 minutes each time, on level ground at self selected speeds. The type of AFO used was termed "conventional". Walking HR was determined as the average of the last three minutes of walking. For these trials, children also used what ever hand-held assistive devices they normally used to walk. The authors found no relationship between the amount of time per day children habitually wore AFO (as reported by parents) and the difference in the cardiovascular cost of walking between the two trials. Walking HR was also not significantly different between these trials. The cardiovascular cost of walking was lower by an average of .17 beats per metre when children used AFO. The authors question the clinical relevance of their findings for the group as a whole; however they note there was great variability in individual responses to AFO. Differences in the cardiovascular cost of walking due to AFO ranged from a decrease of 59% to an increase of 41%. They suggest that individual monitoring of children using

their methods may assist clinicians in determining the efficacy of AFO and perhaps predict who would comply with the prescription for braces.

The changes in the cardiovascular cost of walking due to AFO may again be obscured in Mossberg and colleagues' study due to other environmental factors that influence HR. In addition, no criteria were described for the resting data collection period. Although an accurate resting HR does not affect the pattern of individual responses to AFO, it may affect comparisons of their data to that in the literature. More importantly, although they note that children reached steady state, these authors do not report their criteria for steady state. The study is however, the first published (to this author's knowledge) to show an improvement due to AFO, in any index of the physiologic cost of walking for this population.

Rose et al. (1985) assessed the effect of two different types of walking aids on the cardiovascular cost of walking, using the same index as in the other two studies. Twelve children, five of whom usually used walkers, seven who usually used quad canes, were assessed. It is not known how the children were accommodated to the new walking aid. Again, the criteria for steady state were not reported. The data were not analysed using inferential statistics. Two groups of children were identified, one group for whom the cardiovascular cost of walking did not appear to differ between the devices, and another group for whom the use of the walker minimised the cardiovascular cost of walking. Most children in the first group habitually used walkers, most in the second, used canes. As there were some exceptions to this rule, the authors suggest that their measure could be used in a clinical setting to determine which device minimises the cardiovascular cost of walking for a specific child.

Only one study appears to have assessed the effect of a therapeutic intervention using measures other than HR. Dahlbäck and Norlin (1985) investigated changes in several cardiopulmonary and metabolic variables following a variety of lower limb tendon lengthenings and muscle transfers. Six, 9-15 year old children with spastic diplegia were tested during steady state walking on the treadmill prior to surgery and retested under the same conditions 4-6 months later. Children first walked for 9 min on a level treadmill at a self selected, comfortable walking

speed and for another 10 min while the treadmill was raised 2% per minute. The protocol was identical following surgery. Cardiopulmonary and metabolic variables showed no difference following surgery with the exception of $\dot{V}O_2$ per kg body mass during level walking, which showed a 5% decrease. The researchers note their findings may be somewhat difficult to interpret however, because they allowed children to hold the treadmill handrails at will. It was their impressions that children held on more during the first session, especially during the inclined walk. This holding on might have decreased the real differences in $\dot{V}O_2$ following surgery, since $\dot{V}O_2$ decreases with the degree of support the subject receives from the handrails (Green and Foster, 1991). Of more interest however, may be their finding of premature fatigue in these children. All children were exhausted by the end of the inclined treadmill walk, yet all physiological variables were below the expected anaerobic threshold. Heart rate average was only 150 bpm. The RER and the ventilatory equivalent for oxygen ($\dot{V}E/\dot{V}O_2$) were also indicative of submaximal exercise. The authors conclude that the premature exhaustion was indicative of local muscle fatigue, rather than a cardiopulmonary limitation. Again, because children were hanging on to the handrails, the authors caution any firm conclusions about exhaustion and the physiologic variables. It is unknown if children were able to walk unsupported on level ground, although no statement to the contrary was made.

The slow speed used on the treadmill may have indeed resulted in the above study being a test of endurance. By contrast Hoofwijk et al. (1995) reported that a similar, but slightly older group of children (mean age 13.5 years), were able to successfully perform a maximum walking test on the treadmill. The walking speed for the inclined walk however was the children's maximum, rather than comfortable speed, as was used in Dahlbäck and Norlin's research.

The Use of Ankle Foot Orthoses in Cerebral Palsy

Ankle foot orthoses are a popular intervention to increase ambulation ability for children with CP (Butler et al., 1992; Carmick, 1995; Hainsworth et al., 1997; Knutson and Clark, 1991; Lough, 1990; Middleton et al., 1988; Mossberg et al., 1990; Olney and Wright, 1994; Ounpuu et

al., 1996; Radtka et al., 1997; Ricks and Eilert, 1993). These braces are theoretically designed to improve walking function by supporting the joints of the ankle and foot in such a way that gait mechanics are improved compared to walking without orthoses (Knutson and Clark, 1991). For children with spastic diplegia, whose bilateral involvement usually requires bilateral bracing, the main effect of using AFO appears to be more normal ankle motion in the stance phase of gait (Carmick, 1995; Hainsworth et al., 1997; Lough, 1990; Middleton et al., 1988; Ounpuu et al., 1996; Radtka et al., 1997).

Studies using either gait analysis (Lough, 1990; Middleton et al., 1988), or visual comparison of photographs of the gait cycle (Carmick, 1995), propose that for patients with spastic diplegia, hinged AFO, which allow some degree of free ankle dorsiflexion but limit ankle plantarflexion, may improve gait mechanics to a greater degree than rigid AFO, where the ankle joint is fixed between 0° and 5° of dorsiflexion. Use of AFO, especially hinged AFO, may also maintain extensibility of the triceps surae. A recent study (Hainsworth et al., 1997) used an ABAB design to assess the affects of AFO. In this study, 9 of the 12 children wore hinged AFO, and 8 of the 12 had spastic diplegia. At baseline, all children had worn AFO for at least 4 months. The AFO were withdrawn for 2 weeks, children wore them again for 5-15 months and then AFO were withdrawn for two weeks. After each 2 week period out of braces, there was a significant loss in passive ankle dorsiflexion (5°-7°) as measured by goniometry and a trend for a deterioration in gait (less obvious heel strike) as assessed by rating videotapes of children walking barefoot.

In adults with tibial nerve paralysis (Lehmann et al., 1986) or hemiplegia (Lehmann et al., 1987), walking with AFO that are adjusted to an optimal position (between 5° of plantar- and dorsiflexion) also results in a reduction in the O₂ cost of walking.

In summary, there appear to be numerous methodological problems in studies investigating whether interventions commonly used to improve walking ability in this population also have an effect on the physiologic cost of walking. Thus, studies to date have failed to provide a great deal of evidence regarding whether these interventions actually improve the physiologic cost of walking in children with CP.

Hypothesis

Children with spastic diplegia adopt a more mature walking pattern wearing hinged AFO. This is reflected by a decrease in the cardiovascular cost of walking. We therefore expected that with AFO on, there should have also been a corresponding decrease in the cardiopulmonary and metabolic cost of walking, improved gross motor function in activities related to walking, and improved walking economy.

Objectives

This study was intended to determine the effects of wearing hinged AFO on steady state physiologic responses in children with spastic diplegia, during walking at three different speeds on a motorised treadmill. Secondly, we wished to investigate the effects to physiologic variables, of the interaction between speed and AFO. The specific physiologic responses measured or calculated were heart rate, pulmonary ventilation, absolute oxygen uptake, ventilatory equivalent for oxygen, mass adjusted oxygen uptake, net oxygen uptake, absolute oxygen uptake per metre walked, mass adjusted oxygen uptake per metre walked, respiratory exchange ratio, gross energy expenditure and net energy expenditure. To calculate net oxygen uptake, we also measured oxygen uptake at rest. Thirdly we were interested in determining the effects of wearing hinged AFO on gross motor ability. Specifically, we measured children's comfortable and maximum walking speed on the ground, with AFO off and on. We also scored children on the Standing, and Walking, Running and Jumping dimensions of the Gross Motor Function Measure, again, with AFO on and off.

METHODS

Subjects

Ten children (8 boys, 2 girls), ages 7.3 to 13.1 years, ($9.0 \text{ M} \pm 2.1 \text{ SD}$), participated in this study. Four other children, 2 boys and 2 girls similar in age to the study participants, also volunteered but were unable to successfully complete any part of the Visit III treadmill. Two of them, although able to walk indoors independently, were unable to do so on the treadmill. Two other children found it difficult to walk on the treadmill independently for an entire two minutes while being connected to the metabolic cart. They complained of having to breathe through the mouth piece.

Individual anthropometric and body composition data for subjects (arm span 133.0 ± 17.6 cm; body mass 30.0 ± 11.0 kg; sum of 4 skinfolds 33.9 ± 18.4 mm) and comparisons to healthy children of the same age are summarised in Table 1. Seventy percent of children were below mean body mass for age, while 60% were below mean for the sum of 4 skinfolds and 60% were below mean stature as measured by arm span. These data agree with a large study ($n=154$) by Stallings et al. (1993). This group reported wide variability in body composition and anthropometric measures in children with diplegic or hemiplegic CP, but overall found children with CP to be below the mean of same-aged, healthy children for body mass, skinfold thickness (subscapular and triceps) and stature.

Study participants were recruited through the physical therapy departments of children's rehabilitation centres in the Hamilton, Oakville and Toronto areas. All participants had a diagnosis of spastic diplegic CP, as confirmed by their physical therapist who had access to the medical chart. They were habitual users of hinged AFO (Table 2), and were able to walk indoors and outdoors independently with braces on and off, although one girl occasionally used forearm crutches for very long distances; e.g., going to an amusement park. Fifty percent of parents and children felt it was easier for subjects to walk with AFO on (Table 2). The AFO of all children were

reported by the parents and children to be fitting properly. All AFO were hinged, allowing 5° or more dorsiflexion at the ankle. For eight of the 10 children, plantarflexion of the AFO was severely limited (5° or less). All subjects participated to the best of their ability in a regular physical education program at school, and either attended a physical activity program or were reported by parents to be physically active (e.g., cycling, roller skating) for at least one hour weekly outside of school hours. No children trained for competitive sports.

The gross motor function of children was classified using the Gross Motor Function Classification Scale (Palisano et al., 1997), a five-level grading system that assumes the assessor has previous knowledge of the gross motor skills, such as those tested by the GMFM, of the child being classified. All subjects but one, Subject 12, were classified as Level I, the level with least gross motor function deficit, in that they could "walk without restrictions and had limitations in more advanced motor skills". Subject 12 was classified as Level II, the next level. Level II children can "walk without assistive devices, but have limitations walking outdoors and in the community". All classifications were done by the author, who was familiar with the measure and with the GMFM.

Although four study participants each had one medical condition aside from CP, none of these conditions restricted physical activity. Aside from one child who was taking antihistamine medication daily for skin allergies, no child was on any medication during the testing period. All children were reported to be well rested and had refrained from eating or drinking (with the exception of water) for at least 2 hours prior to each laboratory visit.

The study was approved by the Ethics Committees of the Faculty of Health Sciences, McMaster University, Hamilton, ON, Canada and the Bloorview MacMillan Centre, Toronto, ON, Canada. Prior to each subject's participation in the study, informed consent was obtained from a parent, preceded by verbal assent from the child. For their time and effort, study participants received a T-shirt imprinted with the study logo and a souvenir photograph of themselves fully instrumented for the Visit III data collection. Parents were reimbursed for gas or parking.

Transportation was provided for families who did not have their own means of travelling to and from the testing site.

Design and Protocols

This study used a repeated measures design, in which each child served as her or his own control. Data collection generally took place over three testing sessions. Nine of the 10 children completed the study within a three week period. One child, the oldest (age 13 years), repeated the final testing session as we had equipment recording problems during Visit III. For this child, 6 weeks elapsed between her second and (successful) third testing session.

Visit I took place at the family home or at another location (school or local children's treatment centre) convenient to the family. Study participants made two visits, Visit II and Visit III, to the lab at the Children's Exercise and Nutrition Centre in Hamilton, ON, Canada. Due to both family and lab scheduling constraints, three children were seen only twice, both times at the lab. For these children, Visits I and II were combined and an extra rest period was given between the respective protocols. To guard against decreasing effort (due to boredom) as this extended testing session progressed, children were given the option of watching an age appropriate video cartoon during the extra rest session.

In four cases, the measurement of resting metabolic rate, usually done during Visit II was repeated at the beginning of Visit III. For 2 children the measure was repeated because they failed to become comfortable with the mouth piece during Visit II. Two other children had to repeat the measurement because of equipment problems in Visit II.

For all visits children wore short, "gym-type" shorts and a T-shirt. At the beginning of each visit, the participants and parents were told what to expect for that particular session. At each stage in the study protocol, participants were also told what was to be measured, what devices would be used, how measurements would be taken, and what they themselves would be expected to do during this time. Children were allowed to examine any piece of equipment with which they would come into direct contact and "practice" with the equipment before its use in the

protocol.

The following was the intended protocol for each visit along with modifications required in certain instances:

Visit I. At the beginning of this session, children and parents were introduced to the study coordinator, the main person who interacted with the children throughout the study. Questionnaires assessing habitual physical activity (modified from Bar-Or, 1983b) and health status were administered. Parents were encouraged to help their child with these questionnaires if needed. The study coordinator or designate was available to answer any questions that arose.

Total body length was estimated by arm span (Stanley metal tape measure, Canadian Tire, Corp., Hamilton, ON, Canada). This was measured in supine to ensure stability of the trunk and optimum positioning of the upper limbs. Arm span rather than height was used to decrease the possibility of measurement error due to subjects' lower limb spasticity, which could have made standing erect difficult. Although upper arm length, tibial length and knee height are all valid and reliable estimates of stature for children with CP up to 12 years of age (Stevenson, 1995); we were unable to use any of these measures as no data correlating these measures to stature are available for children with CP who are 12 years and older.

Relative body adiposity was estimated by summing skinfold thickness measures (Harpندن calliper, Loton, England) taken from four sites: biceps, triceps, subscapular and suprailliac. To minimise fatigue and measurement error due to subjects' compromised independent standing balance, data for triceps, biceps and subscapular skinfolds were collected with children in sitting, trunk unsupported. Measurements at the suprailliac site were collected with the subjects standing, supporting themselves with the arm contralateral to the side being measured. Skinfold thickness data from each site were recorded as the average of three trials. All data were collected from the right side. We refrained from using bioimpedance analysis, because its validity for such subjects has not been established.

Gross motor functional ability with AFO on and off was assessed, using the Standing and Walking, Running and Jumping dimensions of the Gross Motor Function Measure (GMFM)

(Russell et al., 1993). These specific subsections of the GMFM have recently been found to relate to walking function in children with CP (Damiano and Abel, 1996; Drouin et al., 1996). Our GMFM test administrator was the author, a paediatric physiotherapist with the recommended training (Russell et al., 1994) and several years experience using this measure.

Order of AFO condition (AFO on or off) was randomised. Since AFO need to be worn with shoes (there is generally no traction on the soles of AFO and shoes help to keep AFO properly positioned on the feet), children also wore the shoes they typically wear with AFO for the GMFM testing and for all subsequent protocols in this study that involved wearing AFO. As this study design called for comparisons between the braced and non-braced condition, children also wore shoes for all non-braced protocols where such comparisons were made. These shoes were not the same as those worn with braces. To accommodate their width, braces usually require a wider cut shoe that is one-half to one size larger than the child's typical shoe.

Visit II Questionnaires updating physical activity and health status since the previous visit and providing information on general content and time of the last meal, were administered. Body mass (Mott Electronic Scale, UMC1000; accuracy ± 20 g ; Ancaster Scale Co. Ltd., Brantford, Ontario, Canada). was measured and a HR monitor (Polar Vantage XL, Polar CIC, Port Washington, New York) was affixed around the child's upper chest. The child wore the same clothes (T-shirt, underwear and shorts) during weighing and for the testing session.

To subsequently calculate net metabolic cost of walking, we measured resting metabolic rate. Once the subject had been sitting quietly for about 15 minutes, resting expired gas and HR were measured for 5 minutes. Children were connected to an open circuit system by a mouth piece (adult size silicon rubber mouth piece, Hans Rudolph Inc., Kansas City Mo., USA) which was adapted to fit the saliva trap and mass flow sensor (SensorMedics Corp., Yorba Linda, CA, USA). Pilot work showed us that for these children, the larger mouth piece generally provided a better seal and guarded against leakage of inspired and expired gas. In one case, a subject with repaired cleft lip and palate required a smaller mouth piece (SensorMedics Corp., Yorba Linda, CA, USA). Resting metabolic rate was measured using the mouth piece rather than the

traditional ventilated hood to allow children some opportunity for habituation to the mouth piece and nose clip and to allow us to evaluate the best sized mouth piece for each child. Subjects were tested in sitting rather than supine as pilot work showed they were better able to maintain a seal around the mouth piece in sitting.

Oxygen uptake, carbon dioxide output, ventilation ($\dot{V}E$), and RER were measured and recorded breath by breath, and stored on the Vmax system's computer. Heart rate was continuously measured by the HR monitor and stored in the receiver as 5 s averages. Prior to collection of metabolic data, gas flow was calibrated with a 3 L calibration syringe and gas analysers (Vmax 29 Pulmonary Exercise System, SensorMedics Corp., Yorba Linda, CA, USA) were calibrated with gases of known concentration. To guard against distraction and boredom during the initial resting period and during resting metabolic and cardiopulmonary data collection, subjects watched a "calm" video cartoon suitable for their age. For some children, the Vmax system initially had difficulty registering their breaths if the volume was not sufficiently high. These children were instructed to perform a couple of forced expiration manoeuvres. With the increased volume of expired gas, the machine began to collect data and continued to do so even if the volume once again became very low.

Following resting measures, children were disconnected from the metabolic cart and, as part of the assessment of gross motor function, their comfortable and maximum walking speed on the ground were assessed with and without AFO. Speeds were calculated as the average of three consecutive trials (time in seconds to walk 30 m). We randomised both the order of speeds under each brace condition (with and without AFO) and the order of brace condition. To minimise the time spent changing brace conditions, study participants walked at both speeds, for a total of six trials, before the brace condition was changed. Children rested in sitting between each trial until HR was within 10% of resting values.

Children were then taught how to mount, dismount, and walk on the treadmill (Quinton, Q65, Seattle, WA). Children were considered accommodated to the treadmill once they were able to walk without support, with AFO on and off, at the starting speed for determining the fastest

walking speed, as described below. Once this process was completed, after about 15 minutes, we determined their fastest treadmill walking speed. The treadmill dial was used to give an approximate indication of belt speed, however the actual belt speed was determined by measuring the time required for 20 revolutions of the treadmill belt (3.705 m) while the child was walking unsupported on the treadmill. Starting speed was the child's preferred ground walking speed, unless during the treadmill teaching session it became obvious that the preferred ground walking speed would be close to the fastest walking speed. In these cases (3 subjects) we started with a speed of 1-1.5 kph below the child's comfortable ground walking speed.

A 3-stage (2-min each) protocol was used to calculate fastest walking speed on the treadmill. This was done with and without AFO. The order of brace condition was randomised to control for order effects. Fastest walking speed was defined as the fastest speed maintained for two minutes on the treadmill without loss of the double support phase of gait. The subjects rested in sitting until HR was within 10% of its resting value. At the end of the session children walked again for no less than 30 s on the treadmill while connected to the metabolic cart. This final walk was intended to help each child become comfortable walking on the treadmill while breathing through a mouth piece and wearing a nose clip. To prevent children from having to support the mouth piece, saliva trap and mass flow sensor, and as an extra safety precaution, the mouth piece system was attached to a bicycle helmet which the child wore while walking on the treadmill (total mass of the helmet and mouth piece system=382.5 g). Children also wore a hair net to allow for easy application and removal of the helmet.

Visit III At the beginning of Visit III, we administered questionnaires updating physical activity and health status since the previous visit. As with Visit II, we also administered a questionnaire regarding the general content and time of the last meal. Body mass was again measured, the HR monitor affixed and shoes or shoes and AFO were then put on. The order of administration of the braces condition (AFO on, AFO off) was randomised to control for order effects.

Our goal was to have children perform three, 2-min walks on the treadmill with and without AFO, for a total of six walks, at the following speeds: 1) comfortable ground walking speed (CWS), 2) 3 kph, and 3) fast walking speed (FWS), which was 90% of the fastest treadmill walking speed. The CWS and FWS values were those determined from Visit II data. When there was a difference between CWS or FWS with AFO on compared to AFO off, the lower of the two speeds was chosen for the Visit III treadmill trials.

It was also our goal to have the order of brace and speed conditions randomised to control for order effects. As with the over ground walking trials, to decrease the amount of time spent changing the brace condition, we had children perform all three trials under the first brace condition before it was changed. Between each of the first three trials, subjects rested in standing until HR was within 10 % of resting HR or 1 minute had passed without a further decrease in HR. While the brace condition was changed, they rested off their feet, in prone, lying over a padded table, for at least 10 minutes. Our choice of criteria for speed selection, however, did not result in three *different* speeds for all children and hence we could not follow our randomisation scheme completely. For three children, CWS and FWS were the same speed. Two of these subjects still did six bouts of walking. A third child only did 2 trials at each brace condition due to equipment limitations. A fourth child, for whom 3 kph=FWS, also only completed 2 trials with AFO on and off. Our experience with him during Visit II showed that he fatigued rather easily and we were concerned that he would not complete a total of six trials. In addition, as his fastest walking speed on the treadmill was also his CWS on the ground, we lowered the CWS on the treadmill to 2.4 kph as he subjectively appeared most comfortable walking at that speed on the treadmill. With a fifth child we collected data at only two speeds conditions (CWS and FWS) as he refused to walk for more trials. Table 3 details the conditions and the intended and actual treadmill speeds for each subject. Blank spaces indicate trials not completed.

Prior to the child mounting the treadmill belt for each trial, the speed was selected using the dial as a guide. We calibrated the actual speed of the treadmill belt during each trial as in Visit II. The child was connected to the metabolic cart as in visit II. By monitoring the real time display

of metabolic data, we were able to check that the Vmax system was also functioning properly. If the Vmax system had difficulty registering breaths, children were again instructed to perform a couple of forced expiration manoeuvres they did prior to collection of resting $\dot{V}O_2$. The treadmill belt was then started at the appropriate speed and the child began walking. The clock was started once it was obvious the child would be able to walk unsupported. Heart rate, $\dot{V}O_2$, carbon dioxide output and $\dot{V}E$ were collected and recorded. Calibration procedures for gas flow and for the gas analysers were performed as in visit II, before the first trial under each condition and at the end of the testing. The mass flow sensor and the gas analysers remained stable, within the limits deemed acceptable by the manufacturer. Prior to the second calibration, the gas tubes were changed.

Calculations and Data Reduction

The GMFM Standing and Walking, Running and Jumping dimensions were scored as described in the test manual (Russell et al., 1993). The test administrator uses a four point scale to rate the child's ability to perform specific gross motor tasks such as "Standing: maintains, arms free, for 20 seconds". (Russell et al., 1993). In general, a rating of "0" corresponds to a failure to initiate any part of the task. Usually this means the child was unable to independently maintain the start position (e.g., standing in the example given above). A rating of "1" corresponds to initiation of the task, but failure to complete at least 10% of the task. A rating of "2" means the child completed 10% to less than 100% of the task. A rating of "3" means the child completed 100% of the task. The GMFM manual contains detailed instructions on what is acceptable motor behaviour at each rating, for each item. The test administrator consults these guidelines immediately after the child attempts to perform each item to ensure rating is correct. Scoring for each dimension is reported as percentage scores; i.e., the total points the child received for each dimension divided by the total possible points for that dimension, multiplied by 100. The Standing dimension contains 13 tasks or items with the highest possible score being 39. The Walking Running and Jumping dimension contains 24 items for a possible highest score of 72. The total

score for this subset of the GMFM is reported as the average of these dimension percent scores.

The O_2 requirement ($L \cdot \text{min}^{-1}$) for walking at each speed under each brace condition ($\dot{V}O_{2\text{abs}}$) was determined by averaging $\dot{V}O_2$ over one minute of steady state exercise. Steady state was defined as a plateau in $\dot{V}O_2$, as seen by examining the trend in graphs of 10 s averages of $\dot{V}O_2$ from each walking trial. This was performed by the author for all trials. In all but one trial, the plateau was evident before the beginning of the final 60 seconds. To be as consistent as possible we averaged the final 60s of exercise $\dot{V}O_2$ data to arrive at the O_2 requirement value in all trials but the one exceptional trial. For this trial we derived the O_2 requirement in $\text{litres} \cdot \text{min}^{-1}$ by averaging over the entire 120 s. The carbon dioxide output ($L \cdot \text{min}^{-1}$), HR (bpm), and $\dot{V}E$ ($L \cdot \text{min}^{-1}$) values for each trial were determined by averaging these data over the this same one minute period of steady state exercise. The RER values were calculated as the ratio of steady state carbon dioxide output to steady state $\dot{V}O_2$. The $\dot{V}E/\dot{V}O_2$ data were calculated as a ratio of $\dot{V}E$ to $\dot{V}O_2$.

We also wished to investigate any differences in $\dot{V}O_2$ that might have been related to the differing masses of children when they wore and did not wear their braces. It was possible that the absolute cost of oxygen might have been increased with the AFO on because of the increased mass of the lower limbs with the braces on. It might have cost more energy to swing a leg that was heavier. To determine if the effect of AFO was affected by total body mass, we calculated a mass adjusted $\dot{V}O_2$, $\dot{V}O_{2\text{mass}}$. This was done by dividing $\dot{V}O_{2\text{abs}}$ by body mass in kg (including helmet and mouth piece, shoes, socks, and when appropriate, AFO), and expressing this value in $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$.

Resting values for these same metabolic and cardiopulmonary variables were determined in much the same way as for exercise, except the time frame chosen for data averaging was the lowest one minute of resting $\dot{V}O_2$ data as visually determined by examining the trend in resting trial graphs of 10 s averages of $\dot{V}O_2$ data. To determine if differing resting $\dot{V}O_2$ would obscure the effect of AFO, we calculated $\dot{V}O_{2\text{net}}$ by subtracting resting $\dot{V}O_2$ from $\dot{V}O_{2\text{abs}}$. This value was expressed in $L \cdot \text{min}^{-1}$.

We calculated two indices of walking economy, an absolute measure $\dot{V}O_{2mw}$, expressed in $L \cdot m^{-1}$ and a mass adjusted value, $\dot{V}O_{2mmw}$, expressed in $ml \cdot kg^{-1} \cdot m^{-1}$. The former index was calculated by dividing $\dot{V}O_{2abs}$ by the walking speed in $m \cdot min^{-1}$. The latter was calculated in the same way using $\dot{V}O_{2mass}$ instead of $\dot{V}O_{2abs}$.

We calculated EE by converting to kJ, the total O_2 expended in litres from the 1 minute steady state or rest analysis period, using the following equation:

$$EE = \text{total } \dot{V}O_2, L \text{ during analysis period} \times (3.815 + 1.232 \cdot \text{RER averaged over analysis period}) \times 4.184 \quad ** \quad (1)$$

* Regression equation created from the data of Lusk (1928)

** Conversion factor for determining energy in kJ from energy measured in kcal (Robergs and Roberts, 1997)

Net EE (EE_{net}) for each treadmill walking trial was calculated by subtracting resting EE from gross (exercise) EE (EE_{gross})

Some minor conversions were also needed to adjust for differences in belt speed between the same speed condition over the two braces conditions. While we made every attempt (looking straight on at the dial to avoid parallax, using two researchers to confirm the dial reading) to ensure belt speeds were the same for the AFO on and AFO off conditions, this was not always the case. To account for differences in speed, we adjusted the metabolic and cardiopulmonary data to represent the intended speed through interpolation or extraction methods. Table 3 shows the intended and actual speeds. The limitations to this method are outlined in the Discussion section.

Statistical Analysis

Repeated measures analyses of variance (ANOVA), and in certain instances t-tests, were used to detect significant differences between brace conditions for ground walking speed, gross motor function (GMFM dimension scores), cardiopulmonary (HR, VE), metabolic ($\dot{V}O_{2abs}$, $VE/\dot{V}O_2$, $\dot{V}O_{2mass}$, $\dot{V}O_{2net}$, $\dot{V}O_{2mw}$, $\dot{V}O_{2mmw}$, RER) and EE (EE_{gross} , EE_{net}) variables. Probability of making a Type I error was set at $p < .05$. We also calculated the Pearson product moment (r) for individual

AFO-on-off pairs of trials to get an indirect indication of reliability of our measure. Due to unequal numbers in each belt speed by condition group, we were unable to analyse all subjects at once for cardiopulmonary, metabolic and EE variables. Had we done analyses using groups of unequal size, we would have risked violating the homogeneity of variance assumption of ANOVA and could not have been assured that our ratios of mean squares would have been distributed as the F distribution. In other words, we risked a greater than .05 probability of making a Type I error (Gravetter and Wallnau, 1992a). For cardiopulmonary, metabolic and EE variables, we therefore did multiple ANOVA, each using a slightly different subgroup of our sample. Thus we used repeated measures ANOVA to compare the effect of braces on cardiopulmonary, metabolic and EE variables at all three speeds (n=5 for HR, n=4 for the other variables in question); at 3 kph and CWS, (n=8, n=9); and at 3 kph and FWS (n=7, n=7). We also performed t-tests at FWS (n=9, n=8). While it is acknowledged that multiple statistical tests also increase the probability of finding differences just by chance (Type I error), these tests were not done on exactly the same children each time and thus each test provided us with slightly different information about the effect of the braces on the variable in question. The ANOVA and t-test calculations were performed using a statistical analysis software program (STATISTICA for Windows, Version 5.1, StatSoft, Inc., Tulsa OK). To determine differences between any two groups, we used a post hoc test, Tukey's Honestly Significant Difference. To calculate the size of effects of interest (main effect for brace) that approached conventional levels of significance, Omega squared was calculated. These last two calculations were done with a pocket calculator (fx-7000GA, Casio Computer Limited, Japan). Correlations were calculated using a graphing analysis program (SigmaPlot, Version 2.01, Jandel Corporation).

RESULTS

Tables 4-16 summarise the mean and SEM data for each sub-sample, for each variable measured or calculated. The F or t statistic and the probability of significance are provided for each main effect (AFO, belt speed and the interaction of AFO and belt speed) tested. Omega squared (effect size) is also shown on the tables when the main effect for AFO or the interaction between AFO and speed approached conventional levels of significance. The effect of speed on cardiopulmonary, metabolic and EE variables was not the purpose of the study and will not be discussed in the following description of the results. The reader is referred to the tables for this information.

Ground Walking Speed

While there was a significant difference ($p=.00002$) in children's comfortable and maximum walking speeds regardless of whether they were wearing AFO or not; the AFO did not have an effect at either speed for the children as a group (Table 4; Figure 1). When individual data were graphed (Figure 2), there was a moderate to high correlation between walking speed with braces on and off. Three outliers were identified on this graph (Subjects 8, 9, 12). Subject 8 showed an 11.9% decrease in maximum walking speed with AFO on compared to AFO off. In terms of gross motor skill, this child was among the most advanced. He received the second highest GMFM score (averaging across the two dimensions) with AFO off and AFO on and was the fastest walker with AFO off. Subject 9 showed a 37.1 % increase in CWS with braces on compared to off and had the slowest CWS regardless of brace condition. While he scored higher in the GMFM (averaged as noted above) with braces off, in both cases his scores were below the mean. Subject 12, who had a 21.2% increase in CWS with AFO on, also had the second slowest walking speed with AFO off or on and was also the only child classified as a level II on the Gross Motor Function Classification Scale.

Gross Motor Function (GMFM)

Children received significantly higher ($p=.05$) scores for the Standing dimension than for the Walking Running and Jumping dimension, regardless of AFO use (Table 5; Figure 3). Subject 12, previously described as more physically involved than the other children, scored the lowest in the Walking, Running and Jumping dimension with AFO on or off (Figure 4). Wearing AFO resulted in a 7.0% increase in his Walking Running and Jumping score. The individual data for the Standing dimension (Figure 4) showed a somewhat weak correlation between the AFO on and off tests, while the correlation between AFO on and off trials for the Walking Running and Jumping dimension was strong.

Cardiopulmonary Variables

Heart Rate

The AFO did not have an effect on HR, nor did braces affect HR differently at any speed (Table 6, Figure 5). Heart rate with braces off was strongly correlated to HR with braces on at all speeds (Figure 6).

Pulmonary ventilation

For subjects who walked at 3 kph and CWS, $\dot{V}E$ was significantly lower ($p<.05$) with braces on, but at the 3 kph speed only (Table 7, Figure 7). Pulmonary ventilation was not affected by AFO when children walked at FWS (Table 7, Figure 7) or for any sub-sample (Table 7). There was a high correlation between the AFO on and off trials at all speeds (Figure 8). Subject 1 appears to have responded somewhat differently to the brace than other children. She showed a 35.7% increase in $\dot{V}E$ with braces on compared to braces off.

Metabolic Variables

Absolute Oxygen Uptake

When children walked at 3 kph and CWS (Table 8), the effect of AFO was different at the two different speeds ($p=.04$). Post hoc analysis showed $\dot{V}O_{2abs}$ to be lower with AFO on at 3 kph ($p<.05$); there was no difference at CWS (Figure 9). When subjects walked at FWS, $\dot{V}O_{2abs}$ was also lower ($p=.007$) with AFO on (Table 8, Figure 9). In the 3 kph-FWS sub-sample, a trend ($p=.08$, omega-squared=.30) for both speeds to show a lower $\dot{V}O_{2abs}$ with braces on (Table 8) was found. No differences due to AFO or AFO and speed were found in the smallest, ($n=4$) 3 speed sub-sample. There was a high correlation between the AFO on- and AFO off-trials at all speeds (Figure 10). Although Subject 7 walked at the same speed for the CWS and FWS conditions; nevertheless at CWS, she had a 6.7% increase in $\dot{V}O_{2abs}$ and at FWS she showed a 1.7 % decrease in $\dot{V}O_{2abs}$. Subject 1 showed a 24.7% increase in $\dot{V}O_{2abs}$ with braces on.

Ventilatory Equivalent for Oxygen

The $\dot{V}E/\dot{V}O_2$ was not affected by AFO (Table 9, Figure 11). An examination of individual data (Figure 12) showed a high correlation between AFO off- and on-trials at all speeds, although the correlation was slightly lower at 3 kph. For individual pairs of trials (AFO on and off at the same speed), data from most children, with the exception of subjects 7 and 15, are clustered around 40, with little variation. Subject 15 demonstrated a 34.6% increase in $\dot{V}E/\dot{V}O_2$ with AFO on.

Mass Adjusted Oxygen Uptake

Subjects walking at FWS demonstrated a significant reduction in $\dot{V}O_{2mass}$ when they wore their AFO ($p=002$). Children in the 3 kph-FWS sub-sample also showed a significantly lower ($p=.03$) $\dot{V}O_{2mass}$, with AFO on, regardless of speed (Table 10). When study participants walked at 3 kph and CWS, we found a trend ($p=.07$, omega-squared=.25) for the effect on $\dot{V}O_{2mass}$ of braces

at 3 kph to be different than at CWS. The AFO did not have any effect on $\dot{V}O_{2mass}$ for the small 3 speed sub-sample. Individual AFO on-off data (Figure 13) were highly correlated at all speeds. As expected, since total body mass was greater with AFO on, more individual points fell below the line of identity. The pattern was otherwise similar to that seen for $\dot{V}O_{2abs}$ (Figure 10). Subject 1 showed a response different from other children with a 22.5% increase in $\dot{V}O_{2mass}$ with AFO on. Since $\dot{V}O_{2mass}$ values were derived from $\dot{V}O_{2abs}$ and adjusted for body mass which was always greater with AFO on, the group analysis (ANOVA) could have been somewhat misleading or biased toward a lower $\dot{V}O_{2mass}$ with braces on, which may not have accurately reflected the influence of the AFO. A bar graph is therefore not shown for this variable.

Net Oxygen Uptake

When young people walked at 3 kph and CWS, the effect of AFO was different at the two different speeds ($p=.04$). Post hoc analysis showed $\dot{V}O_{2net}$ to be lower with AFO on, but only at 3 kph. When subjects walked at FWS, $\dot{V}O_{2net}$ was also lower with the braces on (Table 11, $p=.005$, Figure 14). In the 3 kph-FWS sub-sample we found a trend ($p=.08$, $\omega^2=.30$) for both speeds to show a lower $\dot{V}O_{2net}$ with braces on (Table 11). No differences due to AFO or AFO and speed were found in the smallest, ($n=4$) 3 speed sub-sample. Individual data for each speed were highly correlated (Figure 15). There was no marked change in the pattern for $\dot{V}O_{2net}$ compared to $\dot{V}O_{2abs}$. Subject 7 showed both a 7.7% increase (CWS) and a 1.3% decrease (FWS) in $\dot{V}O_{2net}$ with AFO on compared to AFO off at the same speed (Figure 15). Subject 1 showed a 31.1% increase in $\dot{V}O_{2net}$ with braces on compared to braces off.

Absolute Oxygen Uptake per metre walked

For subjects who walked at 3 kph and CWS, the effect of AFO was different at the two different speeds (Table 12, $p=.02$). Post hoc analysis showed $\dot{V}O_{2mw}$ to be lower with AFO on at 3 kph ($p<.05$); there was no difference at CWS (Figure 16). When children walked at FWS, $\dot{V}O_{2mw}$ was also lower ($p=.009$) with braces on (Table 12, Figure 16). In the 3 kph-FWS sub-

sample, we noted a trend ($p=.1$, ω -squared=.25) towards both speeds showing a lower $\dot{V}O_{2mw}$ with braces on (Table 12). No differences due to AFO or AFO and speed were found in the smallest, ($n=4$) 3 speed sub-sample (Table 12). The AFO on and AFO off trials were highly correlated at all speeds (Figure 17). Subject 7 showed at 3.8% increase (3 kph), a 6.7% increase (CWS) and a 1.1% decrease (FWS) in $\dot{V}O_{2mw}$ with AFO on. Subject 12 showed decreases of 4.3% (3 kph=FWS) and 5.9%. (CWS) with AFO on. The possible different explanations for findings in these two children will be addressed in the Discussion section.

Mass Adjusted Oxygen Uptake per Metre Walked

When subjects walked at 3 kph and CWS, the effect was different at the two different speeds (Table 13, $p=.04$). Post hoc analysis showed $\dot{V}O_{2mmw}$ to be lower with AFO on at 3 kph ($p<.05$); there was no difference at CWS. Children in the 3 kph-FWS sub-sample also showed a lower $\dot{V}O_{2mass}$ due to the brace (Table 13, $p=.003$). The AFO did not have any effect on $\dot{V}O_{2mmw}$ for the small 3 speed sub-sample (Table 13). For individual data (Figure 18), the correlations at all speeds were again high. As expected, since total body mass was greater with AFO on, more individual points fell below the line of identity. The two children (Subjects 2 and 12) with the highest $\dot{V}O_{2mass}$ both demonstrated a reduction in this index with braces on. Subject 1 by contrast demonstrated a 22.5% increase in $\dot{V}O_{2mass}$ with AFO on at CWS (Figure 18).

Respiratory Exchange Ratio

The AFO did not affect RER at any speed (Table 14, Figure 19), although there was a trend ($p=.07$) for RER to be higher with AFO on at FWS. While there was a high correlation for individual data at FWS and at CWS, the correlation was much lower at 3 kph (Figure 20).

Energy Expenditure

Gross Energy Expenditure

When children walked at 3 kph and CWS, braces affected EE_{gross} differently at the different speeds (Table 15, $p=.05$). Post hoc analysis determined that EE_{gross} was lower with braces on, but only at 3 kph (Figure 21, $p<.05$). Gross EE was also lower ($p=.01$) with braces on at FWS (Table 15, Figure 21, $p=.01$). For the 3 kph-FWS sub-sample there was a trend ($p=.19$, $\omega^2=.13$) for AFO on to result in lower EE_{gross} . No effect of AFO was found in the smallest (3 speed) sub-sample. For the individual data, AFO off- and AFO on-trials were highly correlated (Figure 22). Subject 7 showed an increase of 4.8% (CWS) and a decrease of .68% (FWS) for the same actual speed (Figure 22). Subject 1 showed an increase of 27.2% with braces on at CWS (Figure 22).

Net Energy Expenditure

When subjects walked at 3 kph and CWS, braces affected EE_{net} differently at the different speeds (Table 16, $p=.006$). Post hoc analysis determined that EE_{net} was lower with braces on, but only at 3 kph (Figure 23, $p<.05$). Net EE was also lower ($p=.03$) with braces on at FWS (Table 16, Figure 23). For the 3 kph-FWS sub-sample, there was a trend ($p=.14$, $\omega^2=.20$) for AFO on to result in lower EE_{gross} . No effect of AFO was found in the smallest (3 speed) sub-sample. For the individual data, AFO off- and AFO on-trials were highly correlated (Figure 24). Subject 7 showed an 8.4% increase in EE_{net} with AFO on at CWS. Subject 1 showed a 35.1% increase in EE_{net} with AFO on at CWS (Figure 24).

Summary of Results

The following summary of results (Table 17) pertains to all children for the ground walking speed and GMFM variables. For the cardiopulmonary, metabolic and EE variables, the summary pertains only to children who walked at 3 kph and CWS and those who walked at FWS.

Gross motor abilities, whether measured by comfortable and maximum ground walking speed, or by the Standing and the Walking, Running and Jumping dimensions of the GMFM, were increased with AFO on. Increases however, were not significant.

The cardiopulmonary variables, HR and $\dot{V}E$, were usually less with AFO off regardless of belt speed, but differences were never significant. Two exceptions to this generalisation were found. Heart rate was less with AFO on at FWS and $\dot{V}E$ was less with AFO on at 3 kph. Only the latter was significant, however.

The $\dot{V}E/\dot{V}O_2$ and RER were less with AFO off at all speeds, although these differences were not significant.

The metabolic variables, $\dot{V}O_{2abs}$, $\dot{V}O_{2net}$, $\dot{V}O_{2mw}$ and $\dot{V}O_{2mmw}$, and the EE variables, EE_{gross} and EE_{net} , were significantly less with AFO on at 3 kph and FWS. Mass adjusted $\dot{V}O_2$ was also less with AFO on 3 kph and FWS, but differences were significant only at FWS. For children who walked at 3 kph and CWS, a trend ($p<.07$) was found, with 25% of the variability in $\dot{V}O_{2mass}$ explained by the interaction between AFO and speed ($\omega\text{-squared}=.25$). In other words, there was a trend for AFO to reduce $\dot{V}O_{2mass}$ at 3 kph.

DISCUSSION

Unless otherwise mentioned, the following discussion of results for cardiopulmonary, metabolic and energy expenditure variables pertains to children who walked at 3 kph and CWS (n=9) and those who walked at FWS (n=8) as these are the largest data sets available. The discussion of ground walking speed and GMFM data pertains to all children (n=10).

Ground Walking Speed

Children, as a group, were able to differentiate between comfortable and maximum walking speeds, although AFO did not have an effect on either of these speeds (Figure 1). The failure of AFO to influence comfortable ground walking speed in children with spastic diplegia has been previously reported (Mossberg et al., 1990; Ounpuu et al., 1996; Radtka et al., 1997), but in these studies the braces were not hinged. Lough (1990) also found hinged AFO did not affect comfortable walking speed, but in her study some children also used hand-held assistive devices. This is the first study, to our knowledge, to report this finding in children who walked *only* with hinged AFO. The relatively high correlations between AFO off and on at both speeds (Figure 2) gives us an indirect indication that our protocol for determining comfortable and maximum walking speed was reliable.

Although subjects did not walk faster with AFO on, examination of Figure 2 shows two outliers (Subject 9 and 12) who did in fact walk markedly faster at their comfortable speed when they wore their braces. These two children had the slowest comfortable speed and the lowest scores for the GMFM Walking, Running and Jumping dimension, regardless of the brace condition. Conversely, Subject 8, a third outlier, who walked markedly faster without his braces, was both the fastest walker and had the second highest Walking, Running and Jumping dimension score, with AFO on and off. The freely chosen gait velocity of children with spastic CP is known to correlate with GMFM scores (Damiano and Abel, 1996; Drouin et al., 1996), especially

with scores for the Walking, Running and Jumping dimension (Drouin et al., 1996). The above mentioned three outliers seem to follow this pattern. Thus, it may be possible that wearing AFO would be more likely to increase ground walking speed, especially comfortable walking speed, in children more physically disabled (as measured by the Standing, and Walking, Running and Jumping dimensions of the GMFM) than the subjects in this study.

The comfortable speeds of children in this study are comparable to the freely chosen ground walking speeds (3.42 kph-4.3 kph) reported in the literature (Drouin et al., 1996; Hoofwijk et al., 1995; Radtka et al., 1997) for similar-aged children with spastic diplegia who walk without hand-held assistive devices such as canes, crutches or walkers. Studies involving these types children but which also included much younger children who walked with or without hand-held assistive devices (Campbell and Ball, 1978; Lough, 1990; Mossberg et al., 1990; Norlin and Odenrick, 1986; Rose et al., 1990) report similar and lower comfortable speeds (2.25 kph-3.6 kph). On average, healthy children, by comparison, have a faster comfortable speed of 4.2 kph (Waters et al., 1983). Few large studies have reported on maximum walking speed of children with spastic CP. An estimation from graphic data (Norlin and Odenrick, 1986) of a sample of 50 children with spastic CP who walk without hand-held aids gives a maximum speed of 4.5 kph for the 9 year old child. Our higher maximum speed may reflect errors in estimation from the graph or an overall lesser degree of physical disability in our sample. Healthy children are able to reach a higher maximum walking speed. Using a regression equation developed by Norlin and colleagues (1981) from data on 230 healthy children, we estimate that a 9 year old healthy child has maximum walking speed of 6.7 kph.

Gross Motor Function (GMFM)

Gross motor function in standing and walking as measured by the GMFM was not affected by AFO. The AFO off-on tests were highly correlated for the Walking, Running and Jumping dimension, but much less so for the Standing dimension (Figure 4). This difference in correlation may reflect a real difference in the individual variability of the effect of braces on

standing compared to walking running and jumping, or it may reflect a lack of consistency in scores from one trial to the next.

Subject 12 (Figure 4), while not a true outlier with respect to the effect of AFO on GMFM scores, was highlighted to show his low score for the Walking, Running and Jumping dimension. The implications of this were discussed above with respect to the effect of AFO on walking speed.

Our findings agree with Russell et al. (1995) who found no change in GMFM scores due to AFO (type not specified), in a smaller (n=6), but similar group of children. Our GMFM scores were similar to those reported in the literature (86.9%, 88% for the Standing dimension; 79.7%, 80% for the Walking, Running and Jumping dimension) for this population (Damiano and Abel, 1996; Drouin et al., 1996). Healthy children would score 100 % at both dimensions (Russell et al., 1993).

Cardiopulmonary Variables

Heart Rate

Any improvements in walking economy or energy expenditure due to AFO, as reflected by a lower $\dot{V}O_{2abs}$ and related variables (see results, above), were not seen with HR which was unaffected by AFO (Table 6, Figure 5). Heart rate may be a less sensitive indication of the influence of braces on biochemical energy demands of walking since HR can be affected by several factors besides physical exertion (temperature, humidity, arousal or stress level) (Wilmore and Costill, 1994). These factors could obscure the AFO-related changes in biochemical energy demands such as those we found with $\dot{V}O_{2abs}$ and related variables. In fact, the same pattern of less change in HR between conditions can be seen when one compares the HR at 3 kph and CWS. While most metabolic variables showed a significant increase ($p < .05$) at CWS compared to 3 kph, independent of AFO, this increase was only a trend ($p = .20$) for HR. Although HR was not responsive to AFO, the measure itself was likely reliable as indirectly shown by the high correlation between AFO off and on at each speed (Figure 6).

Children with CP as a group may be more sensitive than able-bodied children to the above mentioned emotional or environmental influences on HR. A recent study on a similar population and using a similar treadmill protocol, also failed to demonstrate a difference in HR between 3 kph and FWS (Unnithan et al., 1996a). Furthermore, in a study looking at the effect of AFO on energy cost of gait in spastic diplegic children, Mossberg and colleagues (1990) did not detect a difference in HR due to AFO, although they did note a reduction in the cardiovascular cost of walking with AFO on as determined by the difference between walking and resting HR divided by walking velocity.

Our group mean HR of 148 bpm for CWS on the treadmill is similar to previous findings in similar groups of children with CP for their comfortable speed on the ground (Mossberg et al., 1990) and for 3 kph on the treadmill (Unnithan et al., 1996a). Others (Campbell and Ball, 1978) have reported a slightly lower value of 138 bpm for HR at comfortable ground walking speed. Although differences between these values and ours could be due the greater physical effort and emotional stress of walking on the treadmill compared to on the ground, or the fact that these children walked slower than our subjects; the subjects in the Mossberg et al. (1990) study also walked slower than our subjects and walked on the ground, but as noted above, their average HR was similar to our value. It is difficult to explain exactly why HR values differ among studies given the myriad of possible interactions between different environmental factors, anxiety levels and level of physical disability of subjects. Likewise, it is difficult to explain differences between our average value at FWS (Table 6) and those of Unnithan et al. (1996a), whose average values were 143 bpm and 142 bpm at 3 kph and FWS, respectively. Compared to our subjects, healthy children have a lower HR while walking at a comfortable speed on the ground (114 bpm) (Waters et al., 1983) and on the treadmill at 3 kph (91 bpm) and FWS (127 bpm) (Unnithan et al., 1996a)

There are other data (Dahlbäck and Norlin, 1985; Rose et al., 1985; 1989;1990) on cardiopulmonary and metabolic responses to treadmill walking in this population; however, in these studies children were allowed to hold on to the treadmill railing and the amount and time they held on was neither controlled nor reported. Since holding on to the railing reduces the

energy cost of treadmill walking (Green and Foster, 1991), these data are not comparable to our own and will not be discussed here or in the discussion of metabolic variables.

Pulmonary Ventilation

Pulmonary ventilation was reduced with braces on but, unlike $\dot{V}O_{2abs}$ (see Results, above), only at 3 kph (Table 7, Figure 7) and not also at FWS. One would expect that $\dot{V}E$ would show a response similar to $\dot{V}O_{2abs}$. During progressive, submaximal exercise (usually under 60% of maximum $\dot{V}O_2$), $\dot{V}E$ increases linearly with $\dot{V}O_2$, at least in the healthy population (Bar-Or, 1983c). A comparison of $\dot{V}E$ data from the two extremes in speed (3 kph-FWS sub-sample, $n=7$), showed that subjects did have a significant increase in $\dot{V}E$ at FWS compared to 3 kph (Table 7, $p=.0008$). Thus, like $\dot{V}O_{2abs}$ (Table 8), $\dot{V}E$ also rose with an increase in speed which may be loosely interpreted as an increase in exercise intensity. For this group of children, the linear relationship between $\dot{V}O_{2abs}$ and $\dot{V}E$ may have broken down at the higher exercise intensity of FWS, which may be, at least for some of the children, above 60% of their $\dot{V}O_{2max}$. Since we did not do maximum exercise tests with these children, this is but speculation. Given however, the magnitude of differences in $\dot{V}O_{2abs}$, between the braces on and off conditions (Table 8, Figure 9), even small changes in the relationship between $\dot{V}E$ and $\dot{V}O_{2abs}$ could have influenced our findings of $\dot{V}E$ at FWS for AFO on and off.

A high correlation between AFO off- and on-conditions (Figure 8) suggests that we had good reliability between the AFO off and on tests.

Subject 1 appears to be an outlier in terms of her $\dot{V}E$ response to AFO (Figure 8). She showed a 35.7% increase in $\dot{V}E$ with braces on. A re-examination of her AFO on trial at CWS showed that she had difficulty maintaining steady state during that trial. She achieved steady state by 60 s into the trial, but at 80 s she showed a rapid increase in $\dot{V}O_2$ (and $\dot{V}E$) which then decreased back to the steady state value over the following 20 s. This increase in $\dot{V}E$ and $\dot{V}O_2$ was not reflected by an increase in HR. In retrospect, this trial may have been abnormal and perhaps should not have been included in data analysis. On the other hand, children with CP may

not always reach a perfect steady state and slight fluctuations in metabolic and cardiopulmonary variables may better reflect what is actually occurring during gait. In her other walking trials this child also showed an increase in $\dot{V}E$ with braces on but to a much lesser degree (average 8%).

Pulmonary ventilation is the product of tidal volume and breathing frequency. Although during treadmill walking at the same absolute speed, there is a curvilinear increase in tidal volume with age, breathing frequency decreases linearly (Rowland and Cunningham, 1997). The increase in ventilation with age is therefore less than what would be expected by the change in mass alone (Rowland and Cunningham, 1997). Rowland and Cunningham also showed that for sub-maximal treadmill walking, pulmonary ventilation per kg body mass also decreases as children age. In this study, the authors report a 19.7% decrease in $\dot{V}E$ between the ages of 9 and 12 in a group of healthy children who walked on the treadmill at 5.2 kph, at an 8% grade. By using between-subject mean body mass and absolute mean $\dot{V}E$, we compared $\dot{V}E$ per kg body mass between the subjects in this AFO study and those in the study by Unnithan et al (1996a). At the same absolute speed of 3 kph, $\dot{V}E$ was $.66 \text{ L}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ for our subjects and $.56 \text{ L}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ for those of Unnithan and co-workers. For children with CP, an increase in three years of age resulted in a 15% decrease in $\dot{V}E$, a similar pattern to that seen with healthy children. It remains to be shown whether the tidal volume increases with age are limited in children with CP due to spasticity of respiratory muscles. Such a factor could limit the magnitude of the decrease in $\dot{V}E$ with age.

No data have been reported for the changes in $\dot{V}E$ with age in healthy children walking at the same exercise intensity on the treadmill. In the case of our data and that of Unnithan and his colleagues, when walking at FWS, our younger children again showed the higher $\dot{V}E$. In this case $\dot{V}E$ was $99 \text{ L}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ for our subjects and $.65 \text{ L}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ for those in the Unnithan et al study, a difference of 34%. The larger difference here may reflect differences in the actual exercise intensity, even though in both studies children were walking at 90% of their maximum treadmill walking speed.

Metabolic Variables

Absolute Oxygen Uptake

The total O₂ cost as measured by $\dot{V}O_{2abs}$, was lower with AFO on by 4.6% and 4.1%, at 3 kph and FWS, respectively. There was no difference at CWS, although children varied greatly in their response to AFO at this speed (Figure 10).

There was a wide range of individual trial differences due to AFO at any given speed (Figure 10). Differences ranged from a decrease of 31.4% for Subject 15 at 3 kph to an increase of 24.7 % for Subject 1 at CWS. In addition, it was not surprising that we found only a trend (Table 8, $p=.08$) for a difference in $\dot{V}O_{2abs}$ between 3 kph and CWS, given that for some of our subjects CWS was slower than 3 kph (Table 3) and therefore the actual O₂ cost of walking was greater at 3 kph for these subjects. In the 3 kph-FWS sub-sample (Table 8, $n=7$), where FWS was always faster than 3 kph, subjects responded to the increase in speed with an increase in $\dot{V}O_{2abs}$. Thus this measure was sensitive to changes in actual walking speed in children with CP.

When individual AFO off-on pairs were examined, two outliers appear (Figure 10), both of whom had marked increases in the total O₂ cost of walking with AFO on. Subject 1 at CWS has already been discussed. Subject 7 showed a 6.7% increase in $\dot{V}O_{2abs}$, at CWS and a decrease of 1.1% at FWS, which was the same absolute speed. The effect of further accommodation to treadmill walking (a more stable and perhaps more economical gait pattern) can not be ruled out as a cause for this lack of reliability, as both the FWS trials (AFO on and off) occurred after the two CWS trials in the actual trial order for this child. The responses of Subject 7 certainly highlight the need to better understand the reproducibility of $\dot{V}O_2$ measures during walking in C; which to the best our knowledge has not been explored. In this study we have only one other child, Subject 11, who did two sets AFO off-on trials, CWS and FWS, at exactly the same belt speed. While not highlighted on Figure 10, his pattern of response was more consistent. At CWS, his wearing AFO resulted in a 13.8% decrease in $\dot{V}O_{2abs}$, at FWS this difference was a similar 12.6%

decrease. Reproducibility data from some studies with healthy children (Frost et al., 1995; Unnithan et al., 1995) have shown group stability but marked individual differences in $\dot{V}O_2$ during between-day submaximal treadmill exercise sessions, while others (Rogers et al., 1994) have found significant differences in between-day $\dot{V}O_2$. For healthy children as a group, there appears to be no between-trials differences in $\dot{V}O_2$ (Frost et al., 1995). The discrepancy in the results of these studies may reflect the variation in testing protocol and subjects. Reproducibility of $\dot{V}O_2$ during sub-maximal testing in healthy children and for those with CP, remains unclear.

Ventilatory Equivalent for Oxygen

The $\dot{V}E/\dot{V}O_2$ is a ratio of the litres of air ventilating the lungs per litre of $\dot{V}O_2$. It is therefore a measure of the efficiency of ventilation (Bar-Or, 1983e). The $\dot{V}E/\dot{V}O_2$ was not affected by brace at any speed. Thus, the linear relationship between $\dot{V}E$ and $\dot{V}O_2$ for these children was such that it rendered the measure rather insensitive to changes in exercise intensity. This lack of sensitivity may be due to combined errors in the measurement of $\dot{V}E$ and $\dot{V}O_2$ or this may be a biological phenomenon. The measure however appears reliable in that we did see fairly high AFO off-on correlations at all speeds.

Our $\dot{V}E/\dot{V}O_2$ values were higher than the CP children and the healthy children at both 3 kph and FWS in the Unnithan study (1996a). These authors found no difference in $\dot{V}E/\dot{V}O_2$ between healthy children and those with CP. Our $\dot{V}E/\dot{V}O_2$ values at all speeds, on the other hand, are similar to those for 8 year old children at maximal exercise (Andersen et al., 1974). Lundberg (1984) noted an increase in $\dot{V}E/\dot{V}O_2$ in older children and adolescents with CP compared to healthy controls. She attributed this ventilatory inefficacy to a greater degree of metabolic acidosis during exercise secondary to poorly functioning breathing, possibly due to respiratory muscle spasticity or chest wall distortion. Our results would seem to support ventilatory inefficiency in CP. It is possible that ventilatory inefficiency in CP is more marked in studies such as ours, with younger children, or in studies with more physically involved children (Lundberg, 1984). The $\dot{V}E/\dot{V}O_2$ does decrease with age during childhood (Andersen et al., 1974) in healthy

children. Figure 12 shows that Subject 7, our oldest subject had a markedly lower $\dot{V}E/\dot{V}O_2$ for all trials compared to the other children. Longitudinal data on $\dot{V}E/\dot{V}O_2$ in CP for varying levels of severity are needed before any definitive statements can be made about whether the O_2 cost of breathing is greater in CP than in healthy children.

Subject 15 showed a marked increase in $\dot{V}E/\dot{V}O_2$, with braces on compared to braces off at 3 kph. His $\dot{V}E/\dot{V}O_2$ was also much greater than his own or anyone else's for any other trial. In spite of this higher cost of breathing for the 3 kph trials; he had a markedly reduced $\dot{V}O_{2abs}$ with AFO on at 3 kph. For reasons unknown he appears to have been hyperventilating relative to his metabolic needs when walking at 3 kph.

Mass Adjusted Oxygen Uptake

This study used a repeated measures design, thus children were always compared to themselves. Although the subjects were not similar in body mass, it would still seem unnecessary to adjust for body mass, since we did not directly compare $\dot{V}O_2$ and related values between children, but rather we analysed the pattern of their responses. However, it was possible that the increased overall mass of children when wearing AFO and AFO shoes compared to their mass when simply wearing the non-AFO shoes (an increase 4.3% body mass ± 1.0 compared to an increase of 1.9% ± 0.5 , respectively) had some effect on the O_2 cost of walking as the mechanical force required from the muscles to move the legs must be greater with the added mass of the AFO.

While it is well known that $\dot{V}O_{2abs}$ varies with body mass, and may to a large extent be a reflection of the size or mass of those cardiorespiratory and circulatory factors that contribute to $\dot{V}O_2$ (Rowland, 1996b), the exact relationship remains unclear and is a controversy in developmental exercise physiology (Rowland, 1996a). Given that there is no clear cut normalisation factor, we chose to express $\dot{V}O_{2mass}$ in $ml \cdot kg^{-1}$ (total body mass with AFO and AFO shoes and total body mass just with non-AFO shoes). By adjusting for body mass in this fashion, we were also able to compare our data with other studies describing the O_2 cost of

walking in healthy children and those with CP. The caveats to this method of normalising are discussed below under Study Strengths and Limitations.

It is acknowledged that our group ANOVA for $\dot{V}O_{2mass}$ were of little extra value compared to $\dot{V}O_{2abs}$ analysis. Indeed, since we always adjusted to a greater body mass for all trials with braces on compared to braces off, any between trial differences found with $\dot{V}O_{2abs}$ were systematically increased. Our ANOVA (Table 10) clearly showed that this happened. As with $\dot{V}O_{2abs}$, we continued to see that wearing AFO significantly ($p=.002$) lowered $\dot{V}O_{2mass}$ for children who walked at FWS. The trend (Table 8, $p=.08$) found for braces to lower $\dot{V}O_{2abs}$ for the 3 kph-FWS sub-sample was magnified with $\dot{V}O_{2mass}$ and became significant (Table 10, $p=.03$). Similarly, the magnitude of the difference between AFO off and on increased at CWS and reduced the interaction between brace and speed for children who walked at 3 kph and CWS to a non significant trend (Table 10, $p=.07$). In comparing the two analyses of $\dot{V}O_{2abs}$ and $\dot{V}O_{2mass}$, it appears that the changes in the O_2 cost of walking between AFO on and off for children as a group were largely independent of body mass.

Of more interest, was the behaviour of individual subjects with respect to this measure (Figure 13). It was possible that by accounting for the mass of the child and AFO we may have seen certain patterns of response to AFO that were obscured in the individual data graph (Figure 10). This does not appear to be the case. Subject 7, was no longer an outlier in terms of her response to AFO when we accounted for body mass (Figure 13). The magnitude of her response in terms of $\dot{V}O_{2abs}$ at CWS may be related to her body size. On the other hand, her failure to be an outlier in Figure 13, may be related to the systematic bias of a larger body mass with braces on which would have naturally reduced her large difference in $\dot{V}O_{2mass}$ between the AFO off/on trials. In comparing Figures 10 and 13, it appears that the pattern of individual changes in the O_2 cost of walking between AFO on and off is largely independent of body mass or the mass of the brace.

The highest $\dot{V}O_{2mass}$ values for both brace conditions at FWS belong to Subject 2 (Figure 13, not identified in the legend). These high values, which were not seen at $\dot{V}O_{2abs}$ are

simply a reflection of the combination of very low body mass and a child who walked at the fastest absolute belt speed of any child in the study.

Comparing our values with those in the literature for CP remains difficult. Studies vary in the age and the severity level of subjects. In addition, in some studies children were allowed to use hand-held assistive devices. All these may affect the O₂ cost of walking. Furthermore, only one study (Unnithan et al., 1996a) has reported submaximal $\dot{V}O_{2mass}$ values on the treadmill without the children being allowed to hold on.

Mass adjusted $\dot{V}O_2$ at CWS for our subjects was similar to that reported by Duffy et al. (1996) for comfortable ground walking speed in children with hemiplegic CP. The children with diplegia in this latter study walked considerably slower than our subjects (mean 2.85 kph) and had a mean $\dot{V}O_{2mass}$ slightly above our subjects even when our subjects walked at FWS. Given the slow ground walking speed of subjects in the study by Duffy et al. and the above mentioned relationship between walking speed and gross motor function, our subjects were probably more similar in gross motor ability to the hemiplegics in Duffy and colleagues' study, and hence had a similar $\dot{V}O_{2mass}$ at a similar relative intensity of walking speed. Campbell and Ball (1978) reported on $\dot{V}O_{2mass}$ during freely chosen ground walking for a group of 22 children with spastic diplegia who differed widely in age and ambulatory ability. Again these children as a group walked considerably slower (2.58 kph) than our subjects at CWS and had a group mean of $\dot{V}O_{2mass}$ of 22.9 ml·kg⁻¹·min⁻¹, which was between our values for CWS and FWS. Differences between our findings $\dot{V}O_{2mass}$ and those of the above mentioned two studies may also reflect the inherent difficulties of standardising both CWS on the treadmill and comfortable ground walking speed, as well as a lack of validity in comparing the two.

One study (Unnithan et al., 1996a) measured $\dot{V}O_{2mass}$ using a treadmill protocol similar to our own. The $\dot{V}O_{2mass}$ in their children with CP was greater than our own by 10% at 3 kph and less than ours by 18.6% at FWS. Unnithan and co-workers did not find a difference in $\dot{V}O_{2mass}$ between children with CP and healthy controls at FWS, although significant differences did exist at 3 kph. Our subjects had a mean $\dot{V}O_{2mass}$ at 3 kph, 37.1% higher, and at FWS 18% higher, than

the healthy controls in Unnithan and colleagues' study. The actual belt speeds for FWS were not given in the above study, but our subjects appear to have a lower $\dot{V}O_{2mass}$ than these children at the same actual speed of 3 kph. Differences in $\dot{V}O_{2mass}$ values at FWS may reflect a higher O_2 cost of walking in our subjects, that is not seen at 3 kph as this was, for our children, their most economical speed.

All three of these studies (Campbell and Ball, 1978, Duffy et al., 1996; Unnithan et al., 1996a) reported a greater metabolic cost of walking at least at one speed in children with CP compared to controls (Duffy et al., 1996; Unnithan et al., 1996a) or unpublished norms (Campbell and Ball, 1978). While our subjects may have incurred a lower $\dot{V}O_{2mass}$ during walking, than these published values for children with CP, at least at 3 kph and CWS; their mass relative O_2 cost of walking was still above that incurred by healthy children at 3 kph and FWS on the treadmill. Our CWS values were also above that for healthy children walking at a comfortable pace on the ground (Waters et al., 1983).

Net Oxygen Uptake

Calculating walking $\dot{V}O_{2net}$ gives an indication of the O_2 cost of walking that is incurred over and above the O_2 cost of maintaining homeostasis at rest. To imply that $\dot{V}O_{2net}$ isolates the O_2 cost of the exercise of walking may be untrue as there is no conclusive evidence that $\dot{V}O_2$ at rest reflects the O_2 cost of these same basal metabolic functions during exercise (Stainsby et al., 1980). That being said, we calculated $\dot{V}O_{2net}$ to determine if the pattern of individual differences between AFO off and on would be affected by inter-subject differences in non-exercising $\dot{V}O_2$ between the children. As expected, since we subtracted the same value from $\dot{V}O_{2abs}$ from each pair of AFO off/on trials, our group differences (Table 11, Figure 14) showed the same pattern as $\dot{V}O_{2abs}$ (Table 8, Figure 10), with a lower $\dot{V}O_{2net}$ for AFO on at 3 kph and FWS, but no such finding at CWS due to a lack of a consistent pattern in responses at this speed condition (Figure 15). There are also no differences in the pattern of individual $\dot{V}O_{2net}$ responses to AFO (Figure 15) compared to those for $\dot{V}O_{2abs}$. It does not appear that differences in resting $\dot{V}O_2$ influenced the

effect of AFO on the O_2 cost of walking for individual AFO on-off trials. The AFO off-on correlations were high at each speed (Figure 15) again, indirectly indicating good reliability of this measure.

Absolute Oxygen Uptake per metre walked

Oxygen uptake per metre walked can be considered an index of walking economy (di Prampero, 1986). Thus the children in this study were more economical walkers at 3 kph and FWS (speeds above and below their comfortable speed) when they wore their AFO (Figure 16). At CWS the pattern of response to AFO was inconsistent, some children were more economical walkers with braces on and some more economical with braces off (Figure 17). Differences in the economical benefits of AFO ranged from a 31.4% reduction in VO_{2mw} (Subject 15, 3 kph) to a 24.1% decrease (Subject 1, CWS). Subject 12, the most physically involved child, showed some of the least economical gait at for all his walking trials (Figure 17). His walking economy improved with braces on by 4.4% at 3 kph (=FWS) and by 5.9% at CWS.

Regardless of whether children wore braces or not, walking economy varied with speed, children were more economical at 3 kph than at CWS. For the 3 kph-FWS sub-sample (Table 12), they were also more economical at 3 kph. At first glance this pattern would seem to contradict the literature, at least for healthy adults (Inman, 1981) who incur a lower O_2 cost of walking at self-selected over ground speeds; that is to say, comfortable ground speed. However the literature suggests that CWS as we have defined it, may not be the preferred treadmill walking speed, especially in children with spastic CP. Jeng et al. (1996) found that the preferred walking speed on the treadmill is markedly reduced compared to preferred ground walking speed in 7-12 year children with spastic hemiplegic CP. The speed conditions in Jeng and colleagues' study ranged between 4 kph and 5.85 kph, while preferred treadmill speeds were between 1.2 kph and 3.2 kph. For these children there was also a significantly higher cardiovascular cost at stride frequencies above, but not below their preferred frequency. All the CP subjects in Jeng and co-workers' study were considered functional, independent ambulators. The authors attribute this

preference toward lower treadmill speeds and a slower stride frequency 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 mis-step. Healthy children also prefer a significantly lower treadmill walking speed but the difference is not so marked (Jeng et al., 1996; 1997). Since four of our 10 subjects could not walk at all on the treadmill above their CWS on the ground, yet they were able to walk on the ground at two distinctly different speeds, it would appear likely that CWS on the ground did not translate into CWS on the treadmill. For these four subjects at least, it may have been closer to their FWS on the treadmill!

Mass Adjusted Oxygen Uptake per Metre Walked

For the same reasons as described in the discussion of $\dot{V}O_{2mass}$, adjusting $\dot{V}O_{2mw}$ for mass and calculating $\dot{V}O_{2mmw}$, did not reveal any new information about how walking economy in these children was affected by AFO. Group results (ANOVA, Table 13), must again be interpreted with caution due to the bias imposed by systematically adding greater mass to the AFO on condition. The pattern of improved mass-adjusted walking economy with AFO on for children as a group was the same as for the mass adjusted O_2 cost of walking and will not be discussed further here. Again, see Study Strengths and Limitations for a discussion about normalising by body mass in kg raised to the exponent one. The potential value of normalising per stride rate and length is discussed under Recommendations for Future Research.

Calculating $\dot{V}O_{2mass}$ for these subjects however, does allow us to look at the pattern of individual AFO off-on trials and to some extent, to compare walking economy in our subjects with data reported in the literature. Figure 18 shows that the two children (Subjects 2 and 12) with the highest over all $\dot{V}O_{2mmw}$ (and hence the lowest economy) both demonstrated improved walking economy at all speeds when they wore their AFO. Other children in the middle range of economy however, also did so to a similar extent. Subject 15 on the other hand, appears to have the greatest improvement in walking economy at 3 kph and yet he has the highest overall walking

economy. Subject 1 who has already been discussed, showed pattern here is similar to that seen for other her $\dot{V}O_2$ variables. Thus no new pattern evolved using a mass adjusted index of walking economy. Again our high correlations at each speed indirectly point to good reliability between individual AFO off-on pairs of trials.

There are no data available to the best of our knowledge for mass adjusted walking economy of children with CP on a treadmill who were not holding on to the hand railings. Duffy et al. (1996) reported an average $\dot{V}O_{2mmw}$ for CGS of $.64 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$ for spastic diplegic and $.42 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$ for spastic hemiplegic children with CP. Campbell and Ball's (1978) children with spastic diplegia had a mean $\dot{V}O_{2mmw}$ of $.862 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$. Our subjects appear to be more economical walkers on the treadmill than these previous groups of children walking on the ground. Given that these other groups had a slower ground walking speed than our subjects, and given the gross motor function and comfortable ground speed relationship, it is possible that the above differences in walking economy are related to differences in gross motor function. A further possibility is that children walking on the treadmill received assistance from the treadmill belt in propelling their centre of mass forward (Pearce et al., 1983).

Respiratory Exchange Ratio

In addition to a measure of $\dot{V}O_2$, in order to calculate EE_{gross} we required the steady state RER values for the treadmill walking trials. To calculate EE_{net} we also needed the resting (non-exercise) values for RER. The RER is the ratio of carbon dioxide output to $\dot{V}O_2$ at the mouth and is used in place of the same ratio, called respiratory quotient (RQ) when referring to the cellular level, to indirectly indicate substrate utilisation; since the ratio of carbon dioxide production to O_2 consumption varies for different fuel sources. The contribution of protein is ignored as it is considered to be minimal during exercise. Since fuel sources will vary in the amount of biochemical energy needed to "burn" them, the biochemical EE can be estimated knowing the O_2 requirements and the RER. The RER however, being an indirect estimation of RQ, is also influenced by such things as hyperventilation which can raise carbon dioxide output relative to

and therefore raise RER but not the RQ. Thus, the RER may be somewhat greater than RQ during exercise testing if the subject is hyperventilating due to anxiety or discomfort. Increased ventilation, and therefore an increase in RER, but not in RQ, also occurs when there is a need to remove excessive CO₂, as is produced during high intensity exercise, secondary to bicarbonate production for buffering. The RQ ranges from .70 with pure fat utilisation to 1.00 for pure carbohydrate utilisation. The RER can therefore be greater than one with hyperventilation or during intense exercise (McArdle et al., 1996). Even with these limitations, RER is still useful in studies investigating the energy cost of walking, as it can be used to determine EE_{gross} or EE_{net} during walking, which is necessary if one wants to directly compare the metabolic cost of walking to mechanical power; that is to say, calculate the efficiency of walking.

We analysed the effect of AFO and belt speed on RER to see if RER would influence EE in any pattern different than $\dot{V}O_{2abs}$ and related variables and thus influence our calculations of EE. Given that we did not control for diet, we had a wide range of between-subject RER values. With the short duration of our trials, it was unlikely that any within-child differences in RER would be due to a change in fuel source between trials. It was possible however, for RER to have been systematically affected by different anxiety levels at different speeds or brace conditions. We assumed that randomisation of brace and treadmill speed order controlled for the influence of anxiety, perhaps due to varying levels of treadmill accommodation and habituation. The limitations to this assumption with respect to treadmill accommodation and habituation, are discussed below along with other strengths and limitations of this study.

It appears that speed, but not brace, did affect RER, but only when the speeds were different for each child in absolute terms (Table 14). We therefore did not see a difference in RER between 3 kph and CWS since CWS was not faster than 3 kph for all children. It was only in the 3 kph-FWS sub-sample where FWS was always the faster speed that we saw a significant ($p=.009$) increase in RER. Although braces did not affect RER, there was however, a trend ($p=.07$) for RER to be higher with braces on at FWS (Table 14). This trend did not change our

overall findings with EE_{gross} and EE_{net} . Gross and EE_{net} remained lower with braces on in spite of the trend to a higher RER with braces on.

Our RER values at 3 kph and FWS (Table 14) are lower than those obtained by Unnithan et al. (1996a) for both healthy children and those with CP. Our values at 3 kph and CWS are similar to those reported for healthy children (.87) walking on the ground at FWS (Waters et al., 1983).

We did not achieve a high correlation between AFO off-on trials at 3 kph (Figure 20), although AFO off-on correlations were fairly high at CWS and FWS. The variability in RER may be due to some inherent variability of this measure for children with CP (which is unknown) or it may be due to random, combined errors in the measurement of carbon dioxide output and $\dot{V}O_2$, or perhaps it is due to a combination of causes.

Energy Expenditure

Neither the EE_{gross} , nor EE_{net} analyses revealed any new information about the effect of AFO on EE that was not already seen with the O_2 cost of walking calculations, or with those used to determine walking economy. The reliability, as indirectly shown by the correlations for EE_{gross} , and EE_{net} for AFO off-on trials was high (Figures 22 and 24) and similar to values obtained for $\dot{V}O_2$ and related variables. We therefore did not introduce any extra error by introducing RER into the calculation to estimate EE. A measure of EE in kJ, while not providing new information for this study, is necessary to any future studies explaining metabolic cost by mechanical cost.

Statistical Power

Statistical power refers to the probability of correctly rejecting a false null hypothesis, in other words, correctly identifying real differences between groups or conditions (Gravetter and Wallnau, 1992b). With respect to this study, the differences of interest are those differences in gross motor, cardiopulmonary, metabolic and EE variables between the AFO off- and AFO on-conditions at the same speed for a group of children who acted as their own controls.

Alternately, one could think of power here as a measure of how sensitive this experiment was in terms of being able to detect real differences in the above variables due to AFO. Since the factors that affect power are not all of the same magnitude for each dependent variable, there will be a different estimate of power for each of the variables listed above.

Factors affecting power are (Gravetter and Wallnau, 1992b): 1) size of the treatment effect, 2) alpha level (probability of a Type I error; e.g., of finding a difference between AFO on and off conditions due to chance alone), 3) direction (one-tailed or two-tailed) of the statistical test, 4) sample size and 5) the variability due to error for each effect, for each dependent variable. When the treatment effect is small, power is decreased since the probability distributions of sample means for treatment and control groups overlap more than with a larger treatment effect, resulting in fewer sample means for the treatment group falling in the critical region. The smaller alpha is, again fewer treatment sample means fall in the critical region and power is lower than with a larger. Using a two-tailed test instead of a one-tailed test has the same effect on power (lowering it) as reducing alpha over all. Since smaller sample sizes do not represent a population as well as larger samples, the SEM of small samples is greater, which again increases overlap in the distribution curves mentioned above and thus lowers power. Likewise, when the variability in the dependent variable for any particular effect is high, the SEM will be high and the distribution curves will overlap to a greater extent with the resultant loss in power (Gravetter and Wallnau, 1992b).

While we chose in this study to increase power by setting alpha at $p < .05$ instead of the more conservative $p < .01$, our treatment effects were modest (see Tables 4-16) and that, combined with a small sample size of 8-10 subjects (and sub-samples ranging from 4 to 7 subjects) as well as the necessity of doing a two-tailed test (in case braces resulted in a decrease in walking economy, etc.), served to decrease the power of this experiment. Thus, it is possible that certain effects of the brace not found to be significant were indeed real differences. More specifically it is possible that the trends found in most instances in 3 kph-FWS sub-samples (Tables 6-16), for AFO on to lower cardiopulmonary, metabolic and EE measures compared to

AFO off, may have reached significance had statistical power been greater. Omega-squared values indicate the proportion of the overall variance that can be accounted for by the treatment (e.g., brace). For the $\dot{V}O_2$ variables (Tables 8, 10-12), omega-squared for a main effect (AFO) ranged between .25 and .33). In other words 25%-30% of the variance in $\dot{V}O_2$ was accounted for by the AFO. With the EE variables (Tables 15-16) the variance accounted for by AFO was 13% and 20% for gross and net EE, respectively. In comparison, when a significant main effect was found for AFO in the 3 kph-FWS sub-sample (Table 13, omega-squared not shown), 47% of the variance in $\dot{V}O_{2mmw}$ was accounted for by the AFO. Given the amount of variance accounted for with a significant difference, effects like AFO that account for 25%-30% of the variance are worth consideration. The Omega-squared values for the AFO X Speed interactions, usually found significant for children who walked at 3 kph and CWS, would not necessarily be very much greater than those for the above mentioned trends, since for the interactions, a significant difference is found for AFO only at 3 kph. Omega-squared for the AFO X Speed interaction for $\dot{V}O_{2abs}$ for example, is only .33 (Table 8).

It is all the more probable that low power was an issue since in the two largest sub-samples (3 kph-CWS and FWS) where power was increased due to sample size, braces did significantly ($p < .05$) lower these variables at the same speeds *i.e.*, 3 kph and FWS.

In the case of $\dot{V}O_{2mass}$ (Table 10) the situation was reversed, but low power may still have had an effect. A significant difference ($p = .03$) was found for AFO on to be lower than AFO off at both speeds in the 3 kph-FWS sub-sample. A trend ($p = .07$) for $\dot{V}O_{2mass}$ was found for the interaction between AFO and speed in the 3 kph-CWS sub-sample. In this case, the interaction between AFO and speed accounted for 25% of the variance.

It is unlikely that low statistical power concealed real differences due to AFO in the 3 speed sub-samples in any of the cardiopulmonary, metabolic or EE variables or for any sub-sample for HR (Table 6), $\dot{V}E/\dot{V}O_2$ (Table 9), or RER (Table 14) (with the exception of FWS, where AFO on might have resulted in a significantly higher RER had power been higher) or in the measures of gross motor ability; ground walking speed (Table 4) and the GMFM (Table 5). For

these variables, the error or the variability in how children reacted to brace (subject by condition interaction) was close to, or greater than, the difference in the variability between the AFO on and off conditions (i.e. F-ratio was around or less than one). The error was too large and the treatment effect too small to consider low power as possibly masking real differences.

For the 3 speed sub-sample this failure to find differences likely reflects sampling error; in other words, the between subject difference in response to AFO in such a small sample would not be representative of the population. For the gross motor variables, the failure to find significant differences likely reflected the true state of affairs for the population. Here all 10 children were part of the analysis.. For the GMFM scores (Table 5), error was greater than the effect of the AFO. In the case of ground walking speed (Table 5, omega-squared not shown), only 1.8% of the variance was accounted for by AFO.

Study Strengths and Limitations

Strengths

This study is unique as it was the first to measure the effect of hinged AFO on the O₂ cost of walking and walking economy in children with spastic diplegia. Our data support and further those of Mossberg et al. (1990) who reported cardiovascular walking economy to improve when these children wore AFO. Our findings are all the more relevant in that we found differences due to braces in a group of very mildly disabled children. The possibility exists, and our data suggest this, that the O₂ cost benefits we found due to AFO might be more consistent in more disabled children. Our data also suggest that increases in gross motor ability due to AFO may be greater in more disabled children.

In the methods section we described how we were able to over come several technical difficulties inherent in exercise testing with young, physically disabled children. To the best of our knowledge this was only the second study (Unnithan et al., 1996a) to measure submaximal steady state $\dot{V}O_2$, while the children walked on the treadmill without holding on to hand railings. We have extended the lower limit of the age range for treadmill testing in CP to an average of 9.01 years,

an increase of 3.7 years from that reported by Unnithan's group. This expanded age range increases the potential for more indepth longitudinal studies with these children.

In an attempt to improve generalisability, we did not control for the type of hinged AFO, or the amount of ankle motion allowed. Most braces were similar, but we can not rule out the fact that differences in the design of AFO between subjects introduced variability in our responses. We feel that not controlling for the type of hinged AFO however, is actually a strength of the study. In spite of the possible increased variability in responses, we were still able to see significant effects due to AFO, allowing us to generalise our findings to hinged AFO rather than a specific type of hinged AFO.

Limitations

Our classification of children using the Gross Motor Classification System (Palisano et al., 1997) may have some error. The measure is still in the development stage, undergoing further validity and reliability testing. No intrarater reliability data are available at this point. Interrater reliability shows it is difficult to distinguish between level one and two children in the age group of our subjects. However, the rater for this study was very familiar with both this test and the GMFM, from which many of the criteria for classification are drawn. Her reliability for the GMFM is within acceptable standards (Russell et al., 1989).

It might be argued that due to our multiple statistical analysis, we have greater than acceptable risks of a Type I error (falsely attributing found differences to the AFO). Our analyses however multiple, do not contradict each other, with the exception of those done using the small (n=5 or n=4) three speed sub-sample, which is probably due to sampling error in that sub-group. We therefore find no reason to suggest that our multiple analysis have lead to an unacceptable chance of a Type I error.

The treadmill belt speed changed while children walked on it. The belt speed was, on average, higher by 3.2% with AFO off and by 3.4% with AFO on. Since we had only two speed conditions for the majority of children, we were forced to assume a linear relationship between

metabolic (and cardiopulmonary variables) and speed to address the differences in speed between the AFO off and on conditions. Our method of interpolation or extrapolation to obtain the values for these variables at the intended speeds using a linear regression equation may have underestimated the real difference between the AFO off and on conditions. Ralston (1958) found an exponential relationship between treadmill locomotion speed and the oxygen cost of locomotion in adults:

$$\text{Oxygen Cost } (\dot{V}O_2, \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}) = .00110v^2 + 5.9 \quad (2)$$

Walking speed in this equation is denoted by v . Corcoran and Gelmann (170) found a similar relationship between oxygen cost and walking speed for adults walking on the ground. Mechanical work, which incurs the metabolic and cardiopulmonary cost, is defined as the change in energy level of the 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. Like the relationship between the oxygen cost of walking and walking speed, translational kinetic energy, which has the largest impact on mechanical work during walking, varies with velocity squared (Hamill and Knutzen, 1995). By assuming a linear relationship between the metabolic and cardiopulmonary variables and speed, the actual differences in these variables due to AFO may have therefore been underestimated by our regression equations. AFO may have a greater impact on these variables than we reported. There are however, other data to support a linear relationship between walking speed and $\dot{V}O_2$ in healthy children walking on the ground (Waters et al., 1988) and in children with CP walking on the treadmill (Rose et al., 1989). Waters and his colleagues showed that the oxygen cost (per kg body mass) of walking at different speeds could be estimated using a linear equation:

$$\text{Oxygen Cost } (\dot{V}O_2, \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}) = .188v + 2.61 \quad (3)$$

The values Waters and colleagues (Waters, 1992) report using a similar, linear equation they derived from adult data are very close to those that would be obtained using the equations of Ralston or Corcoran and co-workers, as long as walking speeds are below about 6 kph. The data of (Rose et al., 1989) appear to show a linear relationship between walking speed and oxygen

cost per kg body mass for children with CP when walking just below their maximum speed. The relationship for healthy children in this study appears exponential, although regression equations are not reported. The values and relationships depicted by Rose et al. however do have to be considered with caution, given that gait pattern and oxygen uptake may have been altered by children holding on to the handrails, which they were allowed to do at will. In summary, there appears to be a theoretical, exponential relationship between walking speed and the oxygen cost (or cost of other metabolic or cardiopulmonary variables) of treadmill walking in children with CP. Oxygen uptake varies with speed squared. Experimentally this relationship has been found in healthy adults. It has also been suggested that, for all but extremely slow and very fast walking speeds, the relationship between $\dot{V}O_2$ and walking speed may be essentially linear. Oxygen uptake values in children and adults, obtained using a linear equation, appear to closely approximate those values obtained using a second order equation. Further research however, especially in children, is required before firm conclusions can be made about: 1) how closely the experimental relationship approximates that found theoretically, and 2) whether a linear relationship can be used to predict $\dot{V}O_2$ at certain speeds. With respect to this study, a less than optimum method of predicting the metabolic and cardiopulmonary value at the desired speeds, affects the magnitude of the difference between the braces off and on conditions.

Normalising $\dot{V}O_2$ by body mass simply raised to the exponent one, as we did, may not be the best exponent to minimise between-subject variability. While minimising between-subject variability is not particularly relevant in our study because of its repeated measures design; it is discussed here, as it could be very important in future intervention studies where children's body mass changes over the course of the study. The particular outliers we did and did not identify may also have been changed somewhat, had we used a different exponent for body mass. According to dimensional theory (Åstrand and Rodahl, 1986), $\dot{V}O_2$, which is a volume per unit of time, is proportional to body length squared (body length cubed divided by body length). Since body mass is proportional to body length cubed, then $\dot{V}O_2$ should be proportional to body mass raised to the exponent 2/3. McMahon (1973) however, suggests that theoretically, the elastic

constraints of biological tissue result in $\dot{V}O_2$ during exercise being proportional to body mass raised to the exponent $3/4$. Such a relationship has been shown for animals of different sizes and for men and boys (Kleiber, 1947; Svendenhag, 1995). It may therefore have been more appropriate, especially when looking at outliers, to have normalised by kg raised to the exponent $3/4$. Given that we wished to compare our results with those of other studies however, we would still have had to normalise by kg raised to the exponent one as well. It should also be recognised that other factors, such as differing levels of physical involvement among children, and the effect of the physical disability on body dimensions, makes testing the validity of $3/4$, or any other exponent for normalising, very difficult in this population. In summary, our method of normalising for body mass did not affect the results we used to answer the main questions of this thesis. In the future however, the weighting of body mass needs to be given special consideration, especially if children's body mass changes during the course of the study.

With respect to the methodology, we had two challenges which we have not yet been able to overcome. First, we have not yet determined the optimal methods of accommodating and habituating children to the treadmill. From a practical perspective, accommodation to the treadmill in this study simply meant that the child could perform our treadmill protocol without a great deal of difficulty. Prior to the treadmill walks with AFO on and off, the children's treadmill experience consisted of a 15 minute training session and several walking trials while we determined the fastest treadmill walking speed. While an extra lab session may have allowed children more time to accommodate and habituate (become for stable in responses and more economical in walking) to the treadmill, we limited the protocol to only two lab visits to minimise the time commitment to children and parents. Most families travelled over 1 hour by car to come to the lab. Our experience with recruiting volunteers showed us that time commitment was an important consideration for families when they decided whether or not they would participate in the study. Although we partially controlled for the effects of accommodation and habituation by randomising the order of the brace and speed condition, we may have had an added source of variability due

insufficient accommodation and habituation. It is possible for example, that the unusual response of Subject 1 at CWS with AFO on was due to insufficient accommodation, habituation or both.

Our second methodological challenge to overcome is that of determining a relative intensity on the treadmill that is similar to a child's preferred ground walking speed. It appears that children's CWS on the ground may not be their CWS on the treadmill. Had we been able to determine a relative intensity at CWS that was similar for all children, our results at CWS on the treadmill may shown a clearer pattern.

While we made every effort in this study to minimise fatigue to the child, our children were unable to rest in sitting between trials due to the nature of other measurements being taken during this study. It is possible that the effect of braces may have been magnified due to fatigue. The effect of AFO on energy consumption during fatiguing exercise is in itself an area that warrants study.

While we partially controlled for diet by having children not eat for a minimum time period before the study, we set no other dietary restrictions. It does not appear however that diet severely affected the EE analyses in which RER was corrected, as these results did not conflict with results from our $\dot{V}O_2$ measures.

The lack of formal reliability analysis may limit generalisability of our findings. Since we have reliability data on only two children, we can not make any conclusions about the reliability of our measures. Our AFO-on AFO-off individual data graphs do indirectly point to very good reliability of our AFO off and AFO on trials as a whole, with the exception of the RER data and possibly the $\dot{V}E/\dot{V}O_2$. As one of the two children for whom we have reliability data reacted to AFO in opposite directions for her two pairs of trials, it is possible that our results are not completely reproducible. Children with CP however may not always react in the same manner, whether with or without AFO. Further work in this area needs to be undertaken.

Another limitation to generalisability of our results to the "real world" is the use of the treadmill. Walking on a moving belt is certainly not the same as walking on the ground. The

extent to which treadmill walking would influence the direction of our results is unknown in children with cerebral palsy.

One final limitation is our small sample size which reduces our power to find significant differences. In spite of this, we found significant effects for AFO. It is possible that effects not found in this study; e.g., a main effect for AFO at 3 kph and FWS would have been revealed with a larger sample size.

Coactivation in Spastic Cerebral Palsy

As we have shown, wearing hinged AFO reduced the O₂ cost and increased economy of walking in children with spastic diplegia. One possible explanation for this finding is a reduction in coactivation of antagonistic muscles due to an increase in postural stability while walking in braces. Even though this thesis can not provide data about the effect of coactivation on metabolic cost, the possibility is worthy of discussion.

Coactivation, also known as cocontraction, refers to concurrent activity in antagonistic muscles (Berger et al., 1984). We will use the term coactivation for the rest of this paper. Executing a motor task using an increased amount of coactivation implies increased biochemical energy expenditure, as more muscle must be supplied with energy to perform the task. Hence children who walk using a greater amount of coactivation could incur a greater relative metabolic cost. The relationship between increased coactivation and a less economical gait, while complex, can clearly explain at least some of the differences in walking economy between children of different ages (Frost et al., 1997b). In children with CP, coactivation at both the thigh and the lower leg are major factors that contribute to these children's higher O₂ cost of walking (Unnithan et al., 1996a).

During locomotion, coactivation in healthy adults can be related to stability needs (Falconer and Winter, 1985). This same rationale has been suggested to explain some of the gait related increases in coactivation observed in younger children (Frost et al., 1997b; Okamoto and Kumamoto, 1972; Tata and Peat, 1987). In those with CP, increased coactivation has been

attributed to central nervous system damage (Berger et al., 1984; Bowsher et al., 1992; Brunt and Scarborough, 1988b; Crenna et al., 1992b; Unnithan et al., 1996a; 1996b) as well as to a need for increased postural stability (Berger et al., 1984; Brunt and Scarborough, 1988; Crenna et al., 1992).

The bilateral lesion in spastic diplegia is usually adjacent to the lateral ventricle body, affecting the pyramidal tract as it runs to the internal capsule. Since tract fibres for the legs are closest to the ventricles, they are more vulnerable to damage; hence children with spastic diplegia demonstrate bilateral involvement, more so in the legs than in the trunk or arms (Krägeloh-Manu et al., 1995).

Increased coactivation can result from a lack of supraspinal input to the motoneuron pool as a result of this brain damage. Since Ia afferents and descending tract fibres such those from the pyramidal tract also synapse with interneurons that inhibit antagonist alpha-motoneuron pools (Ia inhibitory interneurons), activation of the antagonist (from stretch due to a reflex or voluntary contraction of the agonist) is "reciprocally inhibited" to greater and lesser degrees depending on the "strength" of the local and descending signals (Burke, 1988). Signals from descending pathways can inhibit the antagonist motoneuron pool before activation of the agonist (feed forward control) (Leonard et al., 1990) providing a means of modulating coactivation. Leonard et al. (1990) tested for feed forward reciprocal inhibition in children with spastic CP by using the H-reflex (electrically stimulating the Ia axon) to determine the excitability of the antagonist (triceps surae) alpha-motoneuron pool just prior to voluntary agonist (tibialis anterior) activation. Compared to healthy controls, who show this inhibitory pattern, these researchers found that there was no inhibition of the antagonist alpha-motoneuron pool prior to agonist contraction in children with spastic CP. Although they do not rule out spinal circuitry abnormality, Leonard and colleagues attribute this lack of reciprocal inhibition to decreased supraspinal influences, since vibration at the agonist tendon, which activates the above mentioned local inhibitory pathway, did result in a decrease in the antagonist H-reflex in children with CP. They further suggest that a weaker

descending signal, and subsequent decreased "reciprocal inhibition," may contribute to the increased coactivation.

The causes of increased coactivation in CP however are likely multifactorial. Spinal circuitry could be abnormal, due to a variety of causes. Research in animals with perinatal cortical lesions (Leonard and Goldberg, 1987) and more recently in children with cerebral palsy (Leonard et al., 1990, 1991) has led to a new theory about hyperreflexia in children with CP, namely that of retained neonatal exuberance (Leonard, 1994). Neonatal neural exuberance refers to an excess of neural projections and connections in comparison to those found in the healthy adult (Leonard, 1994). During early development there is a 50% loss of neurons due to cell death and retraction. Axon retraction peripherally occurs by 8 weeks gestation such that each muscle fibre is innervated by only one axon. Prior to this time there is multiple innervation of muscles fibres (Purves and Lichtman, 1980). Retraction in the brain and spinal cord however, only begins in the third trimester and continues into the first few years of life. Cell death and retraction seems to be driven by competition for a limited quantity of trophic substances, the availability of which seems to be related to synaptic activity (Heffner et al., 1990). Thus, like the cat with pyramidal tract neuron death from a third trimester lesion (Leonard et al., 1991a), children with spastic diplegia, who often also have a third trimester lesion, may have aberrant cortico-cortical and cortico-spinal connections due to this decreased competition. Fibres or axon collaterals that would have normally been eliminated are retained (Leonard, 1994). In the cat, these connections are usually from functionally related areas of the brain (Leonard and Goldberg, 1987). Leonard and Goldberg suggest that the reflex irradiation (tendon tap-induced contraction of antagonists and other muscles along with the agonist contraction) seen in infants and children with spastic diplegia, but not seen to the same extent in adult-onset hemiplegia or in healthy older children and adults, is evidence for the presence of neonatal exuberance in spastic diplegia, as a pathology and in infants as a developmental phenomena. As further proof for the presence of neonatal exuberance Leonard et al. (1991b) note the increase in coactivation in both infants and children with SD who were beginning to walk.

Damage to the pyramidal tract may also have an influence on the brainstem centres that serve to control locomotion. Both the reticulospinal pathway, which plays a part in initiation of locomotion, and the rubrospinal pathway, which is believed to control contralateral flexor activity, receive input from the pyramidal track (Grillner and Dubue, 1988). Increased coactivation as in the infant could reflect the lack of mature input to these areas, whereas as for the child with CP, the lack of sufficient input may be the issue.

While increased coactivation in the lower limbs, regardless of the exact mechanism, might explain the need for braces, it is not likely changed by AFO. Increased coactivation that is compensatory in nature, however, may be modulated by use of AFO. There is evidence to show that hemiplegic children have increased coactivation on the non-involved side (Berger et al., 1982; Crenna et al., 1992). The authors attribute this to a need for increased stability. Leonard et al. (1991b) report that the phasic patterns of antagonistic muscles were similar in the young healthy children and those with spastic CP when both groups were ambulatory, but only with support. Coactivation decreased in healthy young children as they gained proficiency in unsupported walking and become more stable (Leonard et al., 1991; Okamoto and Kumamoto, 1972). Others (Csongradi et al., 1979) have speculated that increased activity and duration in the quadriceps muscles in CP (and possibly increased coactivation at the thigh) may also be due to decreased stability, especially with an equinus posture of the ankle, as this prolonged quadriceps activity has been observed in women wearing high heels (Joseph, 1964).

As noted in the introduction to the study, previous gait studies have found hinged AFO to have their major effect during stance, by allowing for increased ankle dorsiflexion. Children are therefore less likely to be in equinus and perhaps more stable (base of support increased, centre of mass more within the base of support). Research to date, however, does not support a change in coactivation at the ankle secondary to a decrease in equinus. In a pre and post operative EMG analysis of tibialis anterior and triceps surae muscle activation and timing during gait, no difference in coactivation was found although the children were no longer in equinus post operatively (Brunt and Scarborough, 1988). While she did not measure coactivation per se,

Lough (1990) did not find any differences in the phasic pattern or the amplitude of gastrocnemius and tibialis anterior EMG output when children walked with and without hinged AFO. The only difference that Lough did find with respect to EMG data, was at the thigh, where she saw a decrease in amplitude in vastus lateralis at pre-swing with braces on compared to off and an increase in amplitude with braces on at initial contact. While Lough herself admits that her method of processing EMG was not optimal as she did not normalise the data, these data do point to the ability at least of some thigh muscles to respond to a changing gait pattern, as the ankle was more dorsiflexed at midstance with AFO on in Lough's study. In healthy children, the ability of the thigh muscles to respond to changing gait patterns has been shown. There is greater variability in the EMG patterns seen at the thigh compared to the lower leg (Shiavi et al., 1987). These authors suggest that thigh muscles are more adapted to accommodate or respond to different walking styles.

In conclusion, while no studies have documented the effect of hinged AFO on coactivation at the lower leg or the thigh, the thigh muscles may be more responsive to a changing need for stability. This effect may be even more marked proximally, given that children who wear AFO are usually more spastic and have more impairment at the lower leg compared to the thigh. If we wish to explain differences in walking economy due to varying amounts of coactivation, then it would also seem advantageous to have differences occurring in the thigh muscles rather than lower leg muscles as the former are the larger, more O₂ costly muscles. Furthermore, Winter et al. (Winter et al., 1991) suggest that the most efficient location for control of body mass during locomotion is at the hips rather than at the ankles. The load to control from the hips; the head, arms and trunk, is much less than at the ankles, where nearly the total body load would be involved. Thus, if walking without AFO is less stable, then increased coactivation to compensate for the lack of stability may especially occur at the hips. A coactivation index should therefore include thigh muscles that cross the hip such as rectus femoris and the hamstring muscles.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. When children wore their AFO, both their oxygen cost of walking and energy expenditure were reduced and walking economy improved at 3 kph and the fast walking speed. This effect was not seen at the comfortable walking speed where the response varied greatly from child to child, possibly due to the different relative intensity CWS represented for each child.
2. The AFO affected the cardiopulmonary cost of walking to a lesser extent. Heart rate was not affected at all by AFO and pulmonary ventilation only showed a decrease at 3 kph. Breathing efficiency was low in these children, but not affected by AFO.
3. Neither walking speed on the ground nor gross motor function was affected by the brace. Compared to previous reports, our subjects appear to be similar in comfortable walking speed and gross motor function scores to other children with spastic diplegia who walk without hand-held assistive devices.
4. The oxygen cost of walking in our subjects may be greater than some researchers' findings and less than others. Lack of standardisation and insufficient individual subject data in the literature, make direct comparisons difficult.
5. Our subjects appear to be more economical walkers than those reported in the literature. Again comparisons should be taken with caution for the reasons mentioned above.

Recommendations for Further Research

There are numerous unanswered questions regarding the energy expenditure of children with CP. The following points are not intended to provide an exhaustive list. They merely represent the interest of this author. It is therefore this author's opinion that future research:

- **Determine whether, and by how much, incorporating coactivation data would explain the higher metabolic cost of walking without AFO.**

Increased coactivation at the thigh and leg is associated with the increased oxygen cost of locomotion in younger, healthy children (Frost et al., 1997b) and in those with cerebral palsy (Unnithan et al., 1996a). It is unknown if such data would be able to explain intra-individual differences due to interventions such as AFO.

- **Determine whether the addition of EMG measurement in itself would cause changes in oxygen uptake, pulmonary ventilation and heart rate and, conversely, determine whether collecting expired gas modifies EMG output.**

Using a multidisciplinary approach to answering questions about energy expenditure in cerebral palsy may provide us with more insight into factors associated with children's energy expenditure patterns. Accurate interpretation of such data however, requires knowledge of any interactions between measurement techniques. In children with CP, collection of surface EMG during ground walking results in an average 6.3% decrease in cadence and a corresponding, but non significant trend towards a decrease in walking speed (Young et al., 1989). The extent to which these changes affect oxygen uptake, pulmonary ventilation and heart rate is unknown. Wearing a face mask or a mouth piece does not affect the running style of healthy adult men (Siller, 1993). In our study, two children who were able to walk on the treadmill unsupported, were

unable to do so while breathing through the mouth piece. It is unknown if this was associated with a change in muscle activation patterns.

- **Identify the most informative approach to calculating coactivation index**

EMG data cannot be directly compared between individuals given the multitude of factors such as skin resistance and temperature, subcutaneous fat, muscle fibre type and electrode placement that can affect the EMG mV values. Until recently, most studies on coactivation during walking in CP (Berger et al., 1984; Brunt and Scarborough, 1988; Leonard et al., 1991) have therefore been descriptive. Crenna et al. (1992) however, calculated a “geometric measure” of coactivation by determining the overlapping area of normalised (mean EMG value during gait) linear envelopes from antagonistic muscles. Similar to Crenna and co-workers, Unnithan et al. (1996a, 1996b) calculated a coactivation index, a unitless number derived by overlaying the normalised linear envelopes, calculating the area and dividing by the number of data points. By using this index Unnithan showed that children with CP have higher levels of cocontraction at both the thigh and the lower leg than healthy children, regardless of speed. Speed also increases coactivation in both groups of children. Frost (1997b), using the same index also reported that speed increases coactivation in healthy children. Both Frost and Unnithan found their cocontraction measure sensitive to changes in the O₂ cost of walking.

A coactivation index that reflects the EMG output during the same time frame as physiological data are collected may also render the index more reflective of global physiologic measures of energy expenditure. A coactivation index based on ensemble averages (100% of the gait cycle) normalised to the mean EMG value for the walking trial rather than the peak value may be a more stable measure that relates better to steady state physiologic measures of energy expenditure. Normalising to either the peak or the mean value minimises between subject variation for healthy adults (Yang and Winter, 1984). Since children with CP who wear braces may have poor balance and stumble easily while walking, especially on a treadmill, the mean could be the more stable value for them. That being said, the median may be an even more

stable value as it is even more insensitive to outliers, but its use as a normalisation factor in EMG gait analysis to our knowledge is unknown. Since previous gait analysis using EMG have shown that the EMG data from spastic diplegic children varies from one leg to the other (Berger et al., 1984), data from both legs may improve the sensitivity of the measure. The utility an index of coactivation to explain differences in energy expenditure has been shown. The best index to answer these questions is unknown.

- **Identify an optimal muscle group configuration that would yield most information about coactivation in the walking CP patient**

There are no clear cut recommendations from the literature as to the optimal muscles for collection of information on coactivation in cerebral palsy, aside from generalisations such as collecting data from antagonistic muscles at the thigh and at the lower leg. To relate a global measure, such as oxygen uptake, to a more local measure of thigh or leg coactivation discounts other potentially large areas of coactivation, and hence oxygen consumption, such as the trunk.

- **Refine methods to determine comfortable walking speed on the treadmill.**

Treadmill protocols allow ease of collecting EMG output and physiologic data during steady state walking. Comfortable walking speeds on the ground and treadmill may not be the same (Jeng et al., 1996). Refining our methods to determine CWS on the treadmill would increase generalisability of results.

- **Determine effects of AFO on physiological variables and coactivation output during walking on land (on the level, uphill, downhill).**

The effects of AFO may vary with the type and difficulty of the walking task. Examining the effects of AFO during different walking tasks may provide insight into what situations the child will most benefit from wearing AFO, as well as increase generalisability of our results to the field.

- **Determine whether AFO affects the child's fatigability (by using a more prolonged walking protocol)**

It has been suggested that children with CP fatigue earlier than healthy children (Dahlbäck and Norlin, 1985). Although we have found an improvement in walking economy with AFO; the relationship between walking economy and endurance is unknown in CP. Knowledge about the influence of AFO on fatigue would provide more insight into the economy-fatigue relationship as well as give clinicians information to assist in their decision making around AFO prescriptions.

- **Determine accommodation/habituation patterns in children with CP who walk on the treadmill.**

Frost et al. (1995) suggest that healthy children can accommodate to the treadmill within one training session. Unnithan et al. (1996a) appear to accommodate children with CP to the treadmill within a 15 minute training period. No study however, has fully assessed accommodation or habituation in children with CP. One possible method to address accommodation issues might be to compare EMG activity during over ground walking, to which children are well accommodated, to EMG activity during treadmill walking. This would give an indirect indication of the extent to which children compensate while walking on the treadmill. As accommodation occurs, presumably the over ground and treadmill EMG patterns would become more similar. An investigation of habituation patterns requires the use of metabolic and kinematic measures (Frost et al., 1995).

- **Evaluate effects of AFO on children with more severe cerebral palsy.**

Our data suggest that the effects of AFO may be more pronounced in more severely affected children, perhaps even those who also use hand held assistive devices. The investigation of

such children may preclude the use of the treadmill and require refinement of over-ground testing protocols.

- **Determine if children's improved walking economy with AFO is related to a decrease in stride rate.**

Stride length varies with the square root of height (Todd et al., 1989). Since walking speed is the product of stride length and stride rate, as children grow older, stride rate for the same absolute speed therefore decreases (Waters et al., 1983). Muscular efficiency however, is independent of age or size in healthy individuals (Bar-Or, 1983a). Taylor et al. (1982) hypothesise that the decreased locomotive economy of smaller compared to larger animals is due to the higher stride frequencies of the latter. In other words, compared to larger animals, the smaller ones walking at the same speed require more work by muscle and more O_2 , as more steps are needed to move the body forward. An association between stride rate and the oxygen cost of walk has been shown in children. In a longitudinal study, both $\dot{V}O_2$ and stride rate decreased with age, but $\dot{V}O_2$ per stride did not (Rowland and Cunningham, 1995). Todd et al. (1989) reported on one child with spina bifida for whom stride length was greater with braces on. With braces off, this child could increase speed only by increasing stride rate. If bracing children allows them to have an increased stride length, then at the same absolute speed stride rate should be less. A multidisciplinary approach using kinematic and physiologic measures would be required to answer this question.

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Table 1: Gender, age, anthropometric data and relative body adiposity of individual subjects with comparisons to norms.

Subject	Gender	Age (yr)	Mass (kg)	Mass Percentile*	Arm Span	Arm Span Variability**	S4SF*** (mm)	S4SF Percentile*
1	F	8.6	24.6	20	125.0	-1 SD	34	60
2	M	7.3	21.5	10	128.0	+2 SD	17	5
7	F	12.8	54.0	80	164.5	above 2 SD	62	80
8	M	7.5	19.3	5	123.0	-1 SD	21	30
9	M	8.3	32.9	80	148.0	above 2 SD	56	95
11	M	8.7	22.3	5	129.0	-1 SD	21	30
12	M	8.3	29.1	60	128.0	-1 SD	60	95
13	M	8.0	20.1	5	115.5	below 2 SD	21	30
15	M	7.8	18.9	5	114.0	below 2 SD	19	20
25	F	13.1	36.9	5	159.0	mean	34	30

* Normative data from Canada Fitness Survey (1981)

** Normative data derived from Canada Fitness Survey (1981) using the conversion to arm span and variability suggested by Engstrom et al. (1981)

*** Sum of 4 skin folds (S4SF)

Table 2: Details of AFO use.

Subject	1st AFO Age (yr)	1st hinged AFO Age (yr)	AFO worn week-day (hr)	AFO worn weekend day (hr)	AFO age (mo)	AFO used in gym class	Easier to walk on/off? Parent's opinion	Easier to walk on/off? Child's opinion
1	2.25	4	7	0	2	1/2 time	No Diff.	No Diff.
2	1	1	9	8	9	Yes	On	On
7	4	4	8	0	18	No	On	On
8	5	5	7	4.5	10	No	Off	Off
9	1	5	8	2	18	Yes	On	On
11	2	3.5	9.5	3.5	12	Yes	On	On
12	1.5	6.5	8	0	9	Yes	No Diff.	Off
13	3.25	4.25	12	12	12	Yes	On	On
15	2	3	8	8	8	Yes	Off	Off
25	3	3	6	0	12	No	Off	Off

Table 3: Intended and actual belt speeds for individual subjects.

Subject	Condition	Intended Speed (kph)	Actual Speed		Subject	Condition	Intended Speed (kph)	Actual Speed	
			AFO Off (kph)	AFO On (kph)				AFO Off (kph)	AFO On (kph)
1	3 kph	3	3.03	3.02	11	3 kph	3	3.15	3.13
	CWS	3.6	3.58	3.55		CWS	4	4.19	4.19
	FWS	4.65	4.53	4.51		FWS	4	4.20	4.20
2	3 kph	3	2.96	3.03	12	3 kph/ FWS	3	3.18	3.17
	CWS	3.52	3.54	3.52		CWS	2.4	2.60	2.60
	FWS	4.65	4.61	4.70					
7	3 kph	3	3.03	3.04	13	3 kph			
	CWS	4.5	4.56	4.53		CWS	3.5	3.61	3.61
	FWS	4.5	4.58	4.53		FWS	4	4.06	4.10
8	3 kph	3	3.19	3.31	15	3 kph	3	3.17	3.18
	CWS	3.7	3.94	4.04		CWS	4	4.13	4.18
	FWS	4.5	4.65	4.77		FWS	5	5.11	5.02
9	3 kph	3	3.17	3.16	25	3 kph	3	3.16	3.13
	CWS	2.4	2.57	2.53		CWS/ FWS	4	4.10	4.11
	FWS	4	4.16	4.11		FWS			

CWS=Comfortable Walking Speed
FWS=Fastest Walking Speed

Table 4: Sample group means, standard error data and ANOVA results for ground walking speed (n=10).

Speed Condition	AFO Off		AFO On		Effect	F	p
	Mean (kph)	SEM	Mean (kph)	SEM			
Comfortable	3.87	0.211	3.97	0.169	AFO	1.496	.25
Maximum	4.91	0.238	5.10	0.187	Speed	63.222 ⁺	.00002 ⁺
					AFO x Speed	.877	.37

⁺ Maximum walking speed is higher than comfortable walking speed.

Table 5: Sample group means, standard error data and ANOVA results for Gross Motor Function Measure dimension scores (n=10).

Dimension	AFO Off		AFO On		Effect	F	p
	Mean (%)	SEM	Mean (%)	SEM			
Standing	87.38	1.61	87.70	1.70	AFO	.077	.79
Walking, Running and Jumping	83.42	3.16	83.61	2.71	Dimension	5.20 ⁺	.05 ⁺
					AFO x Dimension	.008	.93

⁺ Standing dimension score is higher than Walking Running and Jumping dimension score.

Table 6: Group means, standard error data and ANOVA results for heart rate (HR).

Subjects	Speed	AFO Off		AFO On		Effect	F	p
		Mean (BPM)	SEM	Mean (BPM)	SEM			
3 speeds n=5	3 kph	129	6.16	133	7.02	AFO	1.118	.35
	CWS	137	8.60	140	8.07	Speed	35.456 ⁺	.0001 ⁺
	FWS	168	5.69	167	8.08	AFO x Speed	1.899	.21
3 kph-CWS n=8	3 kph	140	8.23	141	7.67	AFO	.906	.37
	CWS	147	7.23	149	6.44	Speed	1.986	.20
						AFO x Speed	.135	.72
3 kph-FWS n=7	3 kph	133	4.74	134	4.95	AFO	.199	.67
	FWS	165	4.45	165	5.75	Speed	84.001 ⁺	.000095 ⁺
						AFO x Speed	.471	.52
FWS n=9	FWS	169	4.48	168	4.98	AFO	(t) .661	.53

⁺ HR was higher at fast walking speed (FWS) ($p < .05$), compared to any other speed for that sub-sample.

CWS=comfortable walking speed.

Table 7: Group means, standard error data and ANOVA results for pulmonary ventilation (\dot{V}_E).

Subjects	Speed	AFO Off		AFO On		Effect	F	p	Omega-squared
		Mean (L·min ⁻¹)	SEM	Mean (L·min ⁻¹)	SEM				
3 speeds n=4	3 kph	14.850	2.13	13.794	1.92	AFO	.433	.55	
	CWS	17.554	1.53	19.096	2.28	Speed	50.775 ⁺	.0002 ⁺	
	FWS	25.404	2.69	26.712	3.37	AFO x Speed	2.813	.14	
3 kph- CWS n=9	3 kph	19.125	2.25	17.779	2.28	AFO	.655	.44	
	CWS	22.282	2.28	22.554	2.38	Speed	4.063	.08	
						AFO x Speed	6.800 [*]	.03 [*]	
3 kph- FWS n=7	3 kph	17.311	1.82	15.753	1.68	AFO	2.078	.19	.12
	FWS	26.178	2.82	26.045	2.97	Speed	38.082 ^{**}	.0008 ^{**}	
						AFO x Speed	2.720	.15	.17
FWS n=8	FWS	27.800	2.12	27.476	2.19	AFO	(t) .458	.66	

* Significant interaction between AFO and speed. Post hoc testing showed \dot{V}_E was lower at 3 kph with AFO on ($p < .05$).

⁺ Ventilation different at each of the different speeds. Ventilation was highest at fast walking speed (FWS), lowest at 3 kph ($p < .05$).

^{**} Ventilation higher at FWS.

CWS=comfortable walking speed.

Table 8: Group means, standard error data and ANOVA results for absolute oxygen uptake ($\dot{V}O_{2abs}$).

Subjects	Speed	AFO Off		AFO On		Effect	F	p	Omega-squared
		Mean ($L \cdot min^{-1}$)	SEM	Mean ($L \cdot min^{-1}$)	SEM				
3 speeds n=4	3 kph	0.370	0.07	0.355	0.08	AFO	.041	.85	
	CWS	0.469	0.06	0.495	0.06	Speed	55.76 ⁺	.0001 ⁺	
	FWS	0.693	0.09	0.672	0.09	AFO x Speed	2.13	.201	
3 kph- CWS n=9	3 kph	0.504	0.06	0.481	0.07	AFO	.341	.58	
	CWS	0.610	0.09	0.612	0.09	Speed	4.02	.08	
						AFO x Speed	5.827 [*]	.04 [*]	
3 kph- FWS n=7	3 kph	0.467	0.07	0.441	0.07	AFO	4.436	.08	.30
	FWS	0.764	0.09	0.731	0.09	Speed	79.05 ⁺⁺	.0001 ⁺⁺	
						AFO x Speed	.293	.61	
FWS n=8	FWS	0.764	0.08	0.732	0.08	AFO	(t) 3.74 ^{**}	.007 ^{**}	

* Significant interaction between AFO and speed. Post hoc testing showed $\dot{V}O_{2abs}$ was lower at 3 kph with AFO on ($p < .05$).

** $\dot{V}O_{2abs}$ lower with AFO on.

+ $\dot{V}O_{2abs}$ different at each speed. Ventilation was highest at fast walking speed (FWS), lowest at 3 kph ($p < .05$).

++ $\dot{V}O_{2abs}$ higher at FWS.

CWS=comfortable walking speed.

Table 9: Group means, standard error data and ANOVA results for the ventilatory equivalent for oxygen ($\dot{V}E/\dot{V}O_2$).

Subjects	Speed	AFO Off		AFO On		Effect	F	p
		Mean	SEM	Mean	SEM			
3 speeds n=4	3 kph	41.548	2.92	43.753	8.09	AFO	1.520	.31
	CWS	37.956	1.73	38.942	1.67	Speed	.941	.44
	FWS	37.068	1.25	40.088	1.36	AFO x Speed	.105	.90
3 kph- CWS n=9	3 kph	40.022	1.95	40.147	3.76	AFO	.030	.87
	CWS	37.977	1.61	38.264	1.47	Speed	1.153	.31
						AFO x Speed	.004	.95
3 kph- FWS n=7	3 kph	38.900	2.36	39.818	4.90	AFO	.716	.43
	FWS	36.090	1.22	37.803	1.80	Speed	.917	.38
						AFO x Speed	.080	.79
FWS n=8	FWS	36.998	1.39	38.449	1.69	AFO	(t) -1.20	.09

$\dot{V}E/\dot{V}O_2$ was not affected by AFO or speed, nor was the effect of AFO on $\dot{V}E/\dot{V}O_2$ different at different speeds.

CWS=comfortable walking speed.

Table 10: Group means, standard error data and ANOVA results for mass adjusted oxygen uptake ($\dot{V}O_{2\text{mass}}$).

Subjects	Speed	AFO Off		AFO On		Effect	F	p	Omega-squared
		Mean ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	SEM	Mean ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	SEM				
3 speeds n=4	3 kph	15.847	2.78	14.711	2.98	AFO	.960	.40	
	CWS	20.212	2.28	20.635	2.01	Speed	66.805 ^{**}	.00008 ^{**}	
	FWS	29.704	3.30	28.091	3.35	AFO x Speed	2.747	.14	
3 kph- CWS n=9	3 kph	16.422	1.61	15.180	1.64	AFO	1.878	.21	.25
	CWS	19.596	1.39	19.155	1.30	Speed	5.935 ⁺	.04 ⁺	
						AFO x Speed	4.291	.07	
3 kph- FWS n=7	3 kph	15.560	1.55	14.130	1.62	AFO	8.937 [*]	.03 [*]	
	FWS	26.149	2.44	24.376	2.51	Speed	42.376 ⁺	.0006 ⁺	
						AFO x Speed	.660	.45	
FWS n=8	FWS	26.004	2.12	24.300	2.17	AFO	(t) 4.92 [*]	.002 [*]	

* $\dot{V}O_{2\text{mass}}$ lower with AFO.

+ $\dot{V}O_{2\text{mass}}$ lower at 3 kph.

** $\dot{V}O_{2\text{mass}}$ different at each speed. Mass adjusted $\dot{V}O_2$ highest at fast walking speed (FWS), lowest at 3 kph ($p < .05$).

CWS=comfortable walking speed.

Table 11: Group means, standard error data and ANOVA results for net oxygen uptake ($\dot{V}O_{2net}$).

Subjects	Speed	AFO Off		AFO On		Effect	F	p	Omega-squared
		Mean (L·min ⁻¹)	SEM	Mean (L·min ⁻¹)	SEM				
3 speeds n=4	3 kph	0.281	0.06	0.266	0.07	AFO	.041	.85	
	CWS	0.381	0.05	0.406	0.06	Speed	55.76 ⁺⁺	.0001 ⁺⁺	
	FWS	0.605	0.08	0.583	0.09	AFO x Speed	2.126	.20	
3 kph- CWS n=9	3 kph	0.388	0.05	0.365	0.06	AFO	.3364	.58	
	CWS	0.494	0.08	0.496	0.09	Speed	4.026	.08	
						AFO x Speed	6.116*	.04*	
3 kph- FWS n=7	3 kph	0.357	0.06	0.331	0.06	AFO	4.8	.07	.33
	FWS	0.600	0.08	0.564	0.08	Speed	23.38 ⁺	.002 ⁺	
						AFO x Speed	.744	.42	
FWS n=8	FWS	0.607	0.07	0.571	0.07	AFO	(t) 4.02 ^{**}	.005 ^{**}	

* Significant interaction between AFO and speed. Post hoc testing showed $\dot{V}O_{2net}$ to be lower at 3 kph with AFO on ($p < .05$).

** $\dot{V}O_{2net}$ lower with AFO on.

+ $\dot{V}O_{2net}$ highest at fast walking speed (FWS).

++ $\dot{V}O_{2net}$ different at each speed. Net $\dot{V}O_2$ was highest at FWS, lowest at 3 kph ($p < .05$).

CWS=comfortable waking speed.

Table 12: Group means, standard error data and ANOVA results for absolute oxygen uptake per metre walked ($\dot{V}O_{2me}$).

Subjects	Speed	AFO Off		AFO On		Effect	F	p	Omega-squared
		Mean (L·m ⁻¹)	SEM	Mean (L·m ⁻¹)	SEM				
3 speeds n=4	3 kph	0.00740	0.0014	0.00709	0.0015	AFO	.023	.89	
	CWS	0.00769	0.0011	0.00811	0.0012	Speed	12.80 ⁺⁺	.007 ⁺⁺	
	FWS	0.00891	0.0012	0.00864	0.0013	AFO x Speed	1.78	.25	
3 kph-CWS n=9	3 kph	0.01007	0.0012	0.00962	0.0013	AFO	.505	.50	
	CWS	0.01036	0.0012	0.01037	0.0012	Speed	6.971 ⁺	.03 ⁺	
						AFO x Speed	8.04 [*]	.02 [*]	
3 kph-FWS n=7	3 kph	0.00934	0.0014	0.00882	0.0015	AFO	3.73	.10	.25
	FWS	0.01033	0.0012	0.00988	0.0012	Speed	13.092 ⁺	.01 ⁺	
						AFO x Speed	.051	.83	
FWS n=8	FWS	0.01096	0.0012	0.01048	0.0012	AFO	(t) 3.58 ^{**}	.009 ^{**}	

* Significant interaction between AFO and speed. Post hoc testing showed $\dot{V}O_{2mw}$ to be lower at 3 kph with AFO on ($p < .05$).

** $\dot{V}O_{2mw}$ lower with AFO on.

⁺ $\dot{V}O_{2mw}$ lower at 3 kph.

⁺⁺ $\dot{V}O_{2mw}$ different at each speed. Absolute oxygen uptake per metre walked was highest at fast walking speed (FWS), lowest at 3 kph ($p < .05$).

CWS=comfortable walking speed.

Table 13: Group means, standard error data and ANOVA results for mass adjusted oxygen uptake per metre walked ($\dot{V}O_{2mmw}$).

Subjects	Speed	AFO Off		AFO On		Effect	F	p
		Mean ($ml \cdot kg^{-1} \cdot m^{-1}$)	SEM	Mean ($ml \cdot kg^{-1} \cdot m^{-1}$)	SEM			
3 speeds n=4	3 kph	0.317	0.06	0.294	0.06	AFO	.746	.45
	CWS	0.330	0.04	0.337	0.04	Speed	11.55 ⁺⁺	.009 ⁺⁺
	FWS	0.381	0.05	0.361	0.05	AFO x Speed	1.99	.22
3 kph- CWS n=9	3 kph	0.328	0.03	0.304	0.03	AFO	2.23	.17
	CWS	0.345	0.03	0.337	0.03	Speed	8.704 ⁺	.02 ⁺
						AFO x Speed	5.881 [*]	.04 [*]
3 kph- FWS n=7	3 kph	0.311	0.03	0.283	0.03	AFO	7.417 ^{**}	.03 ^{**}
	FWS	0.351	0.03	0.326	0.03	Speed	9.808 ⁺	.02 ⁺
						AFO x Speed	.190	.68
FWS n=8	FWS	0.369	0.03	0.345	0.03	AFO	(t) 4.84 ^{**}	.002 ^{**}

* Significant interaction between AFO and speed. Post hoc testing showed $\dot{V}O_{2mmw}$ to be lower at 3 kph with AFO on ($p < .05$).

** $\dot{V}O_{2mmw}$ lower with AFO on.

+ $\dot{V}O_{2mmw}$ lower at 3 kph.

++ $\dot{V}O_{2mmw}$ different at each speed. This measure was highest at fast waking speed (FWS), lowest at 3 kph ($p < .05$).

CWS=comfortable walking speed.

Table 14: Group means, standard error data and ANOVA results for respiratory exchange ratio (RER).

Subjects	Speed	AFO Off		AFO On		Effect	F	p
		Mean	SEM	Mean	SEM			
3 speeds n=4	3 kph	0.81	0.03	0.83	0.04	AFO	.834	.43
	CWS	0.83	0.03	0.85	0.04	Speed	13.027 ⁺	.007 ⁺
	FWS	0.87	0.04	0.93	0.03	AFO x Speed	.663	.55
3 kph- CWS n=9	3 kph	0.85	0.03	0.86	0.03	AFO	1.472	.26
	CWS	0.86	0.02	0.89	0.03	Speed	1.485	.26
						AFO x Speed	.898	.37
3 kph- FWS n=7	3 kph	0.82	0.03	0.83	0.03	AFO	1.05	.35
	FWS	0.87	0.03	0.91	0.03	Speed	14.823 ⁺	.009 ⁺
						AFO x Speed	1.213	.31
FWS n=8	FWS	0.89	0.03	0.92	0.03	AFO	(t) -2.109	.07

⁺ RER highest at fast walking speed (FWS) for that sub-sample ($p < .05$).
CWS=comfortable walking speed.

Table 15: Group means, standard error data and ANOVA results for gross energy expenditure (EE_{gross}).

Subjects	Speed	AFO Off		AFO On		Effect	F	p	Omega-squared
		Mean (kJ)	SEM	Mean (kJ)	SEM				
3 speeds n=4	3 kph	8.571	2.34	8.527	2.52	AFO	.046	.84	
	CWS	9.488	1.08	10.044	1.22	Speed	12.059 ⁺	.008 ⁺	
	FWS	14.145	1.78	13.895	1.85	AFO x Speed	1.465	.30	
3 kph-CWS n=9	3 kph	10.755	1.38	10.408	1.45	AFO	.087	.78	
	CWS	12.402	1.73	12.528	1.82	Speed	1.795	.21	
						AFO x Speed	5.35 [*]	.05 [*]	
3 kph-FWS n=7	3 kph	10.054	1.57	9.666	1.70	AFO	2.16	.19	.13
	FWS	15.559	1.68	15.017	1.75	Speed	61.423 ⁺	.0002 ⁺	
						AFO x Speed	.428	.54	
FWS n=8	FWS	16.00	1.53	15.31	1.62	AFO	(t) 3.49 ^{**}	.01 ^{**}	

* Significant interaction between AFO and speed. Post hoc testing showed EE_{gross} to be lower at 3 kph with AFO on ($p < .05$).

** EE_{gross} lower with AFO on.

⁺ EE_{gross} highest at fast walking speed (FWS) in that sub-sample ($p < .05$).

CWS=comfortable walking speed.

Table 16: Groups means, standard error data and ANOVA results for net energy expenditure (EE_{net}).

Subjects	Speed	AFO Off		AFO On		Effect	F	p	Omega-squared
		Mean (kJ)	SEM	Mean (kJ)	SEM				
3 speeds n=4	3 kph	5.619	1.27	5.299	1.36	AFO	.0001	.99	
	CWS	7.650	0.97	8.206	1.07	Speed	55.439 ⁺⁺	.0001 ⁺⁺	
	FWS	12.308	1.66	12.057	1.73	AFO x Speed	2.225	.19	
3 kph-CWS n=9	3 kph	7.938	1.18	7.468	1.22	AFO	.192	.67	
	CWS	10.469	1.59	10.603	1.66	Speed	4.904	.06	
						AFO x Speed	13.4*	.006*	
3 kph-FWS n=7	3 kph	7.150	1.12	6.604	1.23	AFO	2.98	.14	.20
	FWS	13.291	1.49	12.749	1.58	Speed	85.29 ⁺⁺	.00009 ⁺⁺	
						AFO x Speed	.0002	.99	
FWS n=8	FWS	13.52	1.35	12.95	1.43	AFO	(t) 2.80 ^{**}	.03 ^{**}	

* Significant interaction between AFO and speed. Post hoc testing showed EE_{net} to be lower at 3 kph with AFO on ($p < .05$).

** EE_{net} lower with AFO on.

⁺⁺ EE_{net} highest at fast walking speed (FWS) for that subsample ($p < .05$).

CWS=comfortable walking speed.

Table 17: Summary of results.

Variable [#]	Speed Higher?		Variable ^{##}	Belt Speed Condition Lower?		
	Comfortable	Maximum		3 kph	CWS	FWS
Ground Walking Speed	AFO On	AFO On	Heart Rate	AFO Off	AFO Off	AFO On
	Score Higher?		Pulmonary Ventilation	AFO On*	AFO Off	AFO Off
Variable [#]			Standing	Walking, Running, Jumping	Absolute $\dot{V}O_2$	AFO On*
	Gross Motor Function Measure	AFO On			AFO On	Ventilatory Equivalent for Oxygen
			Mass Adjusted $\dot{V}O_2$	AFO On*	AFO On	AFO On*
			Net $\dot{V}O_2$	AFO On*	AFO Off	AFO On*
			Absolute $\dot{V}O_2$ per metre walked	AFO On*	AFO Off	AFO On*
			Mass Adjusted $\dot{V}O_2$ per metre walked	AFO On*	AFO On	AFO On*
			Respiratory Exchange Ratio	AFO Off	AFO Off	AFO Off
			Gross Energy Expenditure	AFO On*	AFO Off	AFO On*
			Net Energy Expenditure	AFO On*	AFO Off	AFO On*

[#]Includes all children

^{##}Includes children who walked at 3 kph and comfortable walking speed (CWS) and those who walked at fast walking speed (FWS)

*Significant difference ($p < .05$) between AFO on and off measures

[†]Trend, ($p < .07$) omega-squared=.25

$\dot{V}O_2$ =oxygen uptake

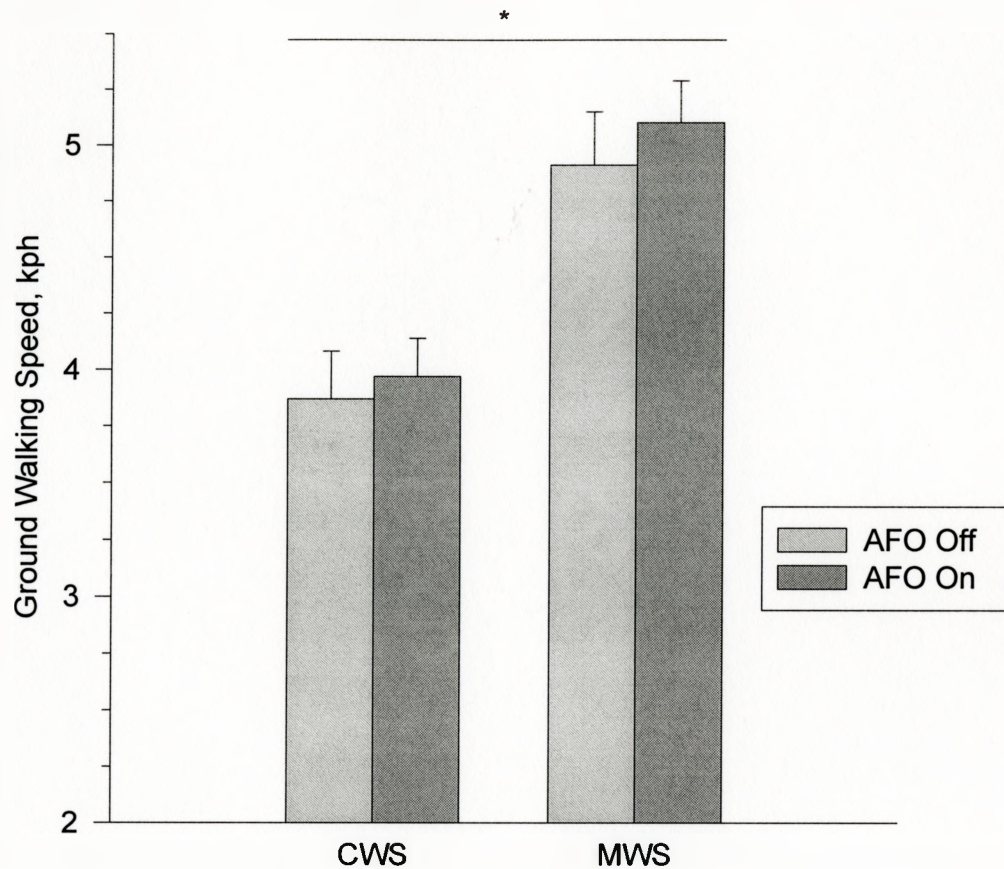


Figure 1: Effect of AFO on ground walking speed at comfortable walking speed (CWS) and maximum walking speed (MWS) conditions. Error bars denote SEM (n=10).

* CWS and MWS were significantly different from each other ($p=.00002$), but there was no difference at either speed condition between AFO on or off.

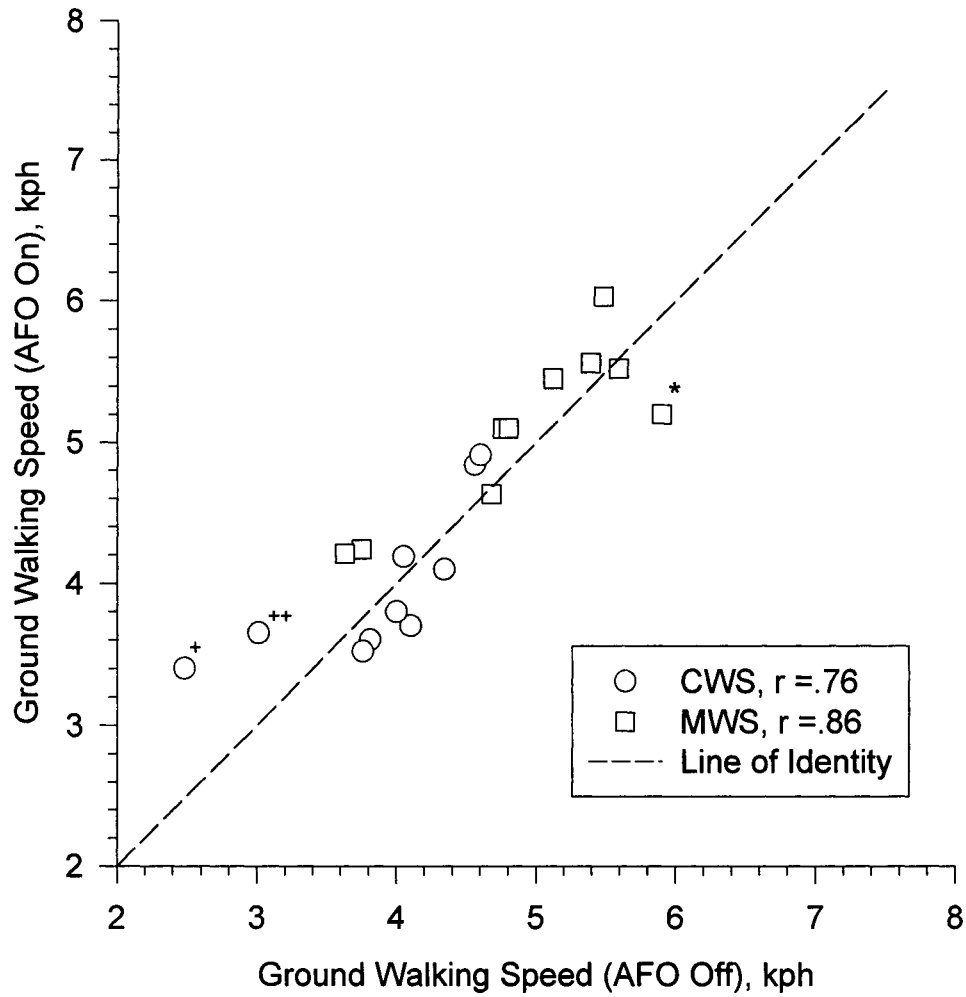


Figure 2: Individual ground walking speed responses to AFO at comfortable walking speed (CWS) and maximum walking speed (MWS) conditions ($n=10$).

* Subject 8.

+ Subject 9.

++ Subject 12.

See text for details on above mentioned subjects.

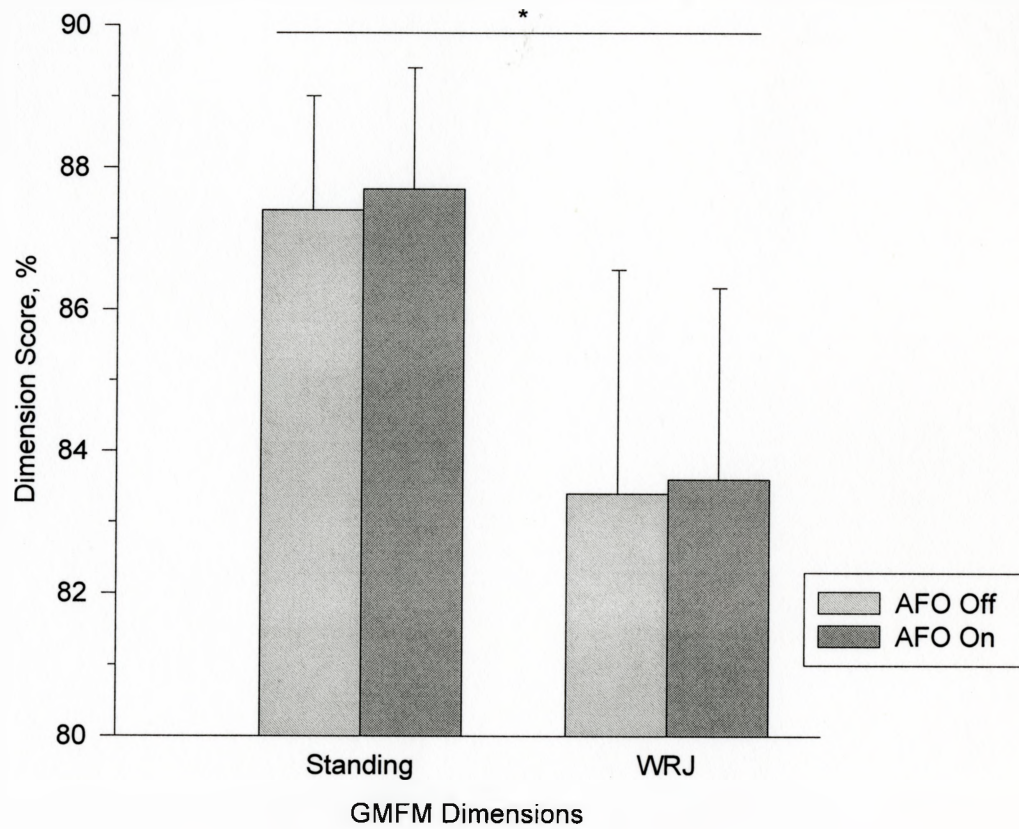


Figure 3: Effect of AFO on the Standing and Walking, Running & Jumping (WRJ) dimensions of the Gross Motor Function Measure. Error bars demote SEM (n=10).

* Standing and WRJ dimension scores were significantly different ($p=.05$) from each other, but there was no difference at either dimension between AFO on or off conditions.

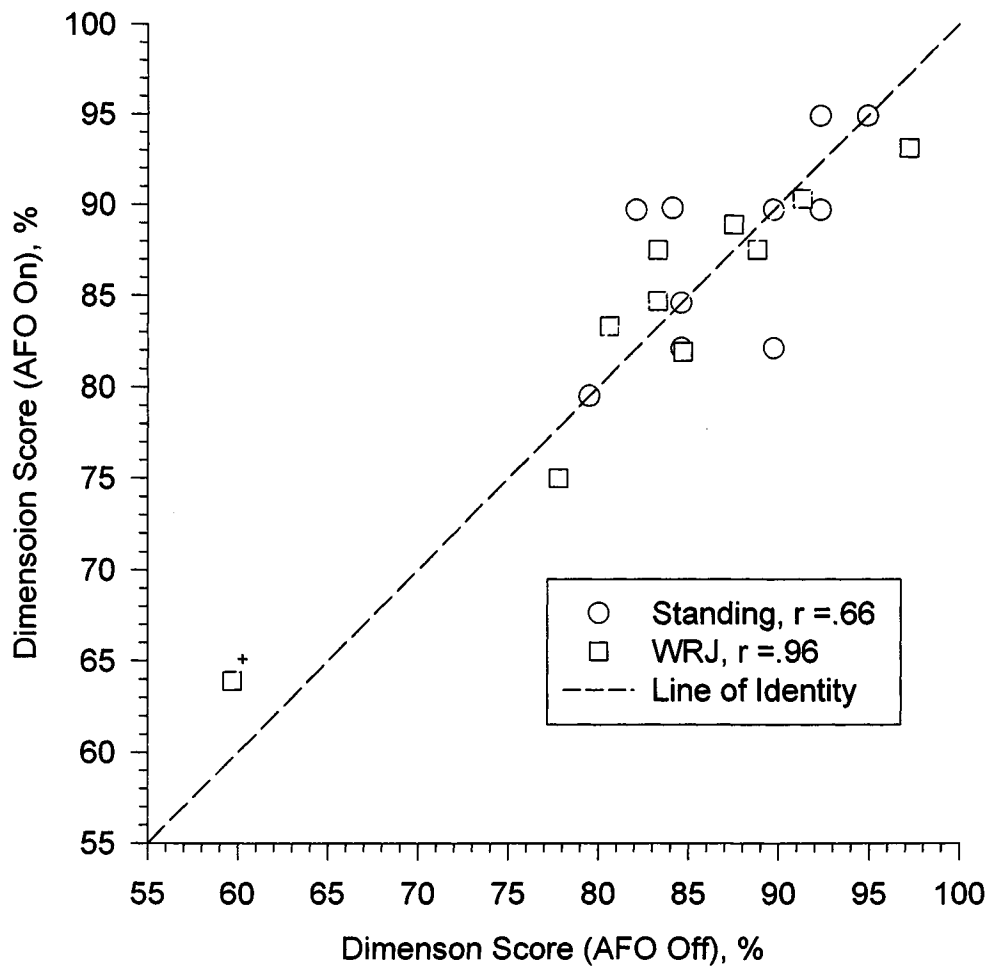


Figure 4: Individual dimension score responses to AFO at Standing and Walking, Running & Jumping (WRJ) dimensions of the Gross Motor Function Measure (n=10).

* Subject 12.

See text for details on above mentioned subject.

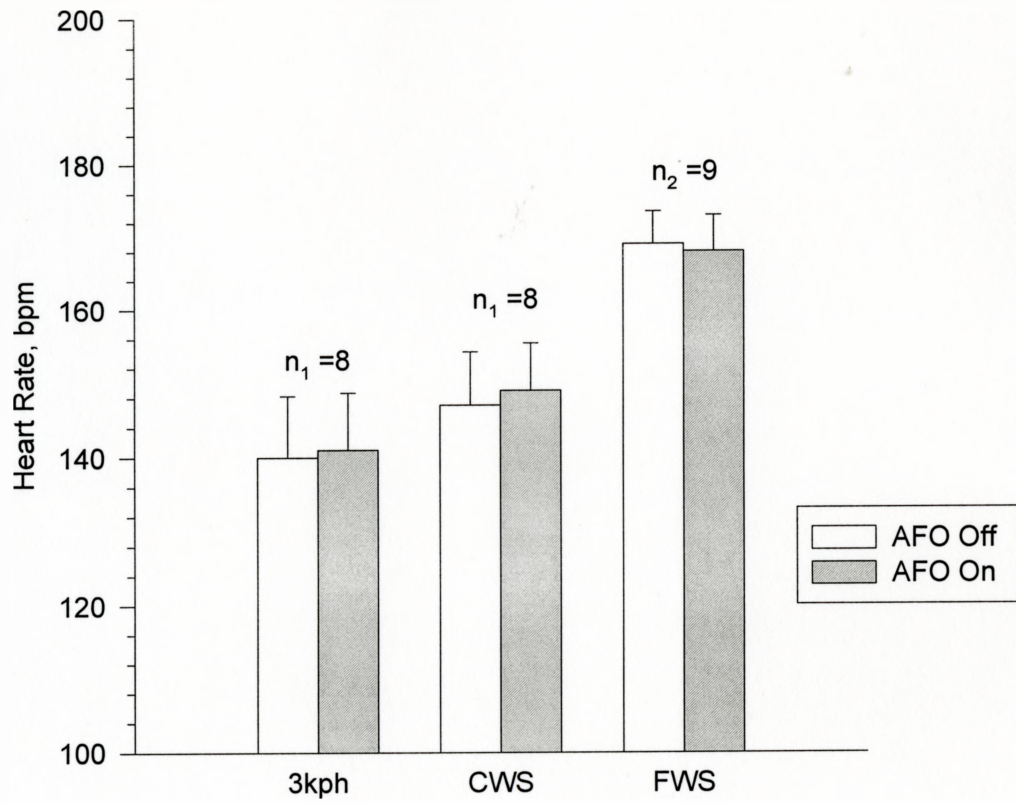


Figure 5: Effect of AFO on heart rate (HR).

n_1 =subjects who walked at 3 kph and comfortable walking speed (CWS); n_2 =subjects who walked at fast walking speed (FWS).

There was no effect on HR due to AFO at any speed.

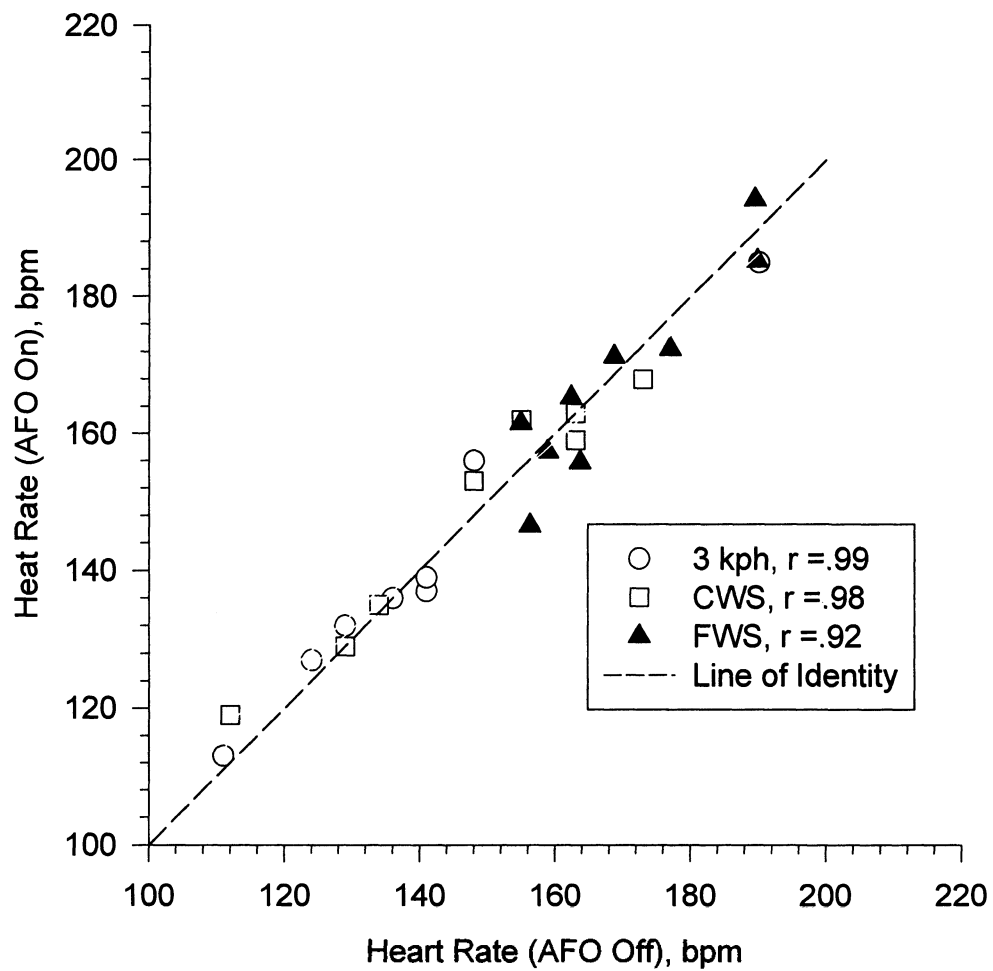


Figure 6: Individual heart rate (HR) responses to AFO. Open shapes denote subjects who walked at 3 kph and comfortable walking speed (CWS) (n=8). Filled triangles denote subjects who walked at fast walking speed (FWS) (n=9).

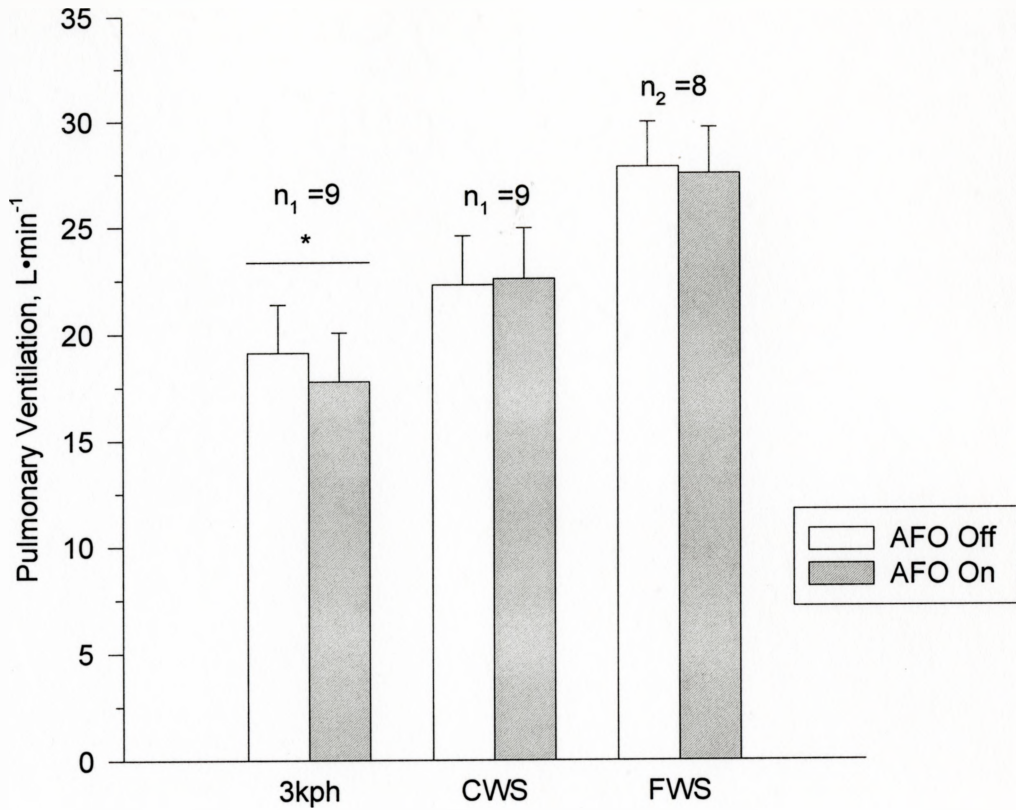


Figure 7: Effect of AFO on pulmonary ventilation (\dot{V}_E).

n_1 =subjects who walked at 3 kph and comfortable walking speed (CWS); n_2 =subjects who walked at fast walking speed (FWS).

* \dot{V}_E was lower ($p < .05$) with AFO on at 3 kph.

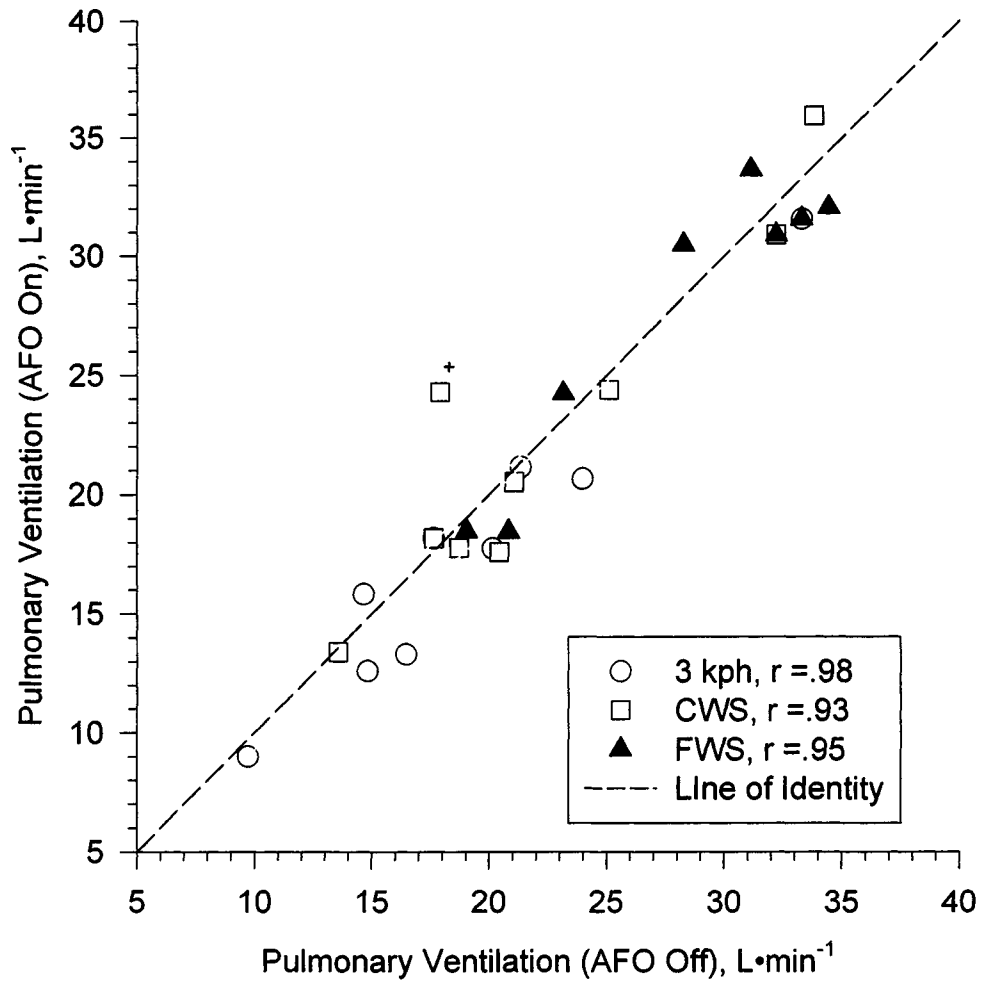


Figure 8: Individual pulmonary ventilation (\dot{V}_E) responses to AFO. Open shapes denote subjects who walked at 3 kph and comfortable walking speed (CWS) ($n=8$). Filled triangles denote subjects who walked at fast walking speed (FWS). ($n=9$).
 * Subject 1.
 See text for details on above mentioned subject.

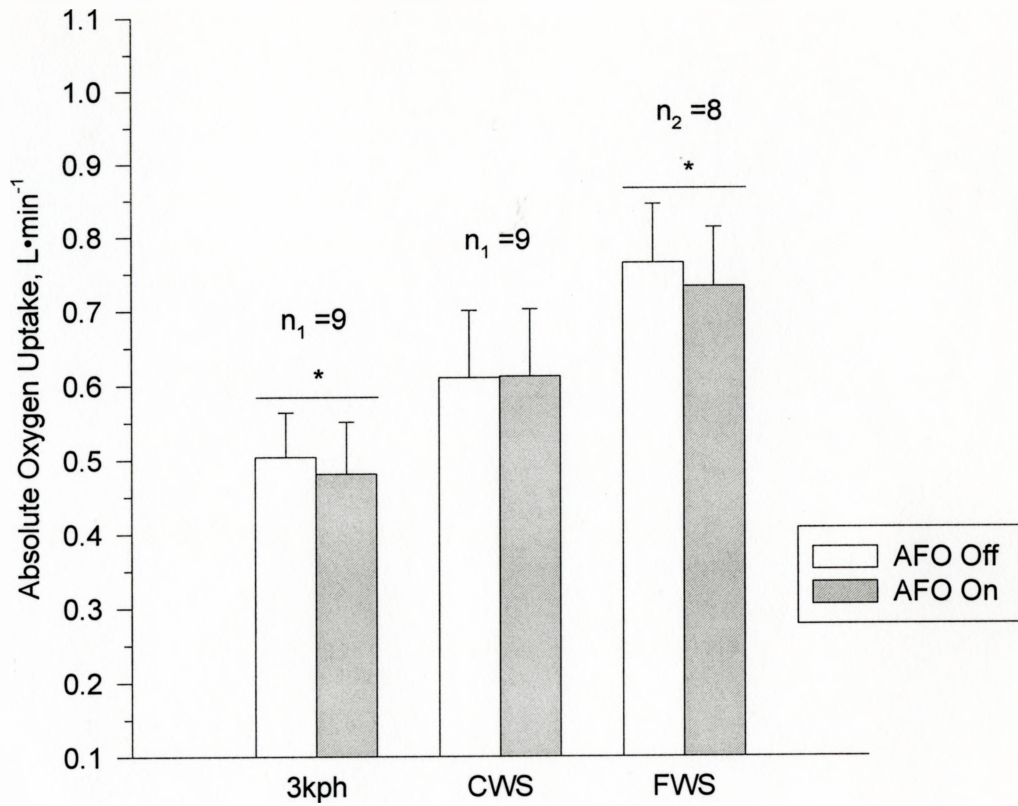


Figure 9: Effect of AFO on absolute oxygen uptake ($\dot{V}O_{2abs}$).

n_1 =subjects who walked at 3 kph and comfortable walking speed (CWS); n_2 =subjects who walked at fast walking speed (FWS).

* $\dot{V}O_{2abs}$ was lower ($p < .05$) with AFO on at 3 kph and at FWS ($p=.007$).

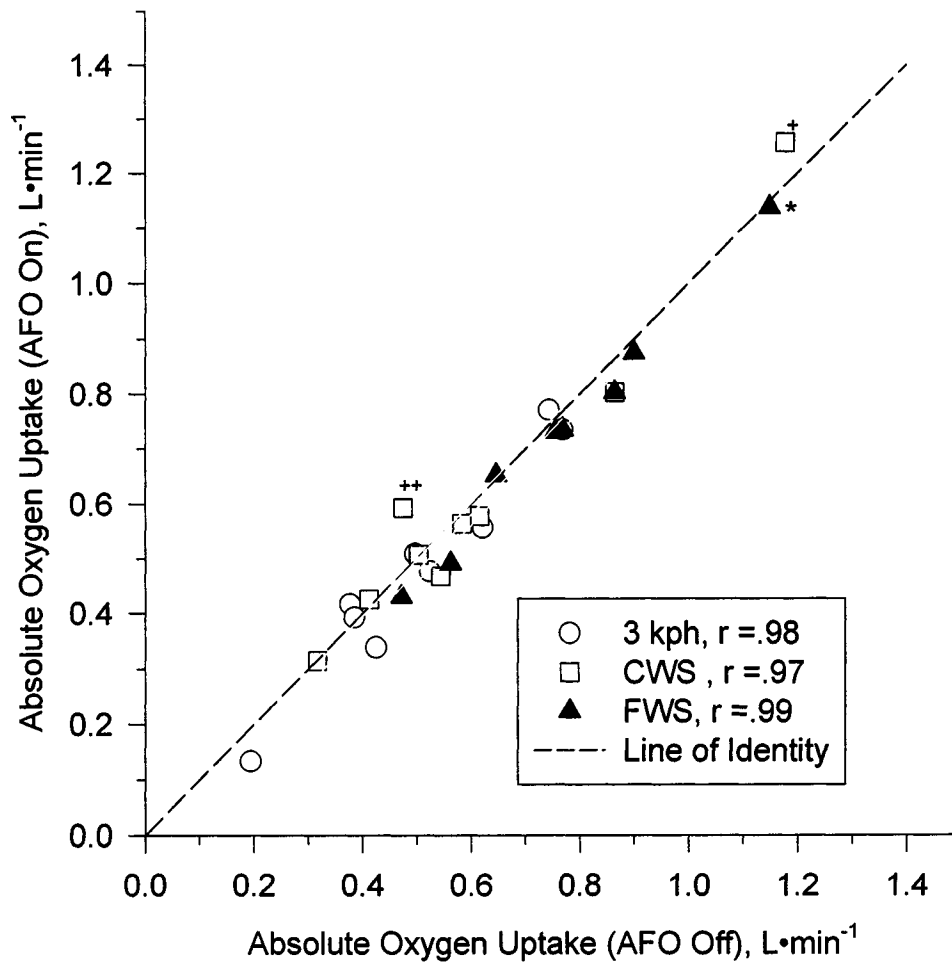


Figure 10: Individual absolute oxygen uptake ($\dot{V}O_{2abs}$) responses to AFO. Open shapes denote subjects who walked at 3 kph and comfortable walking speed (CWS) (n=8). Filled triangles denote subjects who walked at fast walking speed (FWS) (n=9).
 * Subject 7.
 † Subject 7.
 †† Subject 1.
 See text for details on above mentioned subjects.

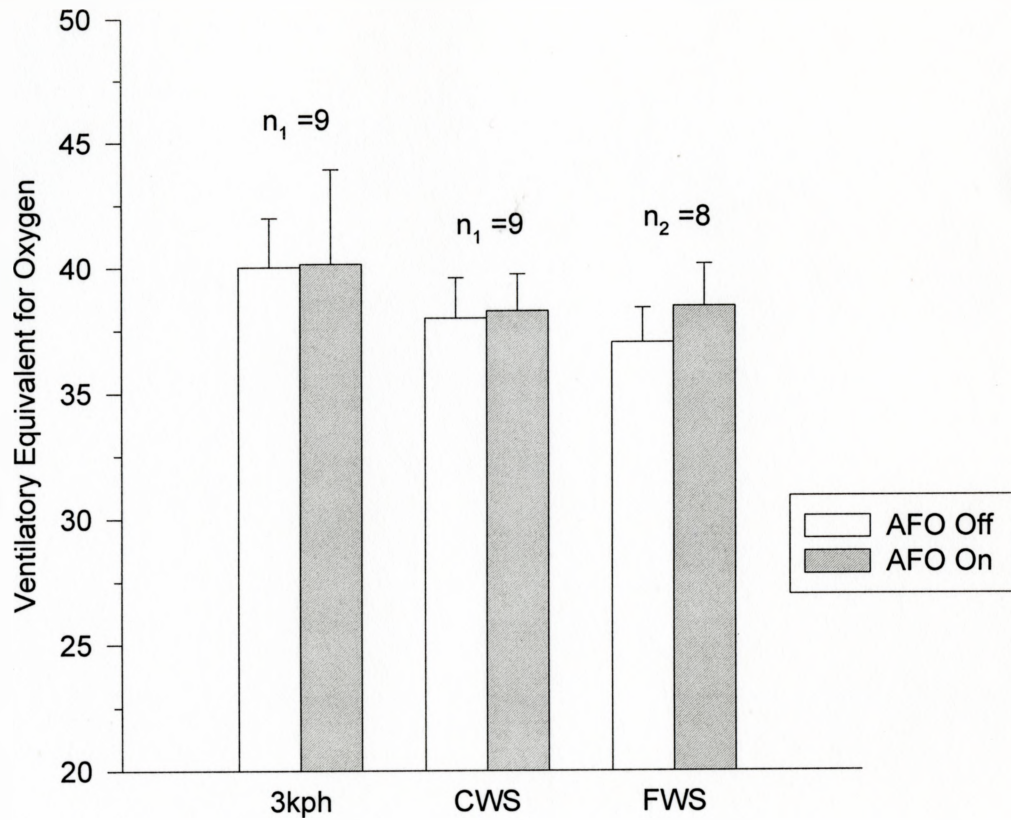


Figure 11: Effect of AFO on the ventilatory equivalent oxygen ($\dot{V}E/\dot{V}O_2$).
 n_1 =subjects who walked at 3 kph and comfortable walking speed (CWS); n_2 =subjects who walked at fast walking speed (FWS).
There was no effect on $\dot{V}E/\dot{V}O_2$ due to AFO at any speed.

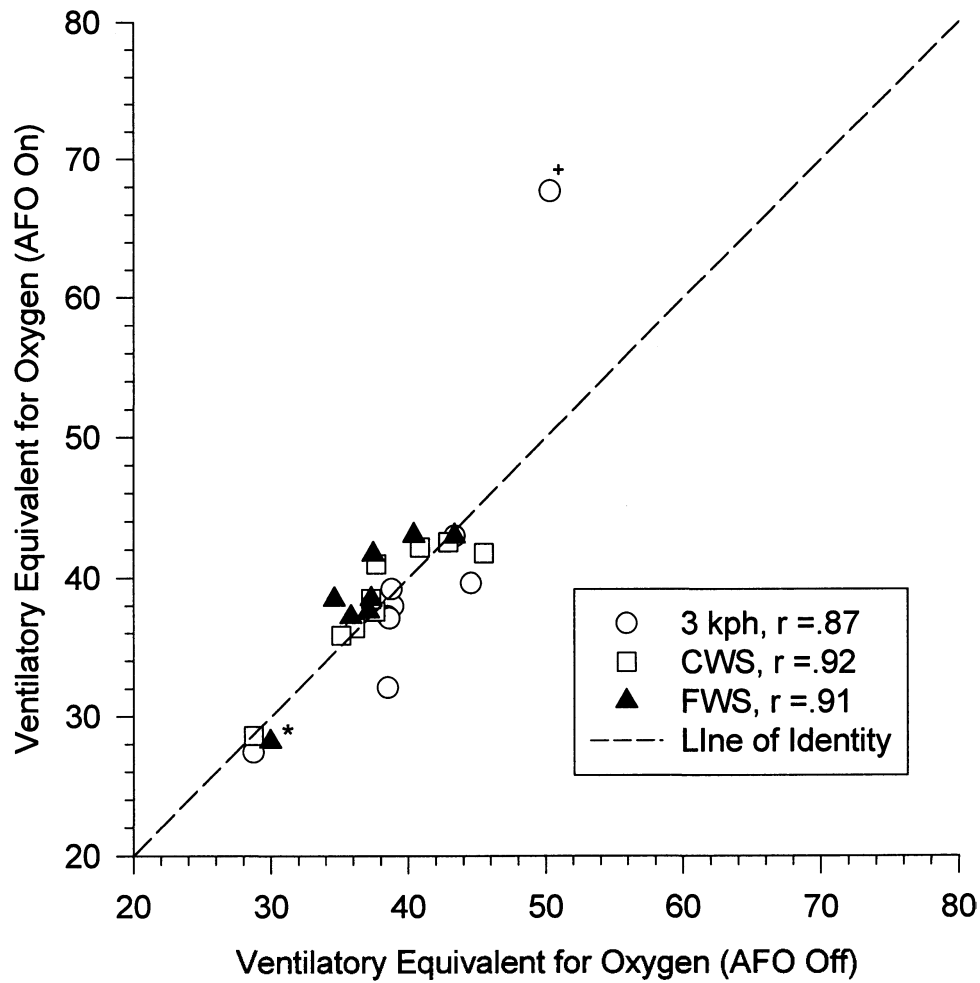


Figure 12: Individual ventilatory equivalent for oxygen ($\dot{V}E/\dot{V}O_2$) responses to AFO. Open shapes denote subjects who walked at 3 kph and comfortable walking speed (CWS). (n=8). Filled triangles denote subjects who walked at fast walking speed (FWS) (n=9). * Subject 7 at 3 kph, CWS and FWS. + Subject 15. See text for details on above mentioned subject.

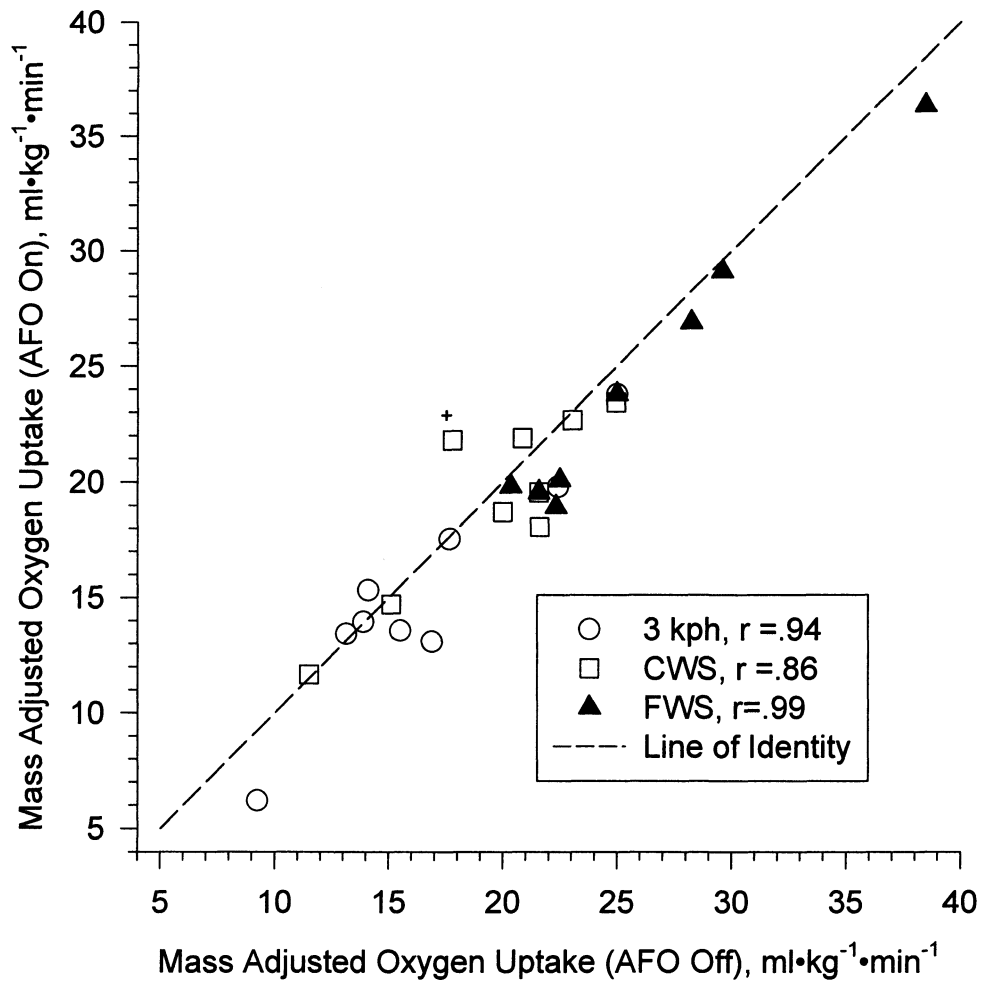


Figure 13: Individual mass adjusted oxygen uptake ($\dot{V}O_{2\text{mass}}$) responses to AFO. Open shapes denote subjects who walked at 3 kph and comfortable walking speed (CWS) ($n=8$). Filled triangles denote subjects who walked at fast walking speed (FWS) ($n=9$).
 + Subject 1.
 See text for details on above mentioned subjects.

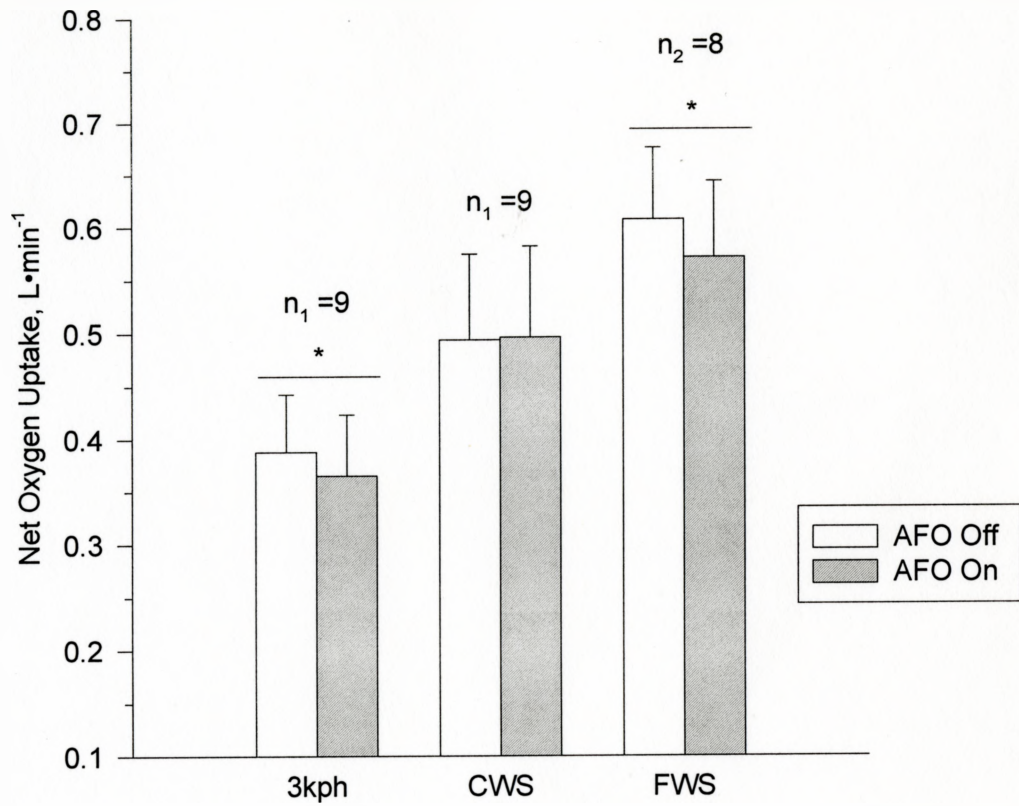


Figure 14: Effect of AFO on net oxygen uptake ($\dot{V}O_{2net}$).

n_1 =subjects who walked at 3 kph and comfortable walking speed (CWS); n_2 =subjects who walked at fast walking speed (FWS).

* $\dot{V}O_{2net}$ was lower ($p < .05$) with AFO on at 3 kph and at FWS ($p = .005$).

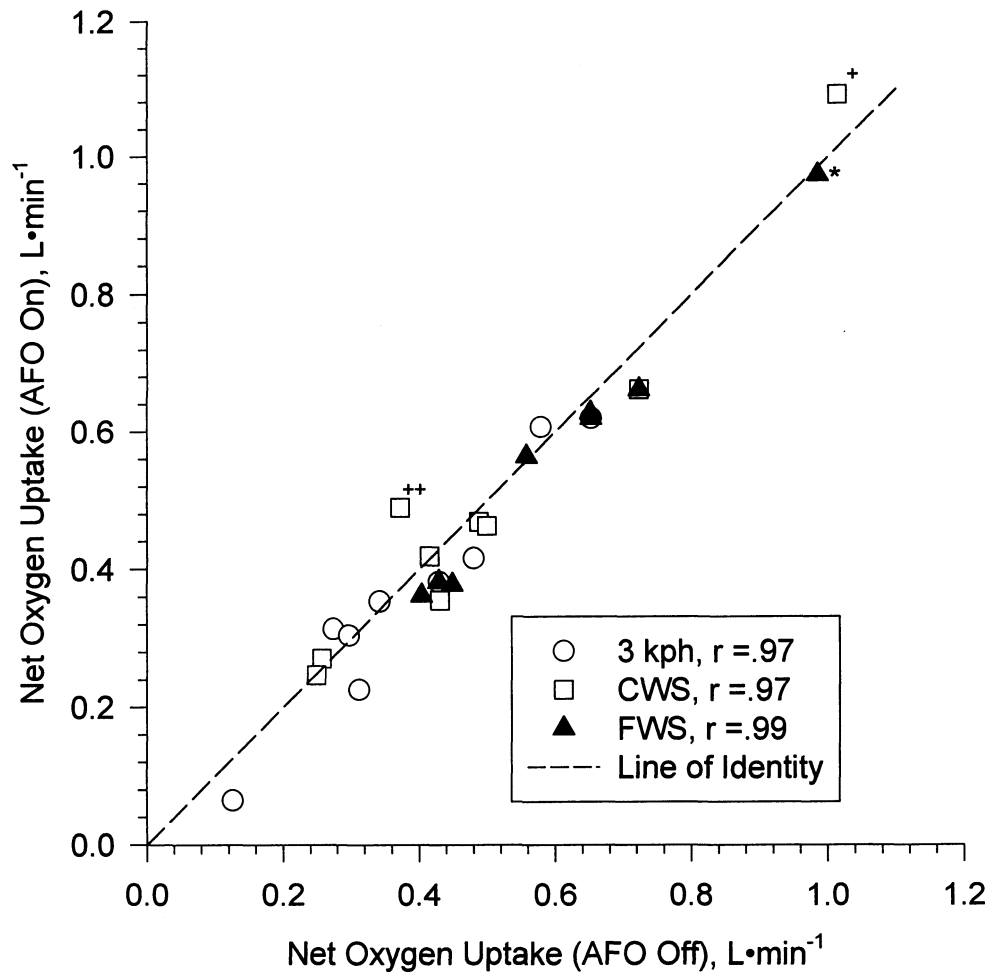


Figure 15: Individual net oxygen uptake ($\dot{V}O_{2net}$) responses to AFO. Open shapes denote subjects who walked at 3 kph and comfortable walking speed (CWS) (n=8). Filled triangles denote subjects who walked at fast walking speed (FWS) (n=9).
 * Subject 7.
 + Subject 7.
 ++ Subject 1.
 See text for details on above mentioned subjects.

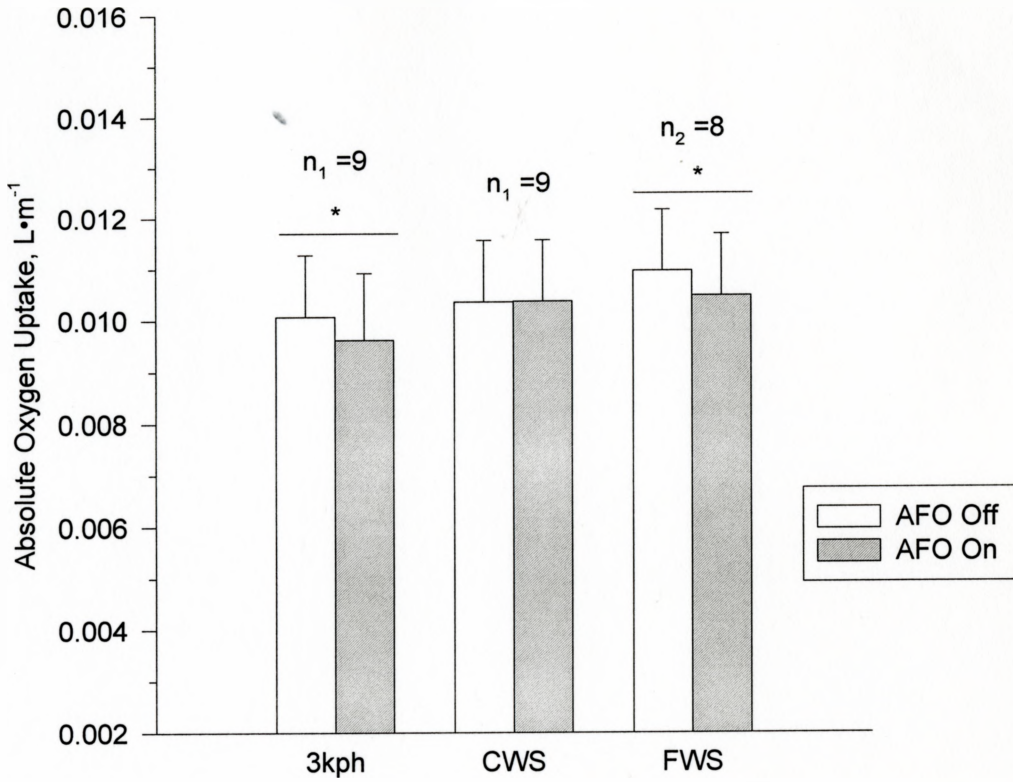


Figure 16: Effect of AFO on absolute oxygen uptake per metre walked ($\dot{V}O_{2mw}$).
 n₁=subjects who walked at 3 kph and comfortable walking speed (CWS); n₂=subjects who walked at fast walking speed (FWS).
 * $\dot{V}O_{2mw}$ was lower ($p < .05$) with AFO on at 3 kph and at FWS ($p=.009$).

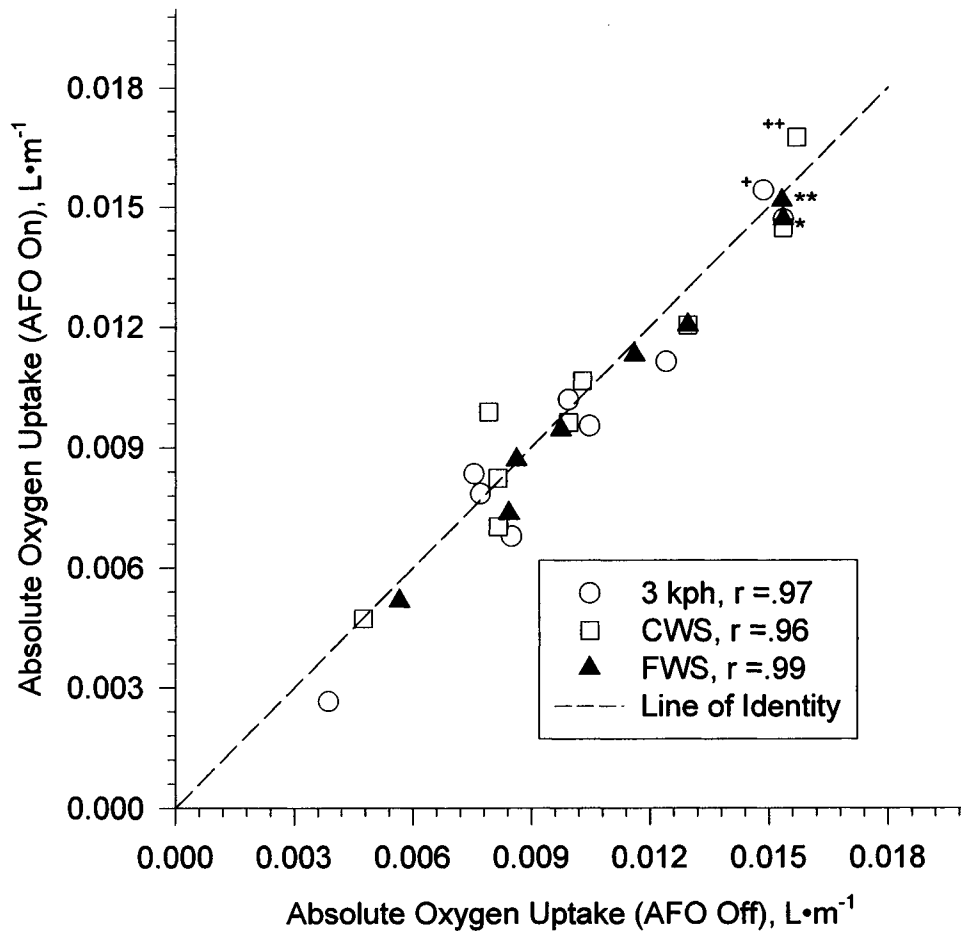


Figure 17: Individual absolute oxygen uptake per metre walked ($\dot{V}O_{2mw}$) responses to AFO. Open shapes denote subjects who walked at 3 kph-comfortable walking speed (CWS) (n=8). Filled triangles denote subjects who walked at fast walking speed (FWS) (n=9).

*Subject 12 at 3 kph (FWS) and CWS

**Subject 7.

+Subject 7.

++Subject 7.

See text for details on above mentioned subjects.

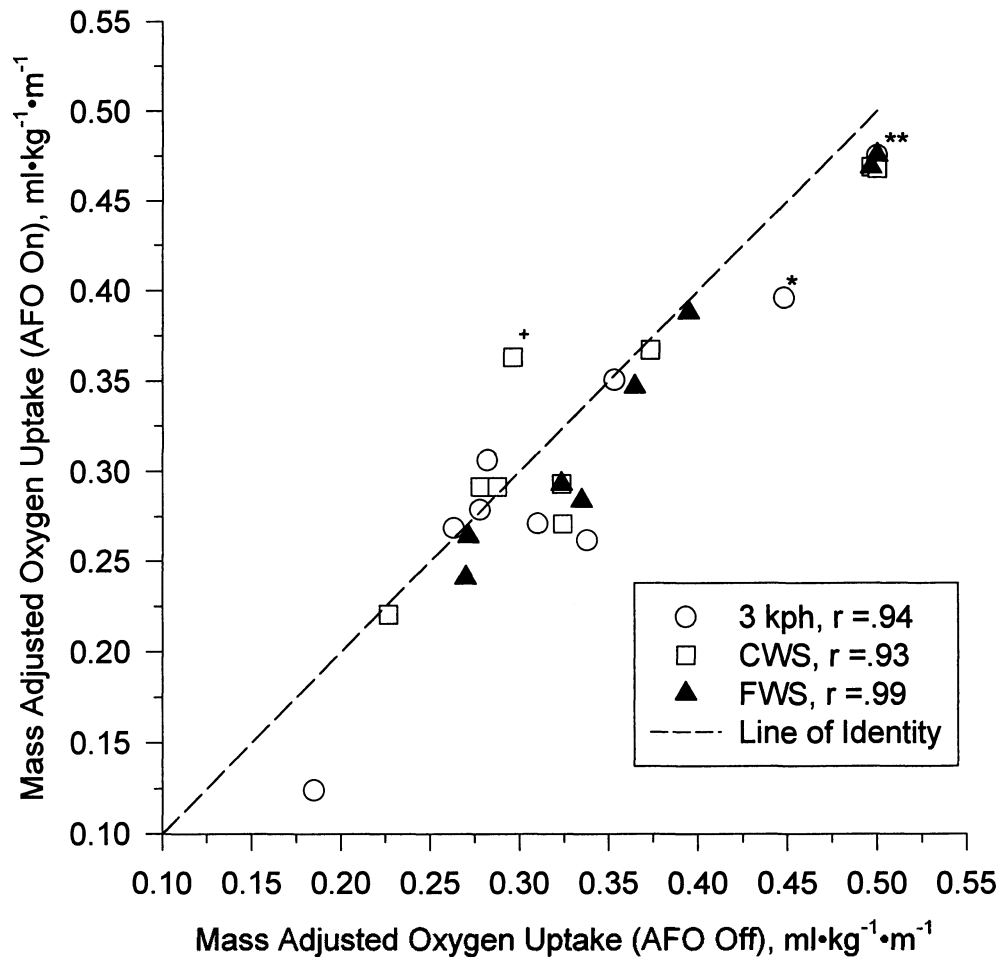


Figure 18: Individual mass adjusted oxygen uptake per metre walked ($\dot{V}O_{2mmw}$) responses to AFO.

Open shapes denote subjects who walked at 3 kph-comfortable walking speed (CWS) (n=8).

Filled triangles denote subjects who walked at fast walking speed (FWS) (n=9).

* Subject 2

**Subject 12 (3 kph=FWS, CWS) and Subject 2 (CWS, FWS)

+ Subject 1.

See text for details on above mentioned subjects.

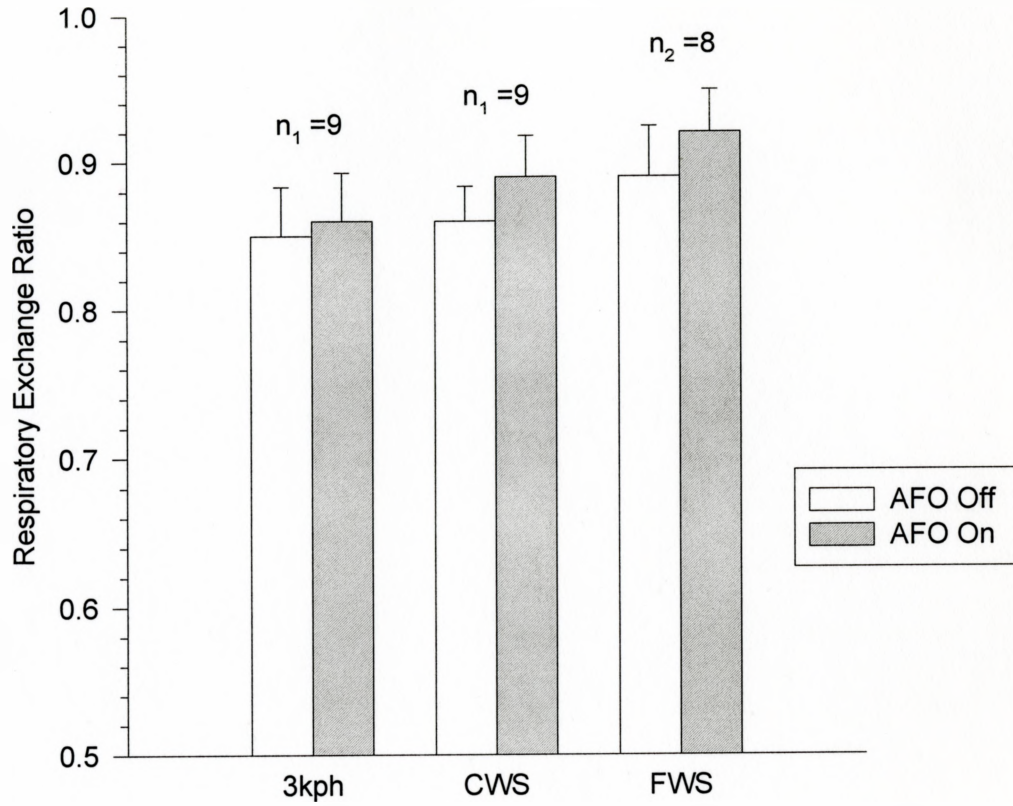


Figure 19: Effect of AFO on the respiratory exchange ratio (RER). n_1 =subjects who walked at 3 kph and comfortable walking speed (CWS); n_2 =subjects who walked at fast walking speed (FWS). There was no effect on RER due to AFO at any speed.

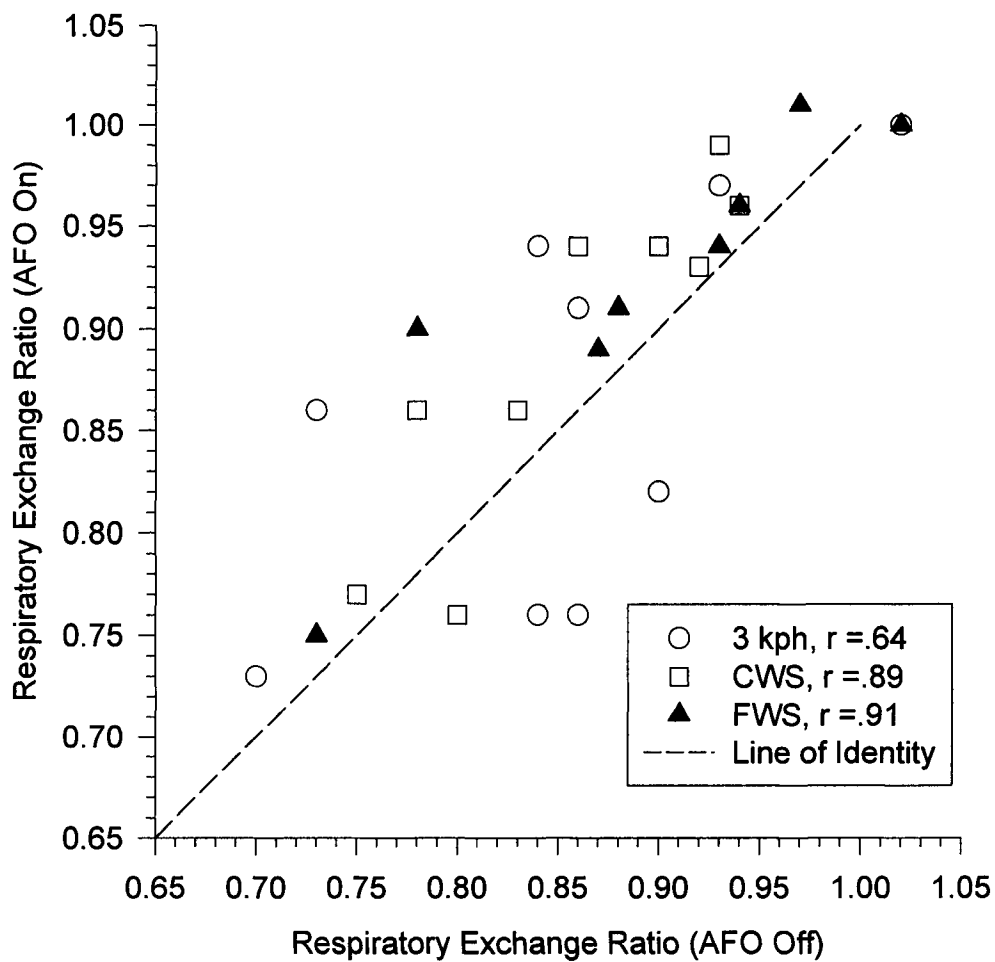


Figure 20: Individual respiratory exchange (RER) responses to AFO. Open shapes denote subjects who walked at 3 kph-comfortable walking speed (CWS) ($n=8$). Filled triangles denote subjects who walked at fast walking speed (FWS) ($n=9$).

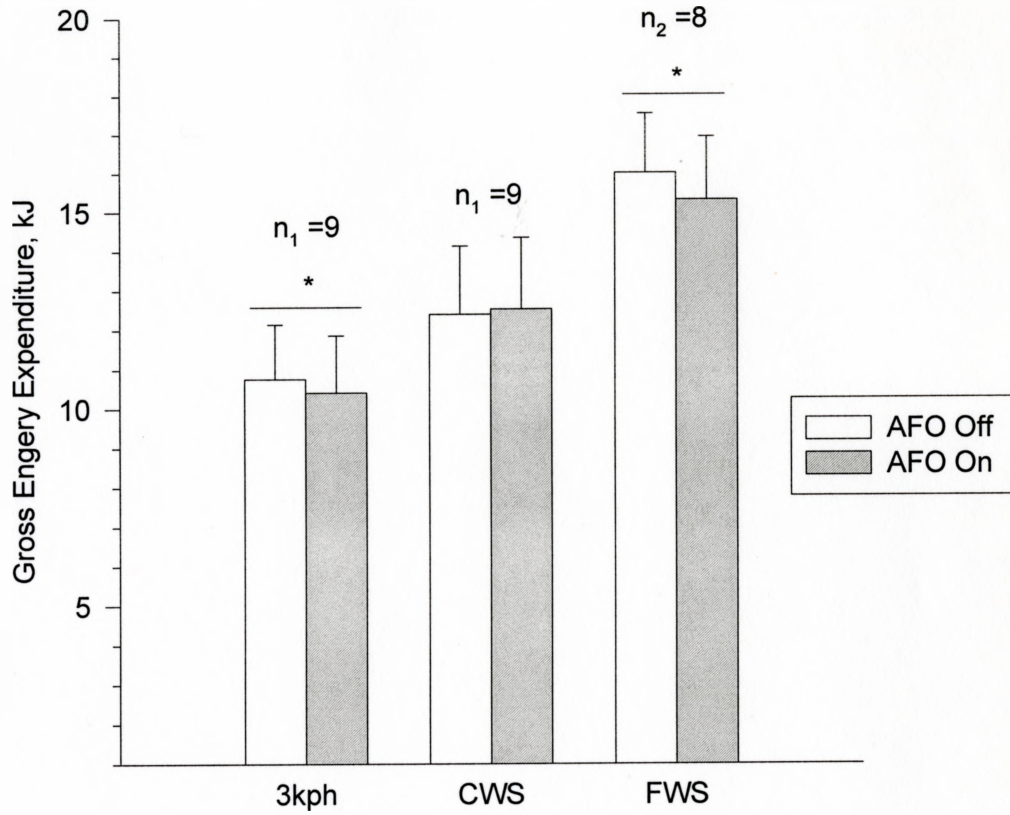


Figure 21: Effect of AFO on gross energy expenditure (EE_{gross}).
 n_1 =subjects who walked at 3 kph and comfortable walking speed (CWS); n_2 =subjects who walked at fast walking speed (FWS).
 * EE_{gross} was lower ($p < .05$) with AFO on at 3 kph and at FWS ($p = .01$).

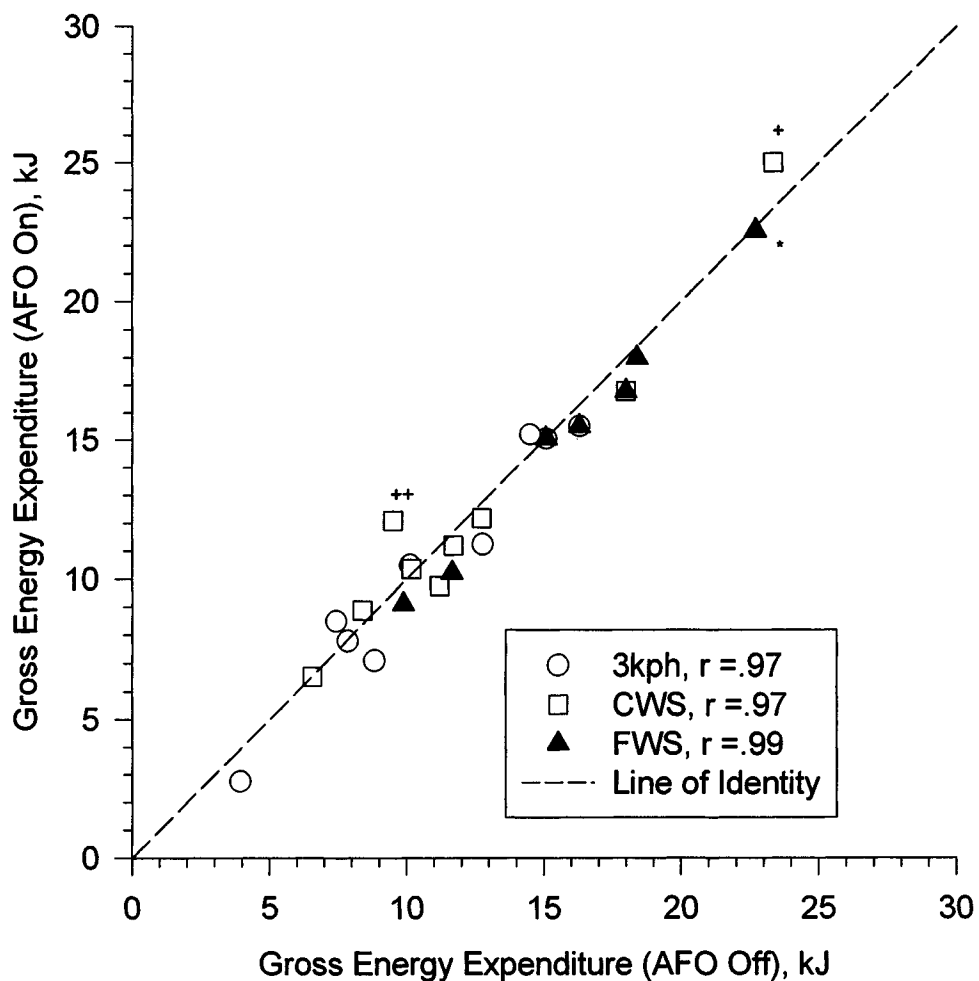


Figure 22: Individual gross energy expenditure (EE_{gross}) responses to AFO. Open shapes denote subjects who walked at 3 kph-comfortable walking speed (CWS) ($n=8$). Filled triangles denote subjects who walked at fast walking speed (FWS) ($n=9$).

* Subject 7.

+ Subject 7

** Subject 1.

See text for details on above mentioned subjects.

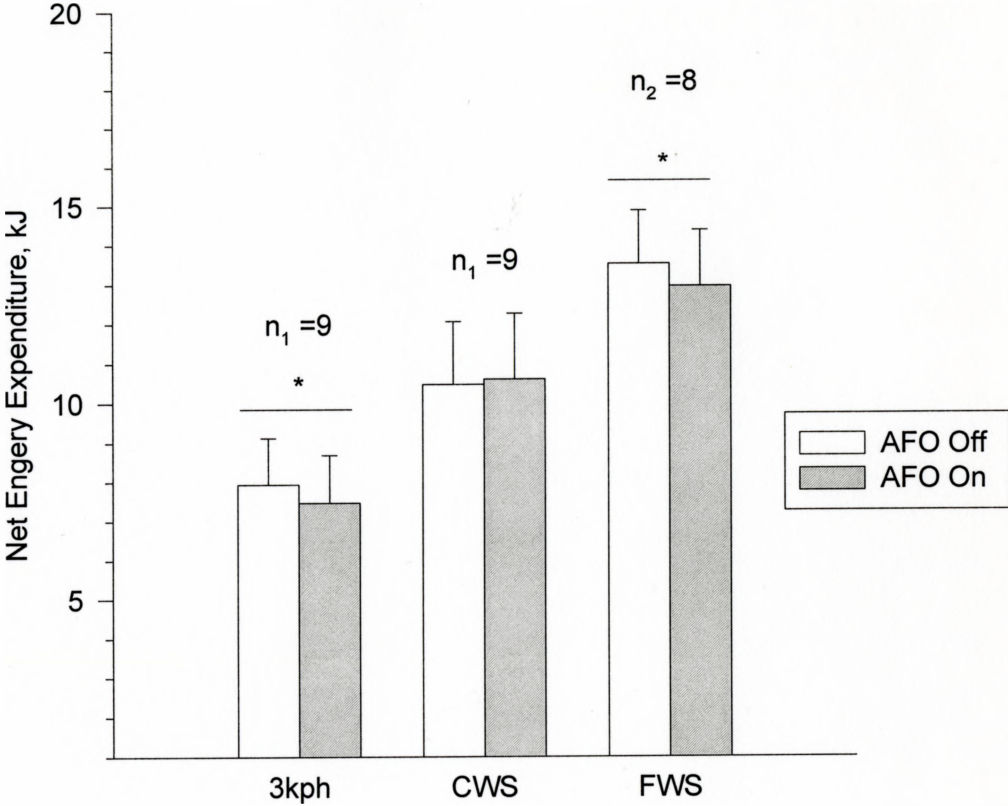


Figure 23: Effect of AFO on net energy expenditure (EE_{net}). n_1 =subjects who walked at 3 kph and comfortable walking speed (CWS); n_2 =subjects who walked at fast walking speed (FWS).
* EE_{net} was lower ($p < .05$) with AFO on at 3 kph and at FWS ($p = .03$).

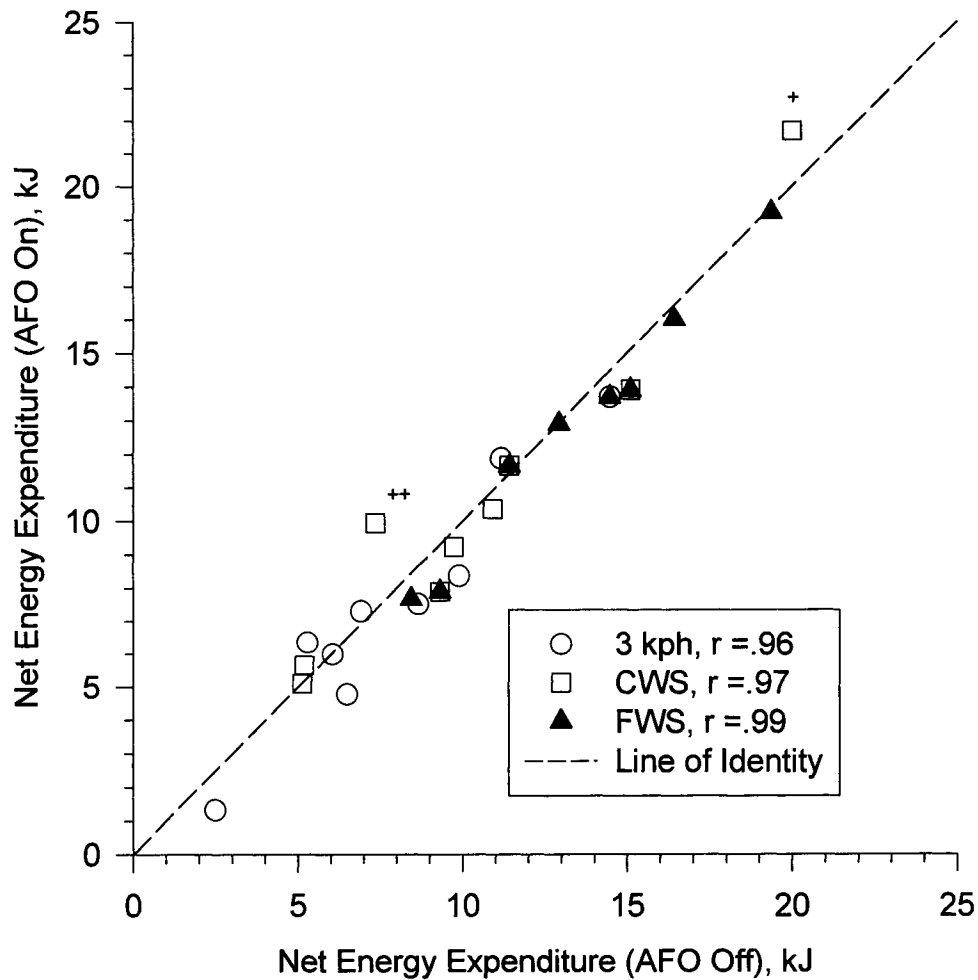


Figure 24: Individual net energy expenditure (EE_{net}) responses to AFO. Open shapes denote subjects who walked at 3 kph-comfortable walking speed (CWS) (n=8). Filled triangles denote subjects who walked at fast walking speed (FWS) (n=9).
 + Subject 7
 ** Subject 1.
 See text for details on above mentioned subjects.

APPENDICES

Appendix A: Information Form

Multidisciplinary Approach to Measuring the Effect of Ankle Foot Orthoses on Walking Economy of Children with Cerebral Palsy

Study Information

One of the recognised treatments of children with cerebral palsy (CP) has been the use of ankle foot orthoses (AFO). Your child has been given the AFO to support the ankle and foot and help improve walking. It is not known, however, whether the AFO changes the amount of energy that the child spends while walking. Investigators at McMaster University intend to study this question.

Participants in this study will visit the Children's Exercise & Nutrition Centre at Chedoke Hospital, Hamilton three times. In the first visit, they will be introduced to the methods to be used in subsequent visits. Their body height and weight will be determined, as well as body fatness (using callipers that measure the thickness of skinfolds). We shall also measure their gross motor function while they wear or do not wear their own AFO. We will do this first visit in your home if you prefer.

In the second visit, we shall measure resting metabolism (child sitting down comfortably, breathing into a machine for 5 minutes, to measure the amount of oxygen taken up by the body). We shall also measure your child's over ground walking speed (while they wear or do not wear the AFO) and teach your child how to walk on the treadmill. The fastest walking speed on the treadmill will be determined with and without the AFO. During this visit your child will wear an elastic strap across the chest (that contains a heart rate monitor) to allow us to measure heart rate.

In the third visit, the child will walk on the treadmill three times with and three times without the AFO. Each walk will last 2 minutes, during which time the child will breathe into a machine, to calculate the energy cost of walking. We shall also attach several small stickers on the skin or AFO, to photograph the movement of body segments. Another measurement during the walks will require placing 4 electrodes over each leg, to monitor the electrical activity of the muscles. During all of these measures your child will again wear the elastic strap across the chest to allow us to monitor and record heart rate.

None of the above measurements will cause pain or embarrassment, nor are there any known risks in performing these procedures. Your child may be somewhat tired at the end of the walks.

Appendix B: Consent Form**Multidisciplinary Approach to Measuring the Effect of Ankle Foot Orthoses on Walking Economy of Children with Cerebral Palsy**

Oded Bar-Or, M.D., Co-Principal Investigator
Michael Pierrynowski, PhD, Co-Principal Investigator
Victoria Galea, PhD, Co-Investigator
Désirée Maltais, BSc (PT), Study Co-ordinator

Consent Form

I, _____, consent to allow my son/daughter _____ to participate in this study designed to measure whether the use of AFO modifies the amount of energy young people with spastic diplegic cerebral palsy use during treadmill walking. Désirée Maltais (905 521 2100, Ext. 7259), the study co-ordinator, has explained that my child will be invited to the laboratory for three visits, as outlined in the information sheet overleaf.

I understand that no known harmful effects occur during or following the above observations, apart from fatigue following treadmill walking. I understand that my child can withdraw at any time from participation in the study even after I have signed this form. This will not jeopardise the treatment given to my child. Any information which is collected will be kept confidential, and will not identify my child in any way. This will also apply if the results are published.

 Name (print)

 Signature

 Date

 Witness (print)

 Signature

 Date

I have explained the nature of this study to the young person's parent (guardian) and believe she/he understood it. I have also explained the study to the young person who has assented to participate in the study.

 Study Co-ordinator (print)

 Signature

 Date

Appendix C: Visit 1 Parent Questionnaire

Subject #: _____
Date & Time: _____

Pre-test Questionnaire (Visit 1)

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 **other chronic conditions** besides cerebral palsy? YES
NO
If yes, please list these conditions.

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 any **change in your child's level of physical activity this past week** (more or less active); i.e., more or less walking than usual, more or less time in bed or resting, more or less time spent being pushed in wheelchair? 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 **back, hips, knees or ankles** 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**.

Type of Pain or Discomfort	How Often/How long?	What Brings It On?

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

Interviewer: _____

Appendix D: Physical Activity QuestionnaireSubject #: _____
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: _____

Appendix E: Visit 2 Parent Information Sheet

Instructions for Visits to the Children's Exercise and Nutrition Centre

Your visits to the Children's Exercise and Nutrition Centre will last about 2.5-3 hours each.

Please ensure that your child has had **nothing to eat or drink** (except water) **for 2 hours** prior to the visit to the Centre.

Please bring:

1. Your child's **hinged Ankle Foot Orthoses (AFO's)**
2. Shoes (or running shoes) and socks regularly used **with** the AFO's
3. Shoes (or running shoes) and socks regularly used **without** the AFO's
4. Bathing suit and T-shirt

Directions to the Children's Exercise and Nutrition Centre

The testing will take place at the *Children's Exercise and Nutrition Centre*, **Evel Building at Chedoke Hospital in Hamilton**. Coming from the east, take the **QEW WEST** to the **403**. Take the **left** branch of the 403, the one that says to Hamilton. Stay on the 403; go **past** the exits into Hamilton. You will then begin to go up a very steep hill and see a sign for Ancaster and **Mohawk Road**. Take the Mohawk Road exit. Stay to the **left** and take the **East** branch of Mohawk Road. At the traffic light, turn **left** (you will actually be going **East on Mohawk Road West!!!!**). Continue going East on Mohawk Road West for about 3 or 4 traffic lights until **Rice Street**. Turn **left** on to Rice. Chedoke Hospital is a collection of buildings on your left in the 2nd or 3rd block on Rice Street. The Evel Building is the last building in the collection. Turn **left** into the parking lot and park close to the Evel Building. Enter through the sliding glass doors. You should see a sign for this study taped to the doors. Take the elevator to the **4th Floor** and turn **left** when you get out of the elevator, then turn **right** and go to the end of the hall and that is where you will find me. I should have posters up directing the way.

You can reach me at home in Toronto (evenings and weekends) at (416) 482-6637 or at the Children's Exercise and Nutrition Centre (905) 521 2100 Ext. 7615.

Thank-you for your participation in this study!

Désirée Maltais

Appendix F: Visit 2/3 Parent Questionnaire

Subject #: _____
Date & Time: _____

Pre-test Questionnaire (Visit 2 & 3)

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 **other chronic conditions** besides cerebral palsy? YES NO
If yes, please list these conditions.

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

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

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

Item	Quantity

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

Medication	How Often	Quantity

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

7. Has there been any **change in your child's level of physical activity this past week** (more or less active); i.e., more or less walking than usual, more or less time in bed or resting, more or less time spent being pushed in wheelchair? YES NO

8. 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

9. Has your child complained of any **pain or discomfort** in the **back, hips, knees or ankles** over the last week? YES NO

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

Type of Pain or Discomfort	How Often/How long?	What Brings It On?

11. Does your child walk better with or without their AFO's? (circle one) WITH WITHOUT

Interviewer: _____