

Research article

MEASURING OXYGEN COST DURING LEVEL WALKING IN INDIVIDUALS WITH ACQUIRED BRAIN INJURY IN THE CLINICAL SETTING

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Received: 23 September 2004 / Accepted: 04 March 2004 / Published (online): 01 June 2004

ABSTRACT

This study examined the test-retest reliability of oxygen cost ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) during level walking in individuals with acquired brain injury (ABI). Ten individuals with ABI (5 men, 5 women) (Traumatic brain injury, 1, central pontine myelinolysis, 1, stroke 8) and 21 healthy controls (11 men, 10 women). Measurements of gross and net (walking minus resting) oxygen consumption ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), and oxygen cost ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$) during level walking at self-selected speeds. Measurements were taken on two occasions within one week. Oxygen cost was significantly lower ($p < 0.05$) in individuals with ABI on the second test versus the first test. Percentage variability in oxygen cost from test to re-test ranged from 14.7 to 17.3% in the control group and from 17.4 to 20.8% in the brain injury group. Clinical populations may demonstrate a significant decrease in oxygen cost between testing occasions. Individuals require at least one period of familiarisation if oxygen cost is used as an outcome measure during level walking in clinical groups. The amount of familiarisation has yet to be investigated in individuals with ABI.

KEY WORDS: Oxygen consumption brain injury, test re-test, level walking.

INTRODUCTION

Pathology that interrupts the normal energy conserving characteristics of trunk and limb motion during the gait cycle may increase energy expenditure during walking (Ralston, 1965; Corcoran et al., 1970; Inman et al., 1981; Mattsson and Brostrom, 1990; Hanada and Kerrigan, 2001). One of the main aims of rehabilitation is to enable individuals to walk safely and quickly in an energy efficient style that is not excessively fatiguing (Kerrigan, 2001). The energy cost of walking is usually determined by oxygen consumption

measures that are considered the criterion measure of internal work during sub maximal exercise (Boyd et al., 1999). An increase in energy expenditure, for walking a set distance, has been reported in individuals with acquired brain injury (Zamparo et al., 1995; Bernardi et al., 1999; Waters and Mulroy, 1999). Zamparo et al (1998) reported decreases in energy cost ($\text{J}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$) and Mattson (1990) decreases in oxygen cost ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) of 5-17% during walking, as a result of treatment interventions. However, no familiarisation session was reported in either of these studies. When considering the findings, of such non-controlled

intervention studies it is interesting that there is little published data on the test-retest reliability of oxygen cost during level walking at self-selected speeds in clinical groups. The limited evidence available in both healthy and clinical populations during level walking suggests that oxygen cost at self-selected walking speeds may vary from test to test (Corcoran et al., 1970; Rieper et al., 1993; Bowen et al., 1998). For example, individuals with cerebral palsy recorded a percentage variability from day to day of around 13% when level walking (Bowen et al., 1998). Closer test, re-test data has been reported in non-neurological groups such as healthy volunteers and cardiac patients with a coefficient of variation (CV) of less than 2% (Linnarsson et al., 1989) and adolescents (CV 4.3%) (Rieper et al., 1993). Intra-individual repeatability of oxygen consumption during treadmill walking, has shown coefficients of variation as large as 15% in women aged 20-65 years (Astrand, 1960) and in adolescents (Wergel-Kolmert and Wohlfart, 1999).

A recent study of same day testing repeated under standard conditions within a 30 minute period, in individuals with stroke, reported moderate repeatability (da Cunha et al., 2003). In practice, testing during intervention studies is carried out on separate testing occasions and so knowledge of day to day or test, re-test variation has clear clinical relevance. To date no study has examined test, re-test data for oxygen consumption on separate occasions in individuals with brain injury. In order to make meaningful interpretation of therapeutic interventions it is important to consider how repeatable oxygen consumption measures are in this group.

The aim of this study was to examine test-retest reliability of oxygen cost ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) during self-selected walking in healthy controls and individuals recovering from brain injury.

METHODS

Participants

Ten individuals with brain injury (5 men, 5 women) (traumatic brain injury, 1, central pontine myelolysis, 1, stroke 8) and 21 healthy controls (11 men, 10 women), age (years) mean \pm SD: ABI 47.3 \pm 18.0; Control 35.1 \pm 20.5. Individuals had a weight (kg) mean \pm SD: ABI 78.1 \pm 14.8, Control 74.9 \pm 14.1; BMI ($\text{kg}\cdot\text{m}^{-2}$) mean \pm SD: ABI 27.94 \pm 5.34, Control 24.6 \pm 3.23. Individuals with ABI were identified through consultant referral in a rehabilitation centre. Consecutively referred individuals with acquired brain injury scoring 7/15 or more on the Rivermead Mobility Index, who were able to walk for 4 minutes and who had residual gait abnormalities, were

included. A heterogeneous sample was chosen in order to examine reliability in a typical cohort of individuals receiving physiotherapy in a rehabilitation centre. Healthy volunteer controls, with no musculoskeletal or neurological pathologies, were recruited locally from a sample known to the researchers.

Body mass was measured to the nearest 0.1 kg using a Seca weight scale, wearing minimum clothing and without shoes. Height was measured to the nearest 0.5 cm using a standard Seca stadiometer. Body mass index (BMI) was calculated by dividing body weight in kilograms by the square of body height in metres.

Informed consent was obtained, after receiving both oral and written information about the study, from all individuals before participation according to the Declaration of Helsinki (World Health Organisation, 1996). After giving informed consent, individuals attended for testing. Subjects were asked to refrain from the consumption of alcohol, cigarettes, food, caffeine, medical drugs and to avoid exercise for a period of two hours prior to testing. Findings from a pilot study and local ethical committee concerns dictated that this period of abstinence was both feasible and acceptable. Testing was carried out utilising the following standardised testing protocol by the same two investigators, at the same time, on two separate occasions within one week (room temperature, 20-25°C). Individuals were asked to attend wearing the same shoes. Information was recorded about age, height, weight, compliance with pre-test requirements, physical activity levels, medication, and general health.

Measurements of expired air were taken at rest and during level walking at a constant walking speed. The expired air was collected by means of light weight respiratory valves and hoses in a 100 litre Douglas bag (Waters et al., 1988). Individuals were initially familiarised to wearing the Hans Rudolf face mask and then rested supine for a period of six minutes, immediately followed by measurement of expired air for a further period of six-minutes. The composition of the expired air was determined by oxygen and carbon dioxide analysers (Servomex Series 1400, Crowborough, East Sussex, UK) and the volume of expired air was determined by means of a dry gas meter (Harvard Apparatus Limited, Edenbridge, Kent). The gas analysers were calibrated at each testing occasion by means of gas mixtures of known concentration. Oxygen consumption was calculated using standard open circuit methodology and the values expressed under standard conditions (STPD).

The walking test was explained verbally and demonstrated to each individual. Subjects were then

Table 1. Walking measures: group comparisons, test 1. Data are means (\pm SD).

Measure	Control	ABI
Walking speed ($\text{m}\cdot\text{s}^{-1}$)	1.25 (0.15)	0.61 (0.30)*
Gross Oxygen Consumption ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	10.79 (1.29)	8.82 (1.10)
Net Oxygen Consumption ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	7.64 (1.41)	6.51 (1.09)
Gross oxygen cost ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$)	0.15 (0.02)	0.29 (0.19)
Net oxygen cost ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$)	0.11 (0.02)	0.21 (0.11)*

* $p < 0.05$ significant difference between means Control versus ABI.

asked to walk at their normal, comfortable walking speed around a predetermined 13m track in a physiotherapy gymnasium. Self-selected walking speeds have been shown to coincide with the lowest oxygen cost ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) on the oxygen cost/walking velocity curve (Walters et al, 1998). Pilot work showed that the clinical group examined in this study could only manage to walk at one speed. During walking trials individuals were accompanied by a researcher to ensure safety. Their self-selected walking speed was determined with a calibrated speedometer (Cat eye-astrale, Osaka, Japan) mounted on a wheelchair pushed behind and out of sight of the subject by a researcher (Linnarsson et al., 1989). To ensure physiological steady state conditions all subjects walked for four minutes in total. During the walking tests, the researcher continuously monitored walking speed. Expired air was collected in a 100-litre Douglas bag, secured to the wheelchair, during min 3-4 of the walk using light weight ducting and a respiratory valve for the determination of oxygen consumption. Steady-state oxygen uptake was expressed as gross (walking) and net (walking minus resting) ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$). From the steady-state oxygen uptake ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), the oxygen cost ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$) was calculated from the mean walking speed during the 60 second sampling period.

Baseline walking measures were compared between ABI and Control using a Student's t-test for independent data. To analyse the repeatability between the measurements of oxygen consumption a plot was made of the differences between the measurements against their mean (Bland and Altman, 1996). The data was tested for normality (Shapiro-Wilks test) and equal variance (F -test). Pearson product moment correlation analysis was performed on the absolute differences between measures taken from test one and two against mean values of the two tests in order to examine heteroscedascity of the data (systematic relationship of size of difference between tests and the mean of the two tests). No heteroscedascity was detected in the data, therefore the mean of the differences between test 1 and 2 was calculated for measures. The hypothesis of zero bias was then tested using a Student's t-test for dependent data. A significance level of $p \leq 0.05$ was chosen to indicate statistical

significance. The upper and lower limits of repeatability were calculated as differences of the mean ± 1.96 SD and reported as bias and random error. Repeatability between test 1 and 2 was further examined using the commonly used intraclass correlation coefficient (ICC) [3, 1]. Finally in order to enable direct comparisons with earlier studies, 'percentage variability' was calculated (averaging the absolute value of the difference between each measurement of the test, dividing this by the average for the tests, and multiplying by 100) (Bowen et al., 1998).

RESULTS

Table 1 shows baseline measures for walking speed and oxygen consumption during level walking in the control and ABI group. Independent, one tailed, unequal variance t-tests revealed that the ABI group walked slower ($t(11.5) = 6.08, p < 0.05$) with higher net oxygen cost ($t(8.3) = 3.35 (p < 0.05)$) than the control group. There was no significant difference in net oxygen consumption per minute between ABI and control groups ($t(17.6) = 1.6, \text{NS}$).

The intra-individual variance *Systematic bias*

Both groups walked slightly faster on test 2 compared with test 1 (NS) (Table 2). Oxygen consumption ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) (gross and net) was lower in test 2 compared with test 1 in the ABI group (NS). The oxygen cost of ambulation ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$) was significantly lower in test 2 compared with test 1 in the ABI group only (Table 2). In the control group oxygen consumption was higher and oxygen cost lower on test 2 (net and gross) (NS) (Table 2). There was less systematic error in net compared with gross oxygen cost ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$) of walking in both control and ABI groups (Table 2).

Random error

The control group showed greater random error, percentage variability and ICC [3,1] than the ABI group in oxygen consumption ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) (Table 2). In contrast the ABI group showed greater random error and percentage variability than the control group in oxygen cost ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$) (Table 2).

Table 2. Test -retest reliability of level walking for Control and ABI.

	Control t test Dependent, equal variance, 2 tailed	Control λ Bias (Random error)	Control ϕ % variability	Control Mean ICC [3, 1]
Walking speed	t (20) = 0.66, NS	-0.02 (0.25)	8.1	0.70
Gross Oxygen Consumption	t (20) = 1.02, NS	-0.30 (2.73)	11.6	0.55
Net Oxygen Consumption	t (20) = 1.53, NS	-0.43 (2.43)	12.7	0.68
Gross oxygen cost	t (20) = 0.32, NS	0.00 (0.05)	14.7	0.42
Net oxygen cost	t (20) = 0.19, NS	0.00 (0.02)	17.3	0.61

	ABI t test Dependent, equal variance, 2 tailed	ABI λ Bias (Random error)	ABI ϕ % variability	ABI Mean ICC [3,1]
Walking speed	t (9) = 0.53, NS	-0.02 (0.28)	13.7	0.89
Gross Oxygen Consumption	t (9) = 0.47, NS	0.18 (2.33)	11.4	0.51
Net Oxygen Consumption	t (9) = 0.65, NS	0.24 (2.02)	10.5	0.64
Gross oxygen cost	t (9)=2.87, *	0.05 (0.10)	17.4	0.97
Net oxygen cost	t (9)=3.02, *	0.04 (0.04)	20.8	0.93

Walking speed ($\text{m}\cdot\text{s}^{-1}$); oxygen consumption ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) and cost ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$).

NS = non-significant. * $p < 0.05$.

ϕ Percentage variability was calculated by averaging the absolute value of the difference between each measurement of the group, dividing this by the average of the group, and multiplying by 100.

λ Bias (mean difference) (\pm Random error) (1.96 SD difference).

The high variability and small sample size within the ABI group, may have increased the ICC [3,1] in this group in measures of oxygen cost and walking speed (Table 2). ICC 's of the intra-individual reliability ranged from moderate to high in all measures except for gross oxygen cost in the control group, which was low (Munro, 1993). Net measures, showed less random error than gross measures in both groups.

DISCUSSION

Individuals in the control group walked around the indoor track for a period of four minutes at self-selected speeds of $1.25 \text{ m}\cdot\text{s}^{-1} \pm (\text{SD}) 0.15$. Individuals in the ABI group walked at slower speeds of $0.61 \text{ m}\cdot\text{s}^{-1} \pm 0.30$ ($p < 0.05$). The self-selected speeds of the control group were within the expected range for healthy walkers (Waters et al., 1988). The ABI group walked at speeds expected for this clinical group (Zamparo et al., 1995). The high inter- individual variability, in the ABI group, in self-selected walking speed and oxygen cost reflects the wide range of physical impairments affecting walking. The controls walked faster with lower oxygen cost than the ABI group who walked slower at a greater oxygen cost. This is in agreement with earlier studies that have recorded high oxygen cost during level walking in individuals with brain injury (Zamparo et al., 1995; Bernardi et al., 1999; Waters and Mulroy, 1999).

Intra-individual reliability

Walking speed did not change from the first to the second test in either the control or ABI groups. There was no significant change in either oxygen consumption or oxygen cost (gross and net) in the control group. Our findings in the control group agree with earlier studies that have found no significant difference in day to day testing in either speed or oxygen consumption (Linnarsson et al., 1989; Wergel-Kolmert and Wohlfart, 1999). In contrast there was a significant reduction in oxygen cost, on the second test in the ABI group ($p < 0.05$). The significant reduction in oxygen cost in individuals with brain injury, recorded in test 2 may be due to a greater effect of familiarisation with the testing equipment and procedures in this group.

Intra-class correlation coefficients of oxygen consumption, from test 1 to test 2 in both the control and clinical group, were rated as moderate to high ICC [3,1](Munro, 1993). In our study the percentage variability of oxygen measures ranged from 10-20%. Similar levels of percentage variability have been reported for healthy women (15%; Astrand, 1960) and for individuals with cerebral palsy (13%; Bowen et al., 1998) during level walking. Less variation, together with higher levels of reliability have been reported in non-neurological groups such as healthy volunteers and cardiac patients ($\text{CV} < 2\%$) (Linnarsson et al., 1989) and adolescents ($\text{CV} 4.3\%$) (Rieper et al., 1993). Certainly a high level of day-to-day variability in behaviour in individuals with

neurological impairments is not unexpected after brain injury (Dawes, 2001). The level of test, re-test variability reported in this study is similar to the percentage reduction in energy cost (17%) recorded as a result of treatment, in a study by Zamparo et al (1995).

Oxygen cost

Both groups showed less variation when net oxygen cost values were used. This agrees with earlier studies in healthy individuals, which reported lower variability when oxygen consumption measures during walking were reported as net values (Baker et al., 2001). Net values take into consideration changes in the testing condition, such as variation in environmental factors and personal routines. In our study we attempted to control individual behaviour for a period of two hours prior to testing. This period of time was considered the minimum required to standardise pre-test conditions that was feasible within the rehabilitation setting. Earlier studies in this clinical group have found controlling behaviour very labour intensive, requiring full time supervision (Dawes, 2001). Studies measuring oxygen consumption to examine the effectiveness of treatment interventions in individuals with ABI, have not described in detail pre-test conditions (Corcoran et al., 1970; Mattsson et al., 1990; Zamparo and Pagliaro, 1998). As lowered oxygen cost of walking has been used as an outcome measure of successful rehabilitation in these studies, the importance of testing rigor in standardising conditions, and care with subject familiarisation must be emphasised.

Walking speed

Although no significant changes in walking speed were recorded in this study, the confounding variable of differing walking speeds when testing individuals during self-selected level walking in repeated measures designs needs careful consideration. Attempts to control walking speed during testing may lead to altered style, which in turn may affect oxygen consumption, and so is not ideal. During pilot work different attempts to control walking speed by auditory feedback appeared to affect spatio-temporal characteristics (Dawes et al., unpublished data). These difficulties may have encouraged other researchers to study walking utilising motorised treadmills, despite the lack of ecological validity. The study of 'free' level walking is important, as walking style measured during level walking differs from that observed during treadmill walking (Dingwell et al., 2001). Certainly further consideration of the optimal means of controlling speed during level walking is required.

CONCLUSIONS

The ABI group walked slower than the healthy controls consequently using less oxygen per minute, but at a greater oxygen cost for every metre walked. In both groups, there was less variation, from day to day, when oxygen cost was reported as net values - supporting the use of net oxygen cost as an outcome measure. There was a significant decrease in oxygen cost on the second test in the ABI group. This fall, presumably as a result of familiarisation, was similar to the previously reported reduction in the oxygen cost of walking as a result of therapeutic interventions. Considering the significant reduction in oxygen cost in our ABI group when walking at self-selected speeds; one off measurements before and following an intervention in studies with no control group may lead to spurious interpretation of results. Further investigation of the number of familiarisation periods is required but certainly studies should ensure at least one period of familiarisation when using novel testing procedures in this clinical group. Intervention studies should ensure that there is a control group until there is a greater understanding of the degree of familiarisation required.

ACKNOWLEDGMENTS

This study was funded by Oxford Brookes University, University of Oxford Department of Primary Care. Ethical approval was granted by Oxfordshire Applied and Qualitative Research Committee (AQREC).

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KEY POINTS

Individuals with brain injury during level walking

- May demonstrate a significant decrease in oxygen cost between testing occasions.
- May require at least one period of familiarisation if oxygen cost is used as an outcome measure
- The degree of familiarisation required in this clinical group needs further investigation

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