©Journal of Sports Science and Medicine (2018) **17,** 01-06
http://www.jssm.org

Research article

Exploring the Metabolic and Perceptual Correlates of Self-Selected Walking Speed under Constrained and Un-Constrained Conditions

David T Godsiff [1], Shelly Coe [1]✉, Charlotte Elsworth-Edelsten [2], Johnny Collett [1], Ken Howells [1], Martyn Morris [1] and Helen Dawes [1]

[1] Oxford Brookes University, Gipsy Lane, Headington, Oxford, UK; [2] Sport and Exercise Science, School of Human & Life Sciences, Canterbury Christ Church University, Canterbury, Kent, UK

Abstract

Mechanisms underpinning self-selected walking speed (SSWS) are poorly understood. The present study investigated the extent to which SSWS is related to metabolism, energy cost, and/or perceptual parameters during both normal and artificially constrained walking. Fourteen participants with no pathology affecting gait were tested under standard conditions. Subjects walked on a motorized treadmill at speeds derived from their SSWS as a continuous protocol. RPE scores (CR10) and expired air to calculate energy cost ($J.kg^{-1}.m^{-1}$) and carbohydrate (CHO) oxidation rate ($J.kg^{-1}.min^{-1}$) were collected during minutes 3-4 at each speed. Eight individuals were re-tested under the same conditions within one week with a hip and knee-brace to immobilize their right leg. Deflection in RPE scores (CR10) and CHO oxidation rate ($J.kg^{-1}.min^{-1}$) were not related to SSWS (five and three people had deflections in the defined range of SSWS in constrained and unconstrained conditions, respectively) ($p > 0.05$). Constrained walking elicited a higher energy cost ($J.kg^{-1}.m^{-1}$) and slower SSWS ($p < 0.05$) versus normal walking. RPE (CR10) was not significantly different between walking conditions or at SSWS ($p > 0.05$). SSWS did not occur at a minimum energy cost ($J.kg^{-1}.m^{-1}$) in either condition, however, the size of the minimum energy cost to SSWS disparity was the same (Froude {Fr} = 0.09) in both conditions ($p = 0.36$). Perceptions of exertion can modify walking patterns and therefore SSWS and metabolism/ energy cost are not directly related. Strategies which minimize perceived exertion may enable faster walking in people with altered gait as our findings indicate they should self-optimize to the same extent under different conditions.

Key words: Self-selected walking speed, energy cost, Froude.

Introduction

People self-optimize walking when selecting preferred gaits and walking speeds (Minetti and Alexander, 1997; Ralston, 1958; Saibene and Minetti, 2003; Waters and Mulroy; 1999) even when walking parameters are artificially constrained (Betram, 2005; Donelan et al., 2001; Holt et al., 1991; Minetti et al., 1995). There are a number of factors known to affect preferred walking speed including: energetics, sensory feedback, and biomechanical movement cost (Betram, 2005; Donelan et al., 2001; Minetti et al., 1995). Sensory feedback tends to be rapid to help select moment to moment preferred speed, perhaps complementing the slower optimization processes that seek to minimize walking energetic cost (Ralston, 1958). The minimal energy hypothesis (Ralston, 1958) suggests self-optimization is controlled from the perception of underlying metabolic demands (Weiser and Stamper, 1977). Empirical studies have supported this theory that fuel utilization may be a factor in determining preferred walking speed and self-optimization of movement in both healthy individuals (Willis et al., 2005) and those with central nervous system (CNS) pathology (Ganley et al., 2007).

William Froude, a mechanic, predicted different sized but geometrically similar hulled boats would be dynamically similar, in terms of wave resistance, when a ratio, now termed Froude number (Fr), was constant (Vaughan and O'Malley, 2005). Schepens et al. (2004) showed that the mechanical and metabolic differences between adults and children disappear when expressed as a function of Fr, with optimum walking speed determined by metabolic energy expenditure associated with an approximate Fr number (Fr =0.25). This is important as energy utilization and energy cost can be modulated through altering movement and diet. A better understanding of the role of fuel utilization in determining preferred walking speeds (self-selected walking speed, SWSS) may determine targets for novel approaches for reducing the perceived effort of walking and increasing activity.

Willis et al. (2005) found ratings of perceived exertion (RPE) to be matched by simultaneous deflections in carbohydrate (CHO) oxidation rate in healthy subjects; suggesting that walking speed may be determined by a drive to conserve CHO, mediated through exertional symptoms. At speeds of less than or equal to SSWS, CHO oxidation rates were low, in a range matched by gluconeogenesis, but at speeds above SSWS, CHO oxidation rates were shown to increase abruptly. Furthermore, Ganley et al. (2007) found in individuals' with CNS pathologies fat was the primary fuel source (at SSWS) whereas carbohydrates were utilized when individuals were encouraged to select faster walking speeds. It was concluded that fat oxidation was low compared to healthy individuals, despite fat being the primary fuel at SSWS; suggesting that fuel selection may contribute to the selection of slower SSWS in individuals' with pathology and that limited fat oxidizing capacity may prevent a higher, more functional SSWS. However, such observations may have limited transfer to everyday conditions as both these studies obtained their results in overnight fasted subjects. To date the study by Ganley et al. (2007) has not been replicated under more ecologically valid unfasted conditions, or investigated alongside individual perceptions of exertion. As exertional symptoms limit exercise intensity

Received: 10 July 2017 / Accepted: 14 November 2017 / Published (online): 01 March 2018

(Weiser and Stamper, 1977) a better understanding of both may be important and offer a route to increase walking speed in pathologies where energy production is known to be affected such as neurodegenerative diseases and Diabetes (Minetti and Alexander, 1997; Ralston, 1958).

We investigated selected energy utilization and perceptual parameters during normal and mechanically altered walking in non-fasted subjects in order to provide ecologically valid conditions and a better understanding of the determination of SSWS in simulated "everyday" walking in healthy individuals. This was in an attempt to provide an insight into energetic mechanisms affecting selection of walking speed. To further explore the results reported by Willis et al. (2005) the present study hypothesized that the relationship between SSWS and a deflection point in CHO oxidation rates (abrupt increase in rate) would hold for both constrained and non-constrained walking. It is important to establish whether the metabolic and perceptual drivers of SSWS are as tightly controlled in non-fasted subjects. As such we explored the relationship of self-selected walking speed under both constrained and unconstrained conditions to rating of perceived exertion, oxygen cost (per unit work) and rate of oxygen utilization (per unit time).

Methods

Participants

Fourteen healthy subjects, 6 men and 8 women (mean ± sd: age 23.1 ± 3.6 years, height 1.76 ± 0.15 m, body mass 73.0 ± 16.2 kg), with prior experience of treadmill walking and with no medical problems that affected gait participated.. Due to time constraints normal versus constrained walking was performed on eight of these subjects (below). Informed consent was obtained before participation according to the Declaration of Helsinki (1986) and ethical approval was granted by the University Ethical Committee.

Procedure

Laboratory testing was carried out under standardised environmental conditions (24 ºC and first thing in the morning; Waters et al., 1988). Prior to experimental testing subjects fasted for a period of 2hrs and strenuous exercise had not been undertaken in the past 24hrs. Height was measured using a wall-mounted stadiometer (Holtain, UK) and body mass was measured to the nearest 0.1kg using a weigh scale (Seca Ltd., UK). Leg length (L) was measured (m) from the anterior superior iliac spine to the medial malleolus in order to derive Froude number (Fr) ($Fr = v^2/gxL$: v = velocity, g = acceleration due to gravity, L =leg length) for each individual at each speed. Calculation of Fr normalizes altering speed for individual differences in leg length (Lusk, 1924; Schepens et al., 2004).

Subjects walked on a motorized treadmill (Woodway, PPS-55, Germany) at a range of speeds up to the walk-run transition with the velocity display covered. By adjusting the treadmill controls subjects determined a comfortable walking velocity (or SSWS). In order to illicit a U-shaped curve that describes the relationship between walking speed and energy cost, individuals then walked for four minutes at –60, -40, -20, +20, +40 and +60 (90% of walk-run transition if above such a speed) of their individually determined SSWS (Collett et al., 2007). This was performed as a continuous protocol during which samples of expired air were collected in Douglas bags during minutes 3-4 at each velocity (Waters et al., 1988).

The composition of expired air was determined by oxygen and carbon dioxide analyzers (Servomex Series 1400, UK) and volume of expired air was determined by a dry gas meter (Harvard Apparatus Limited, UK). The gas analyzers were calibrated on each testing occasion using gas mixtures of known concentration. Oxygen uptake ($\dot{V}O_2$ ml·kg^{-1}·min^{-1}) and carbon dioxide production ($\dot{V}CO_2$ ml·kg^{-1}·min^{-1}) was measured using open circuit spirometry and values expressed under standard conditions (STPD). Respiratory exchange ratio (RER) values were calculated (VCO_2 produced/VO_2 consumed) and from this the proportion estimated to come from CHO was used to determine CHO oxidation rate (J.kg^{-1}·min^{-1}) and assigned an energetic equivalent to O_2. The steady-state oxygen uptake (ml·kg^{-1}·min^{-1}) was measured at each velocity and the corresponding energy cost of walking (J.kg^{-1}·min^{-1}) calculated (Lusk, 1924). A component of the oxygen cost ($\dot{V}O_2$ ml·kg^{-1}·min^{-1}) data, used within the present study, had been previously recorded, using an identical methodology and reported in a study by Elsworth et al. (2006). RPE (CR10) values were recorded at each speed increment using the Borg CR10 scale using the script designed by Noble and Robertson (1996; Borg, 1998).

Within 1 week, eight of the fourteen individuals attended a further test (test 2), following the same procedure and pre-test conditions as test 1, however, the right leg was immobilised using a custom made hip and knee brace (allowing 20º flexion at the knee and 10º movement at the hip, weighing less than 2 kg) in order to provide an altered (‘constrained’) walking condition (Elsworth et al., 2006). Once familiar under the altered walking condition, a new SSWS and %SSWS was determined using the method previously described.

Statistical analysis

Data was imported into SPSS v 11.0 (SPSS inc, Chicago, USA) for statistical analysis. The study did not impute missing data, thus for comparisons between the normal and constrained condition the complete data set was required. P values were set at a value of 0.05 for significance. Repeated Measures ANOVA was used to assess the within-subject differences and contrasts in the parameters measured at the different walking speed. Repeated Measures ANOVA was also used to explore the between-condition differences during normal and constrained walking. A paired samples t-test was used to assess the difference between normal and constrained walking, for the differences between the speed individuals’ self-selected and optimum speed (determined as the minimum metabolic cost). To investigate the relationships between the parameters measured in the present study with Fr, a regression analysis was performed. Curve fitting was performed with the data and relationships determined on the basis of the strength of correlation coefficient (R2), together with the significance of slope coefficients. When a non-linear model best described a relationship, the 'v' slope method (Beaver et al., 1986) was utilised to indicate the point at which there was an increased reliance on CHO metabolism. The 'v' slope method was also used to determine the point at which RPE increased at a greater rate. Specifically, extrapolation of curve deflection points was calculated from the trend-lines in each test condition. This was where the trend-line starts to deflect upward from the existing linear data pattern. Data within a +50 and –50% range of the mean self-selected (typically deflections occurring between Fr0.09 – 0.26 under normal walking and Fr0.06 – 0.17 under constrained walking). This data range was chosen as it incorporates every subject's SSWS and presents a wide opportunity for a deflection in the data pattern to occur, if one is present.

Results

Table 1 shows mean and SD of measures at SSWS and percentages of this speed, during normal and constrained conditions. An altered metabolic demand was successfully achieved during the constrained condition when compared with normal walking. Repeated measures ANOVA was found to produce a significant difference ($p \leq 0.05$) when assessing the within-subject differences and contrasts in velocity ($m \cdot s^{-1}$), Fr, RPE scores (CR10), CHO oxidation rate ($J.kg^{-1} \cdot min^{-1}$) and energy cost ($J.kg^{-1} \cdot min^{-1}$) at the different percentages of SSWS. Each of the within subject differences observed in the experimental parameters; velocity ($m \cdot s^{-1}$), Fr, RPE scores (CR10), CHO oxidation rate and energy cost displayed a linear model fit in normal and constrained walking ($p \leq 0.05$), with the exception of RPE scores (CR10) and CHO oxidation rate. CR10 followed linear trends in normal walking ($p \leq 0.05$) but no trend during constrained walking ($p \leq 0.05$). CHO oxidation rate followed linear trends in normal walking ($p \leq 0.05$) and quadratic trends in constrained walking ($p \leq 0.05$).

Repeated measures ANOVA was also used to explore the between-condition differences in velocity ($m \cdot s^{-1}$), Fr, RPE scores (CR10), CHO oxidation rate and energy *cost* during normal and constrained walking. The above parameters excluding RPE scores (CR10) produced a significant difference between conditions ($p \leq 0.05$). CHO oxidation rate was higher at +40 SSWS and continued to be higher at +60 SSWS in normal walking when compared to constrained walking. RPE (CR10) was not significantly different between walking conditions ($p \leq 0.05$).

Deflection point data analysis: RPE (CR10)

Individual data for RPE (CR10) reflected thirteen quadratic and one linear relationship in normal walking and six quadratic and two linear relationships in constrained walking. Table 2 shows R^2 values and the strength of graph relationships for each individual. When quadratic relationships were examined no deflection points were identified within +50 to-50% range of the mean self-selected Fr.

Figure 1 displays the group RPE (CR10) values with regression models in relation to Fr in normal and constrained walking. A linear fit best described the group data under normal walking and a quadratic fit under constrained walking. Figure 1 shows individuals walked with a similar RPE (CR10), but at slower walking speeds under the constrained condition.

Deflection point data analysis: CHO oxidation rate ($J.kg^{-1}.min^{-1}$)

Figure 2 shows CHO oxidation rate in relation to Fr for three individual raw data sets in normal walking, (linear relationship, $R^2 = 0.92$, quadratic relationship with deflection point, $R^2 = 0.96$ and without deflection point, $R^2 = 0.43$). Raw data graphs were chosen to display trends in CHO oxidation rate as they best represented the wide variance in data. A mean data graph would have been misrepresentative as there was little resemblance in the raw data between individuals as displayed in Figure 2.

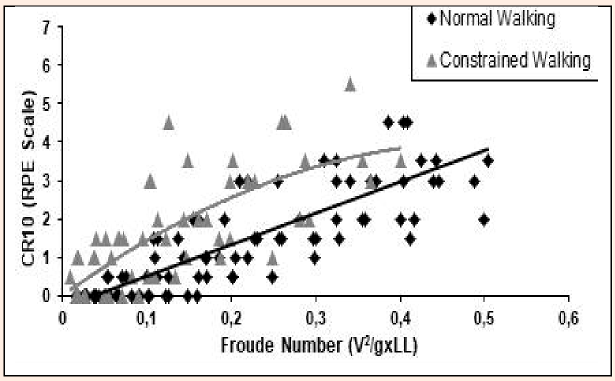

Figure 1. Mean data graph displaying CR10 (RPE) in relation to Fr in normal and constrained walking.

Table1. Walking measures. Data are means (± SD).

Speed	Walking	-60	-40	-20	SSWS	+20	+40	+60
Velocity	Normal	.51 (.07)	.76 (.06)	1.02 (.08)	1.27 (.12)	1.52 (.17)	1.76 (.15)	2.00 (.12)
($m \cdot s^{-1}$)	Constrained	.40 (.06)	.61 (.12)	.84 (.13)	1.03 (.16)	1.23 (.20)	1.46 (.22)	1.66 (.28)
Fr	Normal	.03 (.01)	.06 (.01)	.11 (.02)	.17 (.04)	.25 (.06)	.34 (.06)	.43 (.05)
($=v^2/\sqrt{gh}$)	Constrained	.02 (.01)	.04 (.01)	.08 (.02)	.12 (.03)	.16 (.04)	.23 (.06)	.30 (.09)
Energy Cost	Normal	5.59 (1.02)	4.12 (.54)	3.44 (.53)	3.20 (.42)	3.15 (.34)	3.41 (.39)	4.01 (.55)
($J \cdot kg^{-1} \cdot m^{-1}$)	Constrained	7.20 (.82)	5.51 (.98)	4.55 (.72)	4.37 (.57)	4.05 (.40)	3.85 (.24)	3.99 (.31)
CR10	Normal	.04 (.14)	.15 (.24)	.50 (.58)	.92 (.67)	1.77 (.83)	2.35 (.83)	3.62 (1.14)
	Constrained	.19 (.37)	.56 (.62)	.81 (.65)	1.50 (.85)	2.00 (.85)	2.75 (1.07)	4.06 (.82)
CHO Oxidation	Normal	.56 (.41)	.54 (.40)	.76 (.42)	.81 (.50)	.96 (.65)	1.65 (1.08)	2.64 (1.60)
Rate ($J \cdot kg^{-1} \cdot m^{-1}$)	Constrained	.73 (.56)	.81 (.57)	.97 (.90)	1.21 (.74)	1.19 (.68)	1.37 (.79)	2.00 (1.22)

Fr: Froude Number $=v/\sqrt{gh_m}$, CR10: Rating of Perceived Exertion; CHO: Carbohydrate

Table 2. Regression models that best described the relationships of Rating of Perceived Exertion (CR10) and Carbohydrat Oxidation Rate (CHO) ($J.kg^{-1}.min^{-1}$) with Fr: $=v^2/\sqrt{gh_m}$ individual normal and constrained Walking Graph Relationships.

	CR10		CHO Oxidation Rate	
Walking	**R^2**	**Regression Equation**	**R^2**	**Regression Equation**
Normal	.99	$y=-16.79x^2+18.90x–0.44$	.74	$y=12.42x^2+0.13x+1.10$
	.96	$y=16.75x^2+2.86x–0.21$	.39	$y=-6.79x^2+3.42x+0.57$
	.93	$y=28.24x^2-2.05x+0.37$	.91	$y=17.93x^2-3.05x+0.56$
	1.00	$y=36.80x^2-6.25x+0.19$	.19	$y=3.51x^2-0.77x+0.28$
	.97	$y=7.48x^2+2.90x–0.09$	.96	$y=29.24x^2-8.15x+1.00$
	.97	$y=11.86x^2+8.30x–0.42$	.93	$y=-12.64x^2+9.55x+0.89$
	.99	$y=3.82x^2+2.52x–0.19$	.95	$y=16.16x^2-1.58x+0.81$
	.95	$y=6.52x–0.01$	.76	$y=6.78x^2-0.12x+1.57$
	.99	$y=14.27x^2+1.76x–0.06$	.99	$y=42.27x^2-8.12x+1.02$
	.99	$y=-15.33x^2+18.05x–0.44$	.94	$y=49.82x^2-15.32x+1.17$
	.96	$y=2.78x^2+7.82x–0.35$	.92	$y=39.94x^2-10.54x+1.20$
	.97	$y=14.62x^2-0.53x–0.10$	.43	$y=-10.91x^2+6.66x–0.05$
	.96	$y=-4.06x^2+14.45x–0.65$	.98	$y=14.69x^2+1.01x+0.37$
	.97	$y=10.33x^2+2.45x–0.18$	.79	$y=12.65x^2-3.74x+0.40$
Constrained	.98	$y=46.52x^2+4.97x–0.17$	.47	$y=0.75e^{4.1862x}$
	.99	$y=16.88x–0.20$	.55	$y=11.58x^2-2.25x+0.86$
	.96	$y=-69.29x^2+35.94x–0.39$	.97	$y=8.83x^2+0.28x+0.27$
	.98	$y=252.21x^2-3.04x+0.76$	.10	$y=0.05lx+0.34$
	.98	$y=22.12x^2-0.18x–0.02$	.98	$y=1.66x^2+3.28x+0.56$
	.98	$y=16.50x^2+4.08x–0.15$	.99	$y=-4.36x^2+4.56x+0.43$
	.96	$y=8.82x+0.93$	.96	$y=29.58x^2+0.31x+1.15$
	.99	$y=2.56x^2+7.76x–0.27$	.81	$y=7.89x^2+0.75x+1.93$

Individual relationships (Table 2) reflected fourteen quadratic relationships in normal walking, seven of which offered possible deflection points at different percentages of SSWS, of these only five were in the defined range of SSWS outlined in the methods. Constrained walking displayed six quadratic, one exponential and one logarithmic relationship of which two offered possible deflection points, both of these were in the defined range of SSWS outlined in the methods.

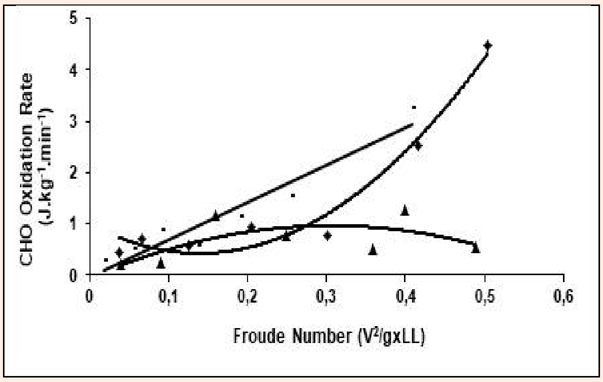

Figure 2. Raw data graph displaying three examples of different responses taken during normal walking of CHO oxidation rate ($J·kg^{-1}·m^{-1}$) in relation to Fr.

Table 2 shows the relationship and R^2 values for individual subject data in both normal and constrained walking. The data shows a lack of pattern in the relationship of CHO oxidation rates in either condition or between conditions.

Deflection point data analysis: Minimum energy cost ($J·kg^{-1}·m^{-1}$)

Figure 3 displays a mean data results graph of energy cost in relation to Fr during normal ($R^2 = 0.59$) and constrained ($R^2 = 0.70$) walking. The lowest point on the U-shaped curve indicates the Fr at which oxygen cost is at its lowest (optimal). Figure 3 shows the shift in oxygen cost-Fr relationship, up and to the left during constrained walking with the latter being more energy costly at slower speeds compared with normal walking. Minimum oxygen cost was recorded at Fr 0.26 in normal walking and Fr 0.21 in constrained walking. These figures are far removed from SSWS Fr, which occurred at 0.17 and 0.12 respectively. SSWS disparity was the same (Fr 0.09) in the two walking conditions ($p = 0.36$).

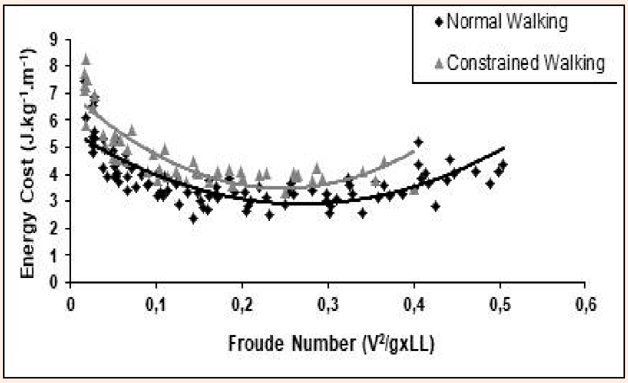

Figure 3. Mean data graph displaying Energy cost ($J·kg^{-1}·m^{-1}$) in relation to Fr in normal and constrained walking.

Discussion

We investigated metabolic and perceptual determinants of SSWS in non-fasted individuals under normal and constrained walking conditions and found minimum energy cost ($J.kg^{-1}·min^{-1}$) was closely associated with, but did not occur at, SSWS. Furthermore, despite the higher energy cost and slower overall walking speeds due to constrained walking, the disparity between SSWS and optimal energy cost (lowest energy cost), walking speed was the same in both walking conditions and similar to those reported by Elsworth et al. (2006). Analysis of both perceptual RPE (CR10) and CHO utilization ($J.kg^{-1}\cdot min^{-1}$) did not find a determinant for SSWS from a deflection point in their relationship with walking speed, as observed in fasted individuals (Willis et al,.2005). There was variability in RPE (CR10) between individuals at all walking speeds, but interestingly no difference in RPE (CR10) at SSWS between conditions, and less variability observed at faster speeds. It is proposed that individuals alter their preferred walking speed on perceptions of exertion which do not relate to the rate of CHO use, but rather to a minimum energy cost - which in turn may relate to a combination of as yet unidentified biomechanical and metabolic factors which could be neurophysiological in origin. Indeed work by Jeng et al. (1996) has shown that cerebral palsied subjects' auto-optimize their gait to limit symptoms such as pain.

We have established that self-optimization occurs in artificially constrained walking, associated with a minimum energy cost ($J.kg^{-1}\cdot min^{-1}$) being displaced down and to the right (Figure 3). Despite research examining minimal oxygen cost and self- optimization under altered step times and lengths, (Betram, 2005; Donelan et al., 2001; Holt et al., 1991; Minetti et al., 1995) to our knowledge there is no data available where both perceptual and energetic factors associated with self-optimization has been examined in this manner in simulated or pathological gait. Walking rehabilitation strategies which minimize perceived exertion should enable faster walking in people with altered gait as our findings indicate RPE was related to SSWS in both conditions.

The CR10 data (Figure 1) showed an alteration from a linear to a quadratic relationship with walking speed for normal versus constrained walking respectively. The non-linear relationship in constrained walking may be due to increased rating of perceived exertion and thus utilization of the CR10 scale which has a curvilinear relationship with underlying physiological markers of energy cost (Noble and Robertson, 1996), and was greater throughout constrained walking. However, in contrast to the findings of Willis et al. (2005) we found no clear point in either walking condition where CR10 deflected upwards as walking speed increased. CR10 appears to play a role in determining SSWS (Kinsman and Weiser, 1975) with CR10 the same at SSWS in both conditions, but this would appear to relate to the individual's feeling of exertion per se. Perceptual markers appear to influence SSWS and so may offer a route for manipulating optimization during walking.

CHO oxidation rate ($J.kg^{-1}\cdot min^{-1}$) did not demonstrate a consistent pattern with walking speed in individuals or under the two conditions when examined in the non-fasted state (Figure 2). As such, we found no evidence to suggest CHO oxidation rate was involved in the selection of SSWS in either normal or constrained walking conditions in non-fasted individuals. Whilst the present investigation was not carried out in the standard 'fasted' conditions associated with metabolism research, if it was a true determinant in everyday conditions the relationship should have held under our testing conditions. Novel technologies may add to tighter breath-by-breath control and understanding of deflection points for CHO utilization, however, our data suggests that in only a limited number of individuals were deflection points close to SSWS (Ralston, 1958). Whilst considering the application of our findings we must consider that we only looked at simulated walking conditions and not in individuals with actual pathology affecting metabolism. Other factors known to be involved in SSWS, such as sensory input, balance, conservation of angular momentum and safety (Herr and Popovic, 2008) was not measured in this study and may have influenced our results and should be considered in future studies using pathological groups.

Conclusions

We observed self-optimization in two walking conditions. Strategies to reduce the energy cost ($J.kg^{-1}\cdot min^{-1}$) of walking and/or lower perceived exertion levels would appear to potentially increase walking speeds. These findings need extending to explore a range of conditions to see if this strategy can act as a potent modulator of ambulation in people with pathological gait and therefore to inform rehabilitation strategies.

Acknowledgements
The experiments comply with the current laws of the country in which they were performed. The authors have no conflict of interest to declare.

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Key points

- Minimum energy cost (J.kg^{-1}·min^{-1}) was closely associated with, but did not occur at, SSWS.
- Perceptual RPE (CR10) and CHO utilisation rate markers did not find a determinant for SSWS.
- People should self-optimise walking to the same extent under different conditions.

AUTHOR BIOGRAPHY

David T. GODSIFF
Employment
Oxford Brookes University, Gipsy Lane, Headington, Oxford, OX30BP, UK
Degree
BM, BSc
E-mail: davidgodsiff@hotmail.co.uk

Charlotte ELSWORTH-EDELSTEN
Employment
Research Fellow in Sport and Exercise Science (School of Human & Life Sciences) Canterbury Christ Church University, Canterbury, Kent, UK
Degree
PhD
Research interests
Control and measurement of movement, gait analysis in individuals with pathological gait, use of electromyography and biomechanical methods to assess movement patterning and timing.
E-mail: lottie110@hotmail.com

Shelly COE
Employment
Oxford Brookes University, Gipsy Lane, Headington, Oxford, OX30BP, UK
Degree
PhD
Research interests
Sports rehabilitation, ageing, exercise and muscle.
E-mail: scoe@brookes.ac.uk

Johnny COLLETT
Employment
Oxford Brookes University, Gipsy Lane, Headington, Oxford, OX30BP, UK
Degree
PhD
Research interests
The control and measurement of movement, in particular gait, and applying this to neurological rehabilitation.
E-mail: jcollett@brookes.ac.uk

Ken HOWELLS
Employment
Oxford Brookes University, Gipsy Lane, Headington, Oxford, OX30BP, UK
Degree
PhD
Research interests
To evaluate factors affecting optimal human performance in health and disease. **E-mail:** kfhowells@brookes.ac.uk

Martyn MORRIS
Employment
Oxford Brookes University, Gipsy Lane, Headington, Oxford, OX30BP, UK
Degree
PhD
Research interests
The effects of exercise intensity on muscle performance using a novel electrical stimulation technique.
E-mail: mgmorris@brookes.ac.uk

Helen DAWES
Employment
Professor, Oxford Brookes University, Gipsy Lane, Headington, Oxford, OX30BP, UK
Degree
PhD
Research interests
Exploring underlying mechanisms affecting performance through to service delivery of subsequently developed interventions and tools.
E-mail: hdawes@brookes.ac.uk

✉ **Dr Shelly Coe**
Oxford Brookes University, Gipsy Lane, Headington, Oxford, OX30BP, UK