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Research article

OXYGEN COST DURING TREADMILL WALKING WITH HIP AND KNEE IMMOBILISED

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ABSTRACT
The aim of this study was to determine the effect of immobilising the knee and hip on the oxygen cost ($ml \cdot kg^{-1} \cdot min^{-1}$) to velocity relationship during treadmill walking. The study was a prospective experimental conducted in a Rehabilitation centre. Ten healthy individuals, five men and five women, with no gait abnormality participated. Following familiarisation five men and five women walked on a treadmill and selected their own, free "comfortable walking velocity" (SSWS). Subjects then performed an incremental test at -60 to +60% of SSWS. Individuals later repeated the test with the knee and hip of one limb immobilised. Samples of expired air were measured at each velocity and the oxygen cost ($ml \cdot kg^{-1} \cdot min^{-1}$) to Froude number (*Fr*) relationship plotted (where calculation of *Fr* normalizes for subjects of differing leg length and acts as an index of velocity). There was a higher oxygen cost, and lower *Fr* at SSWS during immobilised (0.21 ± 0.03 $ml \cdot kg^{-1} \cdot min^{-1}$; $Fr = 0.12 \pm 0.03$) compared with free walking (0.16 ± 0.02 $ml \cdot kg^{-1} \cdot min^{-1}$; $Fr = 0.18 \pm 0.04$) ($p < 0.01$). Statistical analysis demonstrated that during immobilised walking an inverse fit ($y = \beta_0 + \beta_1/x$) and for free walking a cubic fit ($y = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_3 x^3$) best fitted the data. Hip and knee immobilisation increased the oxygen cost at SSWS and altered the oxygen cost to *Fr* relationship. The results have implications in selecting optimal walking velocities in individuals with impairments affecting mobility such as hemiplegic gait.

KEY WORDS: Froude number, oxygen cost, immobilisation, hip, knee, walking**,** hemiplegic gait.

INTRODUCTION

Our everyday movements appear to be constrained by the drive to minimise metabolic energy expenditure (Alexander, 2002; Kinsman and Weiser, 1975). This can be observed during walking, when individuals self-select walking velocities that coincide with the lowest oxygen cost ($ml \cdot kg^{-1} \cdot min^{-1}$) (Waters et al., 1988) and also select a stride frequency that minimizes energy expenditure (Minetti et al., 1995). The energy cost ($kcalkg^{-1} \cdot km^{-1}$) to velocity ($km \cdot h^{-1}$ or $m \cdot s^{-1}$) relationship during walking demonstrates a U-shaped curve with a minimum energy cost occurring at a velocity of approximately 1.3 $m \cdot s^{-1}$ (Margaria, 1976; Minetti and Alexander, 1997). This U-shaped curve can be explained by the mechanical work performed during walking. By raising the body's centre of mass (CoM) external work accounts for 60-75% of the total work done (Cavagna and Kaneko, 1977). The energy required to raise the CoM is minimised by the stance leg working as an inverted pendulum, vertically deflecting the CoM. When walking at an optimum velocity (defined herein as a velocity associated with the lowest oxygen cost) around 65% of the energy acting on the CoM may be conserved by this mechanism (Cavagna et al., 1976). At higher or lower velocities less energy is conserved by the inverted pendulum mechanism and more energy is needed to control torso movement and accelerate and decelerate the legs (producing internal work), thus giving rise to the U-shaped energy cost to (walking) velocity curve (Cavagna and Margaria, 1966; Margaria, 1976).

Although the energy to walking velocity relationship is well described in healthy individuals, little is known about how the energy cost to walking velocity relationship is affected in individuals with pathologies affecting the lower limbs. When a limb is immobilised, individuals walk more slowly, with a general increase in the effort of walking (Hanada and Kerrigan, 2001, Mattsson et al., 1990), as do individuals with conditions such as stroke, where reduced leg mobility is also observed (Witte and Carlsson, 1997). It is unclear whether the pendulum mechanism holds true and if an optimum velocity is still selected under these conditions. A change in the pendulum mechanism could result in disruption in the normal energy cost to velocity relationship (Pohl et al., 2002; Sullivan et al., 2002). A greater understanding of the energy cost to velocity relationship in individuals walking with altered lower limb mechanics may inform rehabilitation strategies for certain pathological gaits.

Individuals with lower limb pathology are often limited in their ability to walk safely at a range of velocities, thus the present study set out to examine the gross oxygen (as an index of energy) cost ($ml \cdot kg^{-1} \cdot min^{-1}$) to velocity relationship in healthy individuals walking with an immobilised hip and knee compared with free walking.

METHODS

Ten healthy subjects, five men and five women (mean ± *s*: age 23.1 ± 3.6 years, height 1.76 ± 8.1 m, body mass 73.0 ± 13.2 kg), with prior experience of treadmill walking and with no medical problems that affected gait participated.

Informed consent was obtained before participation according to the Declaration of Helsinki (1996) and ethical approval was granted by Oxfordshire Applied and Qualitative Research Committee (AQREC). Laboratory testing was carried out under standardised conditions (Waters et al., 1988). Height was measured using a wall-mounted stadiometer and body mass was measured to the nearest 0.1 kg using a weigh scale (Seca Ltd., London). Leg length (*L*) was measured (cm) from the anterior superior iliac spine to the medial malleolus in order to derive a Froude number (*Fr*) for each individual. Calculation of a Froude number normalizes for individual differences in leg length (Schepens et al., 2004; Vaughan and O'Malley, 2005).

Subjects walked on a motorized treadmill (Woodway, PPS-55; Weil am Rhein, Germany) with the velocity display covered. By adjusting the treadmill controls subjects determined a 'comfortable walking velocity' (or 'self-selected walking velocity'; SSWS). Individuals then walked for four minutes at –60, -40, -20, +20, +40 and +60% of their individually determined SSWS. This test (test 1) was performed as a continuous protocol during which samples of expired air were collected in Douglas bags during minutes 3-4 of each velocity (Waters et al., 1988).

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 a dry gas meter (Harvard Apparatus Limited, Edenbridge, UK). The gas analysers were calibrated on each testing occasion using gas mixtures of known concentration. Oxygen uptake (VO_2, $ml \cdot kg^{-1} \cdot min^{-1}$) was measured using open circuit spirometry and values expressed under standard conditions (STPD).

The steady rate oxygen uptake ($ml \cdot kg^{-1} \cdot min^{-1}$) was measured at each walking increment (-60 to +60 SSWS) and the corresponding oxygen cost of walking ($ml \cdot kg^{-1} \cdot min^{-1}$) calculated. Within one week individuals were re-tested at the same absolute treadmill velocities (test 2).

The same individuals attended for a further test (test 3) within seven days, following the same procedure as test 1, however, the right leg was immobilised using a custom made hip and knee brace (allowing 20° flexion at the knee and 10° movement at the hip) when a new SSWS was determined (Simon et al, 1996).

Statistical analysis

To establish the repeatability of oxygen cost measures (test 1 versus test 2), the hypothesis of zero bias was tested at each velocity using a Student's t-test ($p < 0.05$), with the upper and lower limits of agreement calculated as differences of the

Table 1. Test (T1) and re-test (T2) analysis for oxygen cost (ml·kg^{-1}·min^{-1}) of free treadmill walking (SSWS). Mean values for velocity (m·s^{-1}) and oxygen cost. Data are means (±SD).

%SSWS	Velocity	O_2 cost (T1)	O_2 cost (T2)	Bias	Random error	t-test (p)
-60	.52	.27 (.05)	.28 (.05)	-.01	.08	.31
-40	.77	.20 (.03)	.21 (.02)	-.01	.07	.36
-20	1.03	.17 (.03)	.17 (.02)	-.01	.06	.46
SSWS	1.30	.16 (.02)	.17 (.02)	-.01	.05	.20
+20	1.55	.15 (.02)	.16 (.02)	-.01	.05	.14
+40	1.77	.16 (.01)	.17 (.02)	-.01	.04	.17
+60	2.00	.19 (.01)	.19 (.03)	.00	.04	.57

mean ± 1.96 SD and reported as bias and random error (Bland, 1996). Walking velocity was normalised for each individual using a Froude number (Fr = v^2 / gL), where *v* is velocity, *g* the acceleration due to gravity and *L* leg length), *Fr* acting as a dimensionless index of velocity (Vaughan and O'Malley, 2005).

The oxygen cost data from test 2 was used in further analysis and plotted against *Fr*; thus *Fr* was used to scale inter-individual differences in the velocity at which the 'optimum' (defined herein as the lowest) oxygen cost occurred.

Oxygen cost was examined for differences between the men and women during 'free' and 'immobilised' walking. Preliminary statistical analysis (SPSS for Windows Release 12) showed that there was no significant difference between men and women for oxygen cost and *Fr* at SSWS during both free and immobilised treadmill walking. Therefore the male and female data was pooled for subsequent analysis. Analysis showed the oxygen cost data was skewed, however, there was no difference between parametric and non-parametric analysis. Therefore the results are presented throughout using parametric analysis.

RESULTS

There was no significant difference in the oxygen cost of treadmill walking, test 1 versus test 2 (Table 1). At all percentages of SSWS individuals recorded a lower oxygen cost, faster velocity and higher *Fr* during free compared with immobilised walking (Table 2). Curve fitting analysis was performed to determine the line of best fit for oxygen cost (ml·kg^{-1}·min^{-1}) to *Fr* relationship. Cubic regression best described the relationship during free walking ($y = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_3 x^3$) (Figure 1a) and an inverse regression during immobilised walking ($y = \beta_0 + \beta_1/x$) (Figure 1b).

DISCUSSION

When one leg was immobilised, healthy individuals walked with a greater oxygen cost through a similar range of treadmill velocities and the normal U-shaped energy cost (ml·kg^{-1}·min^{-1}) to velocity relationship changed from a cubic to an inverse fit with no minimum (optimum) point for oxygen cost (Figure 1).

During free treadmill walking, individuals walked at a self-selected walking velocity of approximately 1.30 m·s^{-1}. The free SSWS velocity and the associated mean (optimum) oxygen cost (0.16 ± 0.02 ml·kg^{-1}·min^{-1}) compared favourably with an earlier treadmill study (Pearce et al., 1983) but was lower than that reported by Waters et al. (1988) during over ground (terrain) walking.

During free treadmill walking individuals self-selected slower velocities (*Fr* = 0.18; corresponding to 0.16 ml·kg^{-1}·min^{-1}) compared with that suggested as being most 'efficient' (i.e. a velocity associated

Table 2. Velocity (m·s^{-1}, expressed as a percentage of SSWS), Froude number (Fr) and oxygen cost (ml·kg^{-1}·min^{-1}) for free and immobilised walking. Data are means (±SD).

	Free			Immobilised		
	Velocity	Froude (Fr)	O_2 cost	Velocity	Froude (Fr)	O_2 cost
-60	.52 (.08)	.03 (.01)	.27 (.05)	.40 (.05)**	.02 (.00)**	.36 (.07)**
-40	.77 (.07)	.06 (.01)	.20 (.03)	.61 (.10)**	.04 (.01)**	.27 (.05)**
-20	1.06 (.09)	.12 (.03)	.16 (.03)	.83 (.11)**	.08 (.02)**	.22 (.05)**
SSWS	1.30 (.13)	.18 (.04)	.16 (.02)	1.02 (.13)**	.12 (.03)**	.21(.03)**
+20	1.55 (.18)	.26 (.07)	.15 (.02)	1.22 (.16)**	.17 (.05)**	.20 (.02)**
+40	1.77 (.17)	.34 (.07)	.16 (.01)	1.48 (.19)**	.25 (.07)*	.19 (.02)**
+60	2.00 (.11)	.43 (.05)	.19 (.01)	1.67 (.23)**	.31 (.08)**	.20 (.02)

* $p < 0.05$ and ** $p < 0.01$ indicates a significant difference between free and immobilised walking.

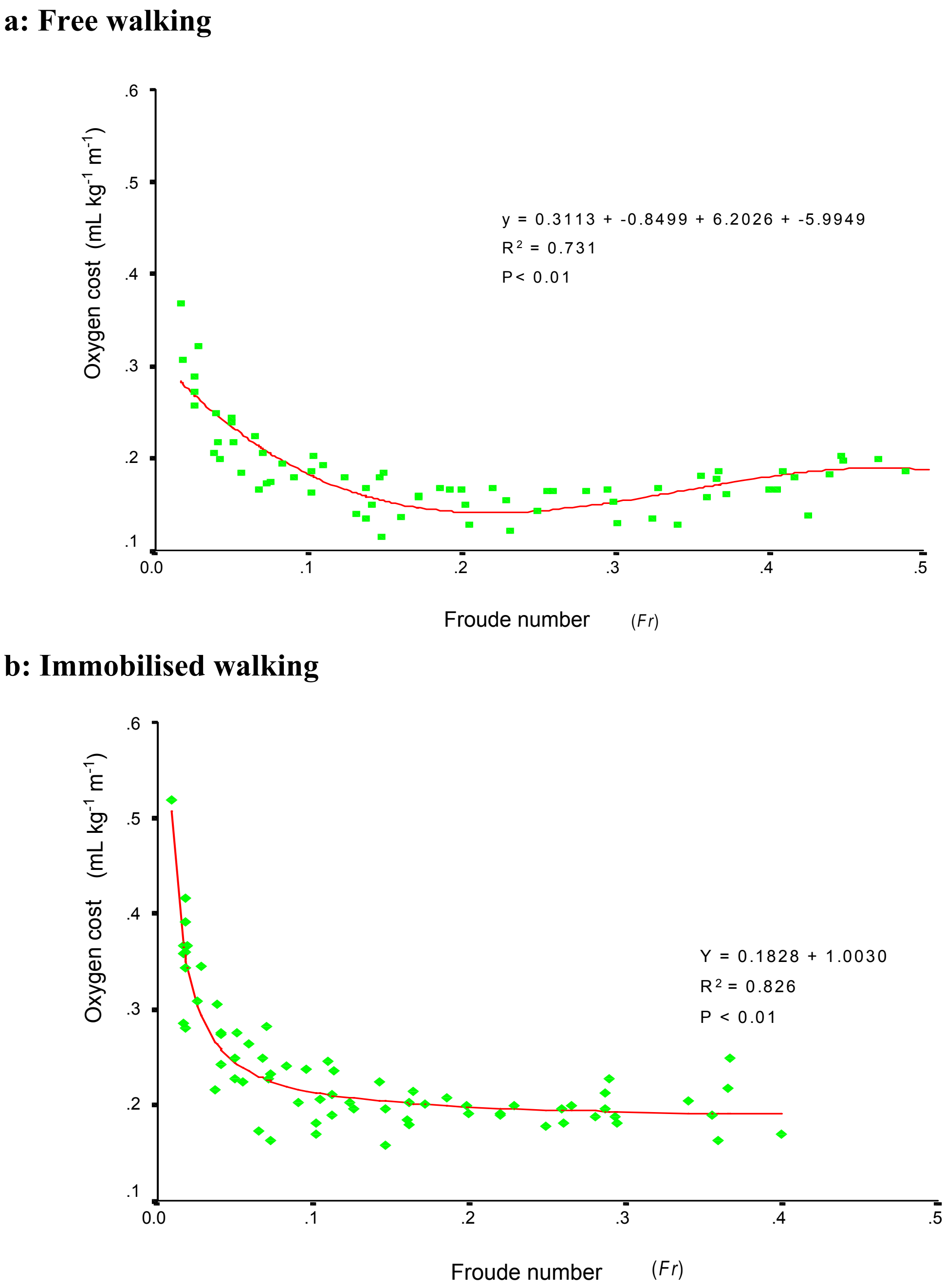

Figure 1. Oxygen cost ($ml \cdot kg^{-1} \cdot min^{-1}$) to Froude number (*Fr*) relationship.

with the lowest energy cost) during over-ground walking by Alexander's dynamic similarity model where *Fr* = 0.25 (Minetti and Alexander, 1997). Thus results from the present study suggests that the dynamic similarity model developed for over-ground walking may not apply to the altered mechanics of treadmill walking, a point also identified by Dingwell et al. (2001). In fact the lowest oxygen cost during free walking was 0.15 $ml \cdot kg^{-1} \cdot min^{-1}$ (*Fr* = 0.26). During immobilised walking the lowest oxygen cost was 0.19 $ml \cdot kg^{-1} \cdot min^{-1}$ (*Fr* = 0.25); and the corresponding measures at immobilised SSWS were 0.21 $ml \cdot kg^{-1} \cdot min^{-1}$ (*Fr* = 0.12) (Table 2).

As expected, when individuals were immobilised they walked at slower velocities (Hanada and Kerrigan, 2001; Mattsson and Brostrom, 1990). A decrease in walking velocity was not surprising as individuals could not achieve an optimal gait when wearing the brace and were observed to compensate by either circumduction or hip hiking to advance the immobilised leg. Waters and Mulroy (1999) and Mattsson and Brostrom (1990) reported that walking with an immobilized knee caused an increase in oxygen cost of approximately 23%, similar to that calculated in the present study. Not only did walking with a hip and knee immobilized lead to a higher oxygen cost ($ml \cdot kg^{-1} \cdot min^{-1}$), but also that the normal energy (oxygen) cost to *Fr* (velocity) relationship changed from a cubic to an inverse relationship.

To the best of the authors' knowledge no previous study has examined the oxygen cost to velocity relationship within a normal population through such a wide range of velocities during limb immobilisation. It was hypothesised that the higher oxygen cost observed at all velocities may be in part due to: the weight of the brace adding to the effort of raising the centre of mass (CoM), and greater vertical displacement of CoM due to the limited stance phase and knee flexion (during both 'stance' and 'swing'), the additional effort required to control the torso and the energy required to initiate and stop limb movement when optimal swing mechanics were prevented.

The change from the normal U-shaped curve suggests that hip and knee immobilisation disrupted the normal pendulum mechanism. It is interesting that during limb immobilisation a minimum oxygen cost was not observed, rather the oxygen cost gradually reduced as walking velocity increased (Figure 1b). These findings support the current trend with neurological patients during rehabilitation which concentrates on increasing walking velocity (Pohl et al., 2002, Sullivan et al., 2002). The results of the present study also suggest that when one limb is immobilised the mechanics of walking are altered, such that subjects were unable to walk optimally (i.e. with a minimum energy / oxygen cost).

Taking into consideration the positive effect of stretching at the hip on movement economy in hemiplegic gait (Mattsson et al., 1990) the results of the present study lend support for further investigation into stretching protocols and interventions that increase hip and knee mobility in individuals with a stiff-limbed gait, and for encouraging faster walking velocities during the rehabilitation process.

The findings from the present study must be considered in light of the knowledge that the inverse curve fit to the data in the immobilised condition may in part be due to the reduced range of walking velocities during lower limb immobilisation. The present study was carried out in healthy men and women, and future studies should attempt to investigate pathological gait using the energy cost to *Fr* relationship before any conclusions for rehabilitation should be drawn.

CONCLUSION

The present study has shown that, when one leg is immobilised, individuals walk with a greater oxygen cost ($ml \cdot kg^{-1} \cdot min^{-1}$) and that the oxygen cost to *Fr* relationship changes from a cubic to an inverse fit. In the immobilised condition, there was no minimum oxygen cost within the observed range of walking velocities. In both conditions, individuals selected a velocity (SSWS) that was slower, with a lower *Fr*, compared with over-ground walking where a self-selected walking velocity coincides with a minimum energy cost. The results of the present study suggest that oxygen (energy) cost may not be the sole determinant of an individual choosing a certain walking velocity. The findings of the present study need replicating in individuals with impairments affecting mobility such as hemiplegic gait in order to determine an appropriate strategy to be used during rehabilitation.

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KEY POINTS

- Walking with one limb immobilised requires greater energy cost than normal free walking.
- This has clinical implications when developing rehabilitation strategies for patients who mobility problems such as those with hemi paretic gait.

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