Eur J Appl Physiol (2006) 96: 1–9
DOI 10.1007/s00421-005-0057-9

ORIGINAL ARTICLE

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Effect of posture on high-intensity constant-load cycling performance in men and women

Accepted: 16 August 2005 / Published online: 13 October 2005

Abstract The time sustained during a graded cycle exercise is ~10% longer in an upright compared with a supine posture. However, during constant-load cycling this effect is unknown. Therefore, we tested the postural effect on the performance of high-intensity constant-load cycling. Twenty-two active subjects (11 men, 11 women) performed two graded tests (one upright, one supine), and of those 22, 10 subjects (5 men, 5 women) performed three high-intensity constant-load tests (one upright, two supine). To test the postural effect on performance at the same absolute intensity, during the upright and one of the supine constant-load tests subjects cycled at 80% of the peak power output achieved during the upright graded test. To test the postural effect on performance at the same relative intensities, during the second supine test subjects cycled at 80% of the peak power output achieved during the supine graded test. Exercise time on the graded and absolute intensity constant-load tests for all subjects was greater ($P < 0.05$) in the upright compared with supine posture (17.9 ± 3.5 vs. 16.1 ± 3.1 min for graded; 13.2 ± 8.7 vs. 5.2 ± 1.9 min for constant-load). This postural effect at the same absolute intensity was larger in men (19.4 ± 8.5 upright vs. 6.6 ± 1.6 supine, $P < 0.001$) than women (7.1 ± 2 upright vs. 3.9 ± 1.4 supine, $P > 0.05$) and it was correlated ($P < 0.05$) with both the difference in $\dot{V}O_2$ between positions during the first minute of exercise ($r = 0.67$) and the height of the subjects ($r = 0.72$). In conclusion, there is a very large postural effect on performance during constant-load cycling exercise and this effect is significantly larger in men than women.

Keywords Cycling performance · Posture · Gender · Oxygen consumption · Height

Introduction

In humans, the time sustained for a maximal graded cycle test is longer by ~10% in an upright compared with a supine posture (Eiken 1988; Koga et al. 1999; Terkelsen et al. 1999). Physiological differences that could help explain this effect appear to manifest only at higher intensities, with the most notable effects in the upright posture being a relatively smaller change in blood lactate at the same submaximal power output and a higher peak $\dot{V}O_2$ (Leyk et al. 1994; Terkelsen et al. 1999). Studies of constant-load exercise also suggest that the responses of muscle blood flow (Egaña and Green 2005; Folkow et al. 1971; MacDonald et al. 1998) and $\dot{V}O_2$ (Convertino et al. 1984; Koga et al. 1999; Leyk et al. 1994) during the early phase of exercise are accelerated in an upright position, and so these responses might also help explain the effect of posture on performance during a maximal graded test.

In contrast to performance data related to maximal graded exercise, the effect of posture on performance during constant-load exercise is not known. The physiological data mentioned above supports the hypothesis that performance during high-intensity constant-load exercise is increased in the upright compared with supine posture. The main aim of the present study was to test this hypothesis, and to provide an insight into the postural effect on performance. We also explored the association between this effect and several anthropometric and physiological variables.

Materials and methods

Overview

All experimental procedures were conducted in accordance with the Declaration of Helsinki (1982) and were

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approved by the Trinity College Dublin Research Ethics Committee prior to the study. Initially, 22 physically active subjects (11 men and 11 women) performed two graded ($\dot{V}O_{2\,max}$) cycling tests (one in the upright and one in the supine posture). Then, of those 22 subjects, 10 (5 men and 5 women) performed three high-intensity constant-load tests to the point of failure (one in the upright and two in the supine posture).

Subjects

Before inclusion in the study all subjects gave informed consent. All subjects were free from overt cardiovascular, metabolic, pulmonary and musculoskeletal disease as assessed using a medical history questionnaire, and only one subject (male) was a regular smoker.

Posture

The graded and constant-load cycle tests were performed in upright and supine positions (Fig. 1a, b). During upright exercise subjects cycled with the upper body and head in the vertical plane with the arms held loosely by the side. This was done to minimise muscle activation and O_2 consumption associated with postural support in the usual cycling position (i.e. gripping the handlebars). During supine exercise subjects lay comfortably behind the ergometer, arms loosely by their side, and were harnessed to the ergometer so that their position remained fixed during exercise. The hip and knee angles were measured so that they were similar between the two positions. The ergometer was raised 20 cm above the floor to enable these angles to be similar and allow sufficient foot clearance above the floor during exercise. Thus, the alignment of body parts was very similar in the two postures with the essential difference being the body's orientation to the gravitational vector.

Exercise and performance

Exercise was performed on an electrically-braked cycle ergometer (Lode Excalibur Sport, Groningen, Netherlands) that maintained power output independent of the cadence. The cadence required during exercise was 60 rpm.

Graded tests Subjects performed two graded ($\dot{V}O_{2\,max}$) tests; one in the upright and one in the supine posture in a randomised order. For men, the exercise test began at 60 W for 3 min, and thereafter the power output was increased in a step-wise manner by 30 W every 3 min until the point of failure. The exercise protocol was the same for women except the initial power output was 30 W. Failure was defined as the inability to maintain a minimum cadence (i.e. 50 rpm) for 3 s. Time to failure was recorded and used to represent cycling performance. Also, final workloads achieved were recorded to determine absolute and relative workloads for subsequent constant-load tests.

Constant-load tests Subjects performed three constant-load tests; one in the upright and two in the supine posture in a randomised order. To test the effect of body position on performance at the same absolute intensity, we compared the upright and one of the supine constant-load tests (supine ABS), where in both tests subjects cycled at an intensity equivalent to 80% of the maximum workload achieved during the upright graded test. To test the effect of body position on performance at the same relative intensity, we compared the upright

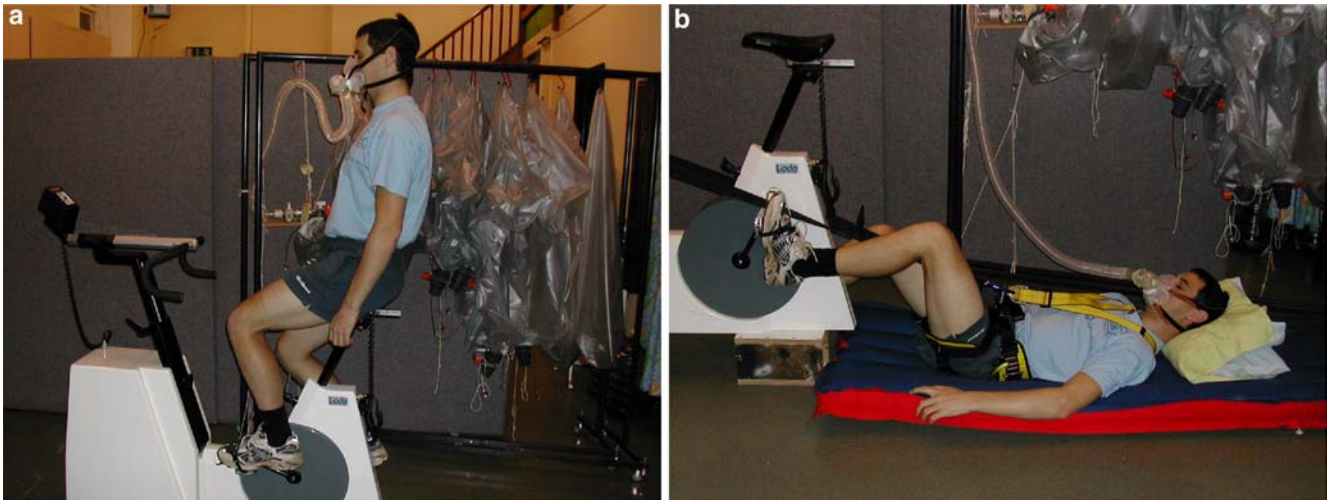

Fig. 1 A subject in the upright posture (**a**) and in the supine posture (**b**). Note that in both postures the knee and hip angles are similar and the arms are held loosely by the side to minimize muscle activation associated with gripping the handlebars. In the supine posture the ergometer is raised 20 cm above the floor to allow sufficient foot clearance and the subject is harnessed to the ergometer to keep a fixed position during the exercise

test (intensity equivalent to 80% of the maximum workload achieved during the upright graded test) with the second supine test (supine REL), where the intensity was set at 80% of the maximum workload achieved during the supine graded test. Previous familiarisation provided that all subjects reached the target workload within 2–3 s of the beginning of the exercise. They were instructed to exercise until failure which was defined as the inability to maintain a minimum cadence (i.e. 50 rpm) for 3 s.

Physiological measurements

Expired air was collected using Douglas bags. For all tests, gas was collected during the last minute of two 5 min periods of rest (prior to exercise), and during the last 30 s of each exercise bout. During the first 5 min period of rest, as a control measurement, subjects were seated on a chair in the quiet testing bay; whereas during the second rest period, subjects assumed the position in which they would exercise (upright or supine) and remained motionless with their feet placed in the pedal straps. During the graded tests, gas was also collected during the last 30 s of each cycling workload. During the constant-load tests, the initial response of $\dot{V}O_2$ was estimated by collecting expired gases over each consecutive 15 s period for the first minute of exercise (i.e. 15, 30, 45 and 60 s), and over each 30 s period during the second minute (i.e. 90 and 120 s). These $\dot{V}O_2$ measurements were plotted at the mean time points of collection (i.e. 7.5, 22.5, 32.5 and 52.5 s for the first min, and 75 and 105 s for the second min). Whole-body oxygen consumption ($\dot{V}O_2$) and minute ventilation ($\dot{V}_E$) were calculated following analysis of the expire gasses collected in the Douglas bags for O_2 and CO_2 (for O_2; P.K. Morgan, Kent, England; and Tylor Servomex Limited, Sussex, England; and for CO_2; Engstrom Eliza, Gambo Engstrom, Bromma, Sweden; and P.K. Morgan Ltd, Kent, England) and total expired volume (U.G.I. Meters Ltd., England; and Cranlea and company, Birmingham, England). Prior to each test the O_2 and CO_2 analysers were calibrated using two test gases, environmental air (21% O_2, 0.04% CO_2 and balance N_2) and an alpha standard certified gas (15% O_2, 5% CO_2 and balance N_2; BOC Ltd., UK). Heart rate (HR) was measured with a transmitter strapped around the chest (Polar S610, Polar Electro, Finland). Peak $\dot{V}O_2$, peak $\dot{V}_E$ and peak HR were taken as the highest values observed.

Anthropometric measurements

Height (cm) was measured using a Seca^{TM} stadiometer (Seca Ltd., Germany) and body mass (kg) was measured using a platform-beam scale (AVERY, England). The magnitude of the hydrostatic pressure acting on the active muscles in cycling can be estimated using the equation, ρgh, where ρ is the density of the fluid (i.e. blood), g is the gravitational constant, and h is the height or length of the column of blood between the heart and arteries feeding the proximal muscles engaged in cycling. To estimate this length for each subject the distance from 5 cm below the manubriosternal angle (point where the right atrium lies) to the midpoint of the two lateral iliac crests was measured. This distance is referred to as the 'hydrostatic column'. To determine lean body mass, body fat percentage was assessed in the 10 subjects that performed the constant-load tests by skinfold thickness measurement using four different sites (Durnin and Womersley 1974).

Statistics

A two-way (between-within) ANOVA was used to identify main effects (gender, posture) or interactions (gender by posture) for performance and all physiological variables. A repeated measures ANOVA was used to identify effects or interactions for the $\dot{V}O_2$ and HR responses during exercise. A Tukey's HSD test was used to locate specific pair-wise differences for significant ANOVA findings. Associations between anthropometric, metabolic and exercise variables were analysed using a Pearson Product Moment correlation coefficient. All data were expressed as mean ± SD. The level of significance was set to $P < 0.05$.

Results

Anthropometric characteristics

Among all subjects ($n = 22$, 25.1 ± 4.6 year) men were significantly taller and heavier than women and the hydrostatic column was longer in men than women. Similarly, among the 10 subjects that performed the constant-load tests men were also significantly taller and heavier and the hydrostatic column was longer than women (Table 1).

Graded exercise

Exercise times and peak physiological responses for all subjects ($n = 22$) are shown in Table 2, and similar responses were also observed for the 10 subjects that performed the constant-load tests. Exercise time, peak power and peak heart rate were larger ($P < 0.01$) in the upright than supine posture, and these effects were similar ($P > 0.05$) between men and women.

Constant-load exercise (same absolute intensity)

At the same absolute power output, exercise time was significantly longer in the upright than the supine posture (main effect = posture, $P < 0.001$, $n = 10$, Fig. 2, Table 3). Moreover, there was a significant interaction between posture and gender ($P < 0.05$) for exercise time,

Table 1 Subjects anthropometric characteristics (mean ± SD)

	MEN		WOMEN	
	Incremental test ($n = 11$)	Constant-load tests ($n = 5$)	Incremental tests ($n = 11$)	Constant-load tests ($n = 5$)
Height (cm)	182 ± 9*	181 ± 8*	164 ± 8	165 ± 2
Weight (kg)	75.9 ± 13.3*	77.3 ± 7.2*	59.9 ± 9.9	62.2 ± 8.0
Age (year)	24.0 ± 3.4	23.4 ± 3.9	26.2 ± 5.7	27.0 ± 5.9
Hydrostatic column (cm)	31.6 ± 3.0*	31.8 ± 2.3*	27.8 ± 3.0	26.9 ± 2.0

* Significantly different from women ($P < 0.05$)

Table 2 Graded test exercise times and peak physiological responses (mean ± SD)

	Men		Sig.	Women	
	Upright	Supine		Upright	Supine
All subjects ($n = 22$)					
Cycle time (min)	20.3 ± 3.7*	18.3 ± 2.9	**	15.4 ± 3.0*	13.9 ± 3.2
Peak power (W)	248 ± 38*	226 ± 34	**	169 ± 31*	150 ± 27
Peak power ($W.kg^{-1}$)	3.31 ± 0.49*	3.02 ± 0.43		2.89 ± 0.73*	2.55 ± 0.58
Peak $\dot{V}O_2$ ($ml.kg^{-1}.min^{-1}$)	41.2 ± 7.7	39.7 ± 8.1	**	31.9 ± 11.4	30.5 ± 12.2
Peak $\dot{V}_E$ ($ml.kg^{-1}.min^{-1}$)	1342 ± 296	1297 ± 318		989 ± 365	829 ± 328
Peak HR ($beats.min^{-1}$)	184 ± 19*	172 ± 21		179 ± 11*	164 ± 11
Subjects who also performed the constant-load tests ($n = 10$)					
Cycle time (min)	21.2 ± 3.6*	18.5 ± 3.1	**	16.4 ± 2.3*	14.0 ± 3.1
Peak power (W)	252 ± 46*	228 ± 40	**	174 ± 25*	150 ± 30
Peak power ($W.kg^{-1}$)	3.3 ± 0.7*	3.0 ± 0.5	**	2.4 ± 0.4*	2.2 ± 0.4
Peak $\dot{V}O_2$ ($ml.kg^{-1}.min^{-1}$)	42.8 ± 4.8	43.1 ± 7.3	**	33.9 ± 3.8	30.7 ± 7.4
Peak $\dot{V}O_2$ ($ml.min^{-1}.kg^{-1}$ lean)	50.6 ± 7.4	51.1 ± 11.8		45.8 ± 3.2	41.5 ± 9.0
Peak $\dot{V}_E$ ($ml.kg^{-1}.min^{-1}$)	1271 ± 326	1476 ± 335		1230 ± 282	1005 ± 390
Peak HR ($beats.min^{-1}$)	179 ± 7*	166 ± 13		182 ± 10*	164 ± 11

* Significantly different from supine ($P < 0.05$)
** Significantly different between men and women ($P < 0.05$)

such that the postural effect on cycle time was significantly larger in men than women. For the whole group (men and women), significant correlations were observed between subject height and the absolute (min) and relative (%) change in cycle time between the inclined and supine posture (Figs. 3a, b), as well as between the hydrostatic column and the absolute change ($r = 0.68$, $P < 0.05$), but not the relative change ($r = 0.53$, $P = 0.12$), in cycle time. In contrast, body weight was not significantly correlated with performance variables. The height of the participants was correlated with the hydrostatic column ($r = 0.93$, $P < 0.001$).

Although resting $\dot{V}O_2$ was similar in the upright and supine postures, $\dot{V}O_2$ during the first two minutes of exercise was significantly higher in the upright compared with the supine posture (Fig. 4a); whereas $\dot{V}O_2$ at the end of exercise was not affected by posture (Table 3). This effect of posture on $\dot{V}O_2$ was established within the first 15 s of exercise because changes in $\dot{V}O_2$ during subsequent periods were not affected by posture (Fig. 4b). The difference in the calculated change in $\dot{V}O_2$ over the first minute $\left(\text{i.e. } \dot{V}O_2 \text{ at 60 s minus pre - exercise } \dot{V}O_2\right)$ between upright and supine exercise was positively correlated with the absolute change in exercise time between the two positions (Fig. 3c).

Resting HR on the chair was similar between the two postures, whereas resting HR on the bike was significantly higher ($P < 0.001$) in the upright compared with the supine ABS posture (76 ± 6 vs 67 ± 8 beats min^{-1}). HR during the first 2 min of exercise was significantly higher during the upright posture at all time points (Fig. 4c). The change in HR over the four 15 s periods in the first minute of exercise was not affected by posture in men or women (Fig. 4d). End-exercise HR (i.e. peak HR) was significantly higher in the upright posture for men and women (Table 3).

Constant-load exercise (same relative intensity)

At the same relative power output, cycling time in the upright posture was not significantly different from the supine REL posture in either men ($P = 0.12$) or women ($P = 0.81$, Fig. 2, Table 3). Despite this, a significant interaction between gender and posture was observed for cycle time (ANOVA $P < 0.05$) at the same relative intensity.

Resting $\dot{V}O_2$ was similar in the upright and supine REL postures. However, $\dot{V}O_2$ was significantly higher in the upright compared with the supine REL posture at all

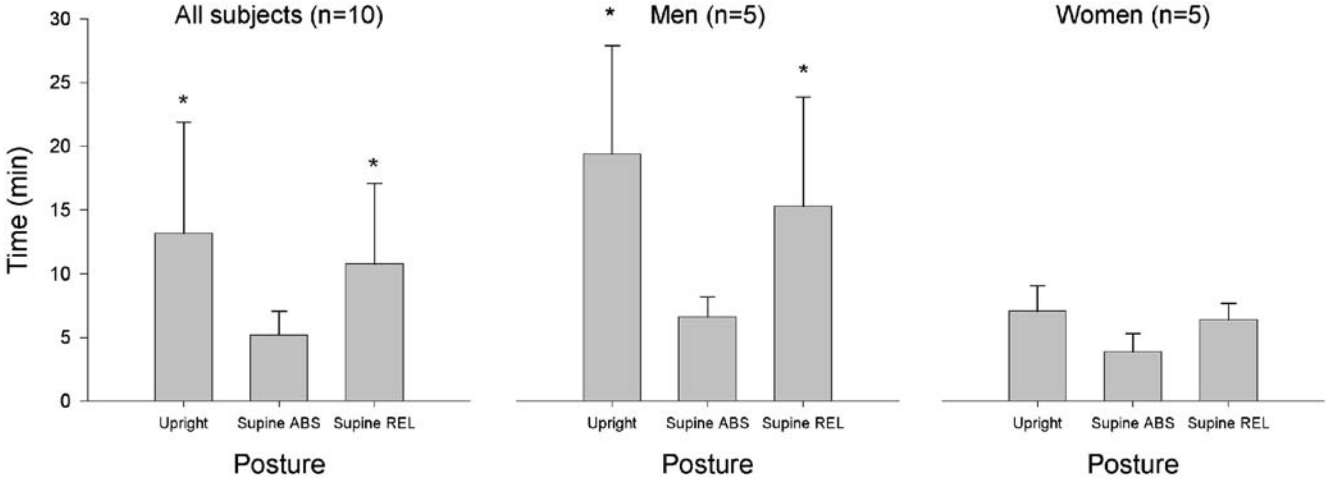

Fig. 2 Exercise times to failure (mean ± SD) during constant-load tests in all subjects ($n = 10$), men ($n = 5$) and women ($n = 5$). Intensities for upright and supine ABS are equivalent to 80% of the maximum workload achieved during the upright graded test whereas for supine REL are equivalent to 80% of the maximum workload achieved during the supine graded test. *Asterisk* (*) indicates significantly different from supine ABS ($P < 0.05$)

data points during the first 2 min of exercise and at the end of the exercise bout (Table 3). Resting HR on the bike was significantly higher in the upright compared with the supine REL posture. Similarly, during the initial 2 min of exercise and at the end of exercise HR was higher in the upright posture (Table 3). These results were expected because the workload used during the upright exercise was significantly higher (170 ± 43 W) than the workload during supine REL (151 ± 42 W).

Peak $\dot{V}O_2$ and HR during the constant-load tests as a percentage of the graded test

The end-exercise values for $\dot{V}O_2$ and HR (peak $\dot{V}O_2$ and HR) for the three constant-load tests (i.e. upright, supine ABS and supine REL), expressed as a percentage of those measured during the graded test in the same position were not different between the positions or between men and women (Table 3).

Discussion

The main findings of the present study were as follows: (1) time to failure during high-intensity constant-load exercise performed at the same absolute power output was greater in the upright than supine position; (2) this effect was larger than that observed for graded exercise; (3) this effect was significantly correlated with height, the hydrostatic column and the postural effect on the early

Table 3 Constant-load exercise times and peak physiological responses (mean ± SD, $n = 10$)

		Men ($n = 5$)	Sig.	Women ($n = 5$)
Cycle time (min)	Upright	19.4 ± 8.5*	‡	7.1 ± 2
	Supine (ABS)	6.6 ± 1.6†		3.9 ± 1.4
	Supine (REL)	15.3 ± 8.6	‡	6.4 ± 1.3
Peak $\dot{V}O_2$ (ml.kg^{-1}. min^{-1})	Upright	33.8 ± 5.1**(79 ± 13%)		28.3 ± 4.5**(84 ± 10%)
	Supine (ABS)	32.1 ± 7.7(78 ± 28%)		25.3 ± 4.9(84 ± 8%)
	Supine (REL)	30.1 ± 5.6(72 ± 21%)		23.5 ± 5.3(80 ± 13%)
Peak HR (beats.min^{-1})	Upright	177 ± 7*, **(101 ± 1%)		175 ± 6*, **(96 ± 5%)
	Supine (ABS)	158 ± 10(96 ± 8%)		162 ± 10(98 ± 4%)
	Supine (REL)	157 ± 6(95 ± 9%)		149 ± 13(90 ± 6%)
Peak $\dot{V}_E$ (ml.kg^{-1}. min^{-1})	Upright	1236 ± 154**		1035 ± 159**
	Supine (ABS)	1174 ± 34†		900 ± 222†
	Supine (REL)	909 ± 167		831 ± 150
Peak RER	Upright	1.04 ± 0.04		1.05 ± 0.12
	Supine (ABS)	1.22 ± 0.13		1.09 ± 0.12
	Supine (REL)	1.12 ± 0.11		1.06 ± 0.07

Values in parentheses are for peak $\dot{V}O_2$ and HR during the constant-load tests as a fraction of the peak $\dot{V}O_2$ and HR achieved in the graded tests at the same posture

* Upright significantly different from supine ABS $P < 0.05$

** Upright significantly different from supine REL $P < 0.05$

† Supine ABS significantly different from supine REL $P < 0.05$

‡ Men significantly different from women $P < 0.05$

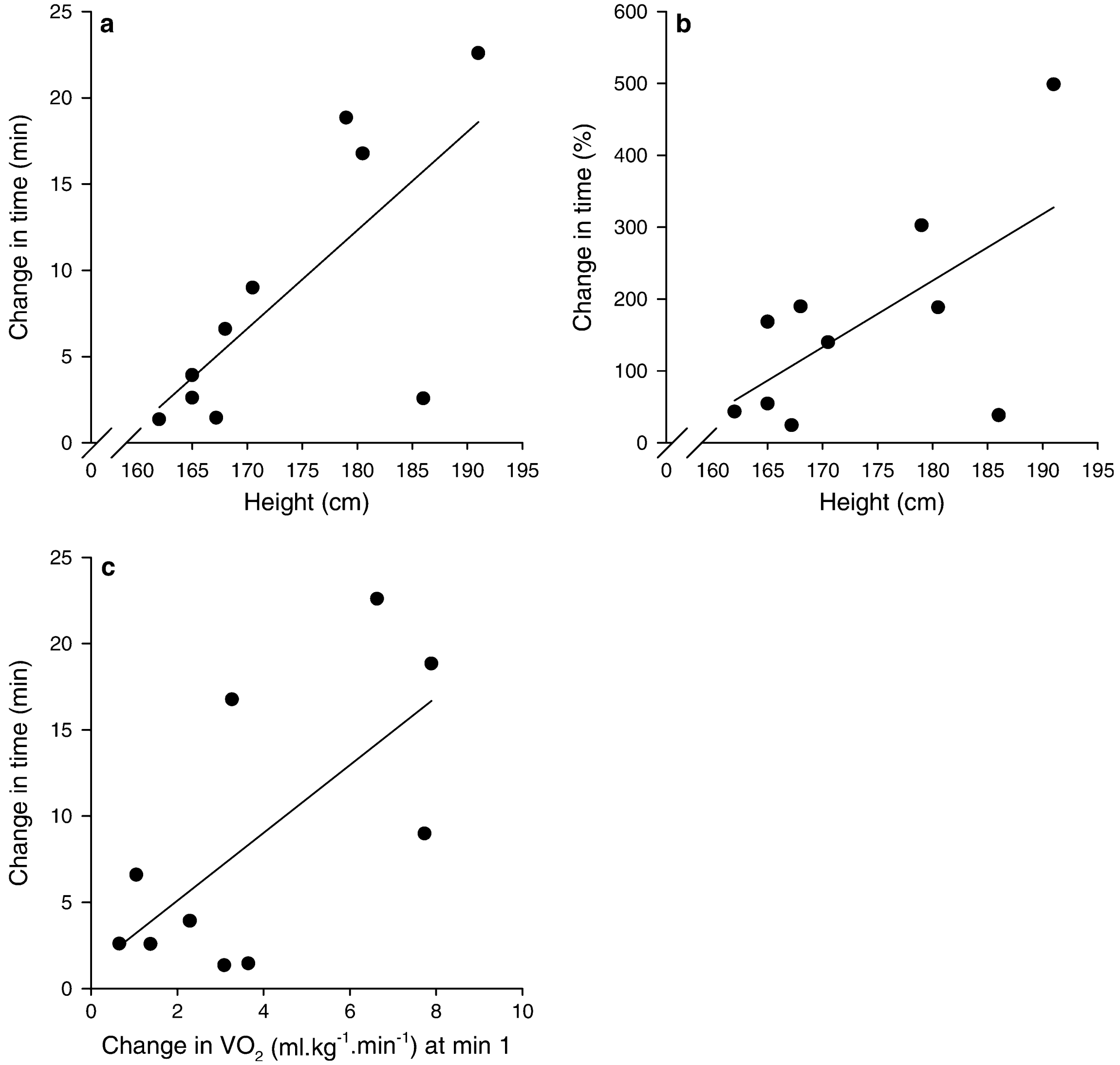

Fig. 3 Correlations between anthropometric, metabolic and exercise variables. **a** Height versus the change in time to failure (min) between upright and supine ABS during constant-load tests at the same absolute intensity; $r = 0.72$, $P < 0.05$. **b** Height versus the percent change in time to failure between upright and supine ABS during constant-load tests at the same absolute intensity; $r = 0.63$, $P < 0.05$. **c** The difference between upright and supine ABS tests for the change in $\dot{V}O_2$ over the first 60 s versus the change in time to failure (upright minus supine ABS) during constant-load tests at the same absolute intensity; $r = 0.67$, $P < 0.05$

$\dot{V}O_2$ response; and (4) the postural effects on performance during constant-load exercise were significantly larger in men than women.

During the graded tests, exercise time was increased by 10% in both men and women in the upright compared with the supine posture ($n = 22$, Table 2). These effects are comparable to the increases (~5–10%) in cycle time observed under similar exercise conditions in studies where the majority of subjects were men (Eiken 1988; Leyk et al. 1994) or equally men and women (Terkelsen et al. 1999). However, none of these studies compared the postural effect on performance between men and women. A novel finding of the present study was that the relative effect of posture on graded exercise performance was similar between men and women.

This is the first study to investigate the effect of posture on performance during constant-load exercise, and there were two important findings. First, time to failure at the same absolute power output was greater by up to 160% in the upright compared with the supine posture ($n = 10$, Fig. 2). This effect was much larger than that observed during the incremental graded exercise in the same subjects (~16%, $n = 10$, Table 2). Second, the postural effect on exercise time was significantly different between men and women for both absolute and relative exercise intensities. Unlike the small postural effect on graded exercise performance, these data demonstrate that changes in posture can exert a very large effect on exercise performance when it is conducted at a constant and high-intensity, and that the magnitude of these effects differs between men and women.

We can only speculate on the physiological basis of these postural effects on performance, and before doing so it is important to consider the non-linear relationship

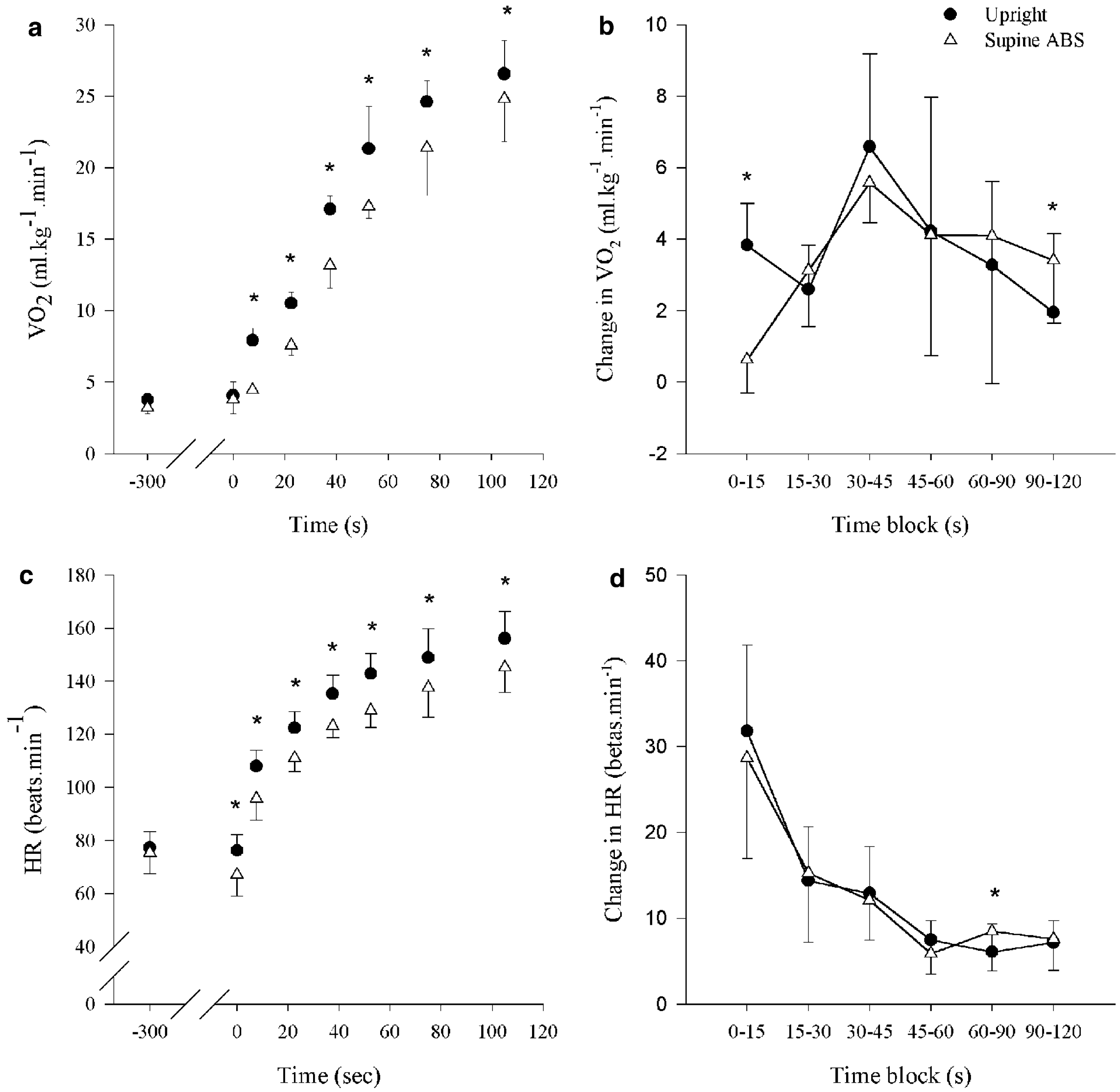

Fig. 4 **a** $\dot{V}O_2$ response (mean ± SD) at the beginning of exercise (0–120 s) for upright and supine ABS tests. **b** Change in $\dot{V}O_2$ (mean ± SD) during upright and supine ABS constant-load tests. Data are presented for time blocks of 15 s during min 1 (i.e. $\dot{V}O_2$ at 15 s minus pre-exercise $\dot{V}O_2$ etc.) and time blocks of 30 s during min 2 (i.e. $\dot{V}O_2$ at 90 s minus $\dot{V}O_2$ at 60 s etc.). **c** HR responses (mean ± SD) at the beginning of exercise (0–120 s) for upright and supine ABS tests. **d** Change in HR (mean ± SD) for time blocks of 15 s during min 1 and time blocks of 30 s during min 2 for upright and supine ABS tests during constant-load tests at same absolute intensity. *Asterisk* (*) indicates significantly different between postures ($P < 0.05$)

between power output and exercise duration to failure (Vandewalle et al. 1989). As the power output is decreased from a maximum value towards a ‘critical power’, the duration over which exercise can be sustained increases exponentially. At intensities between peak power on a graded test (≅ peak $\dot{V}O_2$) and ‘critical power’ that lies below it, variations in power will translate into much larger variations in time to failure (Poole et al. 1990), with larger variations observed at intensities closer to critical power. Since critical power is thought to be supported entirely by aerobic metabolism (Vandewalle et al. 1989), small increases in aerobic metabolic power at or near critical power will also translate into disproportionately larger increases in exercise time.

These considerations about the power–duration relationship might help explain how changes in posture altered constant-load performance much more than performance during a maximal graded test, where time was spent exercising at relatively higher intensities above critical power. That a significant effect of posture on performance was not observed when comparing exercise at the same relative intensity reveals that the effect of posture on performance is related to a lowering of the relative effort during exercise performed at the same power output. This effect can be induced by increasing critical power and/or peak $\dot{V}O_2$, both of which are linked to aerobic metabolism. The power–duration relationship might also help explain how the postural effect on performance was much smaller in women, if the effort for women during constant-load exercise was relatively higher than that for men. This is a possibility given that the duration of the maximal graded test was significantly shorter for women than men and that the women, on the basis of their peak $\dot{V}O_2$, were less fit than men. The shorter graded test duration suggests that the peak power achieved by women could have been higher than that which would be achieved on a longer graded test (Takaishi et al. 1992) as observed in men (Table 3). And the lower peak $\dot{V}O_2$ of the women raises the possibility that critical power, as a fraction of peak power during the graded test, was relatively lower in the women and, consequently, a fixed percentage of peak power (i.e. 80%) represents a relatively more intense effort for them. Further work is clearly needed to clarify the contribution of differences in relative effort between men and women to the interactive effect of gender and posture in the present study.

Although the physiological basis of the postural effect on performance is unclear, a likely candidate that is linked to aerobic metabolism is muscle blood flow. Muscle fatigue during high-intensity exercise is very sensitive to changes in muscle blood flow (Fitzpatrick et al. 1996; Hogan et al. 1994). Upright tilting of the body increases muscle blood flow during exercise (Egaña and Green, 2005; Folkow et al. 1971), an effect that is established within the first few seconds of exercise (Egaña and Green, 2005). This haemodynamic effect is likely to explain how inclining the body tilt angle increases the initial $\dot{V}O_2$ response during both submaximal knee extensor exercise (MacDonald et al. 1998) and cycling (Koga et al. 1999). In the present study, $\dot{V}O_2$ was higher during the first 2 min of exercise in the inclined position at the same absolute power output, and this effect was established within the first 15 s of exercise. In addition, the posture-induced effect on the change in the $\dot{V}O_2$ response over the first minute of exercise was positively correlated with the corresponding change in cycle time. Collectively, these findings support the idea that the posture-induced improvement in performance is linked to a reduction in muscle fatigue caused by an increase in muscle blood flow and $\dot{V}O_2$ during the initial period of exercise.

In addition to muscle blood flow, differences in muscle activity patterns might contribute to differences in muscle fatigue and exercise performance. In the present study the hip and knee angles were not different between the two positions, and when this has been done elsewhere, both the EMG patterns and joint torques in the lower limbs during cycling differed between upright and supine positions (Brown et al. 1996). Total integrated and rectified EMG activity in rectus femoris, biceps femoris and tibialis anterior muscles was higher in the inclined position; but its activity in the triceps surae muscles was lower (Brown et al. 1996). These effects, however, were established at a very low intensity of cycling and at least several seconds after the onset of exercise when differences in muscle blood flow may be apparent. It is not possible to determine how these postural effects on muscle activation would translate to muscle fatigue, particularly at a higher intensity, and it is not clear if such alterations in muscle activity are secondary to changes in muscle blood flow.

The interactive effect of gender and posture on constant-load performance raises the question as to its physiological basis, recognising that differences in relative effort discussed earlier may be important here. Men were significantly taller than women, and an estimate of the column of blood between the heart and the arteries feeding the proximal muscles of the lower limbs (‘hydrostatic column’) was also longer in men than women. Both of these anthropometric measurements were positively correlated with the postural effect on performance, raising the possibility that the different effect of posture in men and women is related to height, rather than to an intrinsic physiological difference between men and women. The body tilt-induced increase in muscle blood flow observed in other studies can be explained by the gain in hydrostatic pressure on the arterial side of the exercising limb (Egaña and Green 2005; Folkow et al. 1971). This gain in hydrostatic pressure raises perfusion pressure and muscle blood flow to an extent that depends on the length of the arterial column of blood between the heart and the exercising muscles. Therefore, it is plausible that the larger postural effect on performance seen in men compared with women is explained partly by differential effects of height on perfusion pressure and muscle blood flow.

There are at least two practical applications of the findings of the present study. First, the recumbent position on bicycles is adopted by recreational cyclists and those setting speed records. Compared with an upright position, the recumbent position offers aerodynamic advantages; but this should be considered against the possible physiological disadvantage of doing so, and further research could explore these counterbalancing effects as they affect cycling performance. Second, in clinical rehabilitation many modes of exercise may be used in the treatment of various disorders, and recumbent exercise devices can often be found in such settings. When prescribing exercise, practitioners should consider that the ability to sustain lower limb exercise may differ substantially between a recumbent and upright ergometer that is considered to be the same mode of exercise (e.g. cycling).

Conclusion

In conclusion, tilting the body from a supine to an upright position significantly improves performance during high-intensity constant-load exercise in men and women. This improvement is an order of magnitude larger than the postural effect seen for graded performance, and it was larger in men than women. Further research is required to understand the mechanisms of this effect.

Acknowledgements M. Egaña was supported by the Technicon Fellowship, Technicon, Ltd, Ireland.

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