TITLE

Effect of low recumbent angle on cycling performance, fatigue and $\dot{V}O_2$ kinetics.

AUTHORS

Mikel Egaña¹, David Columb¹, Steven O'Donnell¹

AFFILIATIONS & ADDRESSES

Department of Physiology, Trinity College Dublin, Dublin 2, Ireland.¹

CONTACT INFORMATION (corresponding author):

Mikel Egaña
Department of Physiology,
Level 2, Trinity Biomedical Sciences Institute
Trinity College Dublin
152-160 Pearse Street
Dublin 2, Ireland.
E-mail: megana@tcd.ie
Telephone: +353 1 896 2213
Fax: +353 1 679 3545

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ABSTRACT

Purpose: To examine the effect of the degree of inclination from upright to supine postures on cycling performance, fatigue and oxygen uptake ($\dot{V}O_2$) kinetics.

Methods: In *experiment 1* ten subjects performed graded and fatigue (exhaustive constant-load heavy exercise with 10s all-out efforts interspersed every min) tests at four cycling postures: upright, 30°R, 15°R and supine. In *experiment 2*, nine different subjects performed two bouts of constant-load heavy exercise in the same four cycling postures. Bout one was brought to failure and the second bout was limited to 6 min, so that the breath-by-breath $\dot{V}O_2$ data from the first 6 min of each bout were averaged and curve-fit. **Results:** The time sustained during the graded test was significantly shorter in the supine compared with the other 3 postures and also shorter in the 15°R compared with the upright. The rate of fatigue was higher in the supine compared with the other three postures and normalised electromyographic activities of three leg muscles at end-exercise were larger in the supine (and in some cases 15°R) compared with upright posture. The time sustained (min) during high-intensity constant-load cycling was significantly longer during upright (12.8 ± 5.3) and 30°R (14.2 ± 6.1) compared with 15°R (8.5 ± 1.7) and supine (6.8 ± 2.0) postures, but the amplitudes of the slow component of the $\dot{V}O_2$ response ($L \cdot min^{-1}$) were larger during 15°R (0.57 ± 0.10) and supine (0.61 ± 0.15) compared with 30°R (0.39 ± 0.12), and also larger in the supine than upright (0.43 ± 0.13) postures. Inert gas rebreathing analysis revealed similar cardiac output responses at 60s into the exercise among postures. **Conclusion:** Lowering the recumbent angle to 15° resulted in shorter performance, larger fatigue and altered $\dot{V}O_2$ kinetics.

Keywords: Recumbent, cycling, $\dot{V}O_2$ kinetics, fatigue, posture

INTRODUCTION

Paragraph Number 1 Recumbent cycling is a popular and well-established mode of exercise that is used in fitness clubs and clinical rehabilitation centres to treat a diverse range of disorders (25, 38). In addition, anecdotal evidence suggests that the number of outdoor recumbent cyclists has increased in recent years and more and more competitive recumbent cyclist races (usually classified under the “Human Powered Races”) are apparent.

Paragraph Number 2 Outdoor recumbent bicycles offer important aerodynamic benefits compared with the more traditional upright bikes leading to improvements in cycling velocity and subsequent performance. However, cycling endurance and fatigue are also sensitive to the vertical distance between the heart and the active muscles involved in cycling due to the gravitational effect acting across these muscles. Gravity enhances the perfusion pressure on active muscles which helps explain the faster rate of increase in blood flow (blood flow kinetics) (13, 35), faster oxygen uptake ($\dot{V}O_2$) kinetics (9, 23, 24, 30) and lower lactate production (15, 33) during exercise when active muscles are below the level of the heart compared with when they are above heart level. These effects appear to contribute to a reduction in the rate of muscle fatigue (17) and endurance improvements in graded (12, 15, 18, 24, 27, 30), as well as, high-intensity constant-load (15-18) cycling during upright compared with supine postures under standard laboratory conditions (i.e. when the effect of air resistance is removed).

Paragraph Number 3 In contrast to the substantial amount of published studies comparing performance outcomes between supine and upright cycling postures, and

despite the increasing popularity of recumbent bicycles, fewer studies have explored these physiological effects at recumbent body angles between supine and upright. For instance, to our knowledge it is not known if graded cycling performance or muscle fatigue & electromyographic (EMG) activities during submaximal cycling are different at body angles between upright and supine. Recently, Egaña *et al.* (2010a) reported that exercise times to failure and $\dot{V}O_2$ kinetics were not altered when high-intensity submaximal cycling was performed at progressively lowering body angles from the upright (90°) to 65° recumbent (R) and 30° R postures; but that exercise times to failure were significantly shorter in the supine (0°) when compared with the three inclined postures. However, in the same study, cardiac output (CO) responses (recorded only during upright, 65° R and 30° R postures) were significantly larger during the two recumbent postures when compared with upright at 30 s into the exercise, raising the possibility that when the heart lies above the level of the active exercising muscles (as is the case when cycling recumbent angles are at or above 30°), the gravity-induced reductions in perfusion pressure in these two recumbent compared with the upright posture may be counteracted by an increased central and/or peripheral circulation (16). However, most competitive recumbent cyclists, as well as many recreational recumbent cyclist, adopt recumbent angles lower than 30° R, often as low as 15° (where the heart lies below the level of most active muscles) to maximize their aerodynamic benefits; but little is known if these low recumbent angles can be detrimental for cycling performance when compared with upright when the effect of air resistance is removed.

Paragraph Number 4 Accordingly, to further explore the postural effect on cycling performance, the main aim of the present study was to compare the endurance, $\dot{V}O_2$

kinetics, muscle fatigue and EMG (from three leg muscles) responses during high-intensity constant-load cycling between a previously unexplored low recumbent angle of 15° R, upright, supine and 30° R postures. In addition, we also compared the exercise time sustained during a graded cycling test among these four postures. It was hypothesised that exercise performance would be reduced, fatigue increased and $\dot{V}O_2$ kinetics impaired during supine and 15° R when compared with 30° R and upright postures.

METHODS

Overview

Paragraph Number 5 Two experiments were performed. *Experiment 1* tested the effect of lower recumbent angle on performance during graded cycling and on muscle fatigue, whereas *Experiment 2* tested the effect of lower recumbent angle on $\dot{V}O_2$ kinetics, CO and performance during constant-load cycling exercise. Ten young male subjects (mean $\pm$ SD; age: 24 ± 4 year; height: 183 ± 4 cm; body mass: 74.4 ± 6.9 kg) who were recreationally active once or twice per week took part in *Experiment 1* which required them to visit the Human Performance Laboratory in the Department of Physiology of Trinity College Dublin, on six days separated by at least 72 hours. Nine different healthy males (mean $\pm$ SD; age: 21 ± 1 year; height: 181 ± 4 cm; body mass: 77.5 ± 7.6 kg) of similar activity levels took part in *Experiment 2* and they visited the same laboratory on five separate occasions (at least 72 hours apart). Informed consent was obtained from all subjects before their participation in this study. All experimental procedures were carried out in accordance with the Declaration of Helsinki and were approved by the Trinity College Dublin Faculty of Health Science Research Ethics Committee.

Paragraph Number 6 Before each testing day subjects were asked to refrain from consuming caffeine and alcohol and avoid any strenuous exercise in the 24 hours prior to testing. For testing days 1 to 4 of *Experiment 1* (i.e. ‘graded tests’ see below) and all five testing days of *Experiment 2* a standard cycle ergometer (Monark 874E, Monark Exercise AB, Vansbro, Sweden) was used. For testing days 5 & 6 of *Experiment 1* (i.e. ‘fatigue tests’ see below) exercise was performed on an electrically braked cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands) controlled via a connected PC running Lode Wingate software (v1.0.12, Groningen, The Netherlands). These two cycle ergometers have been shown to reach comparable power outputs (37). Both ergometers were modified to allow for recumbent cycling by the attachment of an inclining bench to the rear of the ergometer (16). The recumbent seat was ~10 cm below the centre of the crank which is similar to the distance between the crank and seat on most commercially available recumbent bikes. The cycling cadence required for each test was 60 rpm. Failure in any exercise test was defined as an inability to maintain a minimum cadence of 50 rpm for 3 s. During exercise, heart rate (HR) was continuously monitored and recorded every 5 s using a HR monitor (Polar Electro, S725, Kenpele, Finland). In addition, apart from visits 5 & 6 of *Experiment 1*, subjects wore a facemask to continuously collect expired air using an online metabolic system (*Experiment 1*: Metalyser, Cortex Biophysik, Leipzig, Germany; *Experiment 2*: Innocor, Innovision A/S, Odense, Denmark). The Metalyser system measured the expiratory airflow with a volume transducer (Triple V[®] turbine, digital) connected to the metabolic analyser. Expired gases were analysed for oxygen (O₂) with an electrochemical cell and for carbon dioxide (CO₂) output with an infrared analyser. Before each test, the CO₂ and

O₂ analysers of the Metalyser were calibrated against room air as well as a reference gas of known composition (5% CO₂, 15% O₂, and 80% N₂), and the volume was calibrated with a 3-litre gas syringe. The Innocor system measured airflow using a pressure difference pneumotach. Carbon dioxide analysis was performed by using a photoacoustic gas analyzer and oxygen was analysed using an oxygen sensor (Oxigraf Inc., USA) based on the principle of laser diode absorption spectroscopy. The volume was calibrated with a 3-litre syringe, and only the oxygen sensor was regularly calibrated (against room air) prior to each tests by the researcher, as both the oxygen sensor and photoacoustic gas analyser require multi-point calibration performed by the manufacturer periodically (6-12 months). Analysis of expired air allowed determination of O₂ uptake ($\dot{V}O_2$), CO₂ output ($\dot{V}CO_2$), minute ventilation ($\dot{V}_E$) and the respiratory exchange ratio (RER) every 10 s (*Experiment 1*) or breath by breath (*Experiment 2*).

Postures

Paragraph Number 7 During the upright tests, the position of the head and body were maintained in a vertical plane with the arms held loosely by the sides to minimise any involvement from the upper body associated with gripping of the handlebars. In all other postures (30° R, 15° R and supine) subjects lay comfortably behind the ergometer with the recumbent seat angle set as required for each posture, again with the arms lying loosely at the side (16). A harness was worn in the supine and 15° R posture to secure the subject to the ergometer and prevent any rearward movement while cycling. Knee angles were kept constant at the start of the crank cycle between postures by adjusting the distance from the seat to the pedals. The magnitude of the hydrostatic pressure acting on the active muscles during cycling was estimated for

each posture using the equation, ρgh , where ρ is the density of the fluid (i.e. blood), g is the gravitational constant and h is the vertical distance (or height) between the right atrium of the heart (estimated to lie at the level of the 3rd costal space; approximately 5 cm below the sternal angle), and the arteries feeding the proximal muscles engaged in cycling (estimated to lie at the midpoint of the two lateral iliac crests). Other measures specific to each Experiment are described below.

Experiment 1 (graded cycling performance and fatigue & EMG activities during constant-load cycling)

Paragraph Number 8 In *Experiment 1* the maximal performance during graded cycling and muscle fatigue & EMG activities of the lower limbs during constant-load cycling were assessed in the upright, 30° R, 15° R and supine postures. Following a familiarizing session, subjects attended the laboratory on six subsequent separate days. *Graded tests:* On testing days 1 to 4, a graded test to failure was performed each day at one of the four randomly assigned cycling postures. Following a resting period of 3 min in the exercise position, the graded test began with 3 min cycling at 60 W and increased incrementally by 30 W every 3 min until the subject reached 180 W (all subjects reached at least this work rate). Thereafter, the work rate was increased by 15 W every min until failure. The peak work rate achieved was defined as the highest work rate that a subject could sustain for a minimum period of 50 s. Peak $\dot{V}O_2$ was defined as the highest 30-s mean value recorded before the subject's volitional termination of the test. The work rate at which the ventilatory threshold (VT) occurred was determined using the V-slope method by identifying the power output at which a clear steeper increase of $\dot{V}CO_2$ as compared with $\dot{V}O_2$ occurs (2, 5).

Paragraph Number 9 *Fatigue tests:* On testing days 5 & 6 subjects performed on

each day two high-intensity constant-load tests to failure with 10 s efforts of all-out cycling interspersed every min. The two tests were separated by 60 min of passive rest (i.e. sitting on a chair), so that in total, between the two days, four fatigue tests were performed. The fatigue tests were performed at the same four body postures (upright, 30° R, 15° R and supine) and the order of the tests was selected at a counter balanced fashion to remove any potential exercise order effects. The intensity for the fatigue tests was set at the work rate achieved at mid-point between the VT and end-exercise during the graded test performed in the upright posture (50% Δ upright) so that these tests were performed at the same absolute intensities. Initially, to determine the maximal power achievable in each posture subjects completed a single peak effort test comprising 45 s cycling at 100 W followed by 10 s all-out cycling and then 3 min rest. The fatigue test commenced with cycling at each subject's specified work rate (50% Δ upright) for 45 s after which subjects completed 10 s of all-out cycling followed by 5 s of unloaded cycling. This sequence was repeated until failure. The 60 min resting period was chosen because the effect of prior heavy exercise has been shown not to persist beyond ~45-60 min (7) and we were careful to ensure that HR responses prior to the second fatigue test were returned back to the levels seen prior to the initial fatigue test. The peak power achieved prior to the test and during the subsequent all-out cycling efforts was recorded to enable an estimation of the rate of fatigue while cycling in each of the four postures. The decline in peak power during each all-out effort was described using a linear function ($y = a + bx$), where y is power, x is time, parameter a provides power at $t = 0$ (i.e. predicted peak power) and parameter b represents the rate of fatigue. Although fatigue is often a nonlinear function of time, the majority of individuals exhibited a linear response (Fig 2). On this basis, we chose to describe fatigue as a linear function of time. The goodness of

fit of the linear function to the fatigue responses in this study (Fig 2) is reflected in the standard error in estimating the y-intercept of this function. Across the 4 conditions the average standard error of estimates for the y –intercept was $3.9 \pm 0.9\%$. For all the 10 s efforts of all-out cycling the chosen torque factor was .65. A prior pilot study established that this was the most comfortable torque factor to perform the 10 s all-out efforts in the recumbent postures. Individual braking torque was calculated by multiplying the body mass of each subject by the torque factor.

Paragraph Number 10 Surface EMG: In addition, during the fatigue tests surface EMG recordings were taken from three muscles of the right leg: *vastus lateralis* (VL), *biceps femoris* (BF) and *gastrocnemius medialis* (GM). The skin recording sites were selected from the belly of the muscle and prepared by shaving, abrading and cleaning with alcohol (70%). Two bipolar Ag/AgCl recording electrodes were placed on the skin at the recording sites 25 mm apart (centre to centre) and in a plane estimated to be parallel to the direction of the muscle shortening during contraction. A reference electrode was attached to the anterior superior iliac crest. EMG signals were band-pass filtered (10 – 500 Hz) and sampled at 1000 Hz using a Power Lab connected to a PC running Chart recording software (v6.0, AD Instruments, Australia). On completion of the first test, the electrode locations were carefully marked with a permanent marker. The root mean square (rms) values were calculated burst by burst throughout the test. The criteria for the onset and offset activation was based on a voltage threshold (3 SDs above baseline). The average rms value during the initial 30 s of unloaded exercise was subtracted from all rms measures during subsequent exercise, and this latter value was initially normalised to the maximum rms (NEMG) achieved within each posture. This normalisation was followed because the rates of fatigue (see above) were also calculated from the peak power achieved within each

posture. However, given that EMG responses are often normalised to a set 'gold standard', and assuming that the upright posture was the 'gold standard' in the present study, EMG data were also normalised to the upright maximum rms. The maximum rms was calculated by averaging three consecutive bursts when the maximum power output was achieved during the initial 10 s effort of all-out cycling (i.e. pre-fatigue test). NEMG measurements were then calculated during the fatigue test and were based on five consecutive bursts (i.e. crank cycles) recorded between the 20th and 25th s and between the 40th and 45th s during the first min and between the 40th and 45th s (prior to the 10 s all-out efforts) every min thereafter. Δ NEMG was calculated as the difference between end-exercise NEMG and NEMG at the onset of exercise. Due to technical difficulties, data from two subjects were excluded from the final analysis.

Experiment 2 ($\dot{V}O_2$ kinetics, cardiac output and performance during constant-load cycling)

Paragraph Number 11 In *Experiment 2* the performance, cardiac output and $\dot{V}O_2$ kinetics during high-intensity constant-load cycling were assessed during upright, 30° R, 15° R and supine postures. Following a familiarization session, subjects attended the Human Performance Laboratory on five subsequent days. Initially (testing day 1), subjects performed a maximal graded test to failure in the upright posture as described above (see *Experiment 1*; days 1-4) to determine peak work rate and ventilatory threshold (2, 5). Subsequently (testing days 2 to 5), two bouts of *constant-load* cycling were performed each day at an intensity equivalent to the work rate achieved at mid-point between the VT and end-exercise during the upright graded test (50% Δ , mean $\pm$ SD, 229 $\pm$ 37 W). On each of these days, subjects completed the exercise in one of the four randomly assigned postures (upright, 30° R, 15° R or supine). Bout 1

continued until failure followed by a minimum of 60 min of passive rest (i.e. sitting on a chair), while the duration of bout 2 was set at 6 min. As during the fatigue tests, a minimum resting period of 60 min was chosen because it has been shown that ~45 min is sufficient to allow the restoration of 'normal' $\dot{V}O_2$ response following prior high-intensity exercise in young participants (7), and we were careful to allow sufficient recovery time for restoration of HR and $\dot{V}O_2$ values. In addition, on day 5, prior to performing the two constant-load exercise tests, cardiac output (CO) (Innocor, Innovision A/S, Odense, Denmark) was measured using an inert gas rebreathing technique based on the Fick principle as previously described (1, 22, 26, 34), at rest and following an additional short 60 s bout of the constant-load exercise (50% Δ upright) given that stroke volume (SV) has been shown to peak at ~30 s during high-intensity cycling exercise (20, 33). This was performed randomly in each of the four postures (upright, 30°R, 15°R and supine). These short bouts were separated by a 15 min rest period, and were then followed by the two constant-load bouts described above. Stroke volume was calculated as CO/HR.

Paragraph Number 12 Breath-by-breath values for $\dot{V}O_2$ collected during the first 6 min of each bout were linearly interpolated to provide values at 1 s intervals. For each subject, all data sets for the two bouts performed in the same posture were then time aligned and averaged. Data were then smoothed using a 5 s moving average filter and analysed by fitting a three component exponential curve to the results according to the following equation:

$$\dot{V}O_2(t) = \dot{V}O_2(\text{base}) + A_c \cdot (1 - e^{-(t - TD_c)/t_c}) \cdot U_c + A_p \cdot (1 - e^{-(t - TD_p)/t_p}) \cdot U_p + A_s \cdot (1 - e^{-(t - TD_s)/t_s}) \cdot U_s$$

where the three exponential terms represent the ‘cardiodynamic’, ‘primary’ and ‘slow’ components of $\dot{V}O_2$. Baseline $\dot{V}O_2$ (*base*) represents the mean oxygen uptake over the last 90 s prior to the exercise bout; and for each exponential term A_c , A_p , and A_s are the asymptotic amplitudes; τ_c , τ_p , and τ_s are the time constants; and TD_c , TD_p and TD_s are the time delays. The parameters U_c , U_p and U_s are conditional expressions that limit the fitting of a particular phase to the period at and beyond the time delay associated with that phase. Fitting the cardiodynamic phase allowed us to visually determine the transition between the cardiodynamic and primary phase given that when this transition is determined using a set value (i.e. 20 s) the time constant of the primary phase can be overestimated (36). However, the cardiodynamic phase cannot be always described by an exponential term (29), and thus, only the amplitude and duration ($TD_p - TD_c$) of this phase (given that TD_c was not fixed at $t = 0$) are presented. End-exercise $\dot{V}O_2$ was defined as the mean oxygen uptake over the last 30 s of exercise. The physiologically relevant amplitude of the primary component (A'_p) was defined as the sum of $A_c + A_p$. Because the asymptotic value (A_s) of the exponential term describing the $\dot{V}O_2$ slow component may represent a higher value than is actually reached at the end of the exercise, the actual amplitude of the $\dot{V}O_2$ slow component at the end of exercise (A'_s) was **estimated as the difference between the end-exercise $\dot{V}O_2$ and A'_p** . The functional gain of the entire response (i.e. end-exercise gain) was calculated as $(\text{end-exercise } \dot{V}O_2 - \dot{V}O_2 \text{ base} / \Delta \text{Work rate})$. The relative contributions of **the slow component and relevant amplitude of the** primary component to the overall increase in $\dot{V}O_2$ at end-exercise **were** also calculated. In addition, the mean response time (MRT) of the “overall” $\dot{V}O_2$ kinetics response was calculated by fitting a single-exponential curve from the onset to the end of heavy-

intensity exercise. Data that exceeded the 95% prediction intervals during an initial fit of a model were excluded, and no more than thirteen data points were removed from the original time series of data. The models were fitted to the data using a weighted least-squares nonlinear regression procedure (TableCurve 2D, Systat, USA).

Statistical analyses

Paragraph Number 13 Kinetics parameters of oxygen uptake and ‘peak’ responses among postures were analysed using a one-way repeated measures ANOVA. Effects of body posture and time on peak power and EMG activities were identified using a two-way repeated-measured ANOVA. Differences were located using Tukey’s post hoc test. The relationship between the rate of fatigue and the Δ NEMG activities were examined using Pearson’s product moment correlation coefficients. Data are presented as mean $\pm$ SD. Significance was set at $P < 0.05$.

RESULTS

Experiment 1

Paragraph Number 14 *Graded performance:* Exercise times and physiological responses during the graded test at the four postures are shown in Fig 1A and Table 1A, respectively. The time sustained and the peak work rate achieved during the graded test were significantly lower in the supine compared with the other 3 postures and they were also lower in the 15° R compared with the upright posture. The absolute work rate (W) at VT was significantly lower in the supine compared with the upright posture, but was similar among postures when expressed in relative (% peak) terms. Peak HR was significantly higher in the upright compared with the other 3

postures. However, peak $\dot{V}O_2$ ($\text{ml.kg}^{-1}.\text{min}^{-1}$), peak RER and $\dot{V}O_2$ ($\text{ml.kg}^{-1}.\text{min}^{-1}$ & % peak) at VT were not different among the four postures.

Paragraph Number 15 Fatigue tests: Mean cycling time (min) during the fatigue tests was significantly shorter in the supine (2.6 ± 0.6) compared with the other 3 postures (upright: 5.0 ± 1.3 ; 30° R: 4.7 ± 1.8 ; 15° R: 4.4 ± 1.3). Figure 2 shows the individual fatigue responses to the four postures (Fig 2A-D) and the mean normalised fatigue responses (Fig 2E). The rate of fatigue (W.min^{-1}) during the supine posture was significantly greater (-113 ± 77) than in the upright posture (-75 ± 40) but not different compared with 15° R and 30° R postures (-95 ± 52 and -95 ± 58 , respectively). A comparison of the mean normalised fatigue responses (% peak) showed that at min 2, fatigue was significantly larger in the supine (67 ± 14) compared with upright (82 ± 14) but not different than 30° R (78 ± 13) and 15° R (76 ± 9) postures. Power outputs at failure were similar among the four postures and the equivalent of $61 \pm 15\%$ (upright), $56 \pm 13\%$ (30° R), $56 \pm 11\%$ (15° R) and $60 \pm 17\%$ (supine) of the maximum power outputs (i.e. at time = 0). These maximum power outputs (W) (i.e. at time = 0) were not different among the four postures (upright: 742 ± 152 ; 30° R: 761 ± 99 ; 15° R: 792 ± 131 ; supine: 742 ± 170).

Paragraph Number 16 EMG: The maximum rms responses for all three muscles obtained during the initial peak effort test (i.e. time = 0) were not different among the four postures. NEMG responses (% maximum) are shown in Fig 3. Each mean value in the graphs shown in Fig 3 is based on responses of all subjects (i.e. $n = 8$) so that the maximum exercise time for each NEMG response shown (prior to 'failure' time-point) is limited by the subject who failed first. NEMG responses for the *gastrocnemius medialis* showed a significant posture by time interaction so that these responses during the supine and 15° R postures at min 1 & 2 and at failure were

greater than during the upright posture. These NEMG data for GM were also significantly larger at failure than at exercise onset, min 1 and 2 within the supine and 15° R postures, but no time effect was observed for either 30° R or upright postures. NEMG responses for *vastus lateralis* also showed a significant posture by time interaction so that they were significantly higher in the supine compared with the upright posture at failure, and in addition, responses for VL were significantly larger at failure compared with at the onset of exercise for all four postures. *Biceps femoris* NEMG responses also tended to be larger during the supine and 15° R compared with upright (main effect, posture: $P = 0.09$) and showed a significant main effect of time within each of the four postures with no posture by time interaction. The Δ NEMG activities were not affected by body postures for any of the three muscles investigated, and were not correlated to rates of fatigue in any posture.

Experiment 2

Paragraph Number 17 *Constant-load performance:* Cycling times to failure (min) during the constant-load tests were significantly longer in the upright and 30° R postures compared with 15° R and supine postures (Fig 1B and Table 1B). Peak HR were also higher during upright and 30° R compared with 15° R and supine postures but peak $\dot{V}O_2$ and peak $\dot{V}_E$ were not affected by posture (Table 1B).

Paragraph Number 18 *$\dot{V}O_2$ kinetics:* $\dot{V}O_2$ kinetics responses during high-intensity exercise for a representative individual at the four postures are presented in Fig 4. Two subjects failed to complete 6 min of exercise during the two exercise bouts in the supine posture (times to failure for these two subjects were 4 and 5 min, Fig 1B); and thus, the $\dot{V}O_2$ responses for all four postures for these two subjects were limited to the shortest exercise bout. The absolute ($L \cdot min^{-1}$) and relative (% of $\dot{V}O_2$ increase at end-exercise) amplitude of the slow component of the $\dot{V}O_2$ response was significantly

larger during the supine compared with 30° R and upright postures, and the absolute amplitude was also larger during 15° R compared with 30° R posture (Table 2A). Conversely, the relative contribution of the primary component to the overall increase in $\dot{V}O_2$ at end-exercise was significantly larger in the upright and 30° R compared with supine and it was also larger in the upright than 15° R posture. The MRT of the entire response was significantly longer in the supine compared with the upright and 30° R postures. The rest of the parameters were not different among the four postures.

Paragraph Number 19 *Cardiac output, stroke volume and heart rate responses (0-60 s of exercise):* At rest, CO and SV were significantly lower in the upright compared with the other three postures (Table 2B). However, by 60 s into the constant-load bout these variables were similar among all conditions. Heart rate responses did not significantly differ among postures at rest or at 60 s during exercise (Table 2B).

Perfusion pressure The perfusion pressure (mmHg) added by gravity acting on both sides of the vasculature in the quadriceps muscles (at their upper site of origin, near the iliac crest) was significantly reduced (on average between Experiment 1 and 2) from the upright (25.0 ± 0.6) to 30° R (18.4 ± 0.4) and 15° R (14.2 ± 0.3). Perfusion pressure was also lower during 15° R than 30° R, as well as in the supine (~0) when compared with the other three postures.

DISCUSSION

Paragraph Number 20 The main findings of the present study were that the performance of graded exercise was progressively diminished when the body was reclined from the upright to supine postures with significant reductions apparent between upright and 15° R & supine postures; that fatigue was progressively diminished at body angles above zero with significantly larger rates of fatigue in the

supine compared with upright posture; and that the time to failure during high-intensity constant-load cycling was significantly longer during upright and 30° R compared with supine and 15° R postures. The shorter times sustained during the constant-load efforts at 15° R and supine postures were accompanied with larger amplitudes of the slow component of the $\dot{V}O_2$ response and lower relative contribution of the primary component to the overall increase of the $\dot{V}O_2$ response in these two postures.

Graded cycling performance

Paragraph Number 21 Peak work rate during graded cycling exercise has been consistently shown to be significantly (~10%) greater during upright compared with supine posture (12, 14, 15, 24, 27, 30). However, prior to this study, very limited data was available on the effect of recumbent angles between supine and upright postures (i.e. degree of inclination between 0 - 90°) on graded cycling performance. Kato *et al.* (2011) recently reported that peak oxygen uptake during a graded cycling test was significantly higher during high recumbent (~75° R) compared with supine posture, although no data regarding peak work rate or time sustained during the tests were provided (28). To our knowledge, only one previous study investigated the effect of the degree of body inclination from supine to upright postures on graded muscle performance and showed that the time sustained during isometric calf plantar flexion exercise was similar when the body tilt angle was lowered from 90° to 47°, but that performance was significantly higher in these two postures compared with supine (0°) posture (13). The present findings are consistent with these observations and extend them to demonstrate that the time sustained and the peak work rate achieved during a graded cycling exercise are not significantly reduced reclining the body from upright

to 30° R, but that they are significantly reduced during low recumbent (15° R) and supine compared with upright postures.

Paragraph Number 22 However, despite these systematic reductions in peak power and exercise time, peak oxygen uptake responses in the present study were not significantly different among the four postures, suggesting an “excess” $\dot{V}O_2$ in the 15° R and supine postures. It is possible that this extra $\dot{V}O_2$ requirement is related to a larger contribution of fast twitch fibers in the low recumbent postures due to the reduced perfusion pressure. Fast twitch fibers are predominantly activated above VT and are believed to show a less effective $\dot{V}O_2$ response (greater O_2 cost of contraction) than slow twitch fibers which are predominantly recruited at intensities below VT (19, 31, 32). Consistent with this notion, DiMenna *et al.* (2010) have recently reported that the $\Delta\dot{V}O_2 / \Delta W$ slope (calculated by linear regression) above VT during a ramp graded exercise was significantly greater during supine compared with upright cycling, whereas this slope was similar for both postures at intensities below VT (11). In this context, the significantly lower power outputs at VT observed in the present study in the supine compared with the upright posture in the absence of any differences in $\dot{V}O_2$ were unexpected. It could be speculated that the apparent larger oxygen cost during the supine compared with upright posture at the point of VT may be due to a larger activation of inspiratory muscles and/or postural accessory muscles to overcome gravity in the supine position, as some participants might have not laid their backs completely on the bench due to lack of familiarity with this form of exercise. And if these extra postural and respiratory challenges contributed to the excess $\dot{V}O_2$ at intensities below VT in the supine posture, then it is reasonable to think that they also contributed, at least in part, to the excess $\dot{V}O_2$ at end-exercise in the low

recumbent postures. The design of the graded test (i.e. combination of step and ramp increments) employed in the present study was not appropriate to explore the $\Delta\dot{V}O_2 / \Delta W$ relationship given that the slope of this relationship appears to be sensitive to the exercise protocol (step vs ramp increments) (6), and thus, further studies employing either ramp or step graded tests are needed to better understand how cycling efficiency is affected at body angles between the upright and supine.

Fatigue and EMG activities

Paragraph Number 23

As for graded exercise performance, prior to this study there were no data on the effect of recumbent cycling on muscle fatigue responses. The present findings showed that the rates of fatigue (and the times sustained during the fatigue tests) were significantly different between supine and upright postures. The larger fatigue responses during supine cycling were evident by the second min of exercise (Fig 2E) confirming that the postural effect of fatigue is relatively rapid and manifest within the first minute or two of exercise (13, 14, 17, 21, 41, 42). It is possible that the considerable variations in the postural effect on muscle fatigue and times to failure among participants (Fig 2A-D) may have precluded these effects to be significant between low recumbent and upright postures. In the present study the postural effect on fatigue occurred in the absence of any significant postural effect on maximum force or power output prior to the onset of exercise (i.e. time = 0), and this is consistent with previous studies (13, 14, 17, 21, 40, 41). Similarly, the maximum EMG responses for the three muscles assessed during the 10 s all-out efforts prior to the fatigue tests (i.e. time = 0) were not different among the 4 postures and the normalised EMG responses were also similar at the onset of exercise for all postures.

However, there was a progressive divergence of the NEMG responses mainly for GM and at a lesser extent for VL such that NEMG values for the upright and 30° R remained relatively constant (or increased slightly), whereas they increased more dramatically for supine and 15° R postures. Even if NEMG values for BF were not significantly affected by posture, they also tended to be larger in the supine and 15° R compared with upright (main effect, posture $P = 0.09$).

Paragraph Number 24 During intense exercise such NEMG behaviour is normally attributed to a compensatory increase in motor unit recruitment and/or rate coding in the presence of fatigue. This notion is supported by the present findings as differences in fatigue and NEMG responses between upright and supine postures were significant at the same exercise time points, and differences, although not significant, between the 15° R and upright were also apparent at similar exercise time points. The present findings are in agreement with Egaña *et al.* (2010b) who showed significantly larger rates of fatigue in the supine compared with upright posture together with larger NEMG responses in five lower-body muscles by min 1-4 and at the point of failure of a high-intensity (80% peak power) constant-load cycling exercise (17); and with Tachi *et al.* (2004) who reported significantly shorter times during a moderate intensity exhaustive dorsiflexion exercise and larger integrated EMG responses of the *tibialis anterior* at the end of the exercise in the supine compared with upright posture (41). In contrast, Denis and Perry (2006) reported similar EMG activities in VL, *rectus femoris* (RF) and BF muscles during upright and supine high-intensity cycling; however, these observations are likely to be related to the fact that they employed same relative intensities (posture-specific VT plus 25W) (10), as research has previously shown that during relative high-intensity constant-load exercise (posture

specific 80% peak work rate) is similar between upright and supine cycling (15). However, caution needs to be taken interpreting the findings of the present study given that: a) fatigue indices (i.e. rate of fatigue) and Δ NEMG data were not significantly correlated, and b) when EMG (rms) responses were normalised relative to the maximum upright condition (results not presented here), NEMG responses for GM were no longer significantly different across postures. Nevertheless, NEMG responses for VL and BF were not affected by the two different normalization protocols, **and normalising EMG responses to the upright condition when some of the remaining conditions are performed on different days is likely to be less appropriate than normalising EMG data to the posture-specific peak RMS recorded on the same day.**

Performance, cardiac output and $\dot{V}O_2$ kinetics during constant-load cycling

Paragraph Number 25 Given the possibility that the dynamic response of $\dot{V}O_2$ may be linked to the postural effect on muscle fatigue and EMG; in Experiment 2, we explored $\dot{V}O_2$ kinetics responses at the same four cycling postures employing the same exercise intensity (work rate relative to 50% Δ of the upright graded test). In addition, in order to assess cycling endurance at this high-intensity constant-load effort, the first of the two bouts was brought to failure. Cycling endurance during a high-intensity constant-load effort is significantly larger in upright compared with supine cycling (15-18), and this effect is of a larger magnitude ($\geq 100\%$) than the effect observed during graded cycling ($\sim 10\%$) (12, 15, 18, 24, 27, 30). In addition, when the body angle is lowered from the upright to 65° R and 30° R postures the time sustained during a high-intensity cycling constant-load exercise and the $\dot{V}O_2$ kinetics responses are unaffected, but the time sustained is larger at these three postures

(upright, 65° R and 30° R) compared with supine (16). Consistent with Egaña *et al.* (2010a) the present findings showed that exercising times (and the parameters describing the $\dot{V}O_2$ kinetics response) were similar between upright and 30° R postures, but we observed that times to failure were significantly diminished when the body angle was further reduced to 15° R and 0° (supine) postures compared with both upright and 30° R postures.

Paragraph Number 26 In addition, these shorter exercising times at 15° R and supine postures were accompanied by larger amplitudes of the slow component and smaller relative amplitudes of the primary component of the $\dot{V}O_2$ kinetics response measured during the initial 6 min of exercise. In addition, the MRT was significantly longer during the supine posture compared with both, upright and 30° R postures. This notion is consistent with observations of lower amplitudes of the primary component but larger amplitudes of the slow component of $\dot{V}O_2$ (30), as well as an overall slower kinetic response of the $\dot{V}O_2$ response (12, 24, 33) in the supine compared with upright high-intensity cycling. It has been suggested that the $\dot{V}O_2$ slow component is, at least in part, caused by increased motor unit activation as high-intensity exercise proceeds with increased recruitment of fast-twitch fibres that show longer time constant and greater oxygen cost of contraction than slow-twitch fibres (3, 4, 19, 31, 32, 39). Therefore, the present EMG findings from the fatigue tests are consistent with a greater slow component amplitude during the supine and 15° R conditions.

Paragraph Number 27 In the present study the perfusion pressure acting on the active musculature was significantly reduced lowering the body from the upright to 30° R, 15° R and supine postures, by causing a shift of blood volume towards the heart, which, in turn, augmented resting CO and SV, as shown elsewhere (16, 33). However, during dynamic exercise perfusion pressure is removed from the venous side upon muscle relaxation when the venous volume has been expelled during the preceding muscle contraction. This results in a greater increase in perfusion pressure in the upright compared with the recumbent and supine postures where the gravity-induced hydrostatic pressure component is lower or absent. As a consequence, by min 1 of the heavy constant-load exercise the upright CO values were similar to the recumbent and supine values, suggesting that central circulatory adaptation may not be responsible for the differences observed in performance. This is consistent with Leyk *et al.* (1994) who reported similar CO responses between supine and upright postures at the onset of heavy intensity exercise (33). Further studies exploring the dynamic response of blood flow among these postures are needed to confirm the likely role of the peripheral circulation.

Limitations

Paragraph Number 28 In the present study participants in *Experiment 1* (days 5 & 6) completed two fatigue tests within the same session (separated by 60 min); and participants in *Experiment 2* completed the constant-load submaximal test to failure and the 6 min submaximal bout also within the same session (separated by 60 min). While there is evidence that a period of 60 min following high-intensity exercise is sufficient for complete recovery to occur (i.e. to have no effect on $\dot{V}O_2$ kinetics during subsequent exercise (7)), we cannot exclude the possibility that the completion of the initial fatigue test had an impact upon the physiological responses to the second

fatigue test. To minimize this limitation the order of the fatigue tests was selected at a counter balanced fashion to remove any potential exercise order effects. For practical reasons we did not normalize the work rate relative to each participant's critical power (CP) during the constant-load tests to failure during *Experiment 2*, and we cannot exclude the possibility that some participants could have exercised below their CP and others above. However, when intensities ~5% below CP were employed during upright cycling, Burnley *et al.* (2006) reported that 9 out of their 11 participants were able to complete at least 30 min of cycling, while at exercise intensities ~5% above CP exhaustion occurred within 13 min (8). Thus, given that the mean time to exhaustion in the upright posture in the present study was <13 min and that 8 out of the 9 subjects reached exhaustion in less than 20 min, it is likely that most (if not all) subjects in the present study exercised above their CP.

Paragraph Number 29 In conclusion, this study showed that the time sustained during both graded cycling exercise as well as high-intensity constant-load cycling exercise is significantly reduced by supine & low recumbent (15° R) postures compared with 30° R and upright postures. The reductions in performance during the constant-load exercise during supine and 15° R postures were, in turn, accompanied with larger amplitudes of the $\dot{V}O_2$ slow component and larger electromyographic activities of some of the active muscles involved in cycling. Future studies should explore the potential ergogenic effects achieved due to reduced air resistance during low-recumbent compared with upright cycling at different degrees of air resistance to better understand under which environmental wind conditions the aerodynamic benefits associated with the 15° R posture would overcome the gravity-induced negative physiological repercussions.

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FIGURE CAPTIONS:

Figure 1 Individual and mean ($\pm$ SD, bar graph) exercise times to failure during graded cycling exercise (A, $n = 10$), and during constant-load cycling exercise (B, $n = 9$) during upright, 30° R, 15° R and supine postures. * Significantly different from supine ($P < 0.05$); † Significantly different from 15° R ($P < 0.05$).

Figure 2 A-D: individual normalised fatigue responses (% peak power) during upright (A), 30° R (B), 15° R (C) and supine (D) postures ($n = 10$). E: mean ($\pm$ SD) normalised fatigue responses (% peak power) during upright (closed circles), 30° R (open circles), 15° R (closed triangles) and supine (open triangles) postures ($n = 10$). * Significantly different from supine ($P < 0.05$).

Figure 3 NEMG responses (% peak) for all three leg muscles during the fatigue tests during upright, 30° R, 15° R and supine postures (times in each posture are limited to the worst performer, $n = 8$). Values are means $\pm$ SD. * Significantly different from supine ($P < 0.05$); † Significantly different from 15° R ($P < 0.05$).

Figure 4 Oxygen uptake responses (*open circles*) in a representative individual during cycling in the upright, 30° R, 15° R and supine postures. Responses predicted from the fitting of the triphasic function are also shown (*solid lines*). Note the larger amplitudes of the slow component (A'_s) during the 15° R and supine postures.

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Table 1

Table 1. Peak physiological responses during graded and constant-load cycling

	Upright	30° R	15° R	Supine
A) Graded tests (n=10)				
Time to failure (min)	18.8 ± 3.2*†	18.0 ± 3.4*	17.4 ± 2.9*	15.9 ± 2.9
Peak workload (W)	239 ± 47*†	230 ± 45*	219 ± 41*	202 ± 35
Peak HR (beats.min ⁻¹)	191 ± 10 *†‡	185 ± 11	182 ± 11	181 ± 9
Peak $\dot{V}O_2$ (mL.kg ⁻¹ .min ⁻¹)	47.5 ± 5.4	45.4 ± 6.2	44.7 ± 4.6	43.9 ± 5.6
Peak $\dot{V}_E$ (L.min ⁻¹)	128 ± 22 *	116. ± 30	120 ± 27	114 ± 26
Peak RER	1.13 ± 0.03	1.13 ± 0.03	1.12 ± 0.04	1.12 ± 0.05
Workload at VT (W)	169 ± 48 *	150 ± 47	150 ± 45	138 ± 45
Workload at VT	68 ± 10	65 ± 11	68 ± 15	70 ± 16
(% peak power)				
$\dot{V}O_2$ at VT (mL.kg ⁻¹ .min ⁻¹)	27.8 ± 7.5	26.6 ± 6.4	26.2 ± 7.7	24.4 ± 7.4
$\dot{V}O_2$ at VT (% peak $\dot{V}O_2$)	59 ± 11	58 ± 10	58 ± 16	56 ± 17
B) Constant-load tests (n=9)				
Time to failure (min)	12.8 ± 5.3*†	14.2 ± 6.1*†	8.5 ± 1.7	6.8 ± 2.0
Peak $\dot{V}O_2$ (mL.kg ⁻¹ .min ⁻¹)	43.9 ± 3.8	40 ± 3.45	41.7 ± 4.6	41.16 ± 4.2
Peak HR (beats.min ⁻¹)	187 ± 5*†	183 ± 11*†	178 ± 10	178 ± 8
Peak $\dot{V}_E$ (L.min ⁻¹)	113 ± 16	101 ± 18	110 ± 21	111 ± 21

Values are means $\pm$ SD. * Significantly different from supine ($P<0.05$). † Significantly different from 15° R ($P<0.05$). ‡ Significantly different from 30° R ($P<0.05$)

Table 2

Table 2. *Oxygen uptake kinetics parameters and cardiac output responses.*

	Upright	30° R	15° R	Supine
A) $\dot{V}O_2$ kinetics parameters				
$\dot{V}O_2$ base (L.min ⁻¹)	0.53 ± 0.15	0.58 ± 0.13	0.45 ± 0.10	0.61 ± 0.17
A _c (L.min ⁻¹)	0.56 ± 0.33	0.41 ± 0.19	0.41 ± 0.15	0.35± 0.24
TD _p – TD _c (s)	27.5 ± 7.11	26.7 ± 8.1	22.8 ± 7.2	22.1 ± 8.7
A _p (L.min ⁻¹)	1.39 ± 0.24	1.52 ± 0.37	1.43 ± 0.28	1.30 ± 0.52
τ _p (s)	21.2 ± 6.2	21.2 ± 8.3	19.8 ± 11.3	19.1 ± 10.7
A' _p (L.min ⁻¹)	1.95 ± 0.40	1.93 ± 0.53	1.85 ± 0.32	1.64 ± 0.65
A' _s (L.min ⁻¹)	0.43 ± 0.13*	0.39 ± 0.12*†	0.57 ± 0.10	0.61 ± 0.15
TD _s (s)	127.2 ± 25.9	124.0 ± 22.4	114.9 ± 34.4	110.7 ± 29.6
A' _p /(A' _p +A' _s)	0.82 ± 0.05*†	0.82 ± 0.07*	0.76 ± 0.03	0.72± 0.09
A' _s /(A' _p +A' _s)	0.18 ± 0.05*	0.18 ± 0.07*	0.24 ± 0.03	0.28± 0.09
End- $\dot{V}O_2$ (L.min ⁻¹)	2.91 ± 0.39	2.90 ± 0.56	2.86 ± 0.37	2.86 ± 0.61
MRT (s)	67.3 ± 14.2*	70.0 ± 14.7*	77.1 ± 14.3	91.9 ± 10.1
Overall gain (ml.min ⁻¹ .W ⁻¹)	12.8 ± 1.3	12.7 ± 1.5	12.5 ± 1.0	12.5 ± 1.8
B) Cardiac output responses				
CO at rest (L.min ⁻¹)	6.5 ± 1.7*†‡	7.3 ± 1.6	7.3 ± 1.8	7.2 ± 1.6
CO at 60s (L.min ⁻¹)	17.5 ± 2.9	17.2 ± 3.1	16.7 ± 2.3	17.0 ± 2.3
SV at rest (ml)	88.3 ± 38.1*†‡	101.4 ± 35.3	101.6 ± 35.5	101.5 ± 34.6

SV at 60s (ml)	119.0 ± 22.5	118.6 ± 20.8	118.4 ± 18.7	119.3 ± 21.9
HR at rest (beats.min ⁻¹)	77 ± 13	74 ± 9	73 ± 9	73 ± 9
HR at 60s (beats.min ⁻¹)	148 ± 9	145 ± 10	142 ± 8	144 ± 12

Values are means ± SD. * Significantly different from supine ($P<0.05$). †

Significantly different from 15° R ($P<0.05$). ‡ Significantly different from 30° R

($P<0.05$).

Figure 1
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Figure 1

Figure 2
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Figure 2

Figure 3

Figure 4