European Journal of Applied Physiology (2021) 121:1487–1498
https://doi.org/10.1007/s00421-021-04630-7

ORIGINAL ARTICLE

The effect of posture on maximal oxygen uptake in active healthy individuals

Hayley T. Dillon[1,2] · Christophe Dausin[3] · Guido Claessen[1,4] · Anniina Lindqvist[1] · Amy Mitchell[1] · Leah Wright[1] · Rik Willems[4] · André La Gerche[1,5] · Erin J. Howden[1]

Received: 28 July 2020 / Accepted: 5 February 2021 / Published online: 27 February 2021
© The Author(s), under exclusive licence to Springer-Verlag GmbH, DE part of Springer Nature 2021

Abstract

Purpose Semi-supine and supine cardiopulmonary exercise testing (CPET) with concurrent cardiac imaging has emerged as a valuable tool for evaluating patients with cardiovascular disease. Yet, it is unclear how posture effects CPET measures. We aimed to discern the effect of posture on maximal oxygen uptake (VO_2max) and its determinants using three clinically relevant cycle ergometers.

Methods In random order, 10 healthy, active males (Age 27 ± 7 years; BMI 23 ± 2 kg m^2) underwent a ramp CPET and subsequent constant workload verification test performed at 105% peak ramp power to quantify VO_2max on upright, semi-supine and supine cycle ergometers. Doppler echocardiography was conducted at peak exercise to measure stroke volume (SV) which was multiplied by heart rate (HR) to calculate cardiac output (CO).

Results Compared to upright (46.8 ± 11.2 ml/kg/min), VO_2max was progressively reduced in semi-supine (43.8 ± 10.6 ml/kg/min) and supine (38.2 ± 9.3 ml/kg/min; upright vs. semi-supine vs. supine; all $p \leq 0.005$). Similarly, peak power was highest in upright (325 ± 80 W), followed by semi-supine (298 ± 72 W) and supine (200 ± 51 W; upright vs. semi-supine vs. supine; all $p < 0.01$). Peak HR decreased progressively from upright to semi-supine to supine (186 ± 11 vs. 176 ± 13 vs. 169 ± 12 bpm; all $p < 0.05$). Peak SV and CO were lower in supine relative to semi-supine and upright (82 ± 22 vs. 92 ± 26 vs. 91 ± 24 ml and 14 ± 3 vs. 16 ± 4 vs. 17 ± 4 l/min; all $p < 0.01$), but not different between semi-supine and upright.

Conclusion VO_2max is progressively reduced in reclined postures. Thus, posture should be considered when comparing VO_2max results between different testing modalities.

Keywords Oxygen utilisation · Posture · Exercise testing · Echocardiography · Exercise cardiac MRI

Abbreviations

$[La^-]_b$	Blood lactate concentration
avO_2-diff	Arteriovenous oxygen difference
CO	Cardiac Output
CPET	Cardiopulmonary exercise testing
DBP	Diastolic blood pressure
HR	Heart rate
MRI	Magnetic resonance imaging
RER	Respiratory exchange ratio
RR	Respiratory rate
SaO_2	Oxygen saturation
SV	Stoke volume
SBP	Systolic blood pressure
V_T	Tidal volume
V_E	Minute ventilation
VO_2	Oxygen consumption
VO_2max	Maximal oxygen uptake

Communicated by I. Mark olfert.

✉ Erin J. Howden
erin.howden@baker.edu.au

1 Sports Cardiology Laboratory, Baker Heart and Diabetes Institute, Melbourne, VIC 3004, Australia

2 Institute for Physical Activity and Nutrition, School of Exercise and Nutrition Sciences, Deakin University, Burwood, VIC, Australia

3 Exercise Physiology Research Group, Department of Movement Sciences, KU Leuven, Leuven, Belgium

4 Department of Cardiovascular Sciences, KU Leuven, Leuven, Belgium

5 National Centre for Sports Cardiology, St Vincent's Hospital Melbourne, Fitzroy, Australia

W	Watts
W_{peak}	Peak power output

Introduction

Since its conception in the early nineteenth century (Hill and Lupton 1922; Lindhard 1915), cardiopulmonary exercise testing (CPET) has evolved significantly in its technology and scope such that it now represents the gold standard for assessing the integrative functioning of the cardiovascular, pulmonary, haematological and skeletal muscle systems (Albouaini et al. 2007; Guazzi et al. 2012). The key outcome, maximal oxygen uptake (VO_2max), serves a versatile role in both clinical and non-clinical settings. In addition to its role in indicating general fitness (Wasserman et al. 1987) and informing exercise prescription (Guazzi et al. 2012; Pescatello et al. 2014), VO_2max is a strong prognostic indicator and measure of disease severity in several clinical populations (Piepoli et al. 2006; Ferrazza et al. 2009; Howden et al. 2019; Wood et al. 2013; Leite et al. 2009). As such, VO_2max assessment plays a key role in clinical management (Myers 2005; Beniaminovitz and Mancini 1999) and evaluating the success of therapeutic interventions (Howden et al. 2019). In general, a CPET is conducted upright either on a treadmill or cycle ergometer; however, owing to the growing clinical application of CPET—particularly with simultaneous cardiac imaging for the comprehensive evaluation of exercise physiology and specifically cardiovascular disease (Lancellotti et al. 2017; La Gerche et al. 2013)—the use of semi-supine and supine cycle ergometry has become increasingly common. In this regard, it is important to understand the effect of posture on VO_2max and its limiting determinants.

Variations in body position are associated with profound physiological alterations that may influence exercise response, and thus results of a CPET. Indeed, as the body is moved from upright to semi-supine to supine, there is a progressive reduction in both arterial perfusion pressure (via a reduction in hydrostatic pressure) (Folkow et al. 1971) and pulmonary compliance (via cephalic displacement of the diaphragm and abdominal structures) (Katz et al. 2018). Reductions in arterial perfusion pressure have been linked to attenuated skeletal muscle blood flow (Egana and Green 2005; Folkow et al. 1971), likely contributing to an accelerated muscular fatigue and reduced endurance in reclined cycling positions. Postural related differences in VO_2max have been investigated in healthy individuals (Forton et al. 2016; Scott et al. 2006; Poliner et al. 1980; Lopes et al. 2014; Leyk et al. 1994; Forbregd et al. 2019; Cotsamire et al. 1987; Hughson et al. 1991; Åstrand and Saltin 1961), and in individuals with various forms of cardiovascular disease (Walsh-Riddle and Blumenthal 1989; Shen et al. 1985; Quinn et al. 1995; Kramer et al. 1982; Bonzheim et al. 1992). However, the results pertaining to the effect of posture on VO_2max in the current literature remain inconclusive.

Of particular interest, most studies that have examined the effect of posture on VO_2max in adults have compared upright and supine cycle ergometry, while a paucity of studies have compared VO_2max between upright and semi-supine cycle ergometry which, as stated above, is a useful modality for cardiovascular disease assessment (Forton et al. 2016; Quinn et al. 1995; Scott et al. 2006; Walsh-Riddle and Blumenthal 1989). Due to the scarcity of studies comparing upright and semi-supine VO_2max, and the varying effects reported within, the degree to which VO_2max is altered in semi-supine cycle ergometry compared to upright cycle ergometry warrants further investigation. In addition, to our knowledge, no studies have compared VO_2max assessed on the magnetic resonance imaging (MRI) compatible supine cycle ergometer with VO_2max assessed on the conventional upright cycle ergometer or semi-supine echocardiography cycle ergometer. Exercise cardiac MRI, performed on the supine MRI-compatible supine cycle ergometer, has become a gold standard method of assessing cardiac haemodynamics during exercise (La Gerche et al. 2013). Indeed, this rapidly emerging technique of cardiac assessment has unrivalled capability in non-invasively distinguishing normal from pathological changes in cardiac function during exercise, and has been increasingly employed to discern the central contribution to exercise intolerance in a broad range of populations (La Gerche et al. 2013; Howden et al. 2019; Barber et al. 2016). However, in contrast to previously studied supine cycle ergometers, the MRI-compatible ergometer has significantly shorter cranks, altering lower extremity biomechanics, power output, and potentially VO_2max. Thus, discerning the degree to which posture alters VO_2max using clinically relevant cycle ergometers is of great importance.

The primary aim of this study was to investigate the effect of posture on VO_2max using three clinically relevant cycling positions: upright, semi-supine and supine. Specifically, we aimed to elucidate the degree to which VO_2max is altered during semi-supine cycle ergometry compared to conventional upright cycle ergometry. We also sought to update the literature by including a comparison with the MRI-compatible supine cycle ergometer (which has shorter cranks) utilised in the rapidly emerging technique of exercise cardiac MRI. Owing to the aforementioned postural mediated physiological changes, we hypothesised that VO_2max would be highest in upright, followed by semi-supine and then supine. A secondary aim was to investigate the effect of posture on peak cardiovascular, ventilatory, and metabolic parameters to gain an understanding of the potential physiological mechanisms governing the hypothesised variance in VO_2max between postures.

Methodology

Participant population

Ten healthy, active males (age 28 ± 7 years; height 177 ± 8 cm; weight 72.4 ± 9.7 kg; BMI 23 ± 2 kg.m^2; physical activity sessions/week, 4.7 ± 2.2; average session duration, 83.5 ± 31.5 min) participated in this study. After obtaining informed written consent, participants were screened for eligibility and excluded if they were aged < 18 or > 64 years or had known contraindications to exercise testing as per the American College of Sports Medicine guidelines (Pescatello et al. 2014). All experimental procedures were performed in accordance with the ethical standards of the institutional review boards of the Alfred Health Research Ethics committee and with the 1964 Helsinki Declaration.

Study design

Participants performed a ramp protocol CPET with constant load supramaximal verification phase in three clinically relevant cycling positions: upright, semi-supine and supine (Fig. 1). Upright tests were performed on a conventional electronically braked cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands) with a 170 mm crank arm and seat positioned at 90° to the floor. Participants rested their arms on handlebars positioned at their front. Semi-supine tests were performed on an electronically braked reclining cycle ergometer (Ergoselect 1200 EL, Ergoline GmbH, Bitz, Germany) with the seat positioned 45° to the floor. Semi-supine ergometer crank length was 170 mm and participants gripped one handle adjacent to their left ear, while their right arm was supported adjacent to their right hip. Supine tests were performed on the specialised electronically braked MRI compatible ergometer (Lode MR, Groningen, The Netherlands) positioned 0° to the floor. Supine cranks ranged between 55 and 65 mm, depending on foot size, and participants gripped handles adjacent to their body for torso stabilisation. Each test was performed at least 48 h apart within 3 weeks, at the same time of day, and in a randomised order as determined by Latin Square randomisation. Participants refrained from moderate to vigorous physical activity, caffeine, and alcohol for 24 h before each testing visit and fasted for 2 h before each test.

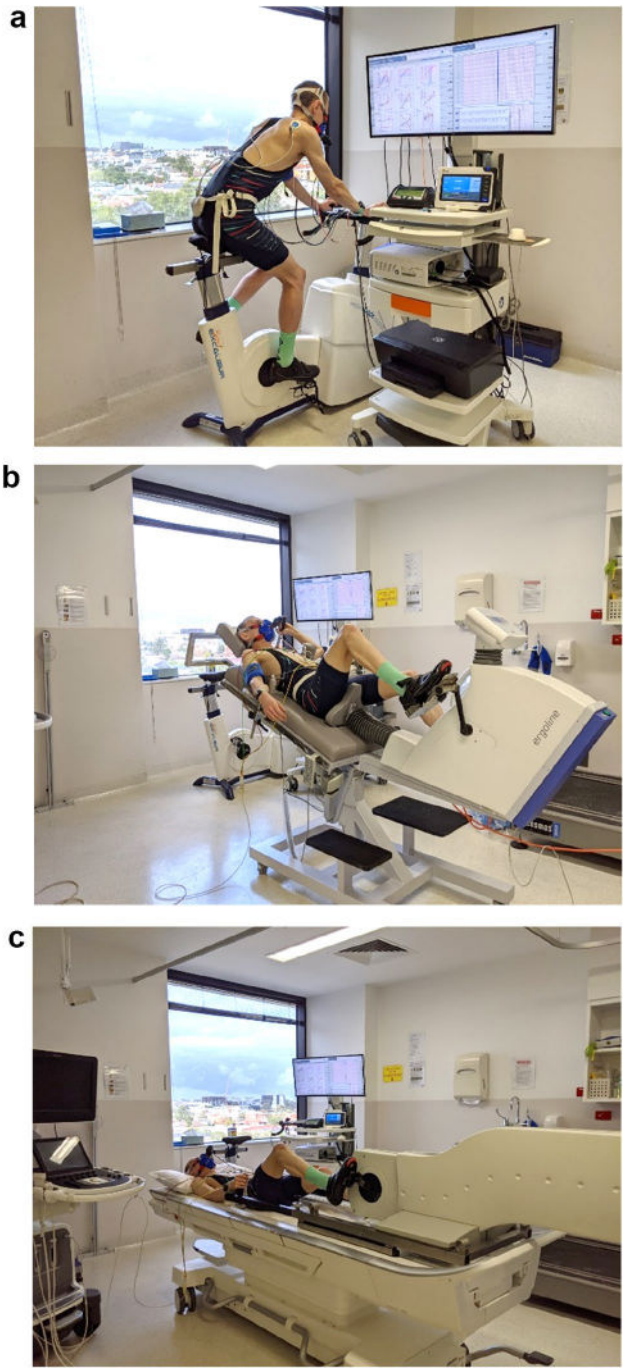

Fig. 1 Visual depiction of the **a** upright, **b** semi-supine, **c** supine cycling ergometers utilised for cardio-pulmonary exercise testing and subsequent constant supramaximal workload verification tests

Exercise testing protocol

The ramp protocol CPET (Fig. 2) began with a 1-min warm-up at 30–50 W and increased at a rate of 20–30 W per minute until volitional exhaustion. At the end of the test, participants were asked to report the reason for exercise cessation (leg fatigue or breathlessness). After a 15-min rest in the tested position, participants performed a constant load verification phase at 105% of the peak power output (W_{peak}) achieved in the ramp test to validate the previously attained 'VO_2max' (Rossiter et al. 2006; Poole and Jones 2017). Specifically, participants completed a 2-min warm-up at a

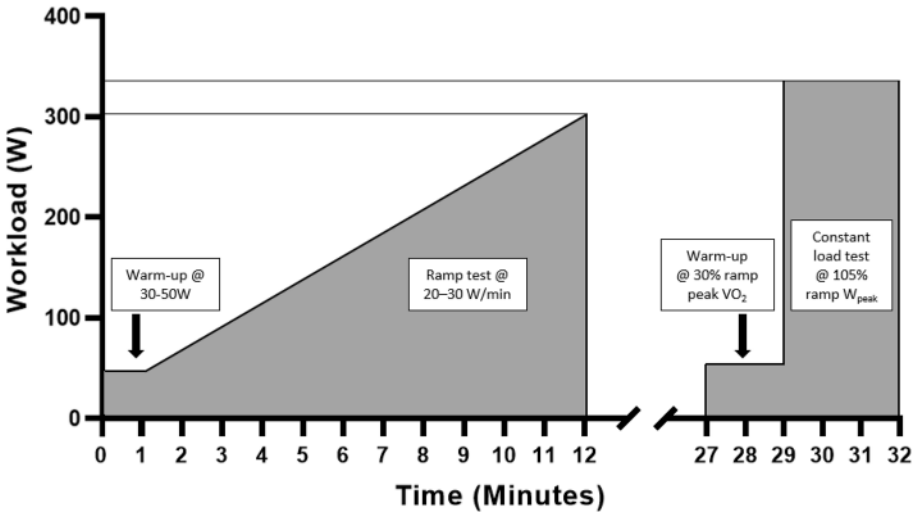

Fig. 2 Schematic of the ramp exercise test and subsequent constant workload verification phase. Ramp protocol consisted of a 1-min warm-up at 30–50 W, increasing by 20–30 W/Min. After a 15-min rest, participants cycled at the workload corresponding to 30% of their ramp peak VO_2 for 2-min before increasing to 105% ramp W_{peak}

workload corresponding to 30% of their ramp test VO_2max, after which, the workload quickly incremented (over 20 s) to 105% ramp W_{peak} (Fig. 2). Participants received verbal encouragement and were instructed to cycle to exhaustion.

Cardiopulmonary exercise testing measurements

Expired gas analysis was performed continuously throughout testing using a calibrated metabolic cart (Vyntus CPX, Carefusion, San Diego, USA) for the measurement of ventilation (V_E), tidal volume (V_T), respiratory rate (RR), and flow rates of expired carbon dioxide and oxygen. Heart rate (HR) was measured continuously with a 12-lead ECG (Vyntus™ CPX, CareFusion, San Diego, CA), while systolic and diastolic blood pressure (SBP and DBP) were measured with an electrosphygmomanometer blood pressure cuff (Suntech, Tango, NC) at 2-min intervals. Oxygen saturation (SaO_2) was monitored continuously using an ear clip pulse oximeter sensor (Nonin Medical, Inc, Plymouth, MN). VO_2max was defined as the average of the six consecutive highest VO_2 values from 5 s averaged data (i.e. 30 s average). The number of participants who satisfied traditionally-used secondary criteria for VO_2max attainment in upright, semi-supine and supine ramp test (two of: peak blood lactate ($[La^-]_b$) ≥ 8 mmol/l, peak HR within 10 beats of age-predicted max, RER ≥ 1.10) was documented. However, VO_2max was only considered verified if the maximal VO_2 achieved in the supramaximal test was ≤ 3% higher than the maximal VO_2 attained in the preceding ramp test (test–retest coefficient of variation) (Rowell 1962), consistent with other studies (Sedgeman et al. 2013; Astorino and White 2010). Peripheral muscle arteriovenous difference (avO_2-diff) was estimated according to the Fick Principle, using VO_2max and peak CO measured by exercise echocardiography (McMichael and Sharpey-Schafer 1944).

Echocardiography measurements

Echocardiography was conducted using the EPIQ 7G (Philips Medical Systems, Andover, MA, USA) equipped with a X5-1 matrix-array transducer. Analysis was performed offline using GE EchoPAC PC (General Electric V 20.2) by a single experienced sonographer. Normal resting cardiac function was confirmed prior to exercise via image acquisition in the apical 4-, 2- and long-axis (three-chamber) views and parasternal long axis. Pulsed wave Doppler of the LV outflow tract (LVOT) was also obtained from the apical 5-chamber view for the Velocity time integral (VTI cm). Exercise images were acquired using multi-beat ECG gating at two stages: final minute of the ramp (ramp peak) and supramaximal tests (supramaximal peak). During exercise (ramp peak and supramaximal peak), Pulsed wave Doppler of the LVOT VTI (cm) was used to calculate peak stroke volume (SV) (LVOT VTI × Cross-Sectional Area (CSA) of the LVOT) and cardiac output (CO) [product of SV and HR (bpm)]. The 3-beat averages were used for all Doppler measures. The LVOT CSA derived in the rest setting was used consistently across all stages to calculate SV. Two participants were excluded from Doppler SV and CO analysis due to poor image quality.

Biochemistry measurements

Peak $[La^-]_b$ was measured from an ear lobe capillary sample using the Lactate Pro 2 Analyser (Arkray, Japan). Measurements were taken 2 min after exercise cessation in the ramp test (ramp peak) and constant load supramaximal test (supra peak).

Statistical analysis

All statistical analyses were performed in GraphPad (Version 8) statistics software. Continuous variables were checked for normal distribution via the Kolmogorov–Smirnov test and are expressed as mean ± standard deviation and categorical variables are expressed as n (%). A one-way, repeated measures analysis of variance was conducted to assess difference in continuous variables between supine, semi-supine and upright cycling positions. Tukey's post-hoc testing was applied when ANOVA met significance ($p < 0.05$). Two-tailed paired *t* tests were performed to investigate differences in peak exercise parameters between the ramp and supramaximal tests.

Results

Exercise capacity measurements

The effect of posture on VO_2max (gross) is presented in Fig. 3a. Compared to upright, VO_2max (ml/kg/min) in semi-supine and supine ramp tests was 6% and 18% lower, respectively (upright vs. semi-supine, $p = 0.003$; upright vs. supine, $p < 0.001$; semi-supine vs. supine, $p = 0.005$). Localised muscular fatigue was reported as the sole reason for CPET cessation in semi-supine and supine, while breathlessness accounted for 60% of test cessation in upright.

The proportion of participants who satisfied traditionally-used secondary criteria for VO_2max attainment in the ramp test was 100%, 90% and 70% for upright, semi-supine and supine, respectively (Table 1). With respect to VO_2max verification, the peak VO_2 values recorded in the ramp and supramaximal constant workload verification cycle tests are summarised in Table 2. The incidence of a true VO_2max (as determined by supramaximal peak $VO_2 \leq 3\%$ higher than ramp peak VO_2) was high for upright (70%) and semi-supine (80%) positions, but a true VO_2max was only achieved by one participant (10%) in the supine position. There was no statistical difference between peak VO_2 obtained from the ramp and supramaximal verification tests for upright. Similarly, there was no statistical difference between peak VO_2 obtained from the ramp and supramaximal verification test for semi-supine, though a trend toward an increased peak VO_2 in the supramaximal compared to the ramp test was observed in supine.

Peak power, haemodynamic and metabolic measurements

The effect of posture on peak power, haemodynamic, and metabolic variables are summarised in Table 3. Compared to upright, the W_{peak} achieved in semi-supine and supine

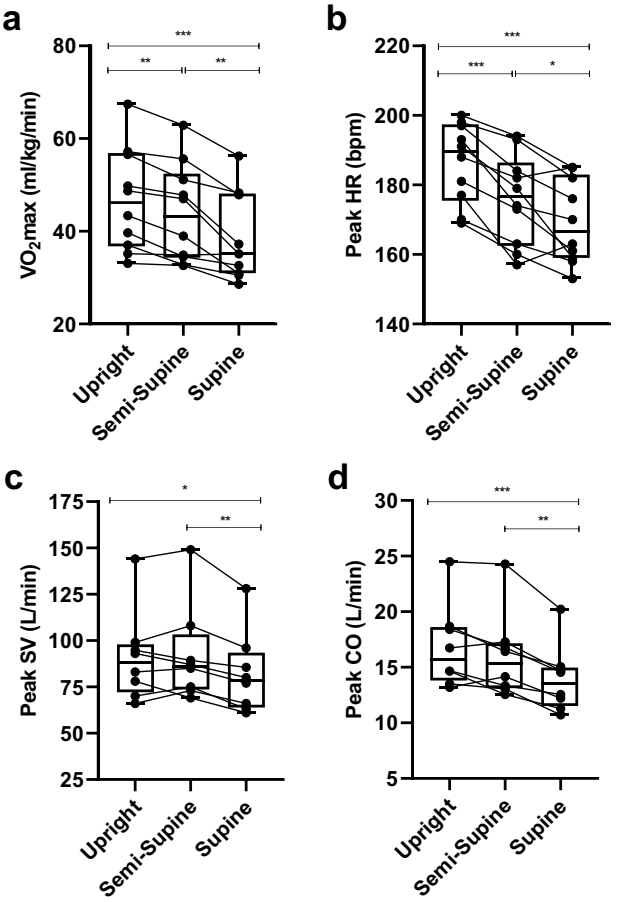

Fig. 3 Impact of posture on **a** VO_2max ($n = 10$), **b** peak HR ($n = 10$), **c** peak SV ($n = 8$) and **d** peak CO ($n = 8$). *Denotes $p < 0.05$, **Denotes $p < 0.01$, ***Denotes $p < 0.001$. VO_2max and peak HR were significantly higher in upright relative to semi-supine and supine positions, and significantly higher in semi-supine relative to supine. There was no difference in peak SV and CO between upright and semi-supine, but peak SV and CO in upright and semi-supine were increased relative to supine

posture were 8% and 38% lower, respectively (upright vs. semi-supine, $p = 0.002$; upright vs. supine, $p < 0.001$; semi-supine vs. supine, $p < 0.001$). Peak avO_2-diff in semi-supine and supine were 19% and 32% lower than upright (upright vs. semi-supine: $p < 0.001$; upright vs. supine, $p < 0.001$; semi-supine vs. supine, $p = 0.01$). Peak $[La^-]_b$ was significantly higher in upright compared to supine ($p = 0.03$), with a trend towards higher peak $[La^-]_b$ in semi-supine relative to supine ($p = 0.07$). There were no statistical differences in peak $[La^-]_b$ between upright and semi-supine ($p = 0.27$). Peak RER was significantly lower in semi-supine compared to supine ($p = 0.04$), but no differences were observed between upright and supine ($p = 0.89$) or semi-supine and supine ($p = 0.93$). No statistical differences were observed in peak SBP (upright

Table 1 Proportion of subjects who satisfied secondary criteria for VO_2max attainment in each cycling position

Criteria	Upright	Semi-supine	Supine
Peak HR within 10 bpm of Age-predicted HR max	8/10 (−6 ± 8 bpm)	4/10 (−16 ± 11 bpm)	0/10 (−23 ± 8 bpm)
Peak RER ≥ 1.10	10/10	10/10	10/10
Peak $[La^-]_b \geq 8.0$ mmol/l	10/10	9/10	7/10
Participants meeting ≥ 2 criteria	10/10	9/10	7/10

Data presented in parentheses are mean ± SD peak HR as it relates to age-predicted HR max

Table 2 Comparison of peak exercise parameters in ramp and supramaximal exercise tests

	Ramp	Supramaximal	*p* value
VO_2max (ml/kg/min^{-1})			
Upright	46.80 ± 11.17	46.72 ± 10.38	0.91
Semi-supine	43.83 ± 10.64	44.19 ± 10.60	0.52
Supine	38.24 ± 9.29	40.74 ± 9.41	0.06
HR (bpm)			
Upright	186 ± 11	182 ± 11*	0.02
Semi-supine	176 ± 13	177 ± 12	0.38
Supine	169 ± 12	177 ± 14*	0.02
Lactate (mmol/l)			
Upright	14.88 ± 3.08	15.19 ± 2.67	0.84
Semi-supine	12.67 ± 3.48	16.41 ± 2.73*	0.003
Supine	9.68 ± 3.41	12.34 ± 3.67*	0.01
RER			
Upright	1.33 ± 0.09	1.20 ± 0.07*	0.003
Semi-supine	1.29 ± 0.10	1.21 ± 0.07*	0.03
Supine	1.31 ± 0.16	1.23 ± 0.11	0.10
SV (mL)			
Upright	90.98 ± 24.47	92.03 ± 26.37	0.75
Semi-supine	91.92 ± 26.09	89.63 ± 24.78	0.49
Supine	82.06 ± 22.08	82.18 ± 30.79	0.98
CO (l/min)			
Upright	16.80 ± 3.74	16.57 ± 4.19	0.33
Semi-supine	15.99 ± 3.82	15.72 ± 3.87	0.60
Supine	13.91 ± 3.03	14.16 ± 3.76	0.61

Data are presented as mean ± SD values ($n = 10$ for VO_2max, HR, RER, lactate; $n = 8$ for SV and CO)

VO_2max maximal oxygen consumption (gross), *HR* heart rate, *RER* respiratory exchange ratio, *SV* stroke volume, *CO* cardiac output

*Denotes $p < 0.05$ compared to ramp

vs. semi-supine vs. supine, $p = 0.06$) or DBP (upright vs. semi-supine vs. supine, $p = 0.38$) between any position.

Ventilation measurements

The effect of posture on peak ventilatory variables are summarised in Table 3. Peak V_E in supine was 25% and 14% lower than upright and semi-supine, respectively ($p < 0.001$ and $p = 0.02$), while peak V_E in semi-supine was 13% lower than upright ($p = 0.01$). Peak V_T was significantly higher in upright relative to semi-supine and supine ($p = 0.02$ and $p < 0.001$), but not different between semi-supine and supine ($p = 0.10$). No statistical differences were observed in RR (upright vs. semi-supine vs. supine, $p = 0.29$) or SaO_2 (upright vs. semi-supine vs. supine, $p = 0.67$) between positions.

Table 3 Impact of posture on peak exercise characteristics

	Upright	Semi-supine	Supine
Power output (W)	325 ± 80	298 ± 72*	200 ± 51*,†
VO_2max (l/min)	3.36 ± 0.85	3.15 ± 0.81*	2.73 ± 0.70*,†
RER	1.33 ± 0.09	1.29 ± 0.10*	1.31 ± 0.16
V_E (l/min)	132 ± 25	115 ± 24*	99 ± 26*,†
V_T (l/min)	2.83 ± 0.45	2.52 ± 0.55*	2.27 ± 0.34*
RR (Breaths/min)	47 ± 8	47 ± 10	44 ± 9
SaO_2 (%)	97 ± 5	96 ± 5	97 ± 4
SBP (mmHg)	213 ± 24	223 ± 28	207 ± 28
DBP (mmHg)	83 ± 13	82 ± 9	78 ± 12
Lactate (mmol/l)	14.88 ± 3.08	12.67 ± 3.48	9.68 ± 3.41*

Data are mean ± SD values ($n = 10$ per position)

VO_2max maximal oxygen uptake (gross), *RER* respiratory exchange ratio, V_E minute ventilation, V_T tidal volume, *SaO_2* oxygen saturation, *RR* respiratory rate, *SBP* systolic blood pressure, *DBP* diastolic blood pressure

*Denotes $p < 0.05$ compared to upright

†Denotes $p < 0.05$ compared to semi-supine

Cardiac measurements

The effect of posture on peak cardiac parameters during exercise are shown in Fig. 3. Consistent with VO_2max and W_{peak}, peak HR was highest in upright, followed by semi-supine and supine positions (upright vs. semi-supine, $p < 0.001$; upright vs. supine, $p < 0.001$; semi-supine vs. supine, $p = 0.05$; Fig. 3b). Peak SV was reduced in supine relative to semi-supine and upright (upright vs. supine, $p = 0.01$; semi-supine vs. supine, $p = 0.003$; Fig. 3c). Consequent to both a reduction in HR and SV, peak CO in supine was 13% and 17% lower than semi-supine and upright, respectively (upright vs. supine, $p < 0.001$; semi-supine vs.

supine, $p = 0.002$; Fig. 3d). There was no statistical difference in peak CO and SV between upright and semi-supine.

Discussion

The results of this study demonstrate that posture markedly alters VO_2max and several of its determining parameters during CPET. Indeed, compared to the conventional upright position, CPET evaluation in the semi-supine and supine positions were associated with progressive reductions in VO_2max, W^{peak}, HR, $V_{E,}$ and aVO_2-diff. Peak $[La^-]_b$, SV and CO were unaffected in semi-supine, but reduced in supine compared to semi-supine and upright. Importantly, this is the first study to quantify the haemodynamic and oxygen transport changes in supine posture using the clinically used supine MRI-compatible ergometer.

The effect of posture on VO_2max

The present study demonstrates that VO_2max is progressively reduced as the body is moved from upright to semi-supine to supine. Our results support several studies that have reported reductions in VO_2max ranging from 4 to 5% (Scott et al. 2006; Walsh-Riddle and Blumenthal 1989) and 2–19% (Kramer et al. 1982; Åstrand and Saltin 1961; Forbregd et al. 2019; Hughson et al. 1991; Stenberg et al. 1967) for semi-supine and supine (relative to upright), respectively. However, this has not been a consistent observation with other groups finding no postural effect on VO_2max (Bonzheim et al. 1992; Leyk et al. 1994; Mizumi et al. 2018; Quinn et al. 1995). The variability in VO_2max results could be attributed to different study populations, leg positioning, and the criteria used to define VO_2max. Specifically, most studies investigating the effect of posture on VO_2max have reported 'peak VO_2' (Åstrand and Saltin 1961; Egaña et al. 2010; Forbregd et al. 2019; Kramer et al. 1982; Leyk et al. 1994; Mizumi et al. 2018; Walsh-Riddle and Blumenthal 1989; Hughson et al. 1991), defined as the highest VO_2 value achieved in the test. However, peak VO_2 does not distinguish between participants who achieve VO_2max and participants who cease exercise prematurely due to low motivation toward exertion (Rowell 1974; Poole et al. 2008). Thus, the varying VO_2 results in the literature might reflect inconsistencies in participant exertion across positions. Some studies reported 'VO_2max' (Bonzheim et al. 1992; Quinn et al. 1995; Scott et al. 2006), validated by a VO_2 plateau and/or achievement of secondary criterion (peak HR within 10 beats of age-predicted maximum, RER > 1.10). While these 'objective' criteria represent the most common method of validating VO_2max (Howley et al. 1995; Midgley et al. 2007), the validity of these criteria have come under scrutiny in recent years (Poole et al. 2008; Poole and Jones 2017). Specifically, many individuals do not elicit a discernible VO_2 plateau, and there is large inter-individual variability in maximal HR, RER, and $[La^-]_b$ (Poole et al. 2008; Poole and Jones 2017). Thus, laboratories have moved to abandon traditional VO_2max criteria over concerns they can significantly underestimate VO_2max, or falsely reject a valid VO_2max (Poole et al. 2008; Poole and Jones 2017).

To circumvent these concerns, we incorporated a subsequent supramaximal bout to verify true VO_2max attainment (Poole and Jones 2017; Poole et al. 2008). Taking this rigorous approach, we confirmed that most subjects (70–80%) achieved true VO_2max in upright and semi-supine (supramaximal VO_2max ≤ 3% higher); though, the achievement of true VO_2max appears to be impaired in supine (10%), despite 70% of participants satisfying traditional secondary VO_2max criteria. One may argue that the lower supine VO_2max is due to tests being 'less maximal'; however, our inclusion of the supramaximal test, wherein supine VO_2max remained lower than semi-supine and upright, validates that the differences in VO_2max are posturally-mediated. Consistent with Poole and Jones (2017), our data support the assertion that secondary criterion can lead to false conclusions regarding the attainment of true VO_2max. In this regard, we caution against the use of traditional secondary criteria for VO_2max confirmation in future practice and advocate for further research into the incorporation of a subsequent, constant supramaximal workload test in different populations. To date, the utility and feasibility of this novel VO_2max verification protocol has been validated during conventional upright cycling in healthy children (Barker et al. 2011), sedentary (Astorino et al. 2009), obese (Sawyer et al. 2015; Wood et al. 2010) and athletic (Weatherwax et al. 2016) adults, and patients with cystic fibrosis (Saynor et al. 2013), and we extend this utility to semi-supine and supine testing modalities in healthy active individuals. However, the safety and feasibility of this verification protocol should be established in diverse clinical populations (i.e. cardiac, cancer). Ultimately, consistent implementation of this robust VO_2max verification protocol, which is not meaningfully impacted by day-to-day variances in physiological responses (Poole and Jones 2017), will ensure direct comparisons can be made between tests.

The effect of posture on the determinants limiting VO_2max

VO_2max is limited by the cardiovascular systems' ability to deliver oxygen to working muscle and the ability of exercising muscle to extract and oxidise metabolic substrates (Bassett Jr and Howley 2000). Given VO_2max was lower in semi-supine and supine, we sought to explore the effect of posture on the determinants limiting VO_2max to elucidate

the mechanisms governing the reduced VO_2max observed in semi-supine and supine.

Studies investigating the effect of posture on central parameters of VO_2max generally report no effect on peak CO (Cotsamire et al. 1987; Forbregd et al. 2019; Forton et al. 2016; Kramer et al. 1982; Mizumi et al. 2018; Poliner et al. 1980; Quinn et al. 1995; Shen et al. 1985). However, our data does not entirely support these findings. We observed comparable peak CO between upright and semi-supine but a marked reduction in peak CO in supine, owing to a lower peak HR and SV. The lower peak HR in supine is consistent with previous research (Åstrand and Saltin 1961; Cotsamire et al. 1987; Forbregd et al. 2019; Forton et al. 2016; Kramer et al. 1982; Mizumi et al. 2018; Poliner et al. 1980; Shen et al. 1985; Terkelsen et al. 1999; Walsh-Riddle and Blumenthal 1989); however, most studies report unchanged (Forbregd et al. 2019; Kramer et al. 1982; Shen et al. 1985) or augmented SV (Cotsamire et al. 1987; Poliner et al. 1980) in reclined postures. It is difficult to reconcile the varying SV results, but differing patient populations, methodologies used to measure SV, and cycle ergometers may play a role. We hypothesise that the skeletal muscle pump is less efficient in augmenting venous return in supine, owing to the smaller muscle mass utilised on the MRI-compatible ergometer. Indeed, previous studies utilised alternative supine ergometers which have markedly longer cranks (170 mm vs. 55–65 mm), and thus, involve the recruitment of larger muscle groups (Martin and Spirduso 2001; Too 1990). It is conceivable that this would translate into augmented preload, explaining the contrasting SV results. Another possible mechanism limiting SV in supine may be related to cephalic displacement of the diaphragm and abdominal organs which may increase intrathoracic pressure and counteract the gravity dependent increase in preload (Katz et al. 2018). Finally, previous studies report reduced sympathetic activation in supine (Takahashi et al. 1995; Shen et al. 1985), which could explain the attenuated peak HR, and SV (via a reduction in sympathetic venoconstriction) (Rothe 1986). However, our use of the Doppler method to calculate SV limits our ability to confirm these hypotheses. Thus, this study should be repeated with comprehensive assessment of cardiac haemodynamics to elucidate the postural-mediated mechanisms governing the reduced SV in supine. Taken together, our findings indicate that the attenuated VO_2max in supine is at least partially mediated by a blunted CO. Though, given VO_2max is attenuated in semi-supine, postural differences in VO_2max cannot be solely explained by CO.

The pulmonary system does not typically affect whether there is a ventilator limitation to VO_2max (Rowell 1974; Bassett Jr and Howley 2000), but it is unclear how postural changes may affect the ventilatory determinants of VO_2max. We observed a progressive reduction in peak V_E as the body was tilted from upright to semi-supine to supine, with reductions driven by an attenuated V_T. These findings contrast some studies (Bonzheim et al. 1992; Forbregd et al. 2019; Mizumi et al. 2018; Quinn et al. 1995), but support others (Forton et al. 2016; Hughson et al. 1991; Scott et al. 2006; Takahashi et al. 1995; Terkelsen et al. 1999). Our results may be explained by cephalic displacement of the diaphragm and abdominal organs in reclined positions, which reduces the space in the thoracic cavity, and thus diaphragmatic motion and inspiratory capacity (Katz et al. 2018). In addition, participants gripped handles adjacent to their body in supine, which may have limited thoracic expansion and the contribution of accessory inspiratory muscles (Katz et al. 2018). However, this did not appear to compromise pulmonary diffusion, and thus VO_2max, given SaO_2 remained constant across positions. Therefore, given peak $[La^-]_b$ was lower in supine, it is plausible that the heightened peak V_E in semi-supine and upright was metabolically mediated, owing to greater muscular involvement and substrate metabolism (Takahashi et al. 1995). Indeed, metabolic acidosis, resulting from insufficient bicarbonate buffering, is an important stimulus for the onset of hyperventilation, or 'respiratory compensation' (Meyer et al. 2004). In this context, the elevated V_E in upright and semi-supine postures might reflect respiratory compensation, and thus the body's attempt to accelerate the removal of carbon dioxide an normalise metabolic acidosis (Meyer et al. 2004).

Postural differences in VO_2max may be ascribed to alterations in skeletal muscle blood flow. Folkow et al (1971) and Egana and Green (2005) have demonstrated a reduction in leg blood flow when the legs are raised toward or above heart level. This has been attributed to a progressive reduction in muscle perfusion pressure, which is particularly evident in supine, where the gravity-induced hydrostatic pressure component is absent (Egana and Green 2005; Folkow et al. 1971). In addition, reductions in skeletal muscle blood flow during exercise can quickly augment muscular fatigue (Egana and Green 2005; Lancellotti et al. 2017). Consistently, we observed a progressive reduction in W_{peak} and estimated aVO_2-diff from upright to semi-supine to supine, These findings, combined with the fact that all participants reported leg fatigue as the limiting factor to exercise continuation in semi-supine and supine, indicates that VO_2max may be reduced in reclined positions due to an accelerated muscular fatigue caused by inadequate skeletal muscle perfusion. However, this should be validated with direct assessments of skeletal muscle perfusion.

Finally, differences in the proportion of active muscle mass might contribute to the postural variance in VO_2max. The general consensus surrounding VO_2max, is that the greater the working muscle mass, the higher the VO_2max (Reybrouck et al. 1975; Larsen et al. 2016), due to a proportional increase in muscle oxidative activity and endurance. Electromyography analysis demonstrates that lower

limb muscular activity is not different between upright and semi-supine (Lopes et al. 2014), but the additional activation of postural muscles likely contributed to the higher upright VO_2max. Moreover, the MRI-compatible supine ergometer utilised in the present study has significantly shorter cranks (relative to our upright and semi-supine ergometers). While we did not measure active muscular involvement on our three cycle ergometers, previous studies demonstrate shorter cranks reduce hip and knee flexion (Schwartz et al. 1991) which negatively alters the length–tension relationship and reduces the proportion of active musculature (Too 1990). Therefore, the accelerated muscular exhaustion and markedly reduced VO_2max observed in supine could be ascribed to a profound reduction in the recruited lower extremity musculature. In addition, there is some evidence that body position and crank size can affect the metabolic cost of cycling, and, therefore, W_{peak} (Gnehm et al. 1997; Too and Landwer 2000; Morris and Londeree 1997). In this study, mechanical efficiency of the maximal exercise was significantly lower in supine (~20%) comparative to semi-supine and upright (~25% and 26%, respectively), likely reflecting the supine position and shorter cranks (and thus, smaller muscle mass) utilised on the MRI-compatible ergometer. This reduction in working muscle mass and associated reduction in mechanical efficiency likely explains the significantly greater reduction in W_{peak} that we observed in supine CPET (relative to semi-supine and upright) compared to previous studies who utilised a supine echocardiography table ergometer with standard cranks (33–39% vs. 7–13%) (Currie et al. 1983; Kramer et al. 1982; Leyk et al. 1994; Quinn et al. 1995). Thus, technicians should consider both body positioning and the specific cycle ergometer when implementing these results into practice.

Practical implications

Our results have important practical implications. The use of semi-supine and supine CPET with simultaneous cardiac imaging provides a non-invasive method of comprehensively evaluating exercise physiology (CO, VO_2, estimated avO_2-diff), and has emerged as a useful tool for evaluating patients with cardiovascular disease. Our data quantifying the degree to which peak exercise parameters are altered during CPET in three clinically relevant cycle postures will enable practitioners to interpret exercise test results in the context of posture, required for sound clinical management. Indeed, our results show that exercise testing on the recumbent echocardiography table and the supine MRI-compatible cycle ergometer is expected to reduce W_{peak} by, on average, 8% and 38%, respectively, and VO_2max by, on average, 6% and 18%, respectively. These data further highlight that posture should be considered when determining the most optimal testing protocol for patients. Extending upon this statement, our data could have important implications for future exercise training prescription. Indeed, as we are moving toward more individualised and tailored exercise training prescription in both clinical and non-clinical settings, accurate exercise capacity data is of great importance. Given the clear effect of posture on peak exercise parameters shown in our study, our data support that peak data (HR, W, VO_2) obtained from CPET in one cycling position cannot be directly utilised to prescribe exercise training in another cycling position (i.e. semi-supine or supine to upright). Therefore, when conducting exercise testing with the intention of utilising the data to prescribe an individualised exercise training program, the testing modality (i.e. upright, semi-supine, supine cycling) should, where possible, reflect the training modality. Finally, while our study was performed in young, healthy subjects and extrapolation to clinical populations should be done cautiously, there is evidence to suggest that the reductions in VO_2 associated with exercise modality and posture changes are similar in healthy controls and subjects with heart failure (Esposito et al. 2010). Though, it is important to anticipate the possibility that gravitational effects may have differing effects dependent upon the pathology. For example, patients with increased right atrial loading (e.g. an atrial septal defect or pulmonary hypertension) may behave differently with gravitational challenges than patients with potential preload insufficiency (Oldham et al. 2016).

Limitations

There are a few limitations associated with our study. Supine testing was performed on the MRI-compatible cycle ergometer which has shorter cranks than the alternatively used echocardiography tilt-table. Given the impact of crank size on lower extremity biomechanics, muscular involvement, mechanical efficiency (Too 1990), and thus VO_2max and W_{peak}, the generalisability of our supine results may be limited to the MRI-compatible ergometer. While it would have been better from a methodology standpoint to have used a supine ergometer with similar sized cranks, we specifically sought to discern the physiological changes that would be observed in the increasingly used MRI-compatible ergometer (comparative to upright and semi-supine ergometers) which is of interest for the specific indication of exercise cardiac MRI. Second, it is important to acknowledge that Doppler echocardiography can underestimate SV, and thus CO (Chin et al. 2014), which when utilised to estimate avO_2 differences via the Fick equation, can result in overestimation. We experienced this in the present study; however, it is unlikely that the degree of CO underestimation, and therefore, avO_2 difference overestimation differed across the three cycling positions. In addition, we did not measure lower extremity muscular involvement or blood

flow in each position. Thus, this study should be repeated using more direct and invasive methods (electromyography, arterial and venous blood sampling, comprehensive cardiac haemodynamics, peripheral muscle Doppler Ultrasound, contrast-enhanced MRI) to validate the proposed postural-mediated mechanisms underpinning the observed difference in $\dot{V}O_2$max. Lastly, this study was not originally powered to detect postural effects on our exploratory measures (peak HR, SV, CO, V_E, $[La^-]_b$, a$\dot{V}O_2$-diff, *W*). However, the magnitude of the detected effect lends support to the validity.

Conclusion

This study demonstrates that $\dot{V}O_2$max reduces progressively as the body is tilted from upright to semi-supine to supine in healthy, active individuals and such postural differences appear to be mediated by a reduction in skeletal muscle recruitment, and skeletal muscle oxygen delivery (via inefficient skeletal muscle perfusion and/or a blunted cardiac output) in more reclined positions. Thus, posture should be accounted for when interpreting and comparing $\dot{V}O_2$max results from different testing modalities. Future studies are now required to comprehensively assess cardiac haemodynamics, as well as skeletal muscle recruitment, blood flow and oxygen extraction during CPET on identical upright, semi-supine and supine ergometers to verify the proposed postural-mediated mechanisms that underpin the postural difference in $\dot{V}O_2$max.

Author contributions CD, EH, HD, GC, RW and ALG contributed to the conception and design of the study. HD, GC, LW, AM, AL conducted the study testing. HD wrote the manuscript; all authors critically revised the manuscript and gave final approval.

Funding GC is supported by the Frans Van De Werf Fund for Clinical Cardiovascular Research and the Mathilde Horlait-Dapsens Scholarship. RW is supported as postdoctoral clinical researcher by the Fund for Scientific Research Flanders. EJH and ALG are supported by National Heart Foundation of Australia Future Leaders Fellowships.

Data availability All data generated or analysed during this study are included in this published article.

Compliance with ethical standards

Conflict of interest No conflicts of interest are declared by the authors.

Ethics approval All experimental procedures were performed in accordance with the ethical standards of the institutional review boards of the Alfred Health Research Ethics committee and with the 1964 Helsinki Declaration. The study was approved by the Alfred Health Research Ethics Committee (No: 327/19).

Consent to participate Written informed consent was obtained from all participants included in the study.

Consent for publication Participants signed informed consent regarding publishing their data.

References

Albouaini K, Egred M, Alahmar A, Wright DJ (2007) Cardiopulmonary exercise testing and its application. Postgrad Med J 83(985):675–682

Astorino TA, White AC (2010) Assessment of anaerobic power to verify VO_2max attainment. Clin Physiol Funct Imaging 30(4):294–300

Astorino T, White A, Dalleck L (2009) Supramaximal testing to confirm attainment of VO_2max in sedentary men and women. Int J Sports Med 30(04):279–284

Åstrand P-O, Saltin B (1961) Maximal oxygen uptake and heart rate in various types of muscular activity. J Appl Physiol 16(6):977–981

Barber NJ, Ako EO, Kowalik GT, Cheang MH, Pandya B, Steeden JA, Moledina S, Muthurangu V (2016) Magnetic resonance-augmented cardiopulmonary exercise testing: comprehensively assessing exercise intolerance in children with cardiovascular disease. Circ Cardiovasc Imaging 9(12):e005282

Barker AR, Williams CA, Jones AM, Armstrong N (2011) Establishing maximal oxygen uptake in young people during a ramp cycle test to exhaustion. Br J Sports Med 45(6):498–503

Bassett DR Jr, Howley ET (2000) Limiting factors for maximum oxygen uptake and determinants of endurance performance. Med Sci Sports Exerc 32(1):70

Beniaminovitz A, Mancini DM (1999) The role of exercise-based prognosticating algorithms in the selection of patients for heart transplantation. Curr Opin Cardiol 14(2):114

Bonzheim SC, Franklin BA, DeWitt C, Marks C, Goslin B, Jarski R, Dann S (1992) Physiologic responses to recumbent versus upright cycle ergometry, and implications for exercise prescription in patients with coronary artery disease. Am J Cardiol 69(1):40–44

Chin CWL, Khaw HJ, Luo E, Tan S, White AC, Newby DE, Dweck MR (2014) Echocardiography underestimates stroke volume and aortic valve area: implications for patients with small-area low-gradient aortic stenosis. Can J Cardiol 30(9):1064–1072. https://doi.org/10.1016/j.cjca.2014.04.021

Cotsamire D, Sullivan M, Bashore T, Leier CV (1987) Position as a variable for cardiovascular responses during exercise. Clin Cardiol 10(3):137–142

Currie PJ, Kelly MJ, Pitt A (1983) Comparison of supine and erect bicycle exercise electrocardiography in coronary heart disease: accentuation of exercise-induced ischemic ST depression by supine posture. Am J Cardiol 52(10):1167–1173

Egaña M, O'Riordan D, Warmington S (2010) Exercise performance and VO_2 kinetics during upright and recumbent high-intensity cycling exercise. Eur J Appl Physiol 110:39–47. https://doi.org/10.1007/s00421-010-1466-y

Egana M, Green S (2005) Effect of body tilt on calf muscle performance and blood flow in humans. J Appl Physiol 98(6):2249–2258

Esposito F, Mathieu-Costello O, Shabetai R, Wagner PD, Richardson RS (2010) Limited maximal exercise capacity in patients with chronic heart failure: partitioning the contributors. J Am Coll Cardiol 55(18):1945–1954

Ferrazza AM, Martolini D, Valli G, Palange P (2009) Cardiopulmonary exercise testing in the functional and prognostic evaluation of patients with pulmonary diseases. Respiration 77(1):3–17. https://doi.org/10.1159/000186694

Folkow B, Haglund U, Jodal M, Lundgren O (1971) Blood flow in the calf muscle of man during heavy rhythmic exercise. Acta Physiol Scand 81(2):157–163

Forbregd TR, Aloyseus MA, Berg A, Greve G (2019) Cardiopulmonary capacity in children during exercise testing; the differences between treadmill, and upright and supine cycle ergometry. Front Physiol 10:1440

Forton K, Motoji Y, Deboeck G, Faoro V, Naeije R (2016) Effects of body position on exercise capacity and pulmonary vascular pressure-flow relationships. J Appl Physiol 121(5):1145–1150

Gnehm P, Reichenbach S, Altpeter E, Widmer H, Hoppeler H (1997) Influence of different racing positions on metabolic cost in elite cyclists. Med Sci Sports Exerc 29(6):818–823. https://doi.org/10.1097/00005768-199706000-00013

Guazzi M, Adams V, Conraads V, Halle M, Mezzani A, Vanhees L, Arena R, Fletcher GF, Forman DE, Kitzman DW, Lavie CJ, Myers J, European Association for Cardiovascular P, Rehabilitation, American Heart A (2012) EACPR/AHA Scientific Statement. Clinical recommendations for cardiopulmonary exercise testing data assessment in specific patient populations. Circulation 126(18):2261–2274. https://doi.org/10.1161/CIR.0b013e31826fb946

Hill A, Lupton H (1922) The oxygen consumption during running. J Physiol 56(1):32–33

Howden EJ, Bigaran A, Beaudry R, Fraser S, Selig S, Foulkes S, Antill Y, Nightingale S, Loi S, Haykowsky MJ (2019) Exercise as a diagnostic and therapeutic tool for the prevention of cardiovascular dysfunction in breast cancer patients. Eur J Prev Cardiol 26(3):305–315

Howley ET, Bassett DR, Welch HG (1995) Criteria for maximal oxygen uptake: review and commentary. Med Sci Sports Exerc 27:1292–1292

Hughson RL, Xing HC, Borkhoff C, Butler GC (1991) Kinetics of ventilation and gas exchange during supine and upright cycle exercise. Eur J Appl Physiol 63(3–4):300–307

Katz S, Arish N, Rokach A, Zaltzman Y, Marcus E-L (2018) The effect of body position on pulmonary function: a systematic review. BMC Pulm Med 18(1):159–159. https://doi.org/10.1186/s12890-018-0723-4

Kramer B, Massie B, Topic N (1982) Hemodynamic differences between supine and upright exercise in patients with congestive heart failure. Circulation 66(4):820–825

La Gerche A, Claessen G, Van de Bruaene A, Pattyn N, Van Cleemput J, Gewillig M, Bogaert J, Dymarkowski S, Claus P, Heidbuchel H (2013) Cardiac MRI: a new gold standard for ventricular volume quantification during high-intensity exercise. Circ Cardiovasc Imaging 6(2):329–338

Lancellotti P, Pellikka PA, Budts W, Chaudhry FA, Donal E, Dulgheru R, Edvardsen T, Garbi M, Ha JW, Kane GC (2017) The clinical use of stress echocardiography in non-ischaemic heart disease: recommendations from the European Association of Cardiovascular Imaging and the American Society of Echocardiography. J Am Soc Echocardiogr 30(2):101–138

Larsen RT, Christensen J, Tang LH, Keller C, Doherty P, Zwisler A-D, Taylor RS, Langberg H (2016) A systematic review and meta-analysis comparing cardiopulmonary exercise test values obtained from the arm cycle and the leg cycle respectively in healthy adults. Int J Sports Phys Ther 11(7):1006–1039

Leite SAO, Monk AM, Upham PA, Chacra AR, Bergenstal RM (2009) Low cardiorespiratory fitness in people at risk for type 2 diabetes: early marker for insulin resistance. Diabetol Metab Syndr 1(1):8. https://doi.org/10.1186/1758-5996-1-8

Leyk D, Eßfeld D, Hoffmann U, Wunderlich H-G, Baum K, Stegemann J (1994) Postural effect on cardiac output, oxygen uptake and lactate during cycle exercise of varying intensity. Eur J Appl Physiol 68(1):30–35

Lindhard J (1915) Ueber das Minutenvolum des Herzens bei Ruhe und bei Muskelarbeit. Pflüger's Archiv für die gesamte Physiologie des Menschen und der Tiere 161(5–7):233–383

Lopes AD, Alouche SR, Hakansson N, Cohen M (2014) Electromyography during pedaling on upright and recumbent ergometer. Int J Sports Phys Ther 9(1):76–81

Martin J, Spirduso W (2001) Determinants of maximal cycling power: crank length, pedaling rate and pedal speed. Eur J Appl Physiol 84(5):413–418

McMichael J, Sharpey-Schafer E (1944) Cardiac output in man by a direct fick method: effects of posture, venous pressure change, atropine, and adrenaline. Br Heart J 6(1):33

Meyer T, Faude O, Scharhag J, Urhausen A, Kindermann W (2004) Is lactic acidosis a cause of exercise induced hyperventilation at the respiratory compensation point? Br J Sports Med 38(5):622–625

Midgley AW, McNaughton LR, Polman R, Marchant D (2007) Criteria for determination of maximal oxygen uptake. Sports Med 37(12):1019–1028

Mizumi S, Goda A, Takeuchi K, Kikuchi H, Inami T, Soejima K, Satoh T (2018) Effects of body position during cardiopulmonary exercise testing with right heart catheterization. Physiol Rep 6(23):e13945

Morris DM, Londeree BR (1997) The effects of bicycle crank arm length on oxygen consumption. Can J Appl Physiol 22(5):429–438

Myers J (2005) Applications of cardiopulmonary exercise testing in the management of cardiovascular and pulmonary disease. Int J Sports Med 26(S1):S49–S55

Oldham WM, Lewis GD, Opotowsky AR, Waxman AB, Systrom DM (2016) Unexplained exertional dyspnea caused by low ventricular filling pressures: results from clinical invasive cardiopulmonary exercise testing. Pulm Circ 6(1):55–62

Pescatello LS, Riebe D, Thompson PD (2014) ACSM's guidelines for exercise testing and prescription. Lippincott Williams & Wilkins, Philadelphia

Piepoli M, Corra U, Agostoni P, Belardinelli R, Cohen-Solal A, Hambrecht R, Prevention TFotIWGoCR (2006) Working Group on Cardiac Rehabilitation and Exercise Physiology of the European Society of Cardiology. Statement on cardiopulmonary exercise testing in chronic heart failure due to left ventricular dysfunction: recommendations for performance and interpretation. Part I: definition of cardiopulmonary exercise testing parameters for appropriate use in chronic heart failure. Eur J Cardiovasc Prev Rehabil 13(2):150–164

Poliner LR, Dehmer GJ, Lewis SE, Parkey RW, Blomqvist CG, Willerson JT (1980) Left ventricular performance in normal subjects: a comparison of the responses to exercise in the upright and supine positions. Circulation 62(3):528–534

Poole DC, Jones AM (2017) Measurement of the maximum oxygen uptake VO_2max: VO_2peak is no longer acceptable. J Appl Physiol 122(4):997–1002

Poole DC, Wilkerson DP, Jones AM (2008) Validity of criteria for establishing maximal O_2 uptake during ramp exercise tests. Eur J Appl Physiol 102(4):403–410

Quinn TJ, Smith SW, Vroman NB, Kertzer R, Olney WB (1995) Physiologic responses of cardiac patients to supine, recumbent, and upright cycle ergometry. Arch Phys Med Rehabil 76(3):257–261

Reybrouck T, Heigenhauser GF, Faulkner JA (1975) Limitations to maximum oxygen uptake in arms, leg, and combined arm-leg ergometry. J Appl Physiol 38(5):774–779

Rossiter HB, Kowalchuk JM, Whipp BJ (2006) A test to establish maximum O_2 uptake despite no plateau in the O_2 uptake response to ramp incremental exercise. J Appl Physiol 100(3):764–770. https://doi.org/10.1152/japplphysiol.00932.20055

Rothe CF (1986) Physiology of venous return: an unappreciated boost to the heart. Arch Intern Med 146(5):977–982. https://doi.org/10.1001/archinte.1986.00360170223028

Rowell LB (1962) Factors affecting the prediction of the maximal oxygen intake from measurements made during submaximal work

with observations related to factors which may limit maximal oxygen intake. University of Minnesota, Minneapolis
Rowell LB (1974) Human cardiovascular adjustments to exercise and thermal stress. Physiol Rev 54(1):75–159
Sawyer BJ, Tucker WJ, Bhammar DM, Gaesser GA (2015) Using a verification test for determination of V [combining dot above] O_2max in sedentary adults with obesity. J Strength Cond Res 29(12):3432–3438
Saynor ZL, Barker AR, Oades PJ, Williams CA (2013) Reproducibility of maximal cardiopulmonary exercise testing for young cystic fibrosis patients. J Cyst Fibros 12(6):644–650
Schwartz RE, Asnis PD, Cavanaugh JT, Asnis SE, Simmons JE, Lasinski PJ (1991) Short crank cycle ergometry. J Orthop Sports Phys Ther 13(2):95–100
Scott A, Antonishen K, Johnston C, Pearce T, Ryan M, Sheel AW, McKenzie DC (2006) Effect of semirecumbent and upright body position on maximal and submaximal exercise testing. Meas Phys Educ Exerc Sci 10(1):41–50
Sedgeman D, Dalleck L, Clark IE, Jamnick N, Pettitt R (2013) Analysis of square-wave bouts to verify VO2max. Int J Sports Med 34(12):1058–1062
Shen WF, Roubin GS, Fletcher PJ, Choong CYP, Hutton BF, Harris PJ, Kelly DT (1985) Effects of upright and supine position on cardiac rest and exercise response in aortic regurgitation. Am J Cardiol 55(4):428–431
Stenberg J, Astrand P, Ekblom B, Royce J, Saltin B (1967) Hemodynamic response to work with different muscle groups, sitting and supine. J Appl Physiol 22(1):61–70
Takahashi T, Tanabe K, Nakayama M, Osada N, Yamada S, Ishiguro T, Itoh H, Murayama M (1995) Cardiopulmonary response during supine and sitting bicycle exercises. J Phys Ther Sci 7(1):33–38
Terkelsen KE, Clark AL, Hillis WS (1999) Ventilatory response to erect and supine exercise. Med Sci Sports Exerc 31(10):1429–1432
Too D (1990) Biomechanics of cycling and factors affecting performance. Sports Med 10(5):286–302
Too D, Landwer G (2000) The effect of pedal crank arm length on joint angle and power production in upright cycle ergometry. J Sports Sci 18:153–161. https://doi.org/10.1080/026404100365054
Walsh-Riddle M, Blumenthal JA (1989) Cardiovascular responses during upright and semi-recumbent cycle ergometry testing. Med Sci Sports Exerc 21(5):581–585
Wasserman K, Hansen JE, Sue DY, Whipp BJ, Froelicher VF (1987) Principles of exercise testing and interpretation. J Cardiopulm Rehabil Prev 7(4):189
Weatherwax R, Richardson T, Beltz N, Nolan P, Dalleck L (2016) Verification testing to confirm VO_2max in altitude-residing, endurance-trained runners. Int J Sports Med 37(07):525–530
Wood RE, Hills AP, Hunter GR, King NA, Byrne NM (2010) VO_2max in overweight and obese adults: do they meet the threshold criteria? Med Sci Sports Exerc 42(3):470–477
Wood WA, Deal AM, Reeve BB, Abernethy AP, Basch E, Mitchell SA, Shatten C, Hie Kim Y, Whitley J, Serody JS, Shea T, Battaglini C (2013) Cardiopulmonary fitness in patients undergoing hematopoietic SCT: a pilot study. Bone Marrow Transplant 48(10):1342–1349. https://doi.org/10.1038/bmt.2013.58

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.