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Title:

Bioreactance is a reliable method for estimating cardiac output at rest and during exercise

Running head:

Reliability of bioreactance during graded exercise

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Abstract:

Background: Bioreactance is a novel non-invasive method for cardiac output measurement that involves the analysis of blood flow-dependent changes in the phase shifts of electrical currents applied across the chest. The present study evaluated the test-retest reliability of bioreactance for assessing hemodynamic variables at rest and during exercise.

Methods: 22 healthy participants (26 (4) years) performed an incremental cycle ergometer exercise protocol relative to their individual power output at maximal O_2 consumption (Wmax) on two separate occasions (trials 1 and 2). Participants cycled for five 3 min stages at 20, 40, 60, 80 and 90% Wmax. Haemodynamic and cardiorespiratory variables were assessed at rest and continuously during the exercise protocol.

Results: Cardiac output was not significantly different between trials at rest (p = 0.948) nor at any stage of the exercise protocol (all p > 0.30). There was a strong relationship between cardiac output estimates between the trials (ICC = 0.95, p < 0.001) and oxygen consumption (ICC = 0.99, p < 0.001). Stroke volume was also not significantly different between trials at rest (p = 0.989) or during exercise (all p > 0.15), and strong relationships between trials were found (ICC = 0.83, p < 0.001).

Conclusions: Bioreactance method demonstrates good test-retest reliability for estimating cardiac output at rest and during different stages of graded exercise testing including maximal exertion.

Key words: Bioreactance, Cardiac Monitoring, Cardiac Output, Graded Exercise

Introduction

Monitoring of cardiac output (CO) has wide clinical application in anesthesiology, emergency care and cardiology. It can improve outcomes, establish diagnosis, guide therapy and help risk stratification in different clinical groups[1]. Measurement of cardiac output is essential in critically ill, injured and unstable patients as it provides an indication of systemic oxygen delivery and global tissue perfusion[2]. Cardiac output monitoring during surgery is associated with reduced length of hospital stay and postoperative complications[3-5]. Measurement of cardiac output under pharmacological and physiological stimulations defines overall function and performance of the heart, predicts prognosis and survival in heart failure can help explain the mechanisms of exercise intolerance, and improves risk stratification[6-10].

Thermodilution and direct Fick[11-13] remain the "gold standard" and reference methods for assessing CO. Whilst "gold standard" these methods have inherent limitations as they are invasive, costly, require specialist skills and associated with noteworthy risks and complications such as catheter-related infections, arrhythmias and bleeding[14 15]. The risk:benefit ratio of these assessment methods has also been brought into question[14]. These limitations preclude the use of invasive cardiac output monitoring in large number of patients limiting the application of this useful diagnostic and prognostic marker.

Over the previous decades several minimally invasive and non-invasive methods for assessing cardiac output have been developed including; trans-esophageal Doppler, transpulmonary thermodilution, pulse contour and pulse power analysis, and non-invasive techniques such as CO_2 and inert gas rebreathing, transthoracic Doppler, thoracic bioimpedance cardiography, and electrical velocimetry (modified bioimpedance)[2 16-18].

Unfortunately whilst these methods are safe they are associated with certain limitations precluding their accuracy and reliability[13 19].

Bioreactance, a novel method for continuous non-invasive cardiac output monitoring, has received increased attention in clinical and research practice in the recent years. The bioreactance method estimates CO by analysing the frequency of relative phase shift of electronic current across the thorax[20 21]. In contrast to impedance cardiography which is based on the analysis of transthoracic voltage amplitude changes in response to high frequency current, the bioreactance analyses the frequency spectra variations of the delivered oscillating current[20]. This approach is supposed to result in the improved precision of the bioreactance system as demonstrated by a 100 fold larger signal-to-noise ratio than that of bioimpedance and thus make it less susceptible to interference from adipose tissue, electrode placement and excessive movement[20 22].

The ability of bioreactance to monitor rapid changes in blood flow has recently been confirmed by Marik, et al.[23]. The authors compared carotid Doppler against bioreactance in patients with unstable cardiac conditions during passive leg raising. A strong correlation was reported in blood flow between the two methods in critically ill patients, with an accelerated response to these volume changes reported by bioreactance. Bioreactance cardiac output monitoring has been used in intensive care unit, during and following cardiac surgery, patients with chronic obstructive pulmonary disease and healthy individuals[19 20 22-25]. Other studies demonstrated that bioreactance measurements of cardiac output at rest and during exertion can identify cardiovascular function abnormalities, indexing disease severity, help prognosis and risk stratification, and track responses to treatment in clinical practice[26 27].

When assessing cardiac output at rest or during physiological challenge, it is essential that method demonstrates acceptable level of reliability i.e. test-retest reliability which refers to the reproducibility of values of a variable when measured the same subjects twice. This is important because even small changes in cardiac output and stroke volume may have significant clinical implications when evaluating the effect of pharmacological and non-pharmacological interventions and risk stratification. Based on available literature, it appears that test-retest reliability of bioreactance, as a novel and potent method for non-invasive continuous cardiac output monitoring has not been evaluated. Based on higher signal-to-noise ratio and improved performance[19 20] we hypothesize that bioreactance method demonstrates acceptable test-retest reliability for evaluating cardiac output at rest and during physiological stimulation such as graded exercise testing. Additionally, we evaluated association between cardiac output and oxygen consumption at peak exercise.

Methods

All experimental procedures were approved by the Faculty's Research Ethics Committee in accordance with the Declaration of Helsinki. In all cases, after being informed of the benefits and potential risks of the investigation all participants completed a standardised health-screening questionnaire, undertook a resting electrocardiogram and gave their written informed consent.

Twenty two healthy individuals (10 males and 12 females) participated in the study. All participants were non-smokers and free from any cardiac and respiratory disorders. All participants attended the exercise laboratory on 2 separate days, day 1 involved an initial assessment of maximal aerobic capacity ($\dot{V}O_{2max}$) and day 2 required 2 visits consisting of an incremental exercise cycle ergometer protocol at individual pre-determined workloads based on participants power output at $\dot{V}O_{2max}$ (Wmax). Participants were required to abstain from eating for a minimum of 2 hours prior to the commencement of each test and from vigorous exercise 24 hours prior to the test. Participants were also instructed not to consume alcohol and caffeine containing foods and beverages on test days.

Participants completed a maximal progressive exercise test on an electro-magnetically braked recumbent cycle ergometer (Corival, Lode, Groningen, Netherlands). All participants began cycling against a resistance of 40 W, this increased continually throughout the test at a ramp rate of 15 W min^{-1}. Cessation of the assessment occurred when participants reached volitional exhaustion or were unable to maintain a cadence of 60-70 revolutions per minute. It was considered that a maximal effort was achieved if participants met any of two of the following criteria: i) a change in $\dot{V}O_2 < 2$ ml kg min^{-1} across two stages of the incremental test; ii) a respiratory exchange ratio of 1.15 or greater, or iii) ≥ 90% age predicted maximum heart rate (220-age)[28]. Expired gases were measured via online metabolic gas exchange system (Cortex metalyser 3B, Leipzig, Germany) and heart rate was measured via short range telemetry (Polar RS400, Finland). Peak oxygen consumption was defined as the average oxygen uptake during the last minute of exercise, expressed as millilitres per kilogram of body weight per minute and litres per minute. The Wmax was defined as the power output expressed in W at the point at which participants reached their individual $\dot{V}O_{2max}$.

Exercise protocol was performed twice on study day 2 with ≥ 3 h interval between trials 1 and 2. Participants were required to complete five 3 min stages (equating to 15 min of cycling) at intensities relative to 20, 40, 60, 80 and 90% Wmax. Cardiac and hemodynamic responses including cardiac output, cardiac index, stroke volume and stroke volume index, and heart rate were recorded at rest and throughout the incremental exercise protocol using a non-invasive bioreactance system (NICOM®, Cheetah Medical, Delaware, USA). Simultaneously, respiratory and gas exchange measurements were recorded (Cortex metalyser 3B, Leipzig, Germany).

The bioreactance system comprises of a radio frequency generator that creates a high frequency current that is introduced across the thoracic cavity. The NICOM® has been described previously[19 20 25]. It analyses the frequency of relative phase shift of electronic current across the thorax. In brief the four dual surface electrodes are used to establish electrical contact with the body. The skin was prepared by shaving where required and using adhesive paper to ensure an optimal signal from the electrodes. Two electrodes were placed over the trapezius muscle on either side of the upper torso and two on the lower posterior torso lateral to the margin of the latissimus dorsi musculature. The electrical current is applied and recorded from right to left of the thorax. The blood that is present in the thoracic cavity absorbs electrons, which results in a delay in the signal, which is proportional to the volume of blood flow. This is called a phase shift and is recorded and the figure is translated to the flow of the blood. The signal that is detected by the electrodes is then processed separately and averaged after digital processing at 30 s intervals. The signal processing unit of the NICOM® determines the relative phase shift ($\Delta\varphi$) between the input signals relative to the output signal. The $\Delta\varphi$ is in response to any changes in blood flow that pass through the aorta. The CO is then derived by CO = (C x VET x $\Delta\varphi$ dt_{max}) x HR, where C is the constant of proportionality and VET is ventricular ejection fraction time[19]. The value of C has been previously validated to account for patient age, gender and body mass[22]. CO can then be calculated from stroke volume and HR.

Statistical methods

Statistical analyses were performed using PASW statistical analysis software (Version 19, IBM, USA). Data are presented as mean (standard deviation). The alpha level of 0.05 was set prior to data analysis and normality of distribution was assessed using a Kolmogorov-Smirnov test. Relative reliability was determined using intra-class correlation coefficients (ICC), calculated using the two-way random method previously described by Weir[29]. Absolute reliability was determined using standard error of measurement (SEM) with 95% confidence intervals (95%CI), which were calculated independently of intra-class correlation coefficients. Systemic bias in the repeatability between trials was assessed using paired sample *t*-tests. The relationship between cardiac output and oxygen consumption was assessed with Pearson's coefficient of correlation. Data analyses were performed on both combined resting and exercise data and data from each individual stage of the incremental exercise protocol for CO, cardiac index (CI), stoke volume (SV), stroke volume index (SVI), heart rate (HR) minute ventilation (VE) and oxygen consumption ($\dot{V}O_2$).

Results

Physical characteristics of study participants are: age 26.3 (4.2) years, height 171.5 (8) cm, body mass 67.4 (7.9) kg, and peak oxygen consumption 41.5 (8.7) ml kg min^{-1}. Data pertaining to the systemic bias between trials for all assessed cardiac and respiratory variables are presented in Table 1. There was a non-significant (< 5%) difference between trials 1 and 2 for all variables ($p > 0.05$).

Table 1 about here

Reliability statistics for cardiac and respiratory responses to the incremental exercise protocol are presented in Tables 2 and 3. These data demonstrate strong relative (Table 2) and test-retest absolute (Table 3) reliability.

Table 2 about here

Cardiac output was similar between the trials 1 and 2 at rest (0.7 (10.3) %) and all stages of the incremental exercise protocol (Figure 1). At low exercise intensity i.e. 20-40% of Wmax the differences in cardiac output between trials 1 and 2 were 4 and 1%, respectively. At moderate (i.e. 60% of Wmax) and high (80 and 90% of Wmax) exercise intensity the difference was only between 1 and 2% (Figure 1).

Table 3 about here

Non-significant differences between the trial 1 and 2 were reported for stroke volume at all stages of the protocol, with mean difference ranging from 1% (at 80% of Wmax) to 7% (at 20% of Wmax, Figure 2). When resting and exercise data points are considered together (n=132), the mean difference between trial 1 and 2 was only 2%.

Figure 1 about here

Participants mean cardiac index and stroke volume index were not significantly different between the trials when data analyses included combined resting and exercise data (Table 1). Furthermore, neither mean cardiac index nor stroke volume index was significantly different between trials at rest or at any exercise stage.

Figure 2 about here

As detailed in Table 1 heart rate, peak oxygen consumption, and mean ventilation were similar between trials. Relative and absolute reliability statistics presented in Tables 2 and 3 demonstrate good reliability. In addition, no significant differences between the trials were found in heart rate, peak oxygen consumption, and mean ventilation at rest or at any of the exercise intensities ($p > 0.05$).

Data demonstrate strong relationship between cardiac output and oxygen consumption at peak exercise for both trials (Trial 1; $r = 0.64$, $p = 0.001$, Trial 2; $r = 0.66$, $p < 0.001$).

Discussion

The primary finding of this study suggests that bioreactance demonstrates acceptable test-retest reliability for estimating cardiac output and stroke volume at rest and during physiological stress induced by exercise testing. Additionally, the exercise protocol employed in the present study elicited similar cardiorespiratory responses between trials and a strong relationship was identified between cardiac output and peak oxygen consumption for both trials. This illustrates the ability of the exercise protocol to elicit reliable hemodynamic and cardiorespiratory responses on separate occasions in the absence of changes in health and clinical status of an individual.

The assessment of cardiac output in a reliable manner is an essential tool to accurately assess any improvements or decrements in cardiac function of numerous patient groups. As previously stated this is of particular importance in cardiac patients as small changes in cardiopulmonary data due to disease or intervention may have significant clinical implications[30]. It may therefore be suggested that inaccurate and unreliable measures may contribute to misinterpretation of data and potentially misdiagnosis. The excellent reliability of bioreactance in measuring haemodynamics (at rest and continuously during exercise) reported in the present study illustrates its potential clinical application. Furthermore, its ability to assess cardiac output noninvasively, inexpensively and without specialist training of the assessor permits its application in an increased number of patient groups when compared to more invasive and "gold standard" catheter based measurement techniques[11 12].

A recent study by Kupersztych-Hagege, et al.[31] evaluated validity and reliability of bioreactance method to estimate cardiac index and cardiac output in critically ill patients at rest and haemodynamic challenge. Our study did not aim to evaluate bioreactance's validity (i.e. comparison with a reference method) but rather test-retest reliability, and therefore direct comparison with previous study is not considered appropriate. Nonetheless the previous study[31] questioned validity of bioreactance and its ability to track changes in cardiac index as a result of volume expansion and passive leg rising. It should however be noted that some of the methodological issues (e.g. device was not used according to the manufacturer's instructions) have been questioned in the letter provided by the manufacturers of the NICOM device[32]. Despite previous findings[31] about limited ability of bioreactance to track cardiac output changes in response to haemodynamic challenge, our study demonstrates that bireactance detected increase in cardiac output and stroke volume from resting to even low levels of physiological stress. It should also be noted that our study participants were young healthy volunteers and not critically ill patients.

The CO values reported in the present study are consistent with recent research employing bioreactance in a comparable population and at similar exercise intensities[19]. The authors Jakovljevic, et al.[19] reported resting CO values of 6.5 L min^{-1} which are similar to those reported in the present study. Similar values were also reported at comparable submaximal and near maximal exercise intensities. Furthermore the CO data previously reported[19] was consistently correlated with CO estimates derived from measured oxygen consumption[33]. We have also demonstrated a strong relationship between cardiac output and oxygen consumption at peak exercise in the present study. Elliott, et al.[25] also reported similar CO as assessed via bioreactance at similar exercise intensities as the present study and previous study[19]. In addition resting and near maximal cardiac index reported in the present study is similar to that previously reported[25]. The data presented in this article further substantiates the previous work[19 25] and demonstrates that bioreactance is accurate and reliable for assessing haemodynamic variables at various exercise intensities. Furthermore, cardiac output data from the present study that are associated particularly with stages of low to moderate intensities are consistent with those identified in different stages of heart failure[26 27]. Overall, data presented in the present study indicate that bioreactance can provide reliable measures of cardiac output independent of any other physiological measures (e.g. oxygen consumption) and potential elevated electrical noise, body motion, perspiration and body temperature associated with graded exercise.

The present study is not without limitations. Firstly, the study participants were young, healthy adults whereas older people and those with chronic conditions were not included. It may be speculated therefore that the present findings cannot be generalized to a wider, clinical applications. However, the study protocol allowed analysis of bioreactance cardiac output test-retest reliability not only at peak exercise but also at low to moderate levels of exercise intensities that are often observed in individuals with chronic conditions and in older people. Secondly, no gold standard for cardiac output measurement (i.e. thermodilution or direct Fick) was included. The additional risks posed to the study participants with these procedures precluded them from being undertaken.

Conclusions

In conclusion, bioreactance method demonstrates good test-retest reliability for estimating cardiac output and stroke volume at rest and during different stages of graded exercise testing including maximal exertion. Future large studies are warranted to assess the reliability of bioreactance at both rest and exercise in different clinical groups where monitoring of cardiac output has been shown to improve risk stratification and clinical outcomes.

Author contributions:

Study conceived and designed by DGJ, TWJ and DH.

Data collection performed by DGJ, TWJ, DH and SC.

Data extraction and analyses performed by TWJ.

Interpretation of data and preparation of manuscript performed by DGJ, TWJ, DH, SC, GAM and MIT.

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Conflict of Interest disclosures:

This study is *not* industry sponsored; TWJ, DH, MIT, SC, GAM and DGJ report no conflict of interests.

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Guarantor statement:

Thomas W. Jones and Djordje G. Jakovljevic take responsibility for the content of the manuscript, including the data and analysis.

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N/A

References

1 Jhanji S, Dawson J, Pearse RM. Cardiac output monitoring: basic science and clinical application. *Anaesthesia* 2008; **63**: 172-81

2 Marik PE. Noninvasive cardiac output monitors: a state-of the-art review. *J Cardiothorac Vasc Anesth* 2013; **27**: 121-34

3 Venn R, Steele A, Richardson P, Poloniecki J, Grounds M, Newman P. Randomized controlled trial to investigate influence of the fluid challenge on duration of hospital stay and perioperative morbidity in patients with hip fractures. *Br J Anaesth* 2002; **88**: 65-71

4 Gan TJ, Soppitt A, Maroof M, et al. Goal-directed intraoperative fluid administration reduces length of hospital stay after major surgery. *Anesthesiology* 2002; **97**: 820-6

5 Sinclair S, James S, Singer M. Intraoperative intravascular volume optimisation and length of hospital stay after repair of proximal femoral fracture: randomised controlled trial. *BMJ* 1997; **315**: 909-12

6 Wilson JR, Hanamanthu S, Chomsky DB, Davis SF. Relationship between exertional symptoms and functional capacity in patients with heart failure. *J Am Coll Cardiol* 1999; **33**: 1943-7

7 Chomsky DB, Lang CC, Rayos GH, et al. Hemodynamic Exercise Testing A Valuable Tool in the Selection of Cardiac Transplantation Candidates. *Circulation* 1996; **94**: 3176-83

8 Tan LB. Cardiac pumping capability and prognosis in heart failure. *Lancet* 1986; **328**: 1360-3

9 Williams SG, Cooke GA, Wright DJ, et al. Peak exercise cardiac power output; a direct indicator of cardiac function strongly predictive of prognosis in chronic heart failure. *Eur Heart J* 2001; **22**: 1496-503

10 Lang CC, Karlin P, Haythe J, Lim TK, Mancini DM. Peak cardiac power output, measured noninvasively, is a powerful predictor of outcome in chronic heart failure. *Circ Heart Fail* 2009; **2**: 33-8

11 Lund-Johansen P. The dye dilution method for measurement of cardiac output. *Eur Heart J* 1990; **11**: 6-12

12 Gawlinski A. Measuring cardiac output: intermittent bolus thermodilution method. *Critical Care Nurse* 2004; **24**: 74-8

13 Warburton DER, Haykowsky MJF, Quinney HA, Humen DP, Teo KK. Reliability and validity of measures of cardiac output during incremental to maximal aerobic exercise. *Sports Med* 1999; **27**: 23-41

14 Sandham JD, Hull RD, Brant RF, et al. A randomized, controlled trial of the use of pulmonary-artery catheters in high-risk surgical patients. *N Engl J Med* 2003; **348**: 5-14

15 Harvey S, Stevens K, Harrison D, et al. An evaluation of the clinical and cost-effectiveness of pulmonary artery catheters in patient management in intensive care: a systematic review and a randomised controlled trial. *Health Technol Assess (Winch Eng)* 2006; **10**: iii-iv, ix-xi, 1-133

16 Mathews L, Singh KR. Cardiac output monitoring. *Ann Card Anaesth* 2008; **11**: 56-68

17 Critchley LA, Lee A, Ho AMH. A critical review of the ability of continuous cardiac output monitors to measure trends in cardiac output. *Anesth Analg* 2010; **111**: 1180-92

18 Jakovljevic DG, Nunan D, Donovan G, Hodges LD, Sandercock GRH, Brodie DA. Comparison of cardiac output determined by different rebreathing methods at rest and at peak exercise. *Eur J Appl Physiol* 2008; **102**: 593-9

19 Jakovljevic DG, Moore S, Hallsworth K, Fattakhova G, Thoma C, Trenell MI. Comparison of cardiac output determined by bioimpedance and bioreactance methods at rest and during exercise. *J Clin Monit Comput* 2012; **26**: 63-8

20 Keren H, Burkhoff D, Squara P. Evaluation of a noninvasive continuous cardiac output monitoring system based on thoracic bioreactance. *Am J Physiol* 2007; **293**: H583-H9

21 Jakovljevic DG, Trenell MI. Bioimpedance and bioreactance methods for monitoring cardiac output. *Best Prac & Res Clin Anaesth* 2014; DOI: 10.1016/j.bpa.2014.09.003

22 Squara P, Denjean D, Estagnasie P, Brusset A, Dib JC, Dubois C. Noninvasive cardiac output monitoring (NICOM): a clinical validation. *Intensive Care Med* 2007; **33**: 1191-4

23 Marik PE, Levitov A, Young A, Andrews L. The Use of Bioreactance and Carotid Doppler to Determine Volume Responsiveness and Blood Flow Redistribution Following Passive Leg Raising in Hemodynamically Unstable PatientsBioreactance and Carotid Doppler. *CHEST* 2013; **143**: 364-70

24 Ballestero Y, López-Herce J, Urbano J, et al. Measurement of cardiac output in children by bioreactance. *Pediatr Cardiol* 2011; **32**: 469-72

25 Elliott A, Hull JH, Nunan D, Jakovljevic DG, Brodie D, Ansley L. Application of bioreactance for cardiac output assessment during exercise in healthy individuals. *Eur J Appl Physiol* 2010; **109**: 945-51

26 Maurer MM, Burkhoff D, Maybaum S, et al. A multicenter study of noninvasive cardiac output by bioreactance during symptom-limited exercise. *J Card Fail* 2009; **15**: 689-99

27 Rosenblum H, Helmke S, Williams P, et al. Peak cardiac power measured noninvasively with a bioreactance technique is a predictor of adverse outcomes in patients with advanced heart failure. *Congestive Heart Failure* 2010; **16**: 254-8

28 Winter EM, Jones AM, Davison RCR, et al. *Sport and Exercise Physiology Testing Guidelines: Volume I–Sport Testing: The British Association of Sport and Exercise Sciences Guide*. London: Routledge, 2006; 1-98

29 Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *J Stren Cond Res* 2005; **19**: 231-7

30 Meyer K, Westbrook S, Schwaibold M, Hajric R, Peters K, Roskamm H. Short-term reproducibility of cardiopulmonary measurements during exercise testing in patients with severe chronic heart failure. *Am Heart J* 1997; **134**: 20-6

31 Kupersztych-Hagege E, Teboul JL, Artigas A, et al. Bioreactance is not reliable for estimating cardiac output and the effects of passive leg raising in critically ill patients. *Br J Anaesth* 2013; **111**: 961-6

32 Denman WT, Hutchison C, Levy B. Bioreactance is not reliable for estimating cardiac output and the effects of passive leg raising in critically ill patients. *Br J Anaesth* 2014; **112**: 943-4

33 Stringer WW, Hansen JE, Wasserman K. Cardiac output estimated noninvasively from oxygen uptake during exercise. *J Appl Physiol* 1997; **82**: 908-12

Tables

Table 1. The mean values and standard deviations for cardiac and respiratory variables obtained at rest and during the incremental exercise protocol.

Variable	Trial 1	Trial 2	t-test (*p*-value)
Cardiac output (L min^{-1})	13.7 (4.4)	13.4 (4.1)	0.518
Heart rate (beats min^{-1})	123.7 (37.8)	124.3 (36.7)	0.905
Stroke volume (ml $beat^{-1}$)	112.9 (22.5)	109.5 (18.7)	0.179
Minute ventilation (L min^{-1})	46.2 (30.0)	47.6 (30.3)	0.732
Oxygen consumption (L min^{-1})	1.6 (0.9)	1.6 (0.9)	0.882

Note: *p* value determined from test-retest data using paired sample t-test for measurement outcomes. Data analyses performed on resting and exercise data combined (n = 22, data points =132).

Table 2. Relative reliability statistics for cardiac and respiratory variables at rest and during the incremental exercise protocol.

Variable	ICC
Cardiac output ($L\ min^{-1}$)	0.95*
Heart rate (beats min^{-1})	0.99*
Stroke volume (ml $beat^{-1}$)	0.88*
Minute ventilation ($L\ min^{-1}$)	0.99*
Oxygen consumption ($L\ min^{-1}$)	0.99*

*Significant correlation between trials 1 and 2 ($p < 0.001$). Data analyses performed on resting and exercise data combined (n = 22, data points =132).

Table 3. Absolute reliability statistics for cardiac and respiratory variables at rest and during the incremental exercise protocol.

Variable	Change in mean (%)	95%CI	Sx	SRD
Cardiac output (L min^{-1})	11.1	±0.7	±3.0	1.2
Heart rate (beats min^{-1})	6.7	±6.4	±26.3	10.3
Stroke volume (ml $beat^{-1}$)	9.8	±3.5	±14.6	5.7
Minute ventilation (L min^{-1})	12.0	±5.4	±21.3	8.4
Oxygen consumption (L min^{-1})	12.1	±0.2	±0.7	0.3

Note: Sx = standard error of the mean, SD = standard deviation, SRD = smallest real difference. Data analyses performed on resting and exercise data combined (n = 22, data points =132).

Figure legends

Figure 1. Mean cardiac output at rest and at individual stages of the incremental exercise protocol on trials 1 and 2. Wmax = power output in Watts (W) at $\dot{V}O_{2max}$ (n = 22).

Figure 2. Mean stroke volume at rest and at individual stages of the incremental exercise protocol on trials 1 and 2. Wmax = power output in Watts (W) at $\dot{V}O_{2max}$ (n = 22).