

Practical considerations for assessing pulmonary gas exchange and ventilation during flume swimming using the MetaSwim metabolic cart

Agreement and repeatability of the MetaSwim metabolic cart

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ABSTRACT

The MetaSwim (MS) metabolic cart can assess pulmonary gas exchange and ventilation in aquatic environments. The aims of this study were: 1) to determine the agreement between minute ventilation (\dot{V}_E), pulmonary oxygen uptake ($\dot{V}O_2$) and carbon dioxide output ($\dot{V}CO_2$) using the MS and Douglas Bag (DB) methods during flume swimming; 2) to assess the repeatability of these and other MS derived parameters. Sixteen trained swimmers completed a combined incremental and supramaximal verification cardiopulmonary swimming test to determine maximal $\dot{V}O_2$, two progressive intensity swimming tests during which MS and DB measurements were made (agreement protocol), and/or three-four constant velocity submaximal swimming tests during which only the MS was used (repeatability protocol). Agreement was determined using limits of agreement (LoA), bias, random error and 95% confidence intervals with systematic bias assessed using paired samples *t*-tests. Within-trial and between trial repeatability were determined using the coefficient of variation (CV) and the repeatability coefficient (CR). Where data were heteroscedastic, LoA and CR were log-transformed, anti-logged and displayed as ratios. MS underestimated peak $\dot{V}O_2$ and $\dot{V}CO_2$ (≤ 0.39 L \cdot min $^{-1}$) and \dot{V}_E (9.08 L \cdot min $^{-1}$), while submaximal values varied between 2-5% for CV and ± 1.09 -1.22 for ratio CR. The test re-test CV during constant velocity swimming for \dot{V}_E , tidal volume, breathing frequency, $\dot{V}O_2$, $\dot{V}CO_2$, and end-tidal pressures of O₂ and CO₂ was < 9% (ratio CR of ± 1.09 -1.34). Thus, the MS and DB cannot be used interchangeably. Whether the MS is suitable for evaluating ventilatory and pulmonary responses in swimming will depend upon the size of effect required.

Key words: Douglas bags, oxygen uptake kinetics, reliability

INTRODUCTION

Because of technological limitations, pulmonary oxygen uptake ($\dot{V}O_2$) and ventilation (\dot{V}_E) during swimming have traditionally been determined using the Douglas bag (DB) method. Expired air has either been collected during swimming exercise (1,18,26,27) or collected after swimming cessation, with backward extrapolation used to determine end-swimming values (12,19,28,35). Although the DB method is considered the gold standard method for assessing respiratory gas exchange (11,30) it is not without limitation. For example, it cannot detect rapid changes in ventilation or the components of ventilation. Neither can the DB method detect rapid changes in expired O_2 or carbon dioxide (CO_2) fractions (30), making it unsuitable for the study of oxygen uptake kinetics, which is gaining popularity in swimming research (31,33,37). It also places a much greater burden on the investigator compared with the ease of more contemporary, portable, open-circuit systems (30).

A number of portable on-line metabolic carts (e.g. Oxylog by P.K. Morgan, the K2 and K4b² by Cosmed, the Oxycon by Jaeger, and Cortex's Metamax 1, II and 3B) have been used to assess \dot{V}_E , $\dot{V}O_2$ and CO_2 output ($\dot{V}CO_2$) during terrestrial activities. The reliability of these and similar systems has typically been determined by comparing resting, submaximal and vigorous/maximal exercise values to those obtained using the DB method (23-25,34,40) When compared to the latter, the Metamax 3b, Oxycon and K2 systems reportedly overestimate $\dot{V}O_2$ by 3-14%, $\dot{V}CO_2$ by 3-17% and \dot{V}_E by 4-8% during moderate and vigorous cycling and rowing exercise collectively (25,34,40). The test re-test variability (percentage difference or coefficient of variation) is also quite variable ranging from < 1%-15% for $\dot{V}O_2$ measured at rest and during both moderate and vigorous exercise, and 2-12% for maximal $\dot{V}O_2$ measures ($\dot{V}O_{2max}$) (23,24,34,40), 3-7% for submaximal $\dot{V}CO_2$, < 1-6% for submaximal \dot{V}_E and < 5% for maximal \dot{V}_E (23,34,40).

Recent technological advances led to the development of two aquatic specific metabolic cart systems. These are the Cosmed Aquatrainer[®], which is used in conjunction with the Cosmed K4b², and the Cortex MetaSwim (MS) device. Both systems can be used conventionally with a mask or in an aquatic environment via a specialised freestyle snorkel. The Aquatrainer[®] is the more popular of the two aquatic specific systems, with a number of agreement (4,15,20) and oxygen uptake kinetic (31,33,37) studies published using this system. However, when compared with the mask and K4b² assembly, the Aquatrainer[®] has been shown to underestimate $\dot{V}O_2$, $\dot{V}CO_2$ and \dot{V}_E during both submaximal and maximal cycling by 4-21% (15,20), with variability greater during the maximal rather than lower intensities (15). In contrast, Baldari *et al.* (4) reported only minimal differences in $\dot{V}O_2$, $\dot{V}CO_2$ and \dot{V}_E but did observe that the variation was greater during swimming compared with cycling exercise.

Collectively, these studies demonstrate that perfect agreement and repeatability between and within different open-circuit spirometry approaches does not exist. This is not surprising, given that biological and technical variability will influence the data (5,13,24). Given that the MS samples expired air at the mouth and can do so on a breath-by-breath basis, the MS is more versatile than the DB method and can provide researchers with information on pulmonary gas exchange that the DB method cannot. The snorkel assembly configuration is also less cumbersome than the Aquatrainer[®], which is the only other aquatic specific alternative. However, it is currently unknown how the agreement and repeatability of MS derived physiological data compare with other open-circuit spirometry approaches, whether on land or during swimming. Similarly, it remains to be seen if the test re-test variability of the MS system

is small enough to permit observation of changes in physiological data over time, or between individuals (16).

The aims of this study were: 1) to determine the agreement between $\dot{V}O_2$, $\dot{V}CO_2$ and \dot{V}_E using the MS and DB methods during flume swimming; and 2) to assess the repeatability of these and other MS derived measures of pulmonary gas exchange and ventilation during flume-based swimming exercise of different intensities.

METHODS

Experimental approach to the problem

The study consisted of two phases which were preceded by a single familiarisation session and combined incremental and supramaximal verification test (Figure 1) to determine swimmers $\dot{V}O_{2max}$ and gas exchange threshold (GET). Phase 1 was designed to assess the agreement between $\dot{V}O_2$, \dot{V}_E and $\dot{V}CO_2$ using the MS and DB methods when swimming at different intensities. It was also used to assess within-trial and between-trial repeatability of $\dot{V}O_2$, $\dot{V}CO_2$ and \dot{V}_E using the MS versus DB methods. Phase 2, which occurred on different days to phase 1, was designed to assess the between-day variation and hence repeatability of MS derived ventilatory measures (tidal volume (VT); breathing frequency (f_r)) and pulmonary gas exchange parameters during constant velocity sub-maximal swimming based on GET. In addition to $\dot{V}O_2$, \dot{V}_E and $\dot{V}CO_2$, this included the end-tidal pressures of O₂ and CO₂ ($P_{ET}O_2$ and $P_{ET}CO_2$, respectively).

All testing was completed using the front crawl stroke and in the same swimming flume (SwimEx 600-T Therapy pool, length 4.2 m, width 2.3 m, depth 1.5 m) housed within a climate controlled chamber. Although swimmers could take part in both phases, only two swimmers completed the protocol due to the required time commitment. Additionally, during each $\dot{V}O_{2\max}$ test and each experimental trial of phases 1 and 2 a flow turbine meter (Model 001, Current flow metre, ValePort, UK) was used to independently assess flume speed.

****Figure 1****

DB and MS overview

Briefly, DB collections were made using a modified snorkel connected via standard respiratory tubing (32 OD, Hans Rudolf, Germany) to a DB rig containing multiple 150 litre bags (Cranlea, UK). Standardised equations (11) were used to calculate $\dot{V}O_2$ (STPD), $\dot{V}CO_2$ (STPD) and \dot{V}_E (BTPS) from the measured fractions of expired O_2 and CO_2 (Rapidox 3100 gas analyser, Sensotec, Cambridge, UK), bag volume (dry gas meter, Harvard Apparatus, USA) and expired air temperature (MCP multi digital thermometer, India).

Breath-by-breath changes in \dot{V}_E , V_T , f_r , $\dot{V}O_2$, $\dot{V}CO_2$, $P_{ET}O_2$ and $P_{ET}CO_2$ were measured using the MS. A triple V digital flow sensor (manufacturer reported resolution of 7 mL, accuracy of $\pm 2\%$) was placed at the end of the snorkel and was protected by two light weight splash protectors. The snorkel contains a twin-tube and was connected to a tube-in-tube gas sample line via a hydrophobic filter (Figure 2). Expired O_2 and CO_2 were sampled at the mouth and were analysed by an electrochemical sensor for O_2 and a nondispersive infrared sensor for CO_2 housed within the MetaSwim device (Figures 2 and 3).

Before testing, the gas analyser and MS were calibrated using ambient air and gases of a known concentration in line with the manufacturer instructions, and the MS flow sensor was calibrated using a calibrated 3 litre syringe supplied with the MS (Cortex, Germany).

****Figure 2****

****Figure 3****

Subjects

Sixteen trained club-level competitive swimmers (10 female) volunteered for this study, which consisted of two phases. Means and standard deviations (SD) for absolute and body mass relative maximal $\dot{V}O_2$ ($\dot{V}O_{2max}$), which was measured at the start of the study during front crawl, age, body mass and stature were $3.49 \text{ L}\cdot\text{min}^{-1}$, $48.5 \pm 10.7 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, 22 ± 5 years, $72.0 \pm 10.4 \text{ kg}$ and $1.75 \pm 0.07 \text{ m}$. All participants provided fully informed written consent and institutional ethical approval was granted before the study commenced.

Procedures

Familiarisation & $\dot{V}O_{2max}$ determination

Participants were first familiarised with the operation of the swimming flume and became fully accustomed to swimming in the flume wearing the relevant snorkels before any testing took place: swimmers had used the swimming flume and a snorkel before familiarisation, either by participating in other swimming research studies or, in the case of the snorkel, in training. . Following this, participants determined a self-selected warm-up velocity that could be comfortably sustained for 10 minutes without any increase in perceived effort. This velocity

($0.93 \pm 0.09 \text{ m}\cdot\text{s}^{-1}$) was then selected as the warm-up and cool-down velocity for all subsequent phase 1 or 2 tests. The familiarisation session lasted approximately 20 minutes.

The $\dot{V}O_{2\text{max}}$ test was completed in the same testing session as the familiarisation session following 15 minutes rest. After a 5 minute warm-up, swimmers completed a progressive intensity swimming test consisting of two minutes stages until the limit of tolerance. At the end of each 2 minute stage, velocity was increased by $0.05\text{-}0.10 \text{ m}\cdot\text{s}^{-1}$ until the limit of tolerance (inability to maintain velocity). Following this, swimmers undertook a 5 minute cool-down, followed by 10 minutes of passive seated rest on poolside. Participants then completed a supramaximal constant-velocity test to verify that their measured $\dot{V}O_{2\text{peak}}$ reflected $\dot{V}O_{2\text{max}}$. A 3 minute warm-up preceded an individualised step transition to a work rate corresponding to 105% of the final velocity achieved during the incremental $\dot{V}O_{2\text{max}}$ test (adapted from reference 36). This velocity differed from swimmer to swimmer as it was dependent on the final velocity achieved during the $\dot{V}O_{2\text{max}}$ test. Participants were required to swim at this velocity until reaching their limit of tolerance. The highest 10 s average value achieved during either the $\dot{V}O_{2\text{max}}$ or verification test was taken to represent $\dot{V}O_{2\text{max}}$ (Figure 1).

The GET was identified from the incremental test using the V-slope method and verified using the ventilatory equivalents for O_2 and CO_2 , and the end tidal gas tension methods (7,11) by two independent observers trained in the technique. The GET was subsequently used to set the swimming velocities in phase 1.

Phase 1 procedure

Nine swimmers (5 female; age: 22 ± 6 years; height: 1.77 ± 0.06 m; body mass: 77.6 ± 8.8 kg; $\dot{V}O_{2\text{max}}$: $48.6 \pm 13.3 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) completed two variable intensity swimming tests (barometric

pressure: 764 ± 4 mmHg; ambient temperature: 20.1 ± 0.7 °C; water temperature: 27.7 ± 0.4 °C). Swimmers completed a 5 minute warm-up (velocity did not exceed velocity of stage 1), followed by 10 minutes of swimming at an intensity 15% below GET (stage 1: low) and 10 minutes of swimming at an intensity at the velocity immediately below GET (stage 2: mod) (modified from 4). Stage 1 and 2 velocities were chosen to ensure that the participants would reach a steady-state in 3 minutes, so MS and DB collections could be made interchangeably during the 10 minute stage. Swimmers wore a nose clip throughout, along with the MS snorkel connected to the MS metabolic cart or a modified snorkel connected to the DB rig during the relevant part of each data collection stage.

During each 10 minute stage (low, mod), 5 minutes were designated as a MS collection phase and 5 minutes were designated as a DB collection phase. Expired air was only collected in 60 s bouts in the final 2 minutes of each 5 minute phase (minutes 3-5) per 10 minute stage. This permitted $\dot{V}O_2$, $\dot{V}CO_2$ and \dot{V}_E to be calculated per 60 s of the 2 minute MS and DB data collection phases per stage (Figure 1).

Following completion of stage 2, the velocity was increased (0.05 - 0.10 m·s⁻¹) every 2 minutes until the limit of tolerance was reached (stage 3). The highest $\dot{V}O_2$, \dot{V}_E and $\dot{V}CO_2$ values observed during stage 3 were recorded as peak values. Because stage 3 required non-steady state swimming, expired air was collected continuously per 60 s of each 2 minute stage using only the MS in one test, and DB only in the other test. The selection of either MS or DB for test one in participant one was determined using a coin-toss and then counterbalanced for all participants thereafter. In test 2, stages 1 and 2 were collected in an identical order, however if stage 3 was collected using the DB in test 1, it was collected using the MS in test 2 and vice versa (Figure 1). Although the order of MS and DB collections and number of 2 minute stages

were identical per participant per variable intensity test (excluding stage 3), the order of MS and DB collections was counterbalanced between participants.

Phase 2 procedure

Nine swimmers (6 female, age: 22 ± 7 years; height: 1.72 ± 0.07 m; body mass: 70.0 ± 13.2 kg; $\dot{V}O_{2\max}$: 44.4 ± 7.8 mL·kg⁻¹·min⁻¹) completed three or four, 6 minute constant velocity swimming tests (barometric pressure: 767 ± 2 mmHg; ambient temperature: 24.1 ± 0.7 °C; water temperature: 27.8 ± 0.1 °C) on different days. The velocity of these swims was based on critical velocity. Critical velocity (VCrit: 1.08 ± 0.13 m·s⁻¹) was determined separately by backward extrapolation from a 400 m (346.1 ± 48.7 s) and 800 m (721.7 ± 95.5 s) time trial pool swim, administered in a counterbalanced order and completed on separate days after a standardised competition warm-up (22). VCrit was chosen because it reflects the highest sustainable swimming intensity that can be maintained (14) and demarcates the heavy and severe intensity exercise domains providing a measure of swimming endurance (38).

Each 6 minute constant velocity swimming test began with 10 minutes of seated rest. Participants were then instrumented with the MS snorkel and donned a nose clip, which they wore for the remainder of the trial. They then undertook 3 minutes of prone floating (baseline:during which a low current was switched on to aid buoyancy), followed immediately by 6 minutes of constant velocity swimming at a pace 5% slower than critical velocity (VCrit_{5% slower}). After a 30 minute seated poolside recovery, participants again floated for 3 minutes in the flume, followed immediately by 6 minutes of constant velocity swimming at a pace 5% faster than critical velocity (VCrit_{5% faster}).

Statistical analyses

All data were first assessed for normality using a Shapiro-Wilk test and were normally distributed. $\dot{V}O_{2\max}$ was calculated as the mean and SD of all 16 swimmers. The agreement and within-trial DB and MS repeatability data (Phase I) were based on all nine swimmers completing phase 1. The MS repeatability data (Phase 2) were based on all nine swimmers completing phase 2.

Phase 1: variable intensity tests

$\dot{V}O_{2\text{peak}}$, $\dot{V}CO_{2\text{peak}}$ and $\dot{V}E_{\text{peak}}$ were compared between MS and DB (DB-MS) using limits of agreement (LoA) along with bias, random error and 95% confidence intervals (CI), in accordance with methods reported previously (5,9,10). Paired samples *t*-tests (IBM SPSS, v24, $\alpha = 0.05$) were used to assess for significant bias between MS and DB measurements per stage and per variable.

As heteroscedasticity was present in some stage 1 and 2 data, $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}E$ were logarithmically transformed (natural log), anti-logged and displayed as ratios (5,9,10). Consequently, $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}E$ were compared between DB and MS (DB-MS) using ratio LoA, bias, random error and 95% CI in accordance with the methods of Bland & Altman (9,10). Specifically, the last 2 minutes of stages 1 and 2 of each variable intensity test were averaged and compared per test between methods. The replicate measurements for these 2 minute averages between the two variable intensity tests were analysed as two separate repeatability studies so the estimates of each method's agreement could be compared (5).

To determine the within-trial repeatability for MS and DB, each 60 s of the 2 minute collection per stage were compared using the coefficient of variation (CV) and repeatability coefficient (CR). The CV was determined by dividing the standard deviation (SD) by the mean and

multiplying by 100 (2). CR was determined by multiplying the within-subject SD (square root of the residual mean square) by 2.77 (1.96 multiplied by the square root of 2) (5,39): the CR accounts for both random and systematic error and is preferred over Pearson's r and the intraclass correlation coefficient (39). As heteroscedasticity was evident in some stage 1 and 2 $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}E$ data, this CR data were logarithmically transformed (natural log), anti-logged and expressed as ratio data, including the geometric mean, and displayed along with the 95% LoA (1,5,9,39). Additionally, the CV and CR for achieved velocity per stage (within-trial) and between tests were calculated as a whole (only mechanical variation and not biological variation would be present) and CR expressed in the original units of measurement.

Phase 2: swimming above and below V_{Crit}

Along with measured velocity, the final minute of baseline and exercising data ($\dot{V}E$, V_T , f_r , $\dot{V}O_2$, $\dot{V}CO_2$, $P_{ET}O_2$ and $P_{ET}CO_2$) were averaged and compared between each of the 3-4 replicate tests. Repeatability was determined using the CR and CV as described in phase 1. As some data were heteroscedastic, all CR comparisons were made using ratio data.

RESULTS

$\dot{V}O_{2max}$ and $\dot{V}O_{2max}$ verification

The highest $\dot{V}O_2$ value determined during the $\dot{V}O_{2max}$ test was $3.46 \pm 0.90 \text{ L}\cdot\text{min}^{-1}$ ($48.5 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$). The supramaximal verification test produced a $\dot{V}O_{2peak}$ of $2.05 \pm 0.53 \text{ L}\cdot\text{min}^{-1}$. In only three participants was $\dot{V}O_{2peak}$ higher in the verification test (by 0.14-0.20 $\text{L}\cdot\text{min}^{-1}$).

Phase 1: variable intensity tests

Velocities (CV in parentheses) at stages 1, 2 and 3 were $0.98 \pm 0.14 \text{ m}\cdot\text{s}^{-1}$ ($5.0 \pm 2.8 \%$), $1.15 \pm 0.15 \text{ m}\cdot\text{s}^{-1}$ ($4.8 \pm 1.8 \%$) and $1.47 \pm 0.17 \text{ m}\cdot\text{s}^{-1}$ ($3.2 \pm 1.9 \%$), respectively. The CR for velocity

at stages 1, 2 and 3 was $0.15 \text{ m}\cdot\text{s}^{-1}$. The 95% lower and upper LoA were -0.04 and $0.25 \text{ m}\cdot\text{s}^{-1}$ for stage 1, 0.04 and $0.20 \text{ m}\cdot\text{s}^{-1}$ for stage 2, and -0.02 and $0.18 \text{ m}\cdot\text{s}^{-1}$ for stage 3. The GET occurred at $66 \pm 7\%$ ($2.48 \pm 0.63 \text{ L}\cdot\text{min}^{-1}$) of $\dot{V}\text{O}_{2\text{max}}$.

$\dot{V}\text{O}_{2\text{peak}}$ ($t = 1.588, p = 0.151$), $\dot{V}\text{CO}_{2\text{peak}}$ ($t = 0.95, p = 0.37$) and $\dot{V}\text{E}_{\text{peak}}$ ($t = 1.25, p = 0.25$) were not statistically different between MS and DB methods. Nevertheless, there was a tendency for absolute values to be lower during MS measurements and both bias and random error were large (Table 1; Figure 4).

****Table 1 here****

****Figure 4 here****

Bias ($p > 0.05$) and random error for $\dot{V}\text{O}_2$, $\dot{V}\text{CO}_2$ and $\dot{V}\text{E}$ during low and moderate swimming velocities are presented in Table 2. The CV and CR for $\dot{V}\text{O}_2$, $\dot{V}\text{CO}_2$ and $\dot{V}\text{E}$ were typically as good as, if not better than, DB for within-trial MS measurements in both tests (Table 3).

****Table 2****

****Table 3****

Phase 2: swimming above and below V_{Crit}

The CR and CV for velocity, \dot{V}_E , VT, *fr*, $\dot{V}O_2$, $\dot{V}CO_2$, PETO₂ and PETCO₂ are presented in Table 4. The repeatability of the physiological parameters was better for exercising values than baseline values during both V_{Crit}_{5% slower} and V_{Crit}_{5% faster}.

****Table 4****

DISCUSSION

The aim of this study was to assess the level of agreement between MS and DB derived measurements of $\dot{V}O_2$, $\dot{V}CO_2$ and \dot{V}_E and to determine the repeatability of \dot{V}_E , VT, *fr*, $\dot{V}O_2$, $\dot{V}CO_2$, PETO₂ and PETCO₂ measured using the MS during flume-based swimming exercise. Agreement between the MS and DB methods was poor and that the MS typically underestimated peak and submaximal $\dot{V}O_2$, $\dot{V}CO_2$ and \dot{V}_E . However, the within-trial repeatability for the MS was at least as good as, if not better than, the DB derived values and the test re-test variability (CV) in \dot{V}_E , VT, *fr*, $\dot{V}O_2$, $\dot{V}CO_2$, PETO₂ and PETCO₂ was consistent with that reported in the literature (23,24,34,40), although the CR was large.

Agreement between DB and MS methods and within-test repeatability

When compared to the DB method, the MS underestimated $\dot{V}O_{2peak}$ by 13% (0.39 L·min⁻¹), $\dot{V}CO_{2peak}$ by 9% (0.26 L·min⁻¹) and \dot{V}_{Epeak} by 11% (9.08 L·min⁻¹) (Table 1). This is similar to the observations of Gayda *et al.* (15), who found that maximal $\dot{V}O_2$, $\dot{V}CO_2$ and \dot{V}_E were underestimated by 15% (0.50 L·min⁻¹), 6% (0.22 L·min⁻¹) and 9% (10 L·min⁻¹) respectively, when using the Aquatrainer[®] system vs. the K4b² face mask during cycle ergometry.

The MS also tended to underestimate (bias in parentheses) submaximal $\dot{V}O_2$ (2-17%), $\dot{V}CO_2$ (2-11%) and \dot{V}_E (0-17%). This was slightly better than the underestimation in $\dot{V}O_2$ (21%), $\dot{V}CO_2$ (2-14%) and \dot{V}_E (18%) reported by Gayda *et al.* (15) during submaximal (100 W) cycle ergometry, but worse than that observed by both Keskinen *et al.* (20) and Baldari *et al.* (4) when comparing the K4b² face mask with the Aquatrainer[®] system during cycle ergometry. Keskinen *et al.* (20) reported a pooled mean difference between the face mask and Aquatrainer[®] of 5-7% (174 mL·min⁻¹) for $\dot{V}O_2$, 4-6% (138 mL·min⁻¹) for $\dot{V}CO_2$ and 3-5% (3.05 L·min⁻¹) for \dot{V}_E . Baldari and colleagues (4) reported even smaller differences in $\dot{V}O_2$ (0.9-2.8 mL·min⁻¹), $\dot{V}CO_2$ (5.1-11.3 mL·min⁻¹) and \dot{V}_E (0.10-0.14 L·min⁻¹). However, when only the Aquatrainer[®] system was used during either swimming or cycle ergometry, the mean difference in $\dot{V}O_2$ was 3 fold higher during swimming and 2 fold higher for $\dot{V}CO_2$ and \dot{V}_E (4). This suggests that the variability in $\dot{V}O_2$, $\dot{V}CO_2$ and \dot{V}_E is greater in an aquatic environment compared to a terrestrial one.

Although no statistically significant bias in peak or submaximal $\dot{V}O_2$, $\dot{V}CO_2$ and \dot{V}_E was observed, a high level of random error was present and given the small sample size it would have been difficult to detect statistically significant bias (2). The wide LoA for peak and submaximal $\dot{V}O_2$, $\dot{V}CO_2$ and \dot{V}_E mean that if the same participants were tested again, $\dot{V}O_{2peak}$ determined using the MS could be as much as 1.06 L·min⁻¹ below or 1.84 L·min⁻¹ above DB values (Table 1). Submaximal MS derived $\dot{V}O_2$ may also under- or overestimate DB values by as much as 35% during low intensity swimming and 78% during moderate intensity swimming because of measurement error alone (Table 2). This lack of agreement between DB and MS measurements is not acceptable. Even though the mean difference observed across swimming intensities is consistent with that reported between DB other metabolic carts for $\dot{V}O_2$ (3-14%), $\dot{V}CO_2$ (3-17%) and \dot{V}_E (4-8%) (15,25,34,40), the data indicates that the MS and DB cannot be

used interchangeably during flume swimming. Despite this, the within-test repeatability (CV and CR) for $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}E$ during submaximal swimming was similar between MS and DB measurements for the two repeat tests, with the MS typically exhibiting better repeatability (Table 3).

Repeatability of the MS: test re-test assessments

Only two studies have examined the test re-test performance of metabolic carts and these studies have limited the number of comparisons to only two (23,40). The lack of test re-test metabolic cart data is disappointing, especially as the high variability between breaths can create a low signal-to-noise ratio reducing the confidence of kinetic parameters and their interpretation (21).

The repeatability of $\dot{V}E$, VT, f_r , $\dot{V}O_2$, $\dot{V}CO_2$, $PETO_2$ and $PETCO_2$ was worse at baseline than during swimming with a CV ranging from 4-27% and ratio CR of ± 1.09 -1.75 (Table 4). This could reflect the manner in which these data were collected. During the three minutes of prone floating (baseline) the flume was switched on and a current was applied to aid buoyancy. This created a small amount of natural sway and likely increased convective heat loss due to the flowing water over the skin (29). Although a standard pool temperature of 28°C was used herein, this would not have been thermoneutral during floating (32). Some swimmers reported feeling cold and shivering during this phase, which would be expected to increase the metabolic demand and thus $\dot{V}O_2$ (29). These factors could impact the repeatability of the physiological data at baseline, but during swimming this would have been less of a problem because metabolic heat production will have increased.

All physiological variables measured during swimming (\dot{V}_E , VT, f_r , $\dot{V}O_2$, $\dot{V}CO_2$, $PETO_2$, $PETCO_2$) produced a test re-test CV < 9%, 6-7% for $\dot{V}O_2$ specifically (Table 4). This is consistent with the CV (24,34) or percentage difference (23,40) found in the literature for $\dot{V}O_2$ (< 1-15%), $\dot{V}CO_2$ (3-7%) and \dot{V}_E (<1-6%) during treadmill exercise, cycle ergometry or rowing ergometry. These differences have been shown to be inversely related to work rate (24,30,34). Furthermore, few studies have examined the repeatability of VT and f_r and none have examined $PETO_2$ and $PETCO_2$. The 8% and 4-6% CV observed in VT and f_r is better than the 12% reported for VT and similar to the 5% reported for f_r (15).

Although the exercising CV data of the present study is consistent with others, this does not mean that the test-re-test variability is inconsequential. The LoA for all CR analyses were wide and with a ratio CR of up ± 1.26 for $\dot{V}O_2$ and ± 1.34 for \dot{V}_E (the worst CR observed in all parameters over both intensities), $\dot{V}O_2$ and \dot{V}_E could vary by as much as 26% and 34% respectively in the same participants during repeat testing. A change of at least these magnitudes would be needed in future trials to be 95% confident that a real change in, or difference between, $\dot{V}O_2$ and \dot{V}_E was evident (5,39). This level of variability was similar for $\dot{V}CO_2$ and f_r but slightly better for VT, $PETO_2$ and $PETCO_2$ (Table 4). Whether or not the MS is capable of detecting a real change and is suitable for evaluative purposes will therefore depend on the size of the change expected or the minimum difference that is considered meaningful (16).

Limitations and recommendations

The hydrodynamic and fluid flow differences between flume and pool swimming impact stroke characteristics. Stroke cycle duration is shorter, stroke rate is higher and the catch and glide phases are reduced at a given velocity during flume vs. pool swimming (17). It is not clear

whether such changes to routine stroke kinematics impact the variability of physiological data during flume swimming: swimmers had some experience of swimming in the flume prior to data collection, but this was limited. This could be exacerbated further if the control of velocity is more variable in a flume due to inherent mechanical variation. In the present study the CR for velocity was $\pm 0.15 \text{ m}\cdot\text{s}^{-1}$ during submaximal and maximal swimming in phase 1 with a CV as high as 5%. Phase 2 was slightly better with a ratio CR of ± 1.09 for $\text{VCrit}_{5\% \text{ slower}}$ and ± 1.13 for $\text{VCrit}_{5\% \text{ faster}}$, and test re-test CV of $<3\%$. This CV is worse than that reported ($< 1\%$) between target and achieved velocity when swimming at the same relative intensities ($\text{VCrit}_{5\% \text{ slower}}$ and $\text{VCrit}_{5\% \text{ faster}}$) in an indoor swimming pool (22).

In light of this, it is possible that day-to-day repeatability would improve if data were collected in a swimming pool rather than a flume. Baseline variability could probably also be reduced by decreasing the likelihood of shivering. This could be achieved by reducing the time period over which baseline data is collected if floating in water (although reducing this to less than 3 minutes is questionable), by increasing the temperature of the water, or by undertaking baseline measurements on poolside: prone floating baseline measurements were recorded in the flume to reflect the body position and environment experienced during front crawl. These recommendations require testing and data would still be subject to the biological variability occurring between replicate tests, which can account for as much as 90% of the total variability in $\dot{V}\text{O}_2$ (5,13,24). Additionally, breathing in front crawl is constrained by swimming stroke. How this impacts the repeatability of \dot{V}_E , f_r , PETO_2 and PETCO_2 in comparison to freely breathing activities as well as other swimming strokes has not been investigated.

It should also be acknowledged that all metabolic carts can encounter errors from alinearity of sensors and a temporal mismatch between ventilation and gas fractions during breath-by-breath

sampling (30). It is possible that the water environment itself could exacerbate any such errors and contribute to the level of random error observed. For example, the hydrophobic filter separating the tube-in-tube sample line and the twin-tube can become saturated with water and the latter drawn into the analyser. Although Drierite is used to reduce the water vapor in the sample line, the Drierite was more effective when the tube was placed vertically rather than horizontally as recommended by the manufactures. The intrusion of water into the twin-tube was reduced further by wrapping the filter and other snorkel and electrical interfaces with disposable plastic paraffin film (Parafilm, laboratory film, American National CanTM).

Lastly, condensation of expired air inside the snorkel was frequently observed indicating the temperature of the expired air leaving the mouth was greater than that reaching the flow sensor. The flow measured at the flow sensor would therefore not exactly equal the flow at the mouth (8). Furthermore, the temperature sensor is located within the MS analyser unit and not within the snorkel or flow sensor housing unit. Given that majority of variation in $\dot{V}O_2$ with metabolic carts comes from the measurement of ventilation (6), it is possible that temperature differential errors could have increased the variability in \dot{V}_E and in-turn $\dot{V}O_2$ and $\dot{V}CO_2$.

PRACTICAL APPLICATIONS

The test re-test data of the MS is consistent with other metabolic carts suggesting similar levels of repeatability. The test re-test performance of the MS and DB method are similar, with the MS typically exhibiting smaller CV and CR values. The MS is more convenient to use than the DB method making it appealing for practical use and the breath-by-breath nature of data collection means the MS is more versatile. For example, as well as the traditional parameters of $\dot{V}O_2$, $\dot{V}CO_2$ and \dot{V}_E that can be assessed with the DB method, pulmonary oxygen uptake

kinetics, gas exchange thresholds, and rapid changes in ventilation and oxygen and carbon dioxide expired fractions can be examined with the MS. Although the MS can be used to assess the response of such parameters to training, the level of day-to-day variability is not inconsequential. Whether or not the MS is suitable for use as an evaluative tool will therefore depend upon the size of the effect one wishes to detect.

The poor agreement and wide LoA between the MS and DB indicate that they cannot be used interchangeably during flume swimming. Biological and technical variability make perfect agreement very unlikely and the disparity between MS and DB derived $\dot{V}O_2$, $\dot{V}CO_2$ and \dot{V}_E values is consistent with the variability between other metabolic carts and the DB method. Given that the MS can provide a greater magnitude of physiological data, it is unlikely that the MS and DB would be used interchangeably.

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FIGURE LEGENDS

Figure 1. Schematic of protocol

Notes.

* limit of tolerance

† order of DB and MS collections counterbalanced between participants

Duration denotes duration of stage. Sample denotes time point (min) within a given stage of phase 1 that expired air was measured.

Format: word

Figure 2. MetaSwim and snorkel

Notes. For clarity reasons only one splash protector is shown

Format: ppt and black and white

Figure 3. Participant swimming while instrumented with the MetaSwim

Format: ppt and black and white

Figure 4. Mean difference in $\dot{V}O_{2\text{peak}}$ (A), $\dot{V}CO_{2\text{peak}}$ (B) and $\dot{V}_{E\text{peak}}$ (C) between DB and MS plotted against their means.

Notes.

Heavy line = bias

Solid line = ± 1.96 SD

p = bias

r = absolute difference between DB and MS and the mean

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Table 1. Douglas bag vs. MetaSwim limits of agreement (LoA) and precision of LoA for $\dot{V}O_{2\text{peak}}$, $\dot{V}_{E\text{peak}}$ and $\dot{V}CO_{2\text{peak}}$ determined during variable intensity swimming

Parameter	Absolute value		Absolute values (L·min ⁻¹)								
	DB	MS	95% LoA		Bias			Random error			
	(L·min ⁻¹)	(L·min ⁻¹)	lower	upper	Bias	SE	95% CI	Error	SE	95% CI	
									lower LoA	upper LoA	
$\dot{V}O_{2\text{peak}}$	2.99 ± 0.63	2.60 ± 0.58	-1.06	1.84	0.39	0.25	-0.18-0.96	1.45	0.43	-2.04- -0.07	0.86-2.82
$\dot{V}_{E\text{peak}}$	81.0 ± 21.3	71.9 ± 18.9	-33.7	51.9	9.08	7.3	-7.7-25.9	42.8	12.6	-62.8- -4.6	22.8-80.9
$\dot{V}CO_{2\text{peak}}$	2.95 ± 0.87	2.69 ± 0.76	-1.35	1.86	0.26	0.27	-0.37-0.89	1.60	0.47	-2.44- -0.26	0.77-2.95

Table 2. Douglas Bag vs. MetaSwim ratio limits of agreement (LoA) per stage and per variable intensity test including estimated precision of the LoA

Parameter	Absolute value		Ratio								
	DB	MS	95% LoA		Bias			Random error			
	(L·min ⁻¹)	(L·min ⁻¹)	lower	upper	Bias	SE	95% CI	Error	SE	95% CI	
										lower LoA	upper LoA
Variable intensity test 1											
$\dot{V}O_{2\text{ low}}$	1.68 ± 0.42	1.64 ± 0.29	0.74	1.35	1.00	0.05	-0.12-0.12	1.35	0.09	0.54-0.95	1.15-1.56
$\dot{V}O_{2\text{ mod}}$	2.09 ± 0.45	2.01 ± 0.41	0.68	1.56	1.03	0.07	-0.13-0.19	1.51	0.12	0.41-0.96	1.27-1.83
$\dot{V}E_{\text{ low}}$	39.7 ± 7.2	39.7 ± 4.3	0.75	1.32	1.00	0.05	-0.12-0.10	1.33	0.08	0.55-0.94	1.12-1.51
$\dot{V}E_{\text{ mod}}$	49.0 ± 7.6	50.4 ± 9.8	0.64	1.49	0.98	0.07	-0.19-0.14	1.53	0.12	0.35-0.92	1.21-1.78
$\dot{V}CO_{2\text{ low}}$	1.42 ± 0.35	1.53 ± 0.28	0.69	1.20	0.91	0.05	-0.20-0.02	1.32	0.08	0.51-0.88	1.01-1.39
$\dot{V}CO_{2\text{ mod}}$	1.82 ± 0.40	1.95 ± 0.45	0.59	1.47	0.93	0.08	-0.25-0.11	1.58	0.13	0.28-0.90	1.16-1.78
Variable intensity test 2											
$\dot{V}O_{2\text{ low}}$	1.64 ± 0.43	1.51 ± 0.40	0.82	1.45	1.09	0.05	-0.02-0.20	1.32	0.08	0.63-1.02	1.02-1.64
$\dot{V}O_{2\text{ mod}}$	2.09 ± 0.54	1.74 ± 0.52	0.70	2.20	1.24	0.10	-0.1-0.44	1.78	0.17	0.31-1.09	1.81-2.59
$\dot{V}E_{\text{ low}}$	38.5 ± 6.5	35.5 ± 6.6	0.86	1.38	1.09	0.04	-0.004-0.18	1.27	0.07	0.70-1.02	1.22-1.54
$\dot{V}E_{\text{ mod}}$	50.4 ± 8.0	43.2 ± 10.0	0.80	1.76	1.19	0.07	0.02-0.33	1.48	0.12	0.53-1.07	1.49-2.03
$\dot{V}CO_{2\text{ low}}$	1.40 ± 0.39	1.37 ± 0.35	0.78	1.33	1.02	0.05	-0.08-0.13	1.31	0.08	0.60-0.96	1.15-1.52
$\dot{V}CO_{2\text{ mod}}$	1.83 ± 0.47	1.63 ± 0.50	0.70	1.91	1.15	0.09	-0.05-0.34	1.65	0.15	0.36-1.04	1.57-2.25

Table 3. Repeatability coefficient (CR), coefficient of variation (CV) and absolute data for Douglas bags and MetaSwim during steady state swimming per variable intensity test: within-equipment comparisons

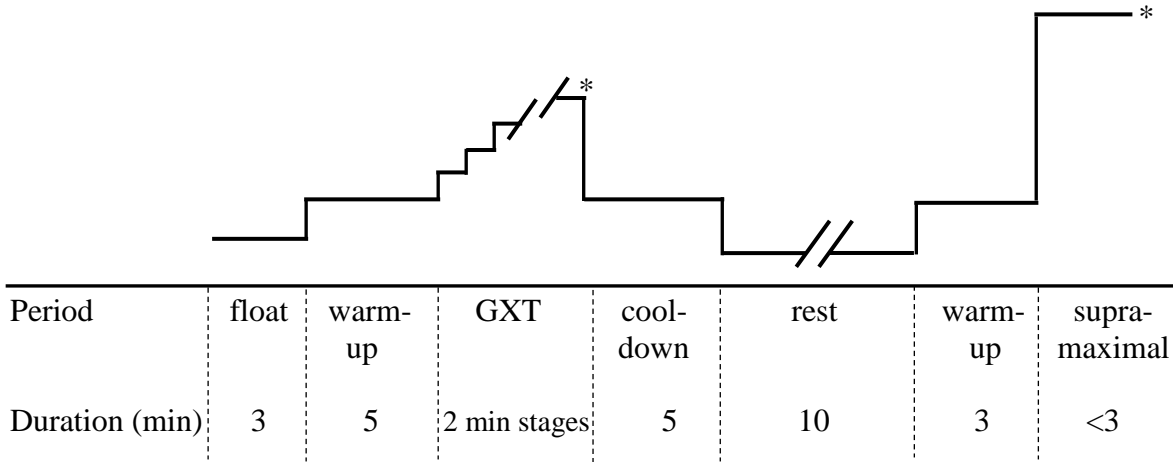
Parameter	MS						DB							
			CR		CV (%)				CR		CV (%)			
	Min 1	Min 2	CR (ratio)	geometric mean (%)	95% LoA (%)		Min 1	Min 2	CR (ratio)	geometric mean (%)	95% LoA (%)			
	(L·min ⁻¹)	(L·min ⁻¹)			lower	upper	(L·min ⁻¹)	(L·min ⁻¹)			lower	upper		
Variable intensity test 1														
$\dot{V}O_{2\text{ low}}$	1.65 ± 0.30	1.64 ± 0.29	±1.09	3.7	-1.7	9.3	2.5 ± 1.92	1.67 ± 0.42	1.68 ± 0.42	±1.09	3.4	-2.8	10.1	2.4 ± 2.3
$\dot{V}O_{2\text{ mod}}$	1.99 ± 0.44	2.04 ± 0.40	±1.13	4.0	-4.5	13.3	2.8 ± 3.07	2.12 ± 0.47	2.06 ± 0.46	±1.22	7.7	-7.4	25.2	5.2 ± 5.4
$\dot{V}_{E\text{ low}}$	40.2 ± 4.4	39.1 ± 4.4	±1.09	4.4	-2.0	11.3	3.1 ± 2.3	39.8 ± 7.4	39.6 ± 7.1	±1.09	4.3	-1.6	10.6	3.0 ± 2.1
$\dot{V}_{E\text{ mod}}$	50.1 ± 10.3	51.1 ± 9.4	±1.13	5.0	-5.1	16.3	3.5 ± 3.7	49.8 ± 7.2	48.3 ± 8.7	±1.22	7.5	-7.9	25.5	5.1 ± 5.5
$\dot{V}CO_{2\text{ low}}$	1.65 ± 0.30	1.64 ± 0.29	±1.09	4.0	-0.8	9.1	2.8 ± 1.7	1.41 ± 0.34	1.43 ± 0.35	±1.09	3.7	-1.4	9.1	2.6 ± 1.8
$\dot{V}CO_{2\text{ mod}}$	1.99 ± 0.44	2.04 ± 0.39	±1.13	4.6	-5.5	15.8	3.2 ± 3.7	1.83 ± 0.39	1.80 ± 0.43	±1.22	7.9	-7.8	26.3	5.4 ± 5.6
Variable intensity test 2														
$\dot{V}O_{2\text{ low}}$	1.52 ± 0.42	1.50 ± 0.39	±1.16	6.4	-3.4	16.8	4.3 ± 3.4	1.65 ± 0.45	1.63 ± 0.42	±1.09	3.0	-3.2	9.6	2.1 ± 2.2
$\dot{V}O_{2\text{ mod}}$	1.73 ± 0.51	1.76 ± 0.53	±1.09	3.3	-2.6	9.6	2.3 ± 2.1	2.10 ± 0.5	2.09 ± 0.55	±1.09	3.5	-2.5	9.8	2.4 ± 2.2
$\dot{V}_{E\text{ low}}$	35.7 ± 6.8	35.2 ± 6.6	±1.13	4.3	-3.5	12.8	3.0 ± 2.8	38.7 ± 7.4	38.2 ± 5.9	±1.16	5.4	-6.7	19.1	3.8 ± 4.4
$\dot{V}_{E\text{ mod}}$	43.3 ± 9.7	43.1 ± 10.7	±1.19	6.9	-5.0	20.3	4.7 ± 4.3	50.1 ± 7.8	50.8 ± 8.3	±1.09	3.4	-2.0	9.1	2.4 ± 1.9
$\dot{V}CO_{2\text{ low}}$	1.37 ± 0.36	1.36 ± 0.34	±1.13	5.0	-2.6	13.1	3.4 ± 2.7	1.65 ± 0.45	1.63 ± 0.42	±1.13	4.7	-4.5	14.9	3.3 ± 3.3
$\dot{V}CO_{2\text{ mod}}$	1.62 ± 0.49	1.64 ± 0.50	±1.09	3.8	-2.6	10.7	3.6 ± 2.3	2.10 ± 0.52	2.09 ± 0.55	±1.09	3.1	-1.5	7.8	2.1 ± 1.6

Table 4. MetaSwim absolute, repeatability coefficient (CR) and coefficient of variation (CV) data at rest (base) and when swimming (swim) 5% below ($V_{\text{Crit}5\% \text{ slower}}$) and 5% faster ($V_{\text{Crit}5\% \text{ faster}}$) than V_{Crit}

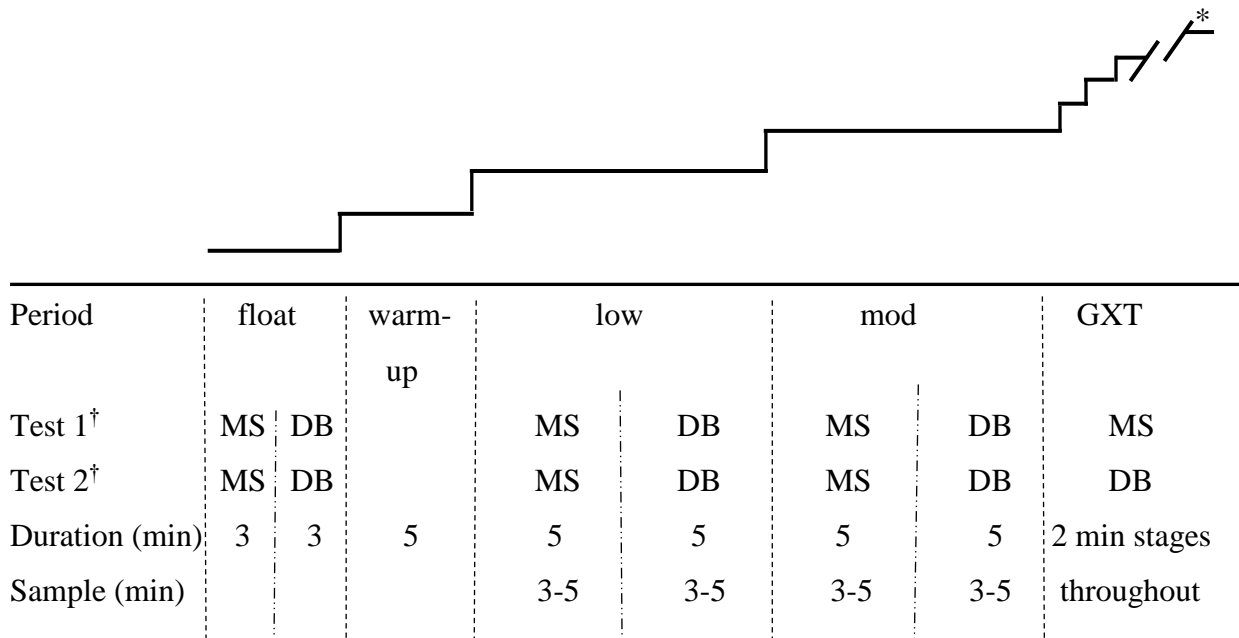
	$V_{\text{Crit}5\% \text{ slower}}$				$V_{\text{Crit}5\% \text{ faster}}$				Absolute data			
	CR		CV (%)		CR		CV (%)		$V_{\text{Crit}5\% \text{ slower}}$	$V_{\text{Crit}5\% \text{ faster}}$		
	CR (ratio)	geometric mean (%)	95% LoA (%)		CR (ratio)	geometric mean (%)	95% LoA (%)					
			lower	upper			lower	upper				
Velocity	± 1.09	5.7	-5.2	18.0	1.0 ± 0.1	± 1.13	6.8	-4.5	19.4	3.1 ± 2.4	1.01 ± 0.14	1.07 ± 0.19
$\dot{V}O_{2 \text{ base}}$	± 1.49	34.9	9.7	65.9	13.9 ± 4.5	± 1.40	27.5	6.4	52.7	11.3 ± 4.1	0.50 ± 0.14	0.58 ± 0.19
$\dot{V}O_{2 \text{ swim}}$	± 1.24	14.2	-6.1	38.7	6.2 ± 4.8	± 1.26	16.5	-5.1	43.1	7.2 ± 4.7	1.97 ± 0.60	2.55 ± 0.56
$\dot{V}E_{\text{ base}}$	± 1.69	45.7	1.3	109.5	17.4 ± 7.9	± 1.52	34.5	5.4	71.8	13.7 ± 5.4	17.4 ± 4.9	19.6 ± 6.6
$\dot{V}E_{\text{ swim}}$	± 1.34	20.0	-2.7	48.1	8.5 ± 4.6	± 1.28	20.3	3.7	39.5	8.8 ± 3.9	49.4 ± 17.5	69.6 ± 18.8
$\dot{V}CO_{2 \text{ base}}$	± 1.63	42.0	-2.3	106.4	15.8 ± 8.0	± 1.42	30.4	9.4	55.3	11.9 ± 3.4	0.50 ± 0.12	0.57 ± 0.16
$\dot{V}CO_{2 \text{ swim}}$	± 1.30	18.1	-7.0	50.0	7.9 ± 5.9	± 1.26	17.0	-1.0	38.3	7.5 ± 3.8	1.89 ± 0.60	2.58 ± 0.61
$f_r_{\text{ base}}$	± 1.63	41.9	1.5	98.2	27.3 ± 12.5	± 1.73	40.9	-16.7	138.2	15.4 ± 10.8	15.1 ± 4.0	14.8 ± 3.4
$f_r_{\text{ swim}}$	± 1.30	18.5	-8.7	53.7	7.7 ± 5.6	± 1.26	16.7	-2.8	40.1	7.5 ± 4.7	25.0 ± 6.7	32.7 ± 7.5
$VT_{\text{ base}}$	± 1.75	48.6	-7.0	137.6	17.2 ± 8.9	± 1.60	37.2	-6.5	101.4	14.8 ± 8.3	1.24 ± 0.22	1.40 ± 0.30
$VT_{\text{ swim}}$	± 1.13	9.6	-0.6	20.8	4.4 ± 2.6	± 1.22	14.0	-1.3	31.8	6.3 ± 3.4	2.00 ± 0.44	2.16 ± 0.39
$PETO_{2 \text{ base}}$	± 1.19	12.4	-3.8	31.2	5.4 ± 3.4	± 1.16	9.7	-4.1	25.4	4.1 ± 2.8	114 ± 6	114 ± 7
$PETO_{2 \text{ swim}}$	± 1.09	6.1	0.7	11.8	2.8 ± 1.2	± 1.09	4.9	-0.7	10.8	2.3 ± 1.3	106 ± 4	109 ± 4
$PETCO_{2 \text{ base}}$	± 1.22	14.2	-0.4	31.0	6.4 ± 3.2	± 1.16	11.4	0.7	23.3	5.1 ± 2.3	35 ± 5	35 ± 5
$PETCO_{2 \text{ swim}}$	± 1.13	8.8	-1.5	20.2	4.2 ± 2.2	± 1.13	7.2	-3.1	18.7	3.4 ± 2.5	42 ± 3	41 ± 3

Note: Absolute data = mean of all trials at that velocity. Velocity = $\text{m}\cdot\text{s}^{-1}$; \dot{V}_E , \dot{V}_{O_2} , $\dot{V}_{CO_2} = \text{l}\cdot\text{min}^{-1}$; $f_r = \text{b}\cdot\text{min}^{-1}$; VT = l; $P_{ET}O_2$, $P_{ET}CO_2 = \text{mmHg}$.

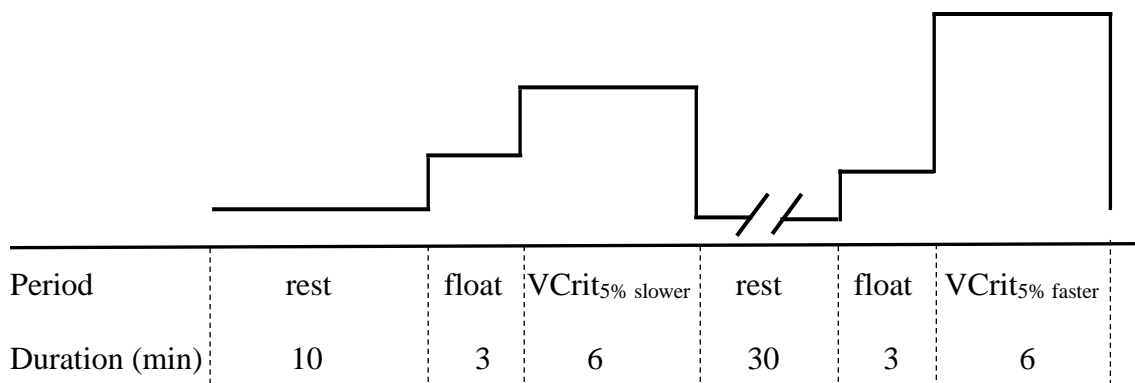
$\dot{V}O_{2max}$ and supramaximal $\dot{V}O_{2max}$ verification



Phase 1 - MetaSwim vs. Douglas bag agreement: variable intensity test 1 (Test 1) and variable intensity test 2 (Test 2)



Phase 2 – Repeatability of ventilatory and gas exchange parameters



repeat 2-3 times on separate occasions

