Reliability and Validity of a Pool-Based Maximal Oxygen Uptake Test to Examine High-Intensity Short-Duration Freestyle Swimming Performance

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Abstract

Nagle, EF, Nagai, T, Beethe, AZ, Lovalekar, MT, Zera, JN, Connaboy, C, Abt, JP, Beals, K, Nindl, BC, Robertson, RJ, and Lephart, SM. Reliability and validity of a pool-based maximal oxygen uptake test to examine high-intensity short-duration freestyle swimming performance. *J Strength Cond Res* 33(5): 1208–1215, 2019—A modality-specific swimming protocol to assess maximal oxygen uptake ($\dot{V}O_2max_{sw}$) is essential to accurately prescribe and monitor swimming conditioning programs. Consequently, there is a need for a reliable and valid graded intensity swimming pool test to accurately assess $\dot{V}O_2max_{sw}$ using indirect calorimetry. The purpose of this study was to assess (a) reliability of an intensity self-regulated swimming pool test of $\dot{V}O_2max_{sw}$ and (b) validity of a $\dot{V}O_2max_{sw}$ test using performance swim (PS) time as the criterion. Twenty-nine men ($n = 15$) and women ($n = 14$) (age, 23 ± 6.4 years; body mass index, 23.5 ± 3.0 kg·m^{-2}) performed 2 swimming pool $\dot{V}O_2max_{sw}$ trials ($\dot{V}O_2max_{sw}$ A and $\dot{V}O_2max_{sw}$ B), and 2 PS tests (45.7 m [31.20 ± 4.5 seconds] and 182 m [159.2 ± 25.5 seconds]). For test-retest reliability (trials A vs. B), strong correlations ($p < 0.05$) were found for $\dot{V}O_2max_{sw}$ (ml·kg^{-1}·min^{-1}) ($r = 0.899$), O_2 pulse (ml O_2·beat^{-1}) ($r = 0.833$), and maximum expired ventilatory volume (L·min^{-1}) ($r = 0.785$). For performance validity, moderately strong correlations ($p < 0.05$) were found between $\dot{V}O_2max_{sw}$ A and 45.7-m ($r = -0.543$) and 182-m ($r = -0.486$) swim times. The self-regulated graded intensity swimming pool protocol examined presently is a reliable and valid test of $\dot{V}O_2max_{sw}$. Studies should consider the suitability of a $\dot{V}O_2max_{sw}$ test for military personnel, clinical populations, and injured athletes.

Key Words: self-regulating intensity, competitive swimmers, maximal aerobic power

Introduction

Maximal oxygen uptake ($\dot{V}O_2max$) has been used extensively to assess aerobic fitness, track adaptations to training, and predict endurance performance (1,30,41). The most common graded exercise testing protocols to measure $\dot{V}O_2max$ use treadmill and cycle modalities because these parameters accurately regulate work intensity in a systematic and incremental fashion (1). Given the health benefits and popularity of swimming (2), pool-based protocols that assess $\dot{V}O_2max_{sw}$ are needed to determine baseline levels of aerobic fitness and monitor training progress to improve performance (9). Owing to the specificity and environment by which it is performed, a maximal oxygen uptake test performed while swimming can be identified as $\dot{V}O_2max_{sw}$ (45). Likewise, swimming protocols that measure respiratory-metabolic responses can be used to determine not only $\dot{V}O_2max_{sw}$ but also energy expenditure and swimming economy (i.e., stroke efficiency) (5). Procedures to measure $\dot{V}O_2max_{sw}$ in water are feasible, in part, because of the recent advancement of portable respiratory gas analyzer (i.e., snorkel) systems that measure breath-by-breath gas exchange with high precision (3,13,26). Such instrumentation provides an accurate measure of $\dot{V}O_2$ during tethered swimming, swimming flume, or swimming pool settings (20,22,23,34,35,62).

Despite these methodological advancements, few standardized laboratory-based measures have used protocols to assess $\dot{V}O_2max_{sw}$ in water because of the complexity and cost of equipment needed, as well as limitations regarding interindividual variation in swimming stroke parameters (11,25). Accurately identifying flow velocities in a swimming flume are essential to calculate energy cost and swimming economy. However, some evidence suggests swimming flume assessments of $\dot{V}O_2max_{sw}$, energy cost, and swimming economy do not correlate well with swimming pool performance (27,64). Compared with the laminar flow characteristics of a pool, a swimming flume's turbulent flow might adversely alter swimming technique and increase physiological demands at a given velocity, thus decreasing time to exhaustion at maximal velocity (v$\dot{V}O_2$max) (21). Alternative, pool-based free (i.e., unrestricted) swimming protocols developed to estimate $\dot{V}O_2max$ have used heart rate (HR) and swimming velocity as predictor variables (29). Timed tests longer than 15 minutes, including the maximal distance covered in 30 minutes (i.e., T-30 test) or repeated trials (i.e., Step Test) (63), have been used for such physiological and performance measurements (36). Using the Australian repeated 200-m Step Test, Pyne et al. used HR and swimming speed to estimate swimming economy and $\dot{V}O_2max$ (51). Reis et al. (52) used the same Australian Step Test protocol in conjunction with indirect calorimetry to assess $\dot{V}O_2max$.

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However, reliability of these protocols and relations to swimming performance remain unknown. In addition, such tests are highly dependent on controlled pacing methods (i.e., underwater LED light signal system) or knowledge of and experience with interval training or competitions. Because swimming performance is strongly related to stroke biomechanics, existing pool-based swimming protocols may not provide a practical or reliable measure for a less economical swimmer (4,10).

A concise, intensity self-regulated pool protocol could shorten test duration, enabling an accurate assessment of $\dot{V}O_2max_{sw}$ during free swimming. Da Costa et al. used a pool-based "beep" test protocol that increased swimming velocities in 25-m increments. The test established reliability and validity of an aerobic endurance test in fitness swimmers using HR and perceived exertion as criterion variables to predict performance (11). Although considered promising for its application, further validation using methods that assess physiological and swimming stroke parameters is warranted. Nagle et al. (43) observed moderate to strong reliability of $\dot{V}O_2max$ measurements in women who underwent a standardized shallow water running test of cardiorespiratory fitness. The shallow water protocol used an incremental paradigm where intensity was self-regulated to produce predetermined OMNI scale ratings of perceived exertion (RPE) (56). The OMNI scale aquatic format provided visual and verbal cues linked to the target RPE. Results of this study were in agreement with previous investigations that demonstrated the accuracy and efficacy of an intensity self-regulated land-based format to assess $\dot{V}O_2max$ (17,19,38). It is probable swimmers are more motivated to perform maximal intensities if distances and durations of the test protocol are comparatively brief (24,32). Kalva-Filho et al. demonstrated that a 3-minute all-out tether protocol to assess critical power during swimming was strongly associated with $\dot{V}O_2max$ and 400-m swimming performance time (31,32,47,49). It follows that an intensity self-regulated free swimming protocol that provides a valid measure of $\dot{V}O_2max_{sw}$ would promote subject motivation and be easily administered to recreational and competitive swimmers. Therefore, the present investigation was designed to examine the reliability and validity of an intensity self-regulated incremental pool-based swimming protocol to measure $\dot{V}O_2max_{sw}$ in recreational and competitive swimmers. A unique feature of the present design was the use of swimming time as the criterion measure to establish "performance validity" of an intensity self-regulated $\dot{V}O_2max_{sw}$ test protocol. The rationale underlying this validation procedure was based on the assumption that maximal responses derived from the swim performance protocol and the incremental swim protocol are similarly regulated by the body's capacity to transport and use oxygen during aerobic exercise (48).

Methods

Experimental Approach to the Problem

This study used a multiple-observation, within-subject, counterbalanced design. Subjects were habituated to the protocol through an orientation practice session. On separate days, 2 incremental freestyle swimming maximal aerobic power tests ($\dot{V}O_2max_{sw}$ A and $\dot{V}O_2max_{sw}$ B) and 2 swim performance trials were administered. The 4 experimental test trials were separated by at least 2 but not more than 7 days.

Subjects

Twenty-nine male ($n = 15$) and female ($n = 14$) subjects (mean ± *SD*: age = 23.1 ± 6.5 years) were recruited from the Greater Pittsburgh area. Physical characteristics of the study subjects are presented in Table 1. Subjects were included in the study if they met the following criteria (1): 18–45 years old (3); comfortable swimming in shallow water (4); intermediate-level swimmer or higher (able to complete 182 m of freestyle with rhythmic breathing in <4 minutes); and (6) currently physically active. After initial contact, potential subjects were screened using a medical inventory and the Physical Activity Readiness Questionnaire (61). If eligible, subjects were informed of benefits and risks of participation, signed the informed consent document, and were scheduled for an orientation session. All procedures were approved by the Institutional Review Board of the University of Pittsburgh (Table 1).

Procedures

Orientation Session. On arrival at the laboratory, standing height (cm) was measured followed by body composition assessment using the Bod Pod Body Composition System (Cosmed, Chicago, IL) by air displacement plethysmography (39). All pool tests were conducted in the University of Pittsburgh's indoor swimming pool, measuring 22.9 m in length. Water depth for testing was 1.3 m and water temperature maintained at 27.5° C. The orientation trial controlled for test familiarization bias that may have occurred in subjects who had not previously undergone a $\dot{V}O_2max_{sw}$ test in a swimming pool.

Subjects were given a written explanation of the protocol and shown a video (filmed by investigators at the pool where test trials were conducted) depicting the pool-based $\dot{V}O_2max_{sw}$ test. Subjects were fitted with the Polar HR monitor (model T131, Port Washington, NY) and Cosmed respiratory mouthpiece and nose clip (Chicago, IL). They then performed two 22.9-m pool lengths per stage of the swimming test protocol as rehearsal for the $\dot{V}O_2max_{sw}$ trial that was conducted on a separate day. To become familiar with test procedures and the Cosmed AquaTrainer (Chicago, IL) metabolic measurement system, test stages were perceptually self-regulated to produce low- (50%), moderate- (70%), and high-intensity (90%) swimming speeds. Expired ventilatory volume (VE) ($L \cdot min^{-1}$; Standard Temperature and Pressure, Dry) and respiratory O_2 consumption ($L \cdot min^{-1}$) and CO_2 ($L \cdot min^{-1}$) production were analyzed in 15-second intervals by the calibrated Cosmed K4b and AquaTrainer (Chicago, IL) portable respiratory-metabolic system during the orientation session, and subsequent aquatic experimental trials. The AquaTrainer and portable metabolic unit were suspended above the subject using a cable pulley system that was moved by a technician in conjunction with self-regulated speeds and permitted a standard freestyle stroke. The AquaTrainer system provided an in-pool, continuous measurement of $\dot{V}O_2$ and calculated respiratory exchange ratio (RER). The pulley system necessitated an "open" style of turn where subjects were required to grasp the pool's edge with their hand while executing a wall push with the feet at the beginning of each pool length. All subjects were required to practice the open-wall turn and transitions. Once subjects felt comfortable with each stage of the protocol, they were familiarized with the Aquatic OMNI (0–10) RPE scale (43,44). A standard set of OMNI scale rating instructions and anchoring procedures was used. The OMNI scale was in full view of the subject during orientation, $\dot{V}O_2max_{sw}$ tests, and performance swim (PS) trials. Ratings of perceived exertion for the overall body were designated a dependent perceptual variable and obtained by having subjects touch the desired numerical category

Table 1

Descriptive characteristics (mean ± *SD*) of subjects.*

Characteristic	Total (*n* = 29)
Age (y)	23.1 ± 6.5
Height (cm)	173.4 ± 8.6
Mass (kg)	70.4 ± 11.4
BMI ($kg \cdot m^{-2}$)	23.5 ± 3.0
Body fat (%)	18.9 ± 8.2
Fat-free mass (kg)	56.1 ± 11.7
45.7-m performance swim (s)	31.2 ± 4.5
182-m performance swim (s) yrd	159.2 ± 25.5
$\dot{V}O_2max_{sw}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	44.2 ± 7.7
HRmax ($b \cdot min^{-1}$)	177 ± 9.0
O_2 pulse ($ml \cdot beat^{-1}$)	0.2 ± 0.0
RERmax	1.0 ± 0.1
VEmax ($L \cdot min^{-1}$)	95.2 ± 20.7
IPE-RPE (OMNI, 0–10)	9.6 ± 0.7
IPE [BLa] ($mmol \cdot L^{-1}$)	10.4 ± 3.1

*BMI = body mass index; HR = heart rate; RER = respiratory exchange ratio.

rating on an OMNI scale attached to the pool's edge. The OMNI scale is used by health-fitness professionals and coaches to objectively evaluate an individual's perceived level of effort, strain, discomfort, and fatigue that is felt during aerobic or resistance exercise (55,56).

$\dot{V}O_2max_{sw}$ Trials. $\dot{V}O_2max_{sw}$ trials A and B were administered using a pool-based, intensity self-regulated incremental swimming protocol similar to the aerobic endurance testing protocol of Da Costa et al. and the shallow water running protocol validated by Nagle et al. (12,43) Subjects were fitted with the Polar HR monitor, facemask, and mouthpiece described previously. The protocol involved swimming a minimum of 229 m (10 pool lengths) using the freestyle stroke. Rest periods regulated by investigators followed each 22.9-m length and decreased systematically from 10 to 3 seconds as the test progressed to termination. During the brief rest periods, subjects were provided both visual and verbal cues related to the required intensity for the subsequent stage. The perceptual cues instructed the subject to produce moderate, hard, very hard, and maximal intensities corresponding to 4–6, 6–8, 8–9, and >9 on the OMNI-RPE scale as required by the incremental test protocol (43,55) (Table 2). These targeted perceptual intensities approximated 40–85% of oxygen uptake reserve ($\dot{V}O_2R$) or 65–95% of HR reserve as specified by the American College of Sports Medicine (ACSM) (1). Following completion of 10 pool lengths, subjects swam continuously at maximal velocity until $\dot{V}O_2max_{sw}$ was achieved or until volitional termination occurred owing to fatigue. This was followed by a cool-down of low-intensity swimming for 3 minutes, or until HR decreased to <110 $b \cdot min^{-1}$ (46).

Immediate postexercise blood lactate (IPE [BLa]), immediate postexercise RPE (IPE-RPE), HR, and RER were measured for each $\dot{V}O_2max_{sw}$ test. A 5-μL plasma capillary lactate sample was obtained from a finger before warm-up and immediately after the test for the 2 incremental swimming trials and the swimming performance tests. Plasma lactate concentration was analyzed using the Lactate Pro (Arkray Inc., Kyoto Japan) monitor. $\dot{V}O_2max_{sw}$ was defined as a change in $\dot{V}O_2$ of <2.1 $ml \cdot kg^{-1} \cdot min^{-1}$ with increasing exercise intensity and the highest $\dot{V}O_2$ achieved at maximal swimming intensities. Secondary $\dot{V}O_2max_{sw}$ test criteria included one or more of the following: (a) a RER >1.10 (defined as ratio of $[CO_2]$: $[O_2]$); (b) HR ± 5 $b \cdot min^{-1}$ of the age-predicted maximum; (c) an RPE-OMNI > 9; (d) volitional termination due

Table 2

$\dot{V}O_2max_{sw}$ swimming pool protocol.*

Stage	Intensity	OMNI-RPE	Lengths†	Rest period
1	50% (moderate)	4–6	4	10 s
2	70% (hard)	6–8	3	5 s
3	90% (very hard)	8–9	2	3–5 s
4	100% (maximal)	>9	4–6	Continuous/termination

*Intensity and OMNI-RPE, targeted perceptual intensities. Rest period, rest time between pool lengths.
†Lengths: 1 pool length = 22.9 m.

to exhaustion (45); and (e) blood lactate >8.0 $mmol \cdot l^{-1}$ (14,15). Procedures for experimental trial B were identical to those for trial A. Within one week, subjects undertook Performance Swim tests: a 45.7- and 182-m PS in a counterbalanced order on the same day. Subjects underwent a swimming warm-up of 250–450 m at a self-selected speed that included 100% of their maximal velocity using a freestyle swimming stroke. A minimum of 10-minute recovery (including 3–5 minutes of swimming at 50% effort or less) or until HR was <110 $b \cdot min^{-1}$ was allowed between performance trials (40,46,65). Performance time measured using an Accusplit digital stopwatch (Pleasanton, CA) was recorded to the nearest 100th of a second. IPE [BLa], RPE, and HR measures were obtained after each performance trial, followed by a swimming cool-down ad libitum or until recovery HR was <110 $b \cdot min^{-1}$.

Statistical Analyses

Sample size calculations showed that 19 subjects would provide 80% power at a 0.05 significance level to reject the null hypothesis that the Pearson's correlation is 0 assuming a true underlying value of 0.60 with 2 tests ($\dot{V}O_2max_{sw}$ trials and PSs). Descriptive statistics were calculated for all variables. The assumption of normality was assessed using Shapiro-Wilk test. The level of significance was set a priori at $p \leq 0.05$, 2-tailed. Test-retest reliability of the pool-based $\dot{V}O_2max_{sw}$ A and B was determined using an Intraclass Correlation (ICC (2, 1)) and 95% confidence intervals (CI) for $\dot{V}O_2max_{sw}$, HRmax, VEmax, IPE-RPE, O_2 pulse ($\dot{V}O_2max_{sw}$/HRmax), and IPE [BLa]. The *SEM* and minimal differences needed to be considered real were also calculated. Validity of the pool-based $\dot{V}O_2max_{sw}$ tests was assessed using Pearson correlation and Spearman coefficients. Correlations were calculated between the graded swim protocol and PS tests (45.7 and 182 m swims) for $\dot{V}O_2max_{sw}$ A, HRmax, VEmax, IPE-RPE, O_2 pulse, and IPE [BLa]. Only data from the $\dot{V}O_2max_{sw}$ A trial were used to simulate application where little to no practice/orientation would typically occur for a subject before an initial swimming session. In addition, Bland-Altman plots were used to evaluate concordance between $\dot{V}O_2max_{sw}$ A and B trials including systematic bias, patterns of error, and a 95% CI for observed differences between methods (limits of agreement) (7).

Results

$\dot{V}O_2max_{sw}$: Test Reliability

Twenty-nine subjects completed the $\dot{V}O_2max_{sw}$ A and $\dot{V}O_2max_{sw}$ B trials. Results of test-retest reliability assessment for cardiorespiratory (CR) and perceptual responses measured during the $\dot{V}O_2max_{sw}$ A and $\dot{V}O_2$ max_{sw} B trials are presented in Table 3 (Table 3). The study sample consisted of approximately equal number of men and women, a distribution representative of the general population. As such,

Table 3
Test-retest reliability of $\dot{V}O_2max_{sw}$ protocol (n = 29).*†

Variable	$\dot{V}O_2max_{sw}$ trial A	$\dot{V}O_2max_{sw}$ trial B	ICC (95% CI)	*p*	*SEM*	MD
$\dot{V}O_2max_{sw}$ (ml·kg^{-1} ·min^{-1})	44.2 ± 7.7	42.9 ± 8.5	0.899 (0.79, 0.95)	<0.001	2.59	7.19
HRmax (b·min^{-1})	177.5 ± 8.5	178.1 ± 9.0	0.586 (0.18, 0.82)	0.004	5.57	15.45
O_2 pulse (ml·beat^{-1})	0.2 ± 0.0	0.2 ± 0.0	0.833 (0.62, 0.93)	<0.001	0.02	0.04
RERmax	1.0 ± 0.1	1.0 ± 0.1	0.538 (0.22, 0.75)	0.001	0.06	0.17
VEmax (L·min^{-1})	95.2 ± 20.7	94.3 ± 21.2	0.785 (0.59, 0.89)	<0.001	9.68	26.84
IPE-RPE (OMNI, 0–10)	9.6 ± 0.7	9.5 ± 0.6	0.043 (−0.46, 0.51)	0.436	0.64	1.78
IPE [BLa] (mmol·L^{-1})	10.4 ± 3.1	10.3 ± 2.5	0.619 (0.32, 0.80)	<0.001	1.72	4.76

*SEM = standard error of measurement; MD = minimal differences needed to be considered real.
†$\dot{V}O_2max_{sw}$ values reported as mean ± *SD*; ICC values reported as r (95% CI).

findings are presented as a combined sample of men and women to better represent the general population. Intraclass correlations indicated strong test-retest reliability for $\dot{V}O_2max_{sw}$ (ICC = 0.899, $p < 0.001$), O_2 pulse (ICC = 0.833; $p < 0.001$), and VEmax (ICC = 0.785; $p < 0.001$) determined for the 2 repeated incremental swim trials. In addition, $\dot{V}O_2$ (ml·kg^{-1}·min^{-1}) by test stage was found to be reliable (ICC = 0.660–0.899; $p < 0.001$) (Table 4). A moderate test, retest reliability was observed for HRmax (ICC = 0.586; $p < 0.004$), RERmax (ICC = 0.538; $p < 0.001$), and IPE [BLa] (ICC = 0.619; <0.001). Intraclass correlation for the IPE-RPE was not significant ($p = 0.436$). Bland-Altman analyses revealed a systematic error for $\dot{V}O_2max_{sw}$ trials with a slightly negative mean bias (−1.29 ml·kg^{-1}·min^{-1}), which indicates that subjects did better during trial A as compared with trial B, but this difference was not statistically significant. The limits of agreement were narrow (−8.14 ml·kg^{-1}·min^{-1}; 5.56 ml·kg^{-1}·min^{-1}), indicating good test-retest reliability (Figure 1).

$\dot{V}O_2max_{sw}$ Validity

To assess validity of the $\dot{V}O_2max_{sw}$ test protocol, CR and perceptual responses were correlated to the 45.7- and 182-m PS swim time (Table 5). Twenty-nine subjects completed both the $\dot{V}O_2max_{sw}$ A and PS time trials. Moderate negative correlations were found between 45.7-m PS time and $\dot{V}O_2max_{sw}$ A ($r = -0.543$; $p < 0.01$), as well as VEmax ($r = -0.628$; $p < 0.01$), and O_2 pulse ($r = -0.501$, $p < 0.01$). There were moderate negative correlations between the 182-m PS time and $\dot{V}O_2max_{sw}$ A ($r = -0.486$; $p < 0.01$) and VEmax ($r = -0.475$; $p < 0.01$) but not O_2 pulse ($r = -0.334$, $p > 0.05$). There were no significant correlations found between 45.7- and 182-m PS tests and IPE [BLa], RERmax, and IPE-RPE ($p > 0.05$).

Discussion

The findings indicated that the intensity self-regulated $\dot{V}O_2max_{sw}$ protocol for a pool-based setting demonstrated strong test-retest reliability. This is the first such paradigm to use indirect calorimetry to measure oxygen consumption during a pool-based, incremental self-regulated maximal oxygen uptake protocol. The test, retest measures of $\dot{V}O_2max_{sw}$ showed stronger reliability ($r = 0.89$) than previous investigations of land-based protocols and a shallow water running protocol that used a self-regulated intensity format (37,42,43).

A number of previous studies have examined $\dot{V}O_2$max using free swimming, tethered swimming, or swimming flume protocols. However, the present investigation used a pool protocol that used a self-regulated incremental intensity strategy similar to land-based protocols (16,18). This intensity self-regulated protocol offers several advantages. The protocol ranged between 6 and 10 minutes in duration and well tolerated by subjects. Stage-by-stage increases in swimming intensities (i.e., velocity) were self-regulated by a perceptual cueing system learned during the orientation session. The cues prompted subjects to regulate swimming intensity to produce the progressive level of effort designated for each stage.

The ICC coefficients for $\dot{V}O_2max_{sw}$, HRmax, VEmax, and O_2 pulse ranged from $r = 0.56$ to 0.89. The ICC values for IPE-RPE and IPE [BLa] were not statistically significant, similar to findings observed by Lim et al. (37). In the present investigation, the nonsignificant relation of IPE-RPE between trials is supported by a low standard deviation observed at maximal swimming velocity. This limited variability during both trials occurred because the final (i.e., highest) numerical category was a 10, and rated accordingly at a maximal intensity (8). The IPE-RPE was approximately 9 (OMNI scale, 0–10) for trials A and B, indicating that subjects attained maximal effort at the point of test termination. Use of RPE as an end point criterion for graded exercising testing is consistent with ACSM guidelines (1). The ICC values between trials A and B for $\dot{V}O_2$ at 50% ($r = 0.66$), 70% ($r = 0.83$), and 90% ($r = 0.73$) were significant ($p < 0.001$). This supports the reliability of each $\dot{V}O_2$ value by stage, demonstrating the efficacy of a standardized $\dot{V}O_2max_{sw}$ pool test for a sample of young healthy male and female swimmers. Although these results may not be generalizable to a novice

Table 4.
Test-retest reliability of $\dot{V}O_2$ (ml·kg^{-1}·min^{-1}) by stage (n = 29).*†

Test protocol	$\dot{V}O_2$ trial A	$\dot{V}O_2$ trial B	ICC (95% CI)	*p*	*SEM*	MD
Stage 1 (50% effort)	31.6 ± 7.0	29.4 ± 7.7	0.660 (0.39, 0.82)	<0.001	4.35	12.06
Stage 2 (70% effort)	36.2 ± 7.9	34.8 ± 8.0	0.829 (0.67, 0.91)	<0.001	3.29	9.11
Stage 3 (90% effort)	39.3 ± 5.8	37.5 ± 8.7	0.733 (0.50, 0.86)	<0.001	3.87	10.72
$\dot{V}O_2max_{sw}$ (100% effort)	44.2 ± 7.7	42.9 ± 8.5	0.899 (0.79, 0.95)	<0.001	2.59	7.19

*MD = minimal differences needed to be considered real.
†$\dot{V}O_2$ values reported as mean ± *SD*; ICC values reported as *r* (95% CI).

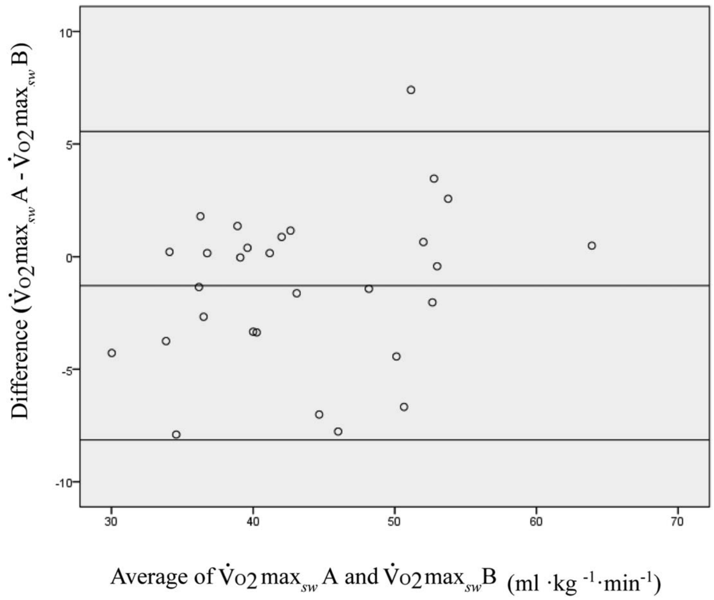

Figure 1. Bland-Altman plot for $\dot{V}O_2max_{sw}$ test reliability. The difference between $\dot{V}O_2max_{sw}$ A and $\dot{V}O_2max_{sw}$ B is shown on the y-axis. The dotted line shows the mean of the differences.

swimmer population, this study provides valuable insights to support the development of a standardized $\dot{V}O_2max_{sw}$ test protocol for military, clinical (i.e., those unable to participate in land-based testing), or nonswimming aquatic competitors (i.e., water polo and synchronized swimming).

The intensity self-regulated swim protocol provided a valid measure of $\dot{V}O_2max_{sw}$ in young adult female and male competitive and recreationally active swimmers. The R-values observed between $\dot{V}O_2max_{sw}$ A and the 45.7- and 182-m swim time indicated that the pool-based protocol yielded a moderately valid measure of maximal aerobic power. These results are slightly lower compared with previous investigations that related $\dot{V}O_2max$ to swimming time for distances of 50 m (r = 0.69), 100 m (r = 0.78–0.84), and 400 m (r = 0.75 to r = 0.93) (57–59). Possible factors explaining these differences could involve methodological issues such as PS trial distance (45.7 vs. 50 m; 182 vs. 100 or 400 m), wall turn method (open vs. flip), or test protocol (graded vs. continuous). The significant correlations for the other respiratory-metabolic responses measured in this study (i.e., HR, O_2 pulse, and VE) support "performance validity" of the intensity self-regulated protocol using 45.7- and 182-m swimming performance time as the criteria.

The present results were similar to other studies that substantiated the importance of aerobic contributions to energy demands of pool performances less than 3 minutes in duration (54,58). Examining the aerobic contribution to sprint swimming performance and related tasks is of value because recent studies have shown up to a 50% aerobic energy contribution to very high-intensity swimming performances such as 100-m events (50,53). This is insightful and may inform coaches regarding important considerations concerning the role of endurance training for sprint and power types of swimming or aquatic activity. This study's 45.7- and 182-m criterion measures of swimming performance were consistent with the experimental design of a larger overarching trial paradigm examining military combat swimming performance. It is likely that a longer duration swimming performance trial (>182 m) within the 7-day experimental testing period would have produced a comparatively stronger measure of "performance validity" because a larger aerobic energy contribution is required for maximal effort swimming greater than 3 minutes in duration (10,54). It should be mentioned that in the larger parent investigation, 14 of 29 subjects in the current study completed a 487-m freestyle performance trial, with a strong relation observed between swim time and $\dot{V}O_2max_{sw}$ ($r = -0.648$; $p < 0.01$), VE ($r = -0.509$; $p < 0.05$), HR, and O_2 pulse ($r = -0.558$; $p < 0.05$). However, these data were collected 8–12 months after the $\dot{V}O_2max_{sw}$ tests. Therefore, the ability to establish true performance validity using these data was limited due to possible temporal changes related to physical training or physical health status.

This investigation used 45.7- and 182-m freestyle swim times as the criteria to establish "performance validity" of an intensity self-regulated $\dot{V}O_2max_{sw}$ test protocol. Typically, $\dot{V}O_2max$ derived from a standardized land-based graded test protocol is used to examine validity of newly developed land-based tests of maximal aerobic power. This paradigm is not appropriate when validating a pool-based graded swim

Table 5

Performance validity of $\dot{V}O_2max_{sw}$ protocol: trial A vs. performance swims (n = 29).*†

Variable	45.7-m swim	182-m swim
$\dot{V}O_2max_{sw}$ (ml·kg^{-1}·min^{-1})	−0.543 (0.002)	−0.486 (0.008)
HRmax (b·min^{-1})	0.110 (0.636)	−0.187 (0.418)
O_2 pulse (ml·beat^{-1})	−0.501 (0.021)	−0.334 (0.139)
RERmax	−0.319 (0.091)	−0.238 (0.214)
VEmax (L·min^{-1})	−0.628 (<0.001)	−0.475 (0.009)
IPE-RPE	−0.025 (0.922)‡	0.176 (0.485)‡
IPE [BLa] (mmol·l^{-1})	−0.005 (0.924)‡	−0.058 (0.763)‡

*HR = heart rate.
†Pearson coefficients reported as r (p value).
‡Spearman coefficient reported as r (p value).

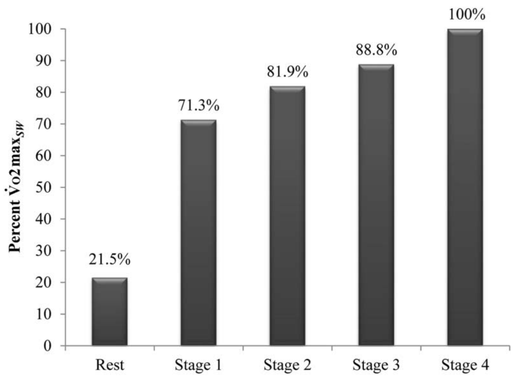

Figure 2. Percent $\dot{V}O_2max_{sw}$ by test stage. The percentage of $\dot{V}O_2max_{sw}$ achieved is shown on the y-axis.

protocol because the physical properties of the performance medium differ between a land-based protocol (i.e., air) and a pool-based graded intensity swim protocol (i.e., water). Maximal/peak physiological responses differ between land and water exercise test protocols when measured in the same individual (43). Therefore, it is inappropriate to use $\dot{V}O_2max$ derived from a land-based test protocol as a criterion measure to establish validity of a graded intensity swim test protocol. As an alternative paradigm, the present investigation used freestyle swim time as a criterion to establish "performance validity" of an intensity self-regulated swim protocol. The rationale underlying this validation procedure was based on evidence that maximal responses derived from both the swim performance protocol and the graded intensity swim test protocol are similarly regulated by each of the rate limiting links within the oxygen kinetic chain i.e., (a) alveolar ventilation, (b) hemoglobin flow rate, and (c) muscle cell oxidative phosphorylation (48). It was anticipated that once "performance validity" was established for the protocol developed presently, it could subsequently be used as the criterion to validate other pool-based graded intensity swim tests of $\dot{V}O_2max_{sw}$.

The pool-based, intensity self-regulated protocol offered several advantages. The test protocol allowed use of a natural freestyle stroke, with total test duration lasting between 6 and 10 minutes. The mean IPE [BLa] (10.4 mmol·L^{-1}) and IPE-RPE (9.6) satisfied the secondary criteria for attainment of a valid measure of $\dot{V}O_2max_{sw}$. Furthermore, the intensity self-regulation strategy met the targeted $\dot{V}O_2$ prescribed for each test stage with the exception of a modest overshoot at stage 1 (Figure 2). This aerobic metabolic overshoot is consistent with previous protocols where intensity exceeded the prescribed level at the onset of a graded exercise test but established congruence with expected metabolic cost for subsequent stages. Such a response was likely due to transient sympathetic outflow with the onset of exercise (28,33).

Future investigations should use a longer practice trial in the orientation session. This modification will provide subjects with additional practice in swimming with the AquaTrainer and pulley system. Using an intensity self-regulated strategy, the present protocol systematically increased aerobic metabolic requirements from the lowest to highest intensity test stage. A follow-up study should explore performance validity of the $\dot{V}O_2max_{sw}$ test protocol using criterion distances greater than 182 m and evaluating individuals who participate in swimming for rehabilitative or noncompetitive health-fitness purposes.

Practical Applications

This study's pool-based self-regulated intensity protocol is a novel approach to assessing maximal aerobic power in recreational and competitive swimmers and offers several application benefits. Assessment of aerobic power is vital to swimming coaches and trainers because it serves as both a baseline measure as well as both a monitoring and motivational tool for the evaluation of training progress. Understanding results of a maximal aerobic power swimming test would assist with training considerations for both competitive endurance (>182 m) and sprint (45.7 and 182 m) events, as well as competitions and tasks where repeated sprint ability is necessary such as water polo, lifeguard rescue, or military operations (6,50,60).

For a recreational, competitive, or vocational (i.e., military) focus where propulsion is essential, a swimming pool protocol can provide the most accurate and reliable modality-specific test of maximal aerobic power. This protocol also offers an alternative for those unable to undergo land-based assessments, such as clinical or injured populations. The development of a pool-side swim test protocol is convenient and may be adapted for pools of various temperatures, lengths, or depths.

A self-regulated intensity protocol allows individual adjustment across a wide effort continuum. The protocol requires short swimming (22.9 m) distances repeated with brief rest periods allotted throughout the test. Given that targeted intensities fell within a preplanned perceptual range, the nature of the present protocol may be ideal and more appealing for testing cohorts of varying swimming abilities or skill level. Furthermore, the inclusion of both physiological and perceptual (i.e., RPE) measures of intensity can identify swimming stages (i.e., 50–100% effort) consistent with effective swimming intensity training zones (i.e., anaerobic threshold). In addition, the inclusion of performance stroke metrics (i.e., wearable monitors) could provide ancillary data regarding swimming efficiency and economy for training recommendations.

For strength and conditioning professionals and coaches, the development of a reliable and accurate test of maximal aerobic power using a pool-based intensity self-regulated protocol is an essential step toward the assessment of swimmers seeking to increase cardiorespiratory fitness and improve aerobic and anaerobic swimming performances.

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