

Simulated swimming: a useful tool for evaluation the VO₂ max of swimmers in the laboratory

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This study was designed to develop a simulated swimming exercise (SS) so that peak VO₂ would be assessed on swimmers in a laboratory setting. The subjects assumed a prone position on an incline bench and performed arm cranking on a Monark Rehab Trainer while performing a flutter kick against tension supplied by elastic cords. The SS test was compared to four peak VO₂ tests: treadmill running (RN), tethered swimming (TW), bicycle ergometry (B), and arm cranking (AC). Eleven male varsity swimmers underwent each of the five VO₂ max tests, and maximal cardiorespiratory indicators (HR, VE, VO₂, O₂ pulse, and RQ) were measured. The percentage of peak VO₂ obtained during SS was compared to RN, TW, B, and AC.

The SS test achieved 78 percent of RN, 91 percent of TW, 81 percent of B, and 124 percent of AC. There were no significant differences in VO₂ in ml/kg.min between SS and TW. As expected, RN and B were significantly higher, while AC was lower. Ten subjects performed the SS test twice on two separate days within one week. The reliability of VO₂ max in ml/kg.min was 0.95. The validity of VO₂ max in ml/kg.min in the SS test vs. RN was 0.68. The SS test is reliable and can be used as effectively as TW to assess the VO₂ max of swimmers in a laboratory setting.

Keywords: Simulated swimming, VO₂ max, tethered swimming

Maximal oxygen uptake (VO₂ max) is generally accepted as the best index of aerobic work capacity and cardiorespiratory fitness. An accurate assessment of VO₂ max or peak VO₂ is essential for evaluating the efficacy of various physical training procedures, since it reflects both the cardiovascular respiratory system's ability to transport oxygen and the muscle's ability to utilize it. The mode of exercise and the test protocol chosen to assess peak VO₂ depend on many factors, such as the age, sex, and fitness status of the athlete.

For the results to have an optimum practical significance, the exercise mode and the protocol must be as sport-specific as possible. In arm-trained athletes, the specificity of muscular adaptation is an

important factor in VO₂ max assessment. In swimmers, peak VO₂ has been performed with tethered swimming¹⁻⁴ and more recently, a swimming flume^{7,8}.

Ideally, swimmers should be tested in a swimming flume, or swimming treadmill. However, this procedure requires expensive apparatus which most laboratories do not have. Furthermore, the measurement of peak VO₂ during swimming is difficult because of environmental factors. In order to solve this problem, we developed a simulated swimming test which focused on upper body activities and was simple enough to be used in laboratories and training centres.

Method

Subjects

Eleven male varsity swimmers volunteered as subjects for this study. The subjects had been swimming regularly for at least three years. Written informed consent and medical clearance were obtained from each subject prior to testing. The physical characteristics of each subject are presented in *Table 1*.

Testing procedures

The subjects were tested once on each of five experimental peak VO₂ tests: treadmill running (RN), bicycling (B), arm cranking (AC), tethered swimming (TW), and simulated swimming exercise (SS). Before experimental testing, subjects were allowed to complete several practice sessions in order to familiarize themselves with the test apparatus and test procedures. The subjects were then randomly assigned to complete RN, B, AC, TW, and SS exercise tests within a three week period.

Table 1. Physical characteristics of the subjects

	Age (yr)	Height (cm)	Weight (kg)	Body fat (%)	LBW (kg)
N = 11	19.4	181.9	80.9	5.5	75.0
	+0.9	+3.6	+4.6	+3.3	+3.2

Values are mean and standard deviation

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Before the first experimental peak VO_2 test, their resting heart rate (HR), blood pressure, and body composition were measured. Each subject was tested in the afternoon and/or in the evening and at approximately the same time each day to avoid the effect of circadian rhythms. A discontinuous, progressive intensity (percentage grade or work load) test protocol was used for RN, B, AC, TW, and SS. Three-minute exercise bouts were alternated with five-minute rest periods. VO_2 and associated physiological parameters were determined during the last minute of each exercise intensity with the exception that during RN the time between one minute and 45 seconds and two minutes and 45 seconds was used as the sampling period.

Treadmill running (RN)

RN was performed using a Quinton motor-driven treadmill. The RN test for VO_2 max utilized Taylor's protocol with the exception that five-minute rest periods were used between bouts⁹. After five minutes of warm-up walking at 394 m/min at a 10 percent grade, the subject began to run at 188 m/min on a zero percent grade. Thereafter the treadmill grade was raised progressively by 2.5 percent for each three-minute exercise bout until the VO_2 values differed by less than 150 ml/min⁹. The peak VO_2 was considered the highest value of VO_2 sampled during this test.

Bicycling (B)

B was performed on a Monark bicycle ergometer. The B test for VO_2 was similar to that described by Astrand with the exception that three-minute exercise periods were used¹⁰. The pedaling frequency was set at 50 complete pedal revolutions per minute and was regulated by a metronome. The resistance scale was carefully calibrated, and the seat height was adjusted for each subject. After a five-minute warm-up pedaling at a work load of 25 watts, the subject began to pedal at a work load of 100 watts. Thereafter bicycle ergometer work load increased progressively by 50 watts for each three-minute exercise bout until the VO_2 leveled off or declined. The criterion for leveling off was an increase in VO_2 of 80 ml or less¹¹.

Arm cranking (AC)

AC was performed on a Monark Rehab Trainer which was securely bolted to a table. The subject sat on a wooden chair with his feet flat on the floor. The height of the axis connecting the crank handles was approximately parallel to each subject's shoulder level. The cranking frequency was set at 50 rpm and was regulated by a metronome. After a five-minute warm-up at zero watts, the subject began to crank at a work load of 25 watts. Thereafter arm ergometer work load increased progressively by 25 watts for each three-minute exercise bout. Each subject was required to crank until he could no longer continue and/or he could not keep cadence with the metronome. The peak VO_2 was considered the highest value of VO_2 obtained during the AC test.

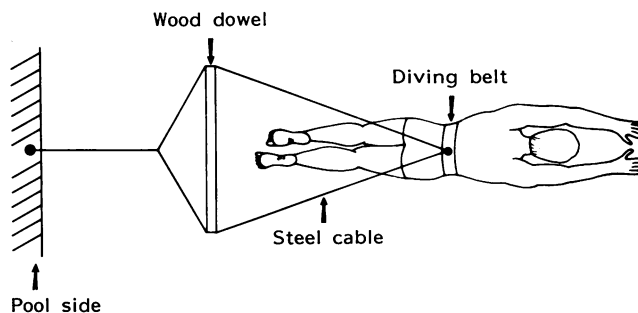


Figure 1. Schematic view of tethered swimming

Tethered swimming (TW)

The apparatus for TW was the same as that originally developed by Yeater *et al.* (Figure 1)¹². The front-crawl TW test was similar to that described by LePere and Porter³ and Magel and Faulkner⁴. The stroke frequency was set at 44 single arm strokes per minute and was regulated by a metronome. When the exercise period was initiated, the subject was required to swim hard enough to maintain the tension of the cable. A discontinuous procedure was repeated until the subject could no longer continue. The peak VO_2 was considered the highest value obtained during TW test.

Simulated swimming exercise (SS)

The SS test for VO_2 max was performed on a standard incline bench which had a 12 degree angle. The SS included both arm and leg exercises. Arm exercise was performed on a Monark Rehab Trainer. The Monark Rehab Trainer was set in front of the incline bench and was adjusted to the level of each subject's shoulder the same way as in the AC test. Leg exercise was performed by attaching elastic cords to the lower leg near the ankle and attaching the cords to two cushioned Swedish bars on the wall (Figure 2). The tension of the cords was adjusted so that it required an equal amount of work to raise the leg as well as to lower it.

The subject was asked to use the flutter kick and kick hard enough to hit the Swedish bars on the top and bottom on each manoeuvre. The arm and leg exercise frequency was set at 50 revolutions per minute. This cadence was regulated by metronome.

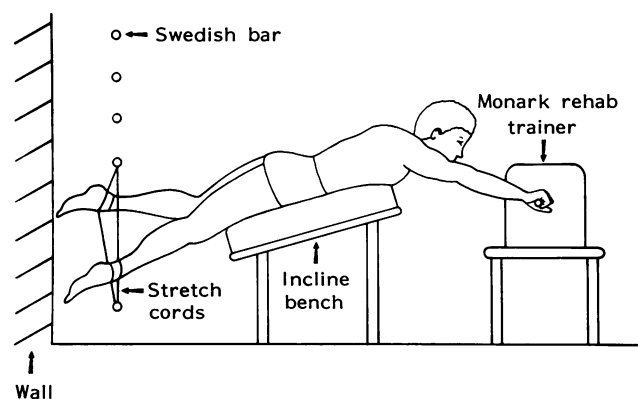


Figure 2. Schematic view of simulated swimming exercise

After five minutes of warm-up, the work load of arm exercise was set at 25 watts. Thereafter the work load of the arm ergometer was increased progressively by 25 watts until the subject could no longer continue and/or there was a decrease in the rate of arm ergometry and leg exercise. The peak VO₂ was considered the highest value of VO₂ obtained during the test.

Metabolic measurement

All metabolic measures obtained during the RN, B, AC, TW, and SS tests were determined by standard techniques of open-circuit spirometry. Expired air samples were collected in Douglas bags. Minute ventilation (VE max) was measured with a CD-4 gas meter (Parkinson-Cowen), and the fractional concentration of O₂ and CO₂ in expired air was analyzed with Beckman OM-11 and LB-2 analyzers, respectively. The analysers were calibrated prior to analysis with known reference gases. During the tests the electrocardiogram was obtained from the V₅ lead position and displayed on a Beckman Dynagraph Recorder and Oscilloscope (R-411). Recovery heart rate (HR) and blood pressure were recorded at the end of each minute through five minutes of recovery or until the HR was below 100 beats per minute.

Body composition

Body composition was determined by hydrostatic weighing using total lung capacity in the prone position¹³.

Reliability determination

A test-retest procedure was used to determine the reliability of the SS exercise. Ten of the subjects performed the SS exercise two times within one week.

Statistical analysis

A randomized complete block ANOVA and Duncan's New Multiple Range Test were used to evaluate the significance of the differences between the SS exercise and the other four types of tests for peak VO₂

and associated physiological variables. Pearson Product-Moment correlations were used to determine the validity coefficient for the SS exercise compared to the other four peak VO₂ tests and the reliability coefficient for the test-retest results. A paired t-test was employed to determine if there was a difference in the means for the test-retest values for the SS exercise. In all analyses, statistical significance was established at the 0.05 level.

Results

The mean and standard deviation of maximal values obtained during the five experimental maximal exercise tests are summarized in Table 2. The mean maximum heart rate (HR max) reached during five VO₂ max tests ranged from 182 beats/min (AC) to 202 beats/min (RN and B). ANOVA results showed no significant differences in the HR max attained in any test. Results of ANOVA showed a significant F ratio for the mean absolute (l/min) and relative (ml/kg.min) VO₂ max among the tests.

That is, the mean VO₂ max (l/min) during both RN (4.65 l/min) and B (4.49 l/min) were significantly higher than those achieved during AC (2.93 l/min), SS (3.65 l/min), and TW (4.03 l/min). The mean VO₂ max (l/min) during SS was significantly lower than RN and B values, 22 percent and 19 percent, respectively. Although the mean VO₂ max (l/min) during SS averaged nine percent below the TW values, no significant differences were found between these two tests.

Similarly, the mean VO₂ max (ml/kg.min) during SS (45.7 ml/kg.min) was significantly lower than that achieved during RN (58.3 ml/kg.min) and B (56.6 ml/kg.min). When comparing SS with TW (50.5 ml/kg.min), however, the mean VO₂ max (ml/kg.min) was not different. The validity coefficients of VO₂ max (ml/kg.min) between SS and TW, and SS and RN were 0.56 ($P = 0.05$) and 0.68 ($P = 0.01$), respectively (Table 3). VE max generally attained levels proportional to the VO₂ max. A significantly higher VE max (l/min) was observed during B (128.0 l/min) and RN (127.9 l/min) in comparison to AC (82.9 l/min); SS (103.7 l/min) was not significantly different from TW (104.0 l/min).

Table 2. Maximum physiologic values during five max tests

	HR _{max} beats/min	VE _{max} l/min	VO ₂ max l/min	VO ₂ max ml/kg.min	O ₂ /P ml/beat	R
RN ¹	202.0 ± 8.1	127.9 ± 17.5	4.65 ± 0.3	58.3 ± 4.2	23.1 ± 1.8	1.01 ± 0.04
B ²	202.0 ± 5.8	128.9 ± 18.1	4.49 ± 0.3	56.6 ± 5.9	22.2 ± 1.5	1.05 ± 0.09
AC ³	182.3 ± 14.2	82.9 ± 16.7	2.93 ± 0.4	36.8 ± 5.4	16.0 ± 2.2	0.91 ± 0.05
TW ⁴	192.5 ± 10.2	104.0 ± 17.8	4.03 ± 0.3	50.5 ± 4.0	20.9 ± 1.4	0.92 ± 0.10
SS ⁵	192.5 ± 6.1	103.7 ± 16.6	3.60 ± 0.3	45.7 ± 5.8	19.0 ± 1.7	0.92 ± 0.14

¹TW = Treadmill running test

²B = Bicycle ergometer test

³AC = Arm cranking test

⁴TW = Tethered swimming test

⁵SS = Simulated swimming test

HR = Heart rate

VE = Minute ventilation

VO₂ = Oxygen uptake

O₂/P = Oxygen pulse

R = Respiratory exchange ratio

Values are mean and standard deviation

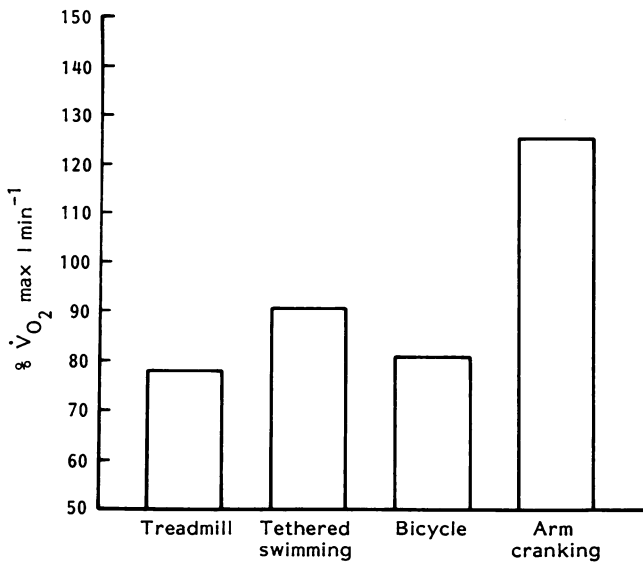


Figure 3. $\dot{V}O_2$ max as percentage of simulated swimming

Maximum oxygen pulse (O_2 /pulse max) was significantly higher during both RN (23.1 ml/beat) and B (22.2 ml/beat) when compared with SS (19.0 ml/beat), but there were no significant differences in O_2 /pulse max observed between TW (20.9 ml/beat) and SS values. Respiratory exchange ratio (R) was significantly higher during B (1.05) than SS (0.92), TW (0.92), and AC (0.91). No significant differences were demonstrated in R values between the TW and SS tests.

The reliability coefficients of $\dot{V}O_2$ max values for the SS test were 0.86 and 0.95 for absolute (l/min) and relative (ml/kg.min), respectively.

$\dot{V}O_2$ max as a percentage of the simulated swimming exercise is shown in Figure 3. The SS test achieved 78 percent of RN, 91 percent of TW, 81 percent of B, and 124 percent of AC.

The physical characteristics of the swimmers are shown in Table 1. These varsity athletes had physical characteristics that were representative of other competitive swimmers previously studied in the literature with a mean height of 181 cm, weight of 80 kg, and a body fat percentage of 5.5 percent.

Discussion

Assessing the $\dot{V}O_2$ max of swimmers is a problem for exercise physiologists. Swimming flumes are expensive and require a large amount of space, while tethered swimming is difficult because it is performed in a pool which requires equipment modification and transportation. Therefore, the purpose of this study was to develop a SS test to assess the $\dot{V}O_2$ max of swimmers in a laboratory using standard equipment. The subjects chosen to evaluate the effectiveness of the SS test were members of the men's varsity swimming team. Their physical characteristics indicate that they were representative of competitive swimmers studied in previous research.

Since the crawl stroke in swimming is performed in the horizontal position with the major force for forward motion being supplied by the arms, the

major components of the SS test included the arm cranking of the arm ergometer and flutter kicking of the leg exercise, with prone body position on the incline bench. No other study can be directly compared with our study. However, several researchers have studied the combined effects of arm and leg exercises versus bicycling or running. These studies indicate that combined arm and leg exercises elicit a $\dot{V}O_2$ max greater than that attained in a bicycling or running alone or equivalent to that attained in graded treadmill running^{9,14-19}. Results from the SS test did not confirm these findings.

The peak $\dot{V}O_2$ during the SS test was significantly lower than the peak $\dot{V}O_2$ observed during treadmill running or bicycling and confirms some previous observations^{5,7,20}. One possible explanation for low peak $\dot{V}O_2$ values is that the arm-to-leg work ratio was not the same in SS as in other studies. That is, Bergh *et al.* noted that the $\dot{V}O_2$ max was the same in running as in arm-plus-leg exercise when the arm workload was 20-30 percent of the total rate of work¹⁴ Bergh *et al.* also presented data on one canoeist who attained a 4.6 percent greater $\dot{V}O_2$ max in combined arm cranking and leg cycling than in treadmill running when arm cranking workload equaled 40 percent of the total combined workload¹⁴. Also, Seals and Mullin indicated that swimmers attained a 4.7 percent higher $\dot{V}O_2$ max in combined arm cranking and leg cycling than in graded treadmill running when arm cranking comprised approximately 20 to 25 percent of the total combined workload¹⁸. The leg work load in the SS test was much less than what would be expected from leg cycling, although the muscle mass utilized during RN or BI was probably greater than that used for the SS test.

RN and TW were used to establish the validity of the SS test because RN is most frequently used to evaluate the cardiovascular condition of athletes, and TW is similar to the real work situation of swimmers. Although the correlations of $\dot{V}O_2$ max (ml/kg.min) between RN and SS, and TW and SS were significant, the validity coefficients were relatively low (0.56 and 0.68, respectively). The validity coefficients of the $\dot{V}O_2$ max (l/min) were quite low and were not significant.

To more carefully evaluate the data, two of eleven subjects were eliminated from the statistical analysis. These two subjects complained of severe tightness in the forearms during the SS test and attained $\dot{V}O_2$ max values that were more than 30 percent below running values. No other subjects had that large a deficit going from RN to SS. The muscular mass used during the arm cranking exercise of the SS test is somewhat different from actual swimming. The subjects are required to use their wrists and fingers in order to grasp and crank the Monark Rehab Trainer. This might result in tightness of the forearm musculature with accompanying discomfort. Validity coefficients obtained on the $\dot{V}O_2$ max (l/min and ml/kg.min) were calculated for a reduced sample consisting of the remaining nine subjects.

When the values of peak $\dot{V}O_2$ (L/min) for the reduced sample were correlated against RN and TW, *r*'s of 0.60 and 0.72 were obtained for RN vs. SS and TW vs. SS, respectively. Validity coefficients of peak

Table 3. Validity coefficients for peak VO₂ comparing SS to RW and TW for 11 and 9 swimmers

		VO ₂ , L/min	VO ₂ , ml/kg/min
N = 11	RW	r = 0.29	r = 0.68*
	TW	r = 0.16	r = 0.56
N = 9	RW	r = 0.60*	r = 0.72*
	TW	r = 0.72*	r = 0.88*

* $P < 0.01$

VO₂ (ml/kg.min) for RN vs. SS and TW vs. SS were $r = 0.72$ and $r = 0.88$, respectively (Table 3).

All of the validity coefficients for both peak VO₂ in L/min and ml/kg.min and ml/kg.min were highly significant ($P < 0.01$). The relatively high correlations between RN and SS, and TW and SS for the reduced sample indicate that the SS test can be used to determine peak VO₂ for those swimmers who do not experience forearm tightness or cramping during the exercise.

The reliability of the SS test was established for two variables: peak VO₂ in L/min and peak VO₂ in ml/kg.min. Based on ten test-retest determinations, the SS test was found to be highly reliable with correlation coefficients of 0.86 (VO₂ max in L/min) and 0.95 (VO₂ max in ml/kg.min). The high reliability of the SS test suggests that a given individual uses the same muscle groups in repeated tests and that the test elicits the peak energy utilization that the active muscle can attain.

To determine whether the SS test could be used to estimate maximal aerobic capacities, the percentage of peak VO₂ (in L/min and ml/kg.min) attained during the SS test as compared to RN and TW was calculated for each subject (Figure 3).

The results of the calculations on peak VO₂ (L/min) in comparison to SS with RN indicated that the swimmers achieved 78.7 percent ($N = 11$) and 81.3 percent ($N = 9$) for their RN values. Similarly, peak VO₂ in ml/kg.min indicated that the swimmers achieved 78.2 percent ($N = 11$) and 80.5 percent ($N = 9$) of their RN values. Other investigators have found similar or higher values for VO₂ in combined arm and leg work and running. Astrand and Saltin reported that subjects achieved 95 percent of their treadmill running values in combined arm and leg work⁵. Bergh *et al.* reported that the VO₂ max during treadmill vs. arm-plus-leg exercise was the same¹⁴. Seals and Mullin reported that the swimmers had 4.7 percent higher VO₂ max in arm-plus-leg exercise than in running values¹⁸.

However, these conclusions were drawn on the basis of data collected while using two conventional bicycle ergometers or arm cranking plus bicycle ergometer exercise in an upright position, while the present study used arm cranking plus flutter kicking in the prone position. In this study, the involved muscle mass was smaller and the intensity of the leg exercise was less as compared to previous studies. Armstrong and Davies reported VO₂ values during a simulated swim test on a biokinetic swim bench²¹. The VO₂ max value on the swim bench (2.49 L/min)

was significantly lower (range from 14 percent to 48 percent mean 35 percent) than that achieved on the treadmill running (3.69 L/min).

This percentage decrement is larger than that obtained by the swimmers in the present study (approximately 21 percent). The reason for the lower VO₂ max in the study of Armstrong and Davies is probably the result of a smaller working muscle mass. Each swimmer only performed his principal competitive stroke (the upper limbs)²¹.

The percentage of RN peak VO₂ (L/min and ml/kg.min) attained in TW ranged from 85.5 to 86.6 percent. Other investigators have demonstrated similar values for VO₂ max in running and swimming. Holmer *et al.* reported that the mean VO₂ max during flume swimming was 94 percent of the value during running in highly trained swimmers⁸. LePere and Porter reported that the mean VO₂ max of recreational swimmers was 19 percent lower during tethered swimming than during running, but that the decrement was only nine percent for the skilled swimmers³. Astrand and Saltin stated that swimming values were 19 percent lower than those attained in graded treadmill running⁵.

The values for skilled swimmers in the present study were about 14 percent lower during the SS test than TW. Although the 14 percent decrement in this study is lower than those other investigators have shown, the differences in methodologies employed in the studies make them difficult to compare. For example, Holmer *et al.*⁸ used the swimming flume, while LePere and Porter adopted a tethered swimming system³. Also, the VO₂ max during running for the subjects of LePere and Porter was lower (4.29 L/min) than the values obtained for peak VO₂ in this study (4.65 L/min), while the VO₂ max during tethered swimming was almost the same, 3.92 L/min for LePere and Porter and 4.03 L/min for the present subjects³.

The results of the calculations on peak VO₂ (L/min) in comparing SS with TW indicated that the swimmers achieved 91.0 percent ($N = 11$) and 94.7 percent ($N = 9$) of the TW value, and similarly peak VO₂ (ml/kg.min) indicated that the swimmers achieved 90.5 percent ($N = 11$) and 94.0 percent ($N = 9$) of their TW value.

Conclusion

The discontinuous, progressively increased workload, maximal SS test is reliable. Its predicted power as defined by percent peak VO₂ obtained in RN in collegiate swimmers is 78 percent, and in TW is 91 percent. There was no significant difference in VO₂ in ml/kg.min between SS and TW. Although the literature on arm-leg work ratios suggests that the SS test might be improved by increasing the intensity of the leg work performed, it can be used as effectively as TW to assess the VO₂ of swimmers in a laboratory setting.

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