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Limb Power Outputs and Cardiopulmonary Responses in Swimmers

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Reproducibility of Limb Power Outputs and Cardiopulmonary Responses to Exercise Using a Novel Swimming Training Machine

RUNNING TITLE: Novel Swimming Training Machine

Abstract

The purpose of this study was to determine the reproducibility of limb power output and cardiopulmonary responses, to incremental whole-body exercise using a novel swimming training machine. Eight swimmers with a mean age of 23.7 ± 4.6 (yrs), stature 1.77 ± 0.13 (m) and body mass of 74.7 ± 2.8 (kg) gave informed consent and participated in repeat exercise testing on the machine. All subjects performed two incremental exercise tests to exhaustion using front crawl movements. From these tests peak oxygen consumption (VO_{2peak}), peak heart rate (HR_{peak}), peak power output (W_{peak}) and individual limb power outputs were determined. Results showed there were no significant differences between test 1 and 2 for any variable at exhaustion, and the CV% ranged from 2.8% to 3.4%. The pooled mean values were; VO_{2peak} 3.7 ± 0.65 $L.min^{-1}$, HR_{peak} 178.7 ± 6.6 $b.min^{-1}$ and W_{peak} 349.7 ± 16.5 W. The mean contributions to the total power output from the legs and arms were (37.3 ± 4.1 % and 62.7 ± 5.1 % respectively). These results show that it is possible to measure individual limb power outputs and cardiopulmonary parameters reproducibly during whole-body exercise using this training machine, at a range of exercise intensities.

Key words

Novel machine, leg-kick, arm-pull

Introduction

Laboratory-based ergometers, such as the swim bench have been used previously to study swimmers [6, 11, 21, 23, 25-27]. This has been mostly to assess arm power [3, 6, 8, 12, 31] but also to assess cardiopulmonary responses to exercise [25, 27, 28]. More recently, Swaine [30] has reported arm and leg power in swimmers during separate laboratory-based ergometer tests which attempted to replicate the front crawl arm-stroke and leg-kick. Konstantaki et al. [14] have reported cardiopulmonary responses to simultaneous front crawl arm and leg exercise. However, there are no previous reports which have measured the individual limb power outputs at the same time as cardiopulmonary parameters during incremental whole-body simulated swimming.

In swimming itself, the relative contribution from each limb to the total power generated during front crawl is unknown. The absence of such data is largely because it has been impossible to measure the individual limb power outputs during swimming itself. This is because the force applied by the swimmer partly results in propulsion but is also partly dissipated in moving water [33]. Knowledge of the relative contributions to the total power output from each of the swimmer's limbs might enhance understanding of the priciples of front crawl swimming.

Previously, it has been possible to measure the propulsive power that results from the work done by the swimmer [9] and the leg-kick was shown to contribute approximately 10% to the total front crawl swimming propulsive power. However, this study reports the resultant propulsive power during swimming and not the power output from the swimmer's limbs. Indeed, in a review by Toussaint and Beek [33] the assumption is made that since most propulsion comes from the arms in swimming, then the power output delivered by the swimmer will mainly come from the arms and trunk. However, there are no direct studies to support this. Quantification of power output from each limb during whole-body exercise on a machine might provide some insight into the contribution that each limb makes to the total power output of the swimmer during front crawl swimming.

The quantification of the contribution of each limb to the total power output during exercise on a swimming machine requires an ergometer capable of measuring power output from each limb and which allows manipulation of exercise intensity. A prototype ergometer has been detailed previously [14, 29]. Such an ergometer would allow incremental testing to exhaustion and it would permit the freely-chosen contribution that each limb makes, to total power output, to be assessed through a range of exercise intensities. This type of measurement has not been made previously. Accordingly, the purpose of this study was to assess the reproducibility of the limb power outputs and cardiopulmonary responses to repeated incremental exercise tests using a novel swimming training machine.

Methods

Subjects

Eight men of mean age 23.7 ± 4.6 (yrs), stature 1.77 ± 0.13 (m) and body mass 74.7 ± 2.8 (kg) (mean ± SD) performed two incremental exercise tests to exhaustion. The mean best times for 400m front crawl swimming within the 3 month period prior to testing were 262.7 ± 50 (s). Six of the eight swimmers were right-arm dominant, and seven were 'bilateral breathers' (with one swimmer breathing right-side only) during training. The participants were trained swimmers who, for the 6 months prior to the testing, completed a minimum of 6 swimming training sessions per week, of 1.5 hours duration. The study was conducted according to the ethical standards of this journal [7] and all participants gave written informed consent prior to participation and the study which was given approval by the University Ethics Committee.

The swimming training machine

Subjects performed exercise testing on a prototype novel whole-body swimming training machine which was built for this study and can be seen in Figure 1. Resistance to the movement of each limb was created by four air-dynes (Lawler Engineering, UK) which were mounted on spindles which rotated upon pay-out of pull-ropes, attached to hand-paddles or foot-plates. The design of the leg-kick ergometer allowed force to be exerted in the upward and downward kicking action but only during the pulling action of the arms, not during the

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recovery phase. On each air-dyne there was a photoelectric sensor which detected the revolution of the air-dyne. The revolution rate that each air-dyne made was passed into a computer where power was derived using software which contained a previously-determined calibration algorithm. Subjects adopted a prone position and were instructed to simulate the front crawl swimming action as closely as possible (including arm recovery), attempting to achieve maximum pull and kick movements in each arm-stroke or leg-kick. Mean power output for leg-kick and arm-stroke was averaged over each arm-pull or leg-kick. After computation, the instantaneous mean power output for the combination of arm stroking and leg-kicking was fed back to the swimmer on a visual display unit. The power output of the swimmer was plotted against a 'target', so that the intensity of exercise could be manipulated. This was done in a similar way to that first detailed in Swaine [25].

Calibration of the air-dynes

For each air-dyne the relationship between force applied and revolution rate was determined by suspending known weights (0.5 to 4.5 kg) from the drive gear of the air-dynes. This calibration technique has been used previously [23, 26]. An algorithm was derived for use in the computer software used to feedback the power output to the swimmer.

Measurement of cardiopulmonary variables

Analysis of expired air was made using a breath-by-breath gas analysis system (Innocor, Innovision, Denmark). This system uses laser diode absorption spectroscopy for oxygen and photoacoustic spectroscopy for carbon dioxide analysis and a differential pressure sensor for determination of ventilatory flow rates. The VO_{2peak} was defined as the highest oxygen consumption value recorded. Heart rates were determined using a Polar heart rate monitor (Polar AB, Finland) which gave instantaneous values at 5 s intervals.

Determination of the reproducibility of peak responses to incremental exercise

Assessment of the reproducibility of the peak responses to exercise required the subjects' attendance at the laboratory on three occasions which were arranged at the same time of day.

The first visit was so that subjects could become accustomed to the swimming training machine and the incremental exercise test procedures. On each visit the swimmers performed an incremental exercise test to volitional exhaustion, however analysis of expired air was only made on the second and third visits. During the incremental test the power output 'target' on the visual display unit commenced at 100 W and was increased by 25 $W.min^{-1}$ and swimmers were permitted to meet the increasing demands through a freely-chosen combination of work from all four limbs at freely-chosen stroke rates. The maximal revolution rates of the air-dyne devices was 15 s^{-1} so that maximal pull velocity and stroke rates were close to those shown previously to best replicate free swimming [27].

Analysis of data

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Reproducibility was assessed by comparison of means (t) for test 1 and 2 and accompanied by coefficient of variation (CV%). Differences in submaximal limb power outputs and cardiopulmonary responses to the two tests were assessed using analysis of covariance (ANCOVA) for comparison of the slopes and elevations of the linear relationships between VO_2 and W, and between HR and W. This comparison was performed on individual and group mean relationships. Differences in individual peak limb power outputs were analysed using one-way analysis of variance (ANOVA) with TUKEY'S honestly significant difference (HSD) post-hoc test. Population normality was checked using Shapiro-Wilks and Levene's test was used to test for equality of variances.

Results

The mean values for VO_{2peak}, HR_{peak} and W_{peak} from test 1 and 2 are given in Table 1, along with statistical test values for differences, CV% and intra-class correlation. A Bland and Altman plot of test-retest differences in VO_{2peak} is given in Figure 2. There were no significant differences between test 1 and 2 for any variable at exhaustion (P<0.05). The CV% (with 95% CI) were 2.8% (1.4 to 3.6) for VO_{2peak}; 3.3% (2.0 to 5.4) for HR_{peak} ; and 3.4% (1.9 to 4.8) for W_{peak}. The pooled mean values of VO_{2peak}, HR_{peak} and W_{peak} were; 3.7 ± 0.65 L.min^{-1}, 178.7 ± 6.6 b.min^{-1} and 349.7 ± 16.5 W respectively. On average at exhaustion, the total power output from each limb was: 111 ± 12.3 W (W-RA_{peak}); 108 ± 13.1 W (W-LA_{peak}); 68.1 ± 9.1 W (W-RL_{peak}) and 62.6 ± 8.3 W (W-LL_{peak}). ANOVA revealed significant differences in these mean limb peak power values (F= 3.6; P=0.012). The Tukey HSD multiple comparisons revealed no significant difference between right and left arm (P<0.05) or between right and left leg (P=0.01), but the legs produced less power than the arms (P<0.01) This equated to approximate contributions of 29%, 33%, 16% and 22% for right arm, left arm, right leg and left leg respectively. The contribution to the total power output from both legs and both arms were (37.3 ± 4.1 % and 62.7 ± 5.1 % respectively). An example of the contribution made by each limb throughout an incremental test for one subject is given in Figure 3.

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The mean data for VO_2 at each incremental power output (W), for test 1 and test 2 are shown in Figure 4. Comparison of the submaximal relationships between VO_2 and W revealed that in all individuals this relationship was linear (r at least 0.89; p<0.05). The slopes were different in 3 of the eight participants (P<0.05), which precluded comparison of elevations. In the remaining 5 participants there was no difference in the slope (P>0.05) or elevation (P>0.05). The group mean relationship showed no difference in either slope (P=0.09) or elevation (P=0.07). For the HR vs W relationship, responses in all individuals were linear (r at least 0.93; p<0.05). The slopes were different in 1 participant (P<0.05), but in the remaining 7 participants there was no difference in the slope (P>0.05) or elevation (P>0.05). Again the group mean relationship for HR vs W showed no difference in either slope (P=0.1) or elevation (P=0.09).

(Figures 1 to 4, Table 1 here)

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Discussion

This study demonstrated that it is possible to assess cardiopulmonary responses to whole-body exercise which mimic the front-crawl swimming movements. Furthermore, it was possible to relate the cardiopulmonary responses to power output of the limbs throughout this exercise. The peak cardiopulmonary reponses to this exercise were shown to have small repeat-test coefficient of variation between 2.8 and 3.4%. There are no previous measures of reproducibility for whole-body exercise using a swimming machine, with which to compare the data from the present study, but these values compare favourably with previous values for arms-only swim bench exercise of 1.0 to 2.1% [26]. These values also compare well with reproducibility of peak cardiopulmonary responses to treadmill running [23] and cycle ergometer exercise [1].

The reproducibility of the responses recorded on the novel swimming training machine can be used to inform sample size requirement for future studies, as advocated by Hopkins [11]. For a crossover or simple test-retest study the number of participants required is based around precision, defined by the 95% confidence limit (deriving a power 0.8). Hopkins [11] calculates sample size as n= $8s^2/d^2$, where n is the sample size, s is the typical error and d is the smallest worthwhile effect. If d is presented as a proportion (%) of mean group score then CV% can be inserted for s. These figures are changed to n=32s2/d2 for a study using an experimental and control group. Using 0.2 of the between-subject variation as the smallest worthwhile change [5], the sample sizes required for these types of studies (based on the VO_{2peak} data) are presented in Table 2. These calculations suggest that this machine, protocol and gas analysis system could be used with relatively small groups of swimmers to detect small changes in VO_{2peak}. Indeed, an expected change in VO_{2peak} of ~2% would require between 4 and 26 participants, based on the current findings. This analysis indicates that the methods used in the present study could comfortably detect the large (11%) training-induced changes in VO_{2peak} reported previously in recreational swimmers [16] and might be able to detect the much smaller changes consistent with ergogenic supplementation.

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(Table 2 here)

There are only two previous studies with which to compare our whole-body incremental exercise measurements [13,14]. Konstantaki *et al.,* [14] reported VO_{2peak} values of 2.85 $L.min^{-1}$ for combined arm-stroke and leg-kick, but their measuresments were made on younger swimmers. Kimura *et al.*, [13] used simultaneous arm-cranking and leg-kicking and measured VO_{2peak} in varsity swimmers. In their study it was 3.6 ± 0.3 $L.min^{-1}$ and in ours it was 3.7 ± 0.63 $L.min^{-1}$, therefore our results confirm those of these previous studies. In the variety of studies that have assessed VO_{2peak} during flume and tethered swimming, the values have been 2.6 to 3.2 $lmin^{-1}$ [2, 10, 15, 20]. Therefore, our results for exercise using this novel swimming training machine appear to be similar to those of free swimming.

The individual limb peak power output values were somewhat surprising, especially the mean contribution made by the leg-kick (37.3%). These results could be suggestive that a much greater proportion of the total power output during swimming might be done by the legs than previously thought. Certainly, these relative contributions from arms and legs cast doubt on the previous suggestions that the power output delivered by the swimmer comes almost entirely from the arms and trunk [33]. Indeed, although we did not make a systematic analysis of the contribution that the legs made through all intensities of exercise, several of our swimmers generated higher power outputs from the legs than from the arms when nearing exhaustion.

There are no previous power output values with which to compare our results for whole-body power output using a swimming training machine. Swaine [28] reported separate peak power output values, at exhaustion, during incremental exercise using front crawl arm-stroke and leg-kick tests. The sum of the separate values from that study (170 W for arm-stroke and 141 W for leg-kick) is similar to our mean of 352 W but perhaps suggests that it is possible to generate a small amount of additional power by combining the upper and lower limbs in a synchronised way. Front crawl swimming is known to involve highly-skilled co-ordination of the leg-kick and arm-stroke in such a way as to achieve greatest forward propulsion [4].

Toussaint *et al*. [32] has reported power output values of swimmers from measurements using the fixed push-off pads of the MAD system [9]. However, measurements were only made for arm-stroke power output (leg-kick power was derived by subtracting arm power from whole-stroke power). Also, in that study it was not possible to precisely manipulate the exercise intensity in the same way that we did. Therefore, it is difficult to compare our power output values to those reported in the study by Toussaint *et al.* [32]. However, his reported power output values, estimated at 1000 W of 'power input', were between 50 and 120 W (as derived from arms-only swimming) which are much lower than our power output values and would represent approximately 20-30% of whole-body exercise power output at exhaustion in our subjects. Unfortunately, it is not possible to determine exactly what relative exercise intensity 1000 W represented in the study of Toussaint *et al.* [32] and therefore it is not possible to directly compare our power output values with such previous studies.

Simultaneous arm and leg work has been studied previously, using arm-cranking and cycling [22]. However, the freely-chosen contribution from the arms and legs was not assessed in this study. Rather, the contribution was set by the investigator. Nevertheless, this study showed that the additional oxygen uptake achieved when adding arm- to leg-work represented approximately 15% in this type of exercise. Similarly, Swaine and Zanker [27] showed that the VO_{2peak} during swim bench arms-only exercise was approximately 2.9 $L.min^{-1}$ and our results of 3.8 $L.min^{-1}$ for whole-body exercise would represent a 0.9 $L.min^{-1}$ or 31% increase in arms-only VO_{2peak}, due to addition of the leg-kick. Therefore, this difference in VO_{2peak} must be considered when interpreting data from previous reports that have used swim bench exercise.

The extent to which combining the arm-stroke and leg-kick enhances the total power output of the swimmer, during whole-body exercise, remains to be determined. It is unlikely to be simply represented by the sum of the separate arm- and leg-power outputs reported by Swaine [30]. The combining of the upper and lower body during swimming is known to enhance total power output by allowing transfer of energy between the limbs [17]. The combining of arm-stroke and leg-kick is likely to affect the total efficiency, at any given exercise intensity. Therefore, it might be expected that the oxygen cost for a given exercise intensity using combined arm-stroke and leg-kick would be lower than the sum of the oxygen cost values for separate arm-stroke and leg-kick. This could be studied by using the whole-body swimming training machine.

Also, it was notable during our investigation that ventilatory thresholds (as identified using breath-by-breath gas exchange) appeared to coincide with changes in the contribution of each limb to the total power output. Although it was not the purpose of this study to identify ventilatory thresholds, it appeared that quite marked changes occurred at these thresholds. Therefore, it might be useful in future studies, to systematically investigate the pattern of change in limb contribution, during incremental simulated swimming, and relate this pattern to the gas exchange or lactate markers of the onset of anaerobiosis. Currently, it is not known how the relative contributions of the arm-pull and leg-kick contribute to fatigue (lactate accumulation) or how fatigue influences the freely-chosen relative contribution from each limb.

Of course, we acknowledge that there are significant differences in the movement patterns of exercise using a machine, compared to 'free swimming' and this presents a limitation to the direct comparison between measurements made in the laboratory and during swimming itself. For example, during exercise on a machine there is restriction of body roll, which is known to be an important aspect of front crawl swimming [19]. However, the arrangement of the swimmer in a suspended 'cradle' appeared to allow greater body roll than that seen in previous swim bench work [25, 27]. Also, the 'cradle' that we used was foreshortened so that it did not restrict the movement of the thoracic cavity as much as has been experienced when using the swim bench [26]. However, it has been shown previously, through EMG measurement, that the movement patterns of dry land training devices are quite different to those of free swimming [18].

In addition to the restricted body roll, the swimming training machine cannot quantify power generated by the swimmer's limbs during many of the lateral or rotational movements of the hands and feet. These movements are known to be important components of the front crawl swimming technique. Indeed, the current arrangement of the pulley-ropes means that tension is only developed in the direction dictated by the fixed point of the pulley. This presents a further limitation of exercise on the swimming training machine. Therefore, machine-based exercise in swimmers has limitations in its direct application to free swimming. Of course, future studies with this novel machine would be required, to establish the extent to which power output from the limbs and cardiopulmonary responses during such exercise are reflective of swimming itself.

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Table 1 Mean values and reproducibility measures for peak oxygen consumption (VO_{2peak}), peak heart rate (HR_{peak}) and peak total power output (W_{peak}) from the novel swimming training machine.

Table 2 Sample size calculations based on the methods described by Hopkins (2000), using the 95% confidence interval for the CV (1.4 – 3.6%). The smallest worthwhile change (d) was derived as 0.2 of the between-subject variation from (a) the pooled data from the current study, (b) the pre-intervention data of Magel et al. (1975), and (c) tethered swimming data from Bonen et al. (1980).

Figure 1 Photograph of the prototype novel swimming training machine showing, the leg air-dynes to the rear, the use of a suspended 'cradle' for body support, and pulley ropes used to drive the four air dynes.

Figure 2 A Bland and Altman plot of individual test-retest differences in VO_{2peak}

Figure 3. An example of the relative contribution of each limb to total power output during incremental whole-body simulated swimming to exhaustion.

Figure 4. The group mean data for VO_2 and total power output (W) during incremental exercise tests 1 and 2, using the novel swimming training machine.

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Figure 1. Photograph of the novel swimming training machine.
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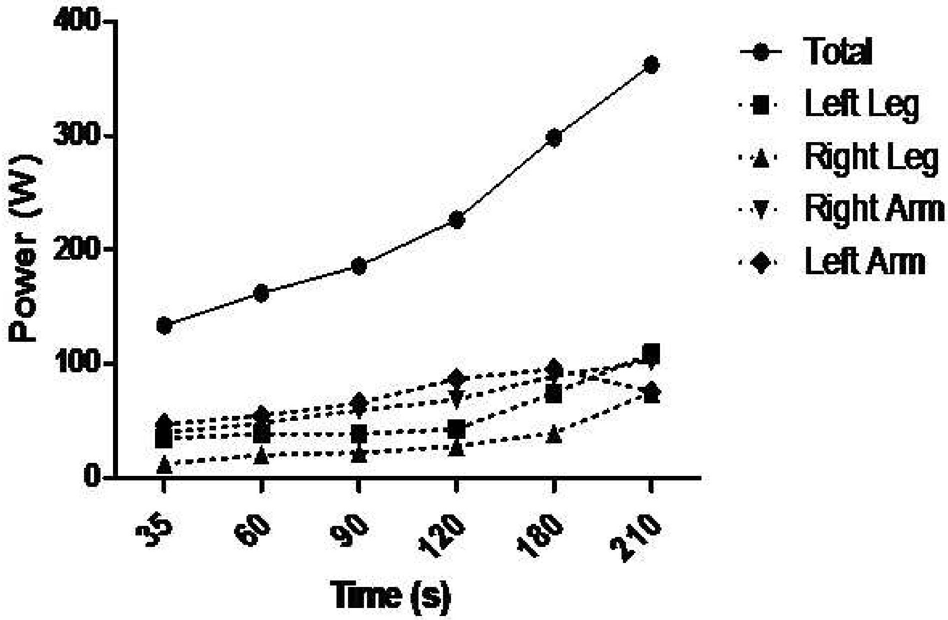

Figure 2. An example of the relative contribution of each limb to total power output during exhaustive incremental exercise using the novel swimming training machine.
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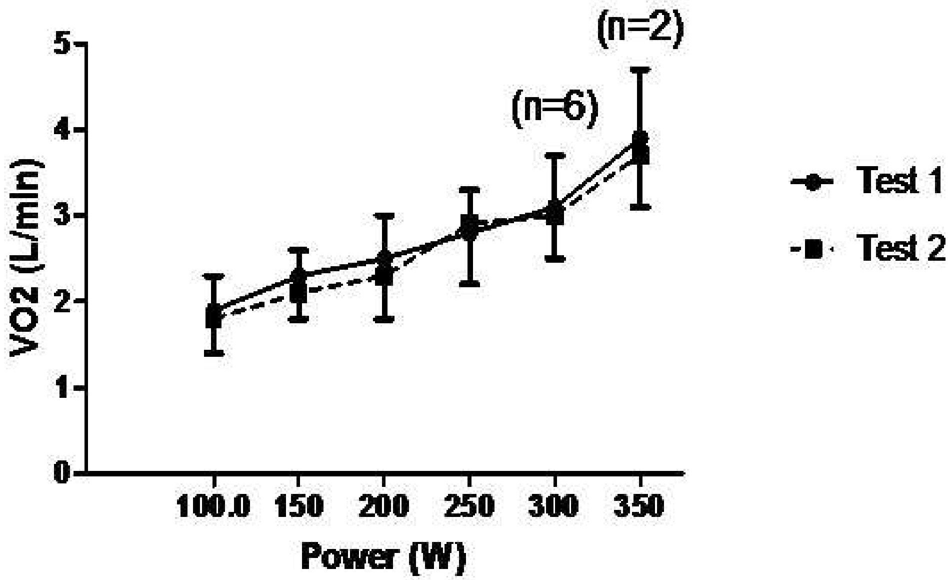

Figure 3. The group mean relationships between VO2 and total power output (W) during incremental exercise test 1 and test 2, using the novel swimming training machine.
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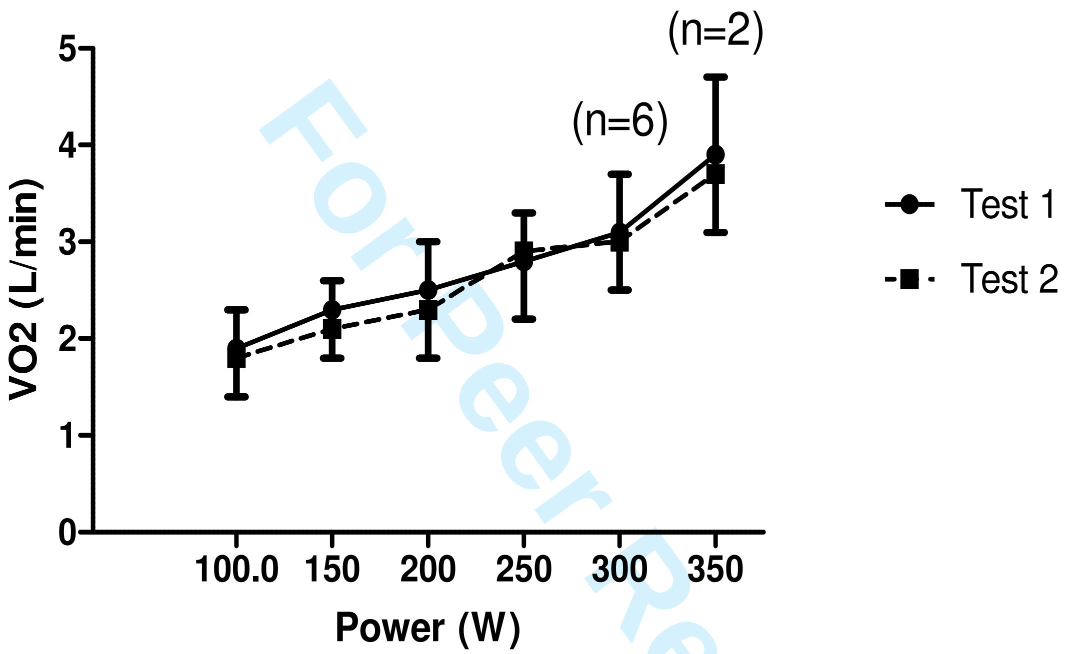

Figure 4. The group mean data for VO_2 and total power output (W) during incremental exercise tests 1 and 2, using the novel swimming training machine.

Table 1 Mean values and reproducibility measures for peak oxygen consumption (VO_{2peak}), peak heart rate (HR_{peak}) and peak total power output (W_{peak}) from the novel swimming training machine.

	Mean test 1	Mean test 2	t-test	CV%	Correlation
VO_{2peak} ($L.min^{-1}$)	3.68± 0.65	3.72 ± 0.61	t=1.4; p=0.7	3.4	r=0.94; p=0.01
HR_{peak} ($b.min^{-1}$)	177.7 ± 6.6	180.2± 6.2	t=3.7; p=0.01	2.8	r=0.92; p=0.01
W_{peak} (Watts)	345.7 ± 15.2	356.7 ± 16.0	t=4.9; p=0.01	3.1	r=0.90; p=0.02

Table 2. Sample size calculations based on the methods described by Hopkins (2000), using the 95% confidence interval for the CV (1.4 – 3.6%). The smallest worthwhile change (d) was derived as 0.2 of the between subject variation from (a) the pooled data from the current study, (b) Magel et al's [15] pre intervention data, and (c) Bonen et al's [2] tethered swimming data.

VO_{2peak}	SD	*d (0.2 SD)*	Participant number required for a simple test retest experiment.	Participant number required for a study with an experimental and control group.
3.70[a]	0.65	3.5%	2 – 9	6 – 34
3.44[b]	0.49	2.9%	2 – 13	8 – 50
3.53[c]	0.27	1.5%	7 – 47	28 – 184