Metabolic evaluation of swimmers and water polo players

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ABSTRACT

RODRIGUEZ F.A. Metabolic Evaluation of Swimmers and Water Polo Players. Kinesiology, Vol. 2, No. 1, pp. 19-29, 1997. The evaluation of the metabolic capacity of swimmers and water polo players has experienced considerable change in the last years, mainly because of more specific field methods. Lactate testing is a paradigm of this development. However, certain restrictions in measuring the aerobic energy expenditure are still imposed by the apparatus required to collect expired gases (free swimming) or by the modifications ot the swimming mechanics (flume or tethered swimming). Even if these difficulties did not prevent to investigate many aspects of the physiological response of the swimming man, they obviously restrict the full expression of performance capacity in specific pool conditions. In order to overcome these barriers, an evaluation procedure based on the combination of oxygen uptake and blood lactate measurements in field conditions for the comprehensive metabolic evaluation of swimmers and water polo players has been developed. The procedure is based on simultaneous measurement of oxygen uptake and blood lactate accumulation during free unimpeded swimming using breath by breath gas analysis and capillary blood samples during the immediate recovery period after three swims at different velocity over 400 and 100-m (Rodriguez 1994). Direct measurements during an experimental discontinuous swimming protocol helped in providing information about different aspects of the metabolic response of competitive aquatic athletes and the evidence has been used to implement the evaluation method. Aerobic power is evaluated from peak VO_2 measurements after a maximal 400-m swim. Aerobic endurance capacity is evaluated from the relationship between blood lactate accumulation and swimming velocity in two 400-m swims Mader et al. 1976). The anaerobic contribution is estimated from the energy equivalent of lactate accumulation in blood (di Prampero et al. 1978). Swimming economy at different swimming velocities can also be explored taking into consideration total energy expenditure. Differential VO_2 increase between two swims at maximal velocity (400 and 100-m) is taken as an indicator of individual oxygen kinetics. A calculation scheme based on individual swimming energetics allows for the estimation of the maximal rate of aerobic and anaerobic energy expenditure in middle and short distance swimming. The metabolic profile of male and female swimmers, and male water polo players during front crawl swimming using this method is compared and the practical applications and limitations of the testing procedure are presented and discussed.

Key words: METABOLIC EVALUATION, TESTING, SWIMMING, WATER POLO, MAXIMAL OXYGEN UPTAKE, BREATH BY BREATH GAS ANALYSIS, LACTATE

The evaluation of the metabolic capacity of swimmers and water polo players has experienced considerable change in the last years, mainly because of the advancement of physiological research in the laboratory (i.e. swimming flumes, tethered swimming, etc.) and the application of more specific field methods. Lactate testing and heart rate measurements are paradigms of this development.

However, certain restrictions in measuring the aerobic energy expenditure are still imposed by the apparatus required to collect expired gases (free swimming) or by the modifications of the swimming mechanics (flume or tethered swimming). Even if these difficulties do not prevent to investigate many aspects of the physiological response of the swimming man, they obviously restrict the full expression of performance capacity in specific pool conditions. On the other hand, unlike the aerobic capacity, there are no direct methods to measure anaerobic capacity in swimming, although several estimates have been developed for this purpose (Costill et al. 1992).

The aim of this paper is to present a testing procedure based in the combination of VO_2 uptake and lactate measurements in field conditions for the comprehensive metabolic evaluation of swimmers and water polo players, and to discuss its practical applications and limitations.

Maximal aerobic power in swimming: the controversy. It is well known that the highest VO_2 values of which a subject is capable is specific to the musculature employed during maximal exercise and to the training mode (Holmer and Astrand 1972; Magel et al. 1975; McArdle et al. 1978; Stromme et al. 1977). This implies that an exercise test, involving a large mass of the specifically trained muscles should theoretically elicit the highest value for VO_2.

However, research results on this particular problem in swimmers are highly controversial. Some authors have reported lower VO_2 peak values measured by the Douglas bag method during swimming on a flume (Holmer 1972, 1974) or during free swimming than during running, walking (McArdle et al. 1971), or cycling. In trained swimmers VO_2 peak values have been reported to be 6-7% lower than in running (Holmer 1972; Holmer et al. 1974; Magel et al 1975), and approximately the same as in cycling (Holmer 1972). Such differences have been attributed to a reduced active muscle mass during swimming (Holmer 1974) or to limitations of the musculature and local circulation during this form of work (Holmer 1972; McArdle et al. 1971). More recent investigations have shown that VO_2 peak during free swimming unimpeded, either measured by the Douglas bag method or estimated by the backward extrapolation of the oxygen recovery curve, was equal or slightly higher than during running on a treadmill (Montpetit et al. 1981).

This problem has important implications on the physiological testing of swimmers, since the evaluation of the specific cardio-respiratory and metabolic adaptations to training is a very important aspect of their training control.

Maximal aerobic power in swimming: a new approach. In a recent study (Rodriguez, submitted) the metabolic and cardio-respiratory response of trained swimmers to 400-m maximal free swimming, treadmill running and cycling maximal exercise tests have been compared using a new testing procedure. Peak VO_2 was measured by the same breath by breath gas analysis apparatus during the maximal laboratory tests (running and cycling) and during the immediate recovery period after a totally unimpeded 400-m maximal swim. This procedure provides immediate measured values and does not require the estimation of VO_2 at the end of exercise by backward extrapolation (Montpetit et al. 1981; Lavoie et al. 1983) or by prediction equations (Costill et al. 1985, 1992).

Two series of experiments were conducted in two groups of trained swimmers of national level. In series A (n = 14), comparisons were made between peak VO_2 and other cardiorespiratory variables in the three different maximal tests: 400-m front crawl swimming, treadmill running and cycling. In series B (n=25), peak VO_2 was directly measured after a voluntary maximal 400-m swimming test and during cycling in a larger and more heterogeneous sample of swimmers, and their results were also compared (Table 1).

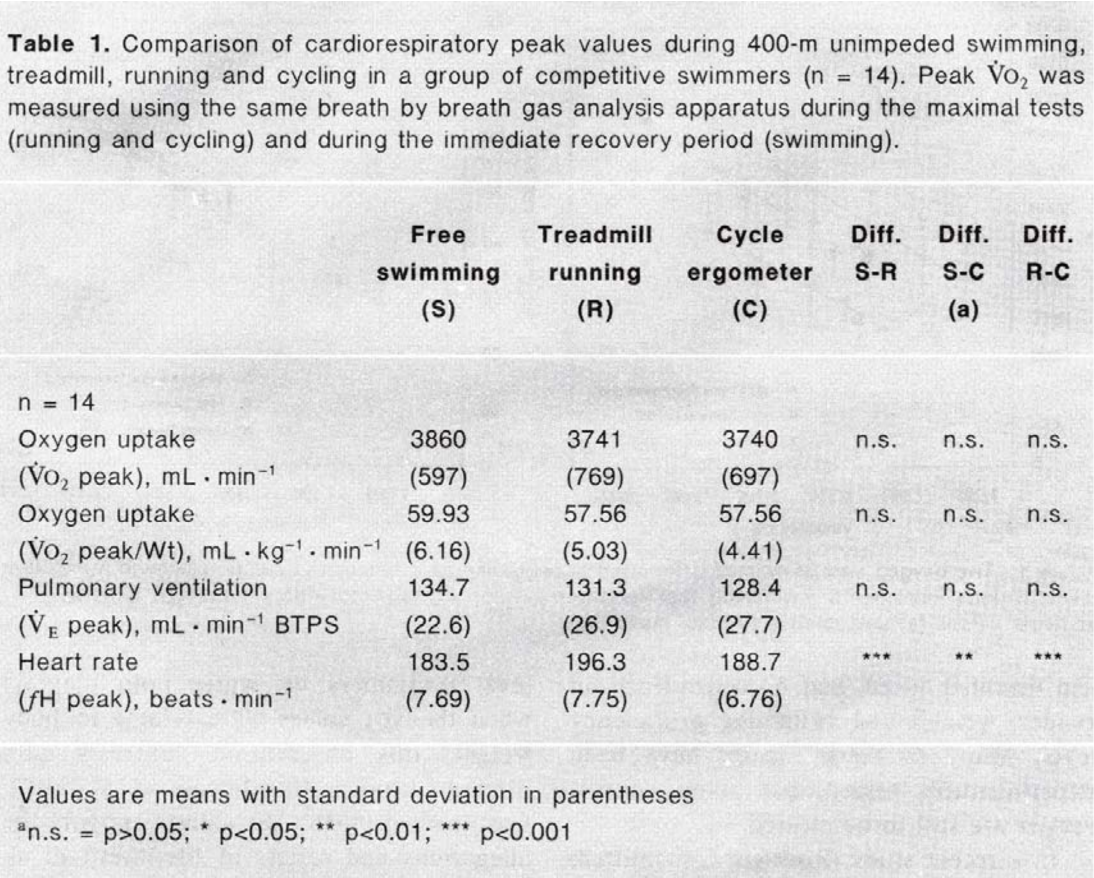

Table 1. Comparison of cardiorespiratory peak values during 400-m unimpeded swimming, treadmill, running and cycling in a group of competitive swimmers (n = 14). Peak $\dot{V}O_2$ was measured using the same breath by breath gas analysis apparatus during the maximal tests (running and cycling) and during the immediate recovery period (swimming).

	Free swimming (S)	**Treadmill running (R)**	**Cycle ergometer (C)**	**Diff. S-R**	**Diff. S-C (a)**	**Diff. R-C**
n = 14						
Oxygen uptake	3860	3741	3740	n.s.	n.s.	n.s.
($\dot{V}O_2$ peak), $mL \cdot min^{-1}$	(597)	(769)	(697)			
Oxygen uptake	59.93	57.56	57.56	n.s.	n.s.	n.s.
($\dot{V}O_2$ peak/Wt), $mL \cdot kg^{-1} \cdot min^{-1}$	(6.16)	(5.03)	(4.41)			
Pulmonary ventilation	134.7	131.3	128.4	n.s.	n.s.	n.s.
($\dot{V}_E$ peak), $mL \cdot min^{-1}$ BTPS	(22.6)	(26.9)	(27.7)			
Heart rate	183.5	196.3	188.7	***	**	***
(fH peak), $beats \cdot min^{-1}$	(7.69)	(7.75)	(6.76)			

Values are means with standard deviation in parentheses

[a]n.s. = $p>0.05$; * $p<0.05$; ** $p<0.01$; *** $p<0.001$

No significant differences were observed between peak VO_2 and pulmonary ventilation values measured in the three modes of maximal exercise. The highest heart rates values were observed during maximal running, followed by cycling and swimming (x diff.=-12.8 beats·min^{-1}). In series B, no significant differences were observed either in peak VO_2 values measured in the two modes of exercise, although swimming values also tended to be slightly higher. Peak heart rate was 6.5 beats·min^{-1} lower in average during swimming.

These results lead to the conclusion that a maximal 400-m front crawl swimming test yields essentially equal or non-significantly higher peak VO_2 and pulmonary ventilation values than during maximal incremental running or cycling tests in trained swimmers. Consequently, direct breath by breath measurements after a 400-m voluntary maximal swim can be considered as a valid and specific method for the evaluation of maximal aerobic power in competitive swimmers.

The oxygen cost of swimming: testing assumptions. The evaluation of maximal aerobic power does not provide information about the efficiency of the aquatic athlete. When VO_2 is related to swimming speed (swimming aerobic effciency or economy) more significant and specific information can be obtained. The evaluation of swimming economy relies on several assumptions, and particularly on the relationship between VO_2 and swimming velocity at submaximal and maximal speed, and its dependence on gender, weight, and swimming proficiency level. Many of these aspects have been experimentally tested, but some controversies are still to be cleared.

In a recent study (Rodriguez, submitted) the aerobic cost of front crawl swimming was measured using the direct breath by breath method mentioned before. Three groups of athletes (male and female competitive swimmers and male water polo players) were tested using an incremental discontinuous protocol in which every athlete swam 5x400 m at increasing velocities (ca. 70-100% of maximal) and 100 m at maximal speed. Based on the results (Figures 1 and 2) the following conclusions were derived: (1) in a wide range of speeds (ca. 1-1.5 ms^{-1}), VO_2 increased linearly as a function of swimming velocity; this is in agreement with the more recent studies both in incremental continuous swimming (Cazorla & Montpetit 1988) and in discontinuous 4 min swims at increasing velocities (Montpetit et al. 1988; Montpetit et al. 1983); (2) no significant differences in the oxygen cost of swimming were observed in relation to gender or swimming proficiency level (swimmers vs. water polo players) when the VO_2 values were related to body weight; this observation contrasts with previous studies (Pendergast et al. 1977; Costill et al. 1985) but clearly support the allegations and results of Montpetit et al. (1988) who did not find differences in absolute values when male and female groups were matched in regard to body size and ability level. These results emphasize the importance of relating VO_2 to body size in comparing groups of subjects with different physical characteristics.

Peak VO_2 in high velocity front crawl swimming. In the same experiment, all subjects reached their peak VO_2 in the maximal 400-m swims, and three subjects did also reach that level in the 100-m maximal swim. In average, swimmers of both sexes reached about 95% of peak VO_2 in the 100-m maximal swim, while water polo players did only reach an average of 88%. Actually, differences in VO_2 between the two maximal swims were not significant in either group of swimmers ($p<0.05$). Although, intraindividual differences were high, these findings are a clear indication of faster VO_2 kinetics in the swimmers, and strongly suggest that a more rapid increase of the aerobic power production plays a significant role in the performance capacity in swimming, particularly in middle distance and most probably even more so in shorter events like 100-m, as it has been hypothesized (Toussaint and Hollander 1994).

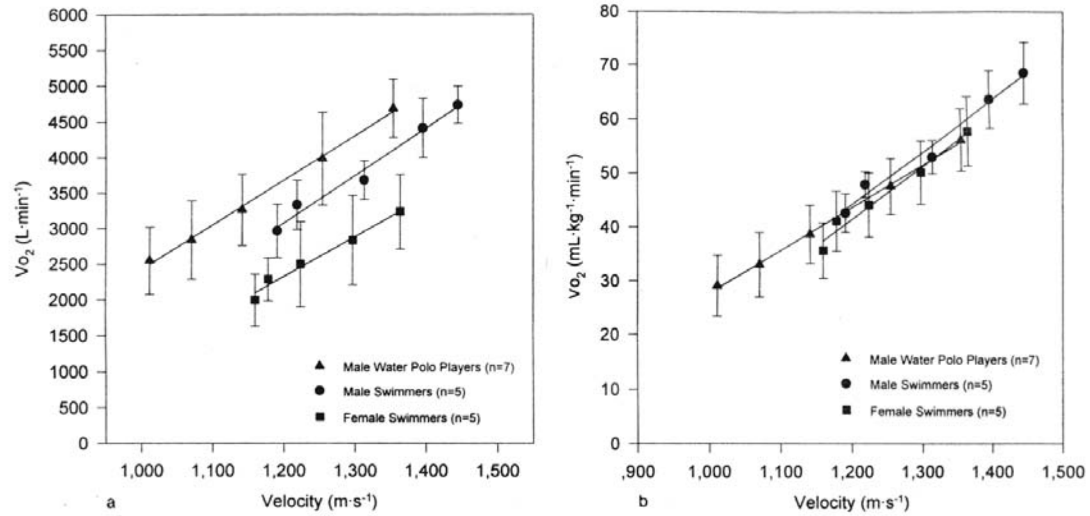

Figure 1. The oxygen cost of swimming the front crawl stroke as a function of mean velocity in a 5x400-m discontinuous incremental swimming test for three groups of subjects. The results are expressed in absolute values (a) and relative to body mass (b).

The anaerobic energy contribution. When the energy requirement is such that a significant accumulation of lactate in blood takes place, the energy for work performance is derived from three sources: oxidative phosphorylations (VO_2); anaerobic glycolysis, leading to a net accumulation of lactic acid in the body; and net depletion of alactic energy stores (di Prampero et al. 1978; di Prampero 1986). As blood lactate concentration ([La]b) increases exponentially in relation to swimming velocity, the velocity corresponding to a comparable level of blood lactate concentration (4 mmolL^{-1} lactate threshold or V4-velocity) can be considered an indicator of swim-specific aerobic endurance (Mader et al. 1976, 1978; Heck and Mader 1985; Olbrecht et al. 1985; Rodriguez 1994). Moreover, different authors have postulated and provided evidence to support the concept that lactate concentration in blood reflects the anaerobic energy contribution to swimming exercise (Mader et al. 1976, 1978; di Prampero et al. 1978; Thevelein et al. 1984).

In a different approach, the accumulated oxygen deficit (AOD) can be assumed to reflect the anaerobic energy production in running (Medbo et al. 1988). The principle for its determination has also been applied to swimming with certain modifications and assumptions from a 4 min swim at the velocity corresponding to the estimated VO_2max (Troup et al. 1992). The most important of these assumptions is the calculation of total energy demands from the extrapolation of the oxygen cost of swimming as a function of the third power of swimming velocity. Even if this assumption is based on theoretical considerations mainly of biomechanical nature (Toussaint and Hollander 1994), this exponent is yet to be determined experimentally.

In the same series of experiments (Rodriguez, submitted), three groups of subjects swam the 5x400-m incremental, and an exponential increase of blood lactate concentration as a function of VO_2 was observed (Figure 2). The steep increase of [La]b occured at a lower velocity in the water polo players as compared to the female and male swimmers, indicating an earlier imbalance between the activation of the glycolytic rate and the oxidation of lactate (Mader and Heck 1986).

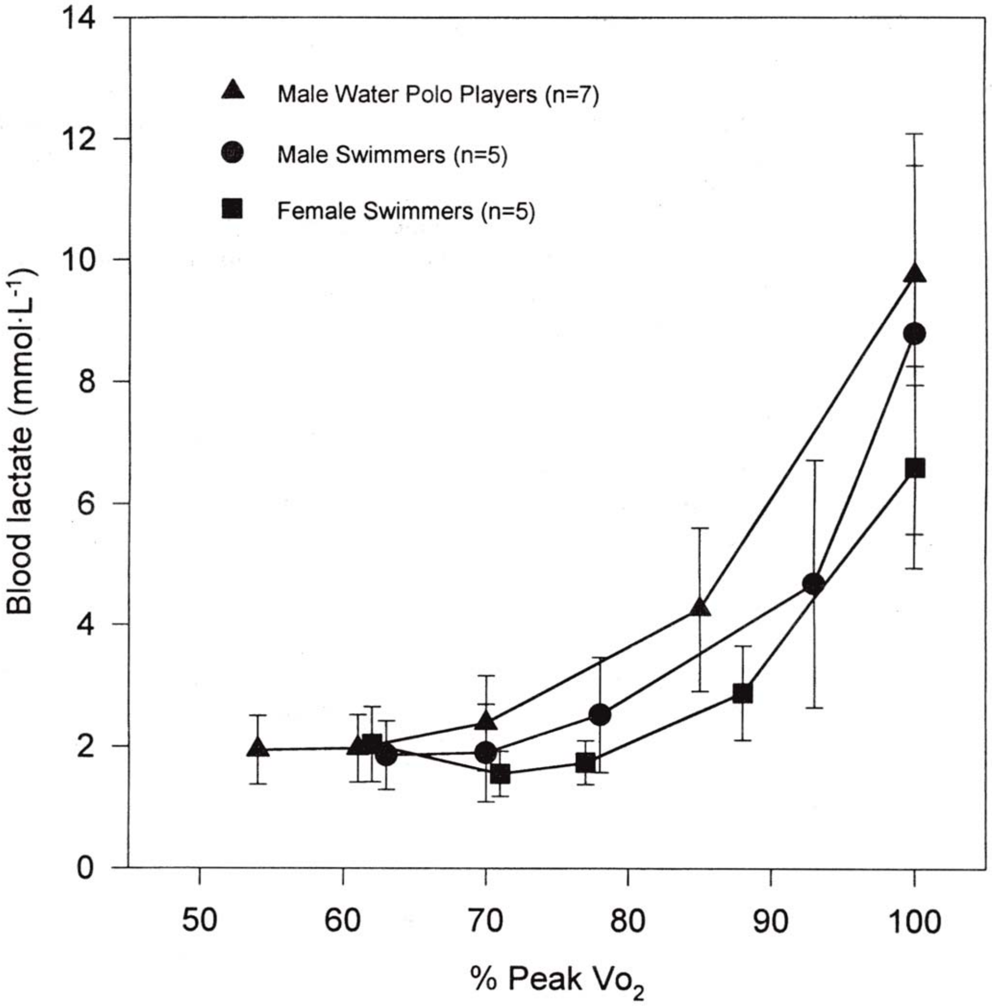

Figure 2. Blood lactate concentration as a function of oxygen uptake in a 5x400-m incremental discontinuous swimming test for the three groups of subjects. SD bars are also shown.

In this study, V4-velocity was highly correlated with mean velocity in the maximal 400-m swim ($r=0.919$; $p<0.001$) and explained 84% of its variance. Even if one accepts that some mathematical coupling might interfere as two velocities are being related, this result confirms the relevance of this parameter as the most valid physiological indicator of performance capacity in middle distance swimming.

Rates of energy expenditure: a practical model. The parameters describing the rate of energy production (maximal aerobic and anaerobic power, as well as oxygen kinetics) are important in assessing the metabolic capabilities of the aquatic athlete (Toussaint and Hollander 1994). Based on the simultaneous measurement of VO_2 and blood lactate accumulation during free unimpeded swimming using breath by breath gas analysis and capillary blood samples during the immediate recovery period after three swims at different velocity over 400 and 100-m (Rodriguez 1994), a calculation scheme has been developed in order to obtain such information in field conditions. This scheme was developed based on a practical model which relies in some theoretical and experimentally tested assumptions.

VO_2 can be taken to reflect the rate of aerobic energy expenditure (E_{aer}) at the different swimming velocities and is best expressed in $mLO_2 \cdot min^{-1}$. As discussed before, the rate of anaerobic lactic energy expenditure ($E_{an,lac}$) can be estimated from the energy equivalent of net blood lactate accumulation after exertion during front crawl swimming, using the 2.7 $mLO_2 \cdot min^{-1} \cdot kg^{-1}$ proportionality constant (di Prampero et al. 1978; di Prampero 1981). The rate of total energy expenditure (E_{tot}, $mLO_2 \cdot min^{-1}$) is calculated by addition of the two terms ($E_{tot} = E_{aer} + E_{an,lac}$), assuming that the energy released by alactic processes is negligible when t>1 min and VO_2 reaches near to maximal values. In high velocity swimming (maximal 100-m), the rate of alactic anaerobic energy contribution ($E_{an,al}$) has to be considered and can also be estimated according to the constant calculated by di Prampero et al. (1978) lor front crawl swimming (18 $mLO_2 \cdot kg^{-1}$).

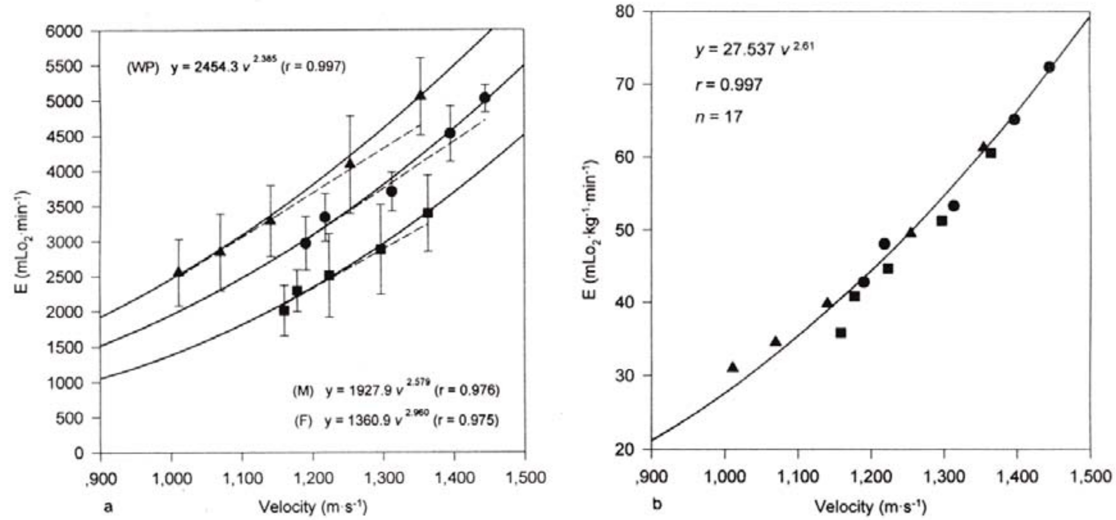

Figure 3. Total energy expenditure rates ($\dot{E}_{tot}$) during 400-m front crawl swimming at different intensities. (a) ($\dot{E}_{tot}$) ($mLo_2 \cdot min^{-1}$) for the three groups of subjects: (■) female swimmers; (●) male swimmers; and (▲) male water polo players. Means and standard deviation bars are depicted. The derived mean power regression equation is also shown for every group. (The derived regression lines for $\dot{E}_{aer}$ in the three groups are also depicted in dashed lines for reference).
(b) Pooled $\dot{E}_{tot}$ values relative to body weight for all subjects ($mLo_2 \cdot kg^{-1} \cdot min^{-1}$). Means and standard deviation bars are depicted. The derived mean power regression equation is also shown (n = 17).

Accordingly, the rate of total anaerobic energy expenditure (E_{an}, $mLO_2 \cdot min^{-1}$) in this case is calculated by addition of the alactic and lactic energy contribution ($E_{an,lac} + E_{an,al}$). Values are normally expressed in O_2 equivalents relative to body weight ($mLO_2 \cdot kg^{-1} \cdot min^{-1}$) in order to have comparable results among subjects with different physical characteristics.

Energy expenditure during an incremental 5x400-m swimming test. Firstly, the results of a 5x400-m incremental swimming test were analyzed according to this model. As mentioned before, in the range of velocities investigated (1-1.5 ms^{-1}) the rate of aerobic energy expenditure (Eaer) increased linearly with swimming velocity, but the rate of total energy expenditure (E_{tot}) increased exponentially as a function of velocity in the three groups (Figure 3). When the experimental data were fitted to a power function by the least square method, the exponents for the three groups were 2.58 (male swimmers), 2.96 (female swimmers), and 2.38 (water polo players), respectively. When values were expressed relative to body weight ($mLO_2 \cdot kg^{-1} \cdot min^{-1}$), no significant differences were observed among neither the constant nor the exponent of the power functions for the three groups. Thus, they were pooled to obtain the mean power regression function (Figure 3b). The derived exponent for the whole group was 2.61 ($r = 0.997$; $n = 17$).

Energy expenditure during a maximal 100-m swimming test. The energy expenditure rates related to body size (E, $mLO_2 \cdot kg^{-1} \cdot min^{-1}$) and mean swimming velocity in a 100-m maximal swim in the three groups of subjects, as well as the significance of the differences among groups are shown in Table 2. When comparing the two groups of male subjects (swimmers and water polo players), for a very close swimming performance the swimmers showed similar levels of total and anaerobic energy expenditure (E_{tot}, E_{an}, $p>0.05$) but a significantly higher aerobic component (E_{aer}). Male swimmers attained a higher swimming velocity as compared to female swimmers and showed a higher rate of total energy expenditure (E_{tot}) related to all aerobic and anaerobic components ($0.05>p< 0.01$). Male water polo players swam faster than female swimmers and showed a higher E_{tot} based on higher anaerobic energy rates ($E_{an,al}$, $E_{an,lac}$, $0.05 >p< 0.01$).

When E_{tot} calculated values in the incremental 5x400 and maximal 100-m swims were pooled and fitted to a power function of swimming velocity, the derived power exponents for the three groups were 2.81 (male swimmers), 3.30 (female swimmers), and 2.47 (water polo players), respectively (Figure 4). No significant differences were observed in the proportionality constants ($E_{tot} = a \cdot v^b$), but the exponent for the female swimmers was significantly higher than that of the male subjects (swimmers and water polo players) ($p<0.05$), indicating a sharper increase in the rate of total energy expenditure in the fastest 100-m swim (no differences had been observed in the 5x400 incremental test).

The calculated rate of total energy expenditure, based only on experimental metabolic measurements, yielding an exponent of 2.8-3.3 for the swimmers and 2.5 for the water polo players, seems to adjust reasonably well to the theoretical model in which the power to overcome drag will equal the drag forces times the velocity, and thus to the cube of velocity (Toussaint and Hollander 1994). On the other hand, the metabolic calculations based on

400-m and 100-m are also consistent with the higher glycolytic rates in shorter distances, and more importantly, the estimated values for 100-m fit well into the derived equation for the incremental 400-m swims.

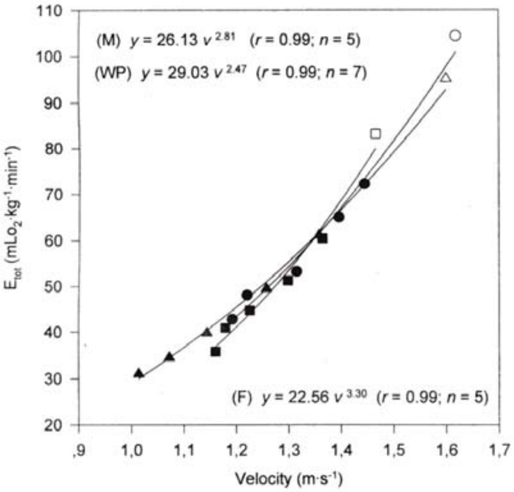

Figure 4. Total energy expenditure rates $\dot{E}_{tot}$ (mLo$_2$ · min^{-1}) during 400 swimming at different intensities and maximal 100-m (empty symbols) for the three groups of subjects: (■) female swimmers; (●) male swimmers; and (▲) male watero polo players. Means and standard deviation bars are depicted. The derived mean power regression equation is also shown for every group.

The model can also be evaluated in how well it relates to performance in 100-m, considering the importance of the anaerobic contribution in this shorter distance. Figure 5 shows the relationship between both total and anaerobic energy expenditure rates and mean velocity for 100-m at maximal intensity. In this model, 57% of the variance in 100-m time can be explained by the total energy rate expenditure, and 53% by the anaerobic rate of energy expenditure.

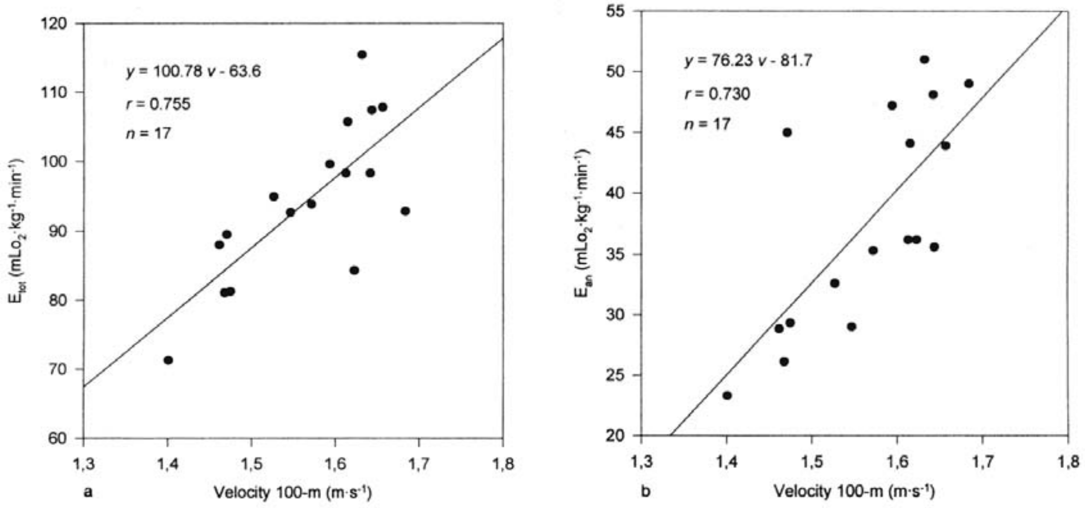

Figure 5. Estimated total energy expenditure rate (a) and anaerobic energy expenditure rate (b) as a function of mean velocity in a maximal 100-m swim. The derived linear regression equation and Pearson's correlation coefficient are shown.

Considering that mechanical and swimming efficiency parameters are not regarded, the model explains reasonably well the performance capacity in a shorter distance.

Practical applications and limitations. During the last years we have routinely conducted a standard testing protocol (Aerobic-Anaerobic Standard Swimming Test) consisting of a two-speed test over 400 m, with a 20-min rest between repetitions (after Mader 1976), followed by a maximal 100 m swim at the swimmer's main stroke (freestyle tor the water polo players) after a recovery period of an hour (Rodriguez 1994). Blood lactate and optional heart rate measurements are obtained. Adding direct oxygen uptake measurements to this procedure and applying the above mentioned calculation scheme provides a testing set up from which information can be derived about the metabolic capacities of swimmers and water polo players and its relation to swim-specific performance capacity.

Besides the specificity and validity aspects that have been discussed, this procedure shows to be reasonably feasible and avoids the barriers imposed by gas analysis apparatus (hoses, masks) or modified swimming technique (flume, tethered swimming). The main limitation is the availability of the gas analyzer by the pool side. As in any testing method, optimal instrument calibration and use are to be emphasized. Hopefully, this procedure may also contribute to a better understanding of some aspects of the metabolic evaluation of aquatic athletes.

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REFERENCES

CAZORLA G, and MONTPETIT R. Metabolic and cardiac responses of swimmers, modern pentathletes, and water polo players during freestyle swimming to maximum. In: Ungerechts B, Wilke K, Reischle (Eds.), *Swimming Science V*. International Series on Sport Sciences. Human Kinetics, Champaign, Illinois, vol 18, 1988.

COSTILL DL, KOVALESKI J, PORTER D, KIRWAN J, FIELDING R, and KING D. Energy expenditure during front crawl swimming: predicting success in middle-distance events. *Int J Sports Med* 6:266-270, 1985.

COSTILL DL, MAGLISCHO EW, and RICHARDSON AB. (Eds.), *Handbook of Sports Medicine and Science*. Swimming. IOC, FINA. Blackwell Scientific Publications, Oxford, 1992.

Di PRAMPERO PE, PENDERGAST DR, WILSON DW, and RENNIE DW. Blood lactic acid concentrations in high velocity swimming. In: Eriksson B, Furberg B (Eds.), *Swimming Medicine IV*. University Park Press, Baltimore, 1978.

Di PRAMPERO PE. The energy cost of human locomotion on land and in water. *Int J Sports Med* 7:55-72, 1986.

HOLMER I and ASTRAND PO. Swimming training and maximal oxygen uptake. *J Appl Physiol* 33:510-513. 1972.

HOLMER I, LUNDIN A, and ERIKSSON BO. Maximum oxygen uptake during swimming and running by elite swimmers. *J Appl Physiol* 36:711-714, 1974.

LAVOIE JM, LEGER LA, MONTPETIT RR, and CHABOT S. Backward extrapolation method of VO_2 from the O_2 recovery curve after a voluntary maximal 400-m swim. In: Hollander, Huijing, De Groot (Eds.), *Biomechanics and Medicine in Swimming.* International Series on Sport Sciences. Human Kinetics, Champaign, Illinois, vol 14, 1983.

MADER A, LIESEN H, HECK H, PHILIPPI H, ROST R, SCHURCH P, and HOLLMAN W. Zur beurteilung der sportsartspezifishen Ausdauerleistungsfihigkeit im Labor. *Sportsatz und Sportsmedizin* 4:80-88; 5:109-112, 1976.

MADER A, HECK H, and HOLLMANN W. Evaluation of lactic acid contribution by determination of postexercise lactic acid concentration of ear capillary blood in middle-distance runners and swimmers. In: Landry F, Orban WAR (Eds.), *The International Congress of Physical Activity Sciences 1976, Exercise Physiology*. Florida, Symposia Specialists, vol. IV, 1978

MADER A, and HECK. H. A theory of the metabolic origin of "anaerobic threshold". *Int J Sports* Med (suppl) 7:45-65, 1986.

MAGEL JR, FOGLIA GF, McARDLE WD, GUTIN B, PECHAR GS, and KATCH FI. Specificity of swim training on maximum oxygen uptake. *J Appl Physiol* 38:151-155, 1975.

McARDLE WD, GLASER RM, and MAGEL JR. Metabolic and cardiorespiratory response during free swimming and treadmill walking. *J Appl Physiol* 30:733-738, 1971.

McARDLE WD, MAGEL JR, DELIO DJ, TONER M, and CHASE JM. Specificity of run training on VO_2max and heart rate changes during running and swimming. *Med Sci Sports* 10:16-20, 1978.

MEDBO JI, MOHN AC, TABATA I, BAHR R, VAAGE O, and SEJERSTED OM. Anaerobic capacity determined by maximal accumulated O_2 deficit. *J Appl Physiol* 64:50-60, 1988.

MONTPETIT RR, LEGER LA, LAVOIE JM, and CAZORLA G. VO_2 peak during free swimming using the backward extrapolation of the O_2 recovery curve. *Eur J Appl Physiol* 47:385-391, 1981.

MONPETIT RR, LAVOIE JM, and CAZORLA G. Aerobic energy cost of swimming the front crawl at high velocity in international class and adolescent swimmers. In: Hollander AP, Huijing PA, de Groot G (Eds.), *Biomechanics and Medicine in Swimming.* International Series on Sport Sciences. Human Kinetics, Champaign, Illinois, vol 14, 1983.

MONPETIT R, CAZORLA G, and LAVOIE JM. Energy expenditure during front crawl swimming: a comparison between males and females. In: Ungerechts B, Wilke K, Reischle (Eds.), *Swimming Science V.* International Series on Sport Sciences. Human Kinetics, Champaign, Illinois, vol IS, 1988.

PENDERGAST DR, Di PRAMPERO PE, CRAIG AB, WILSON DR, and RENNIE DW. Quantitative analysis of the front crawl in men and women. *J AppI Physiol* 43:475-479, 1977.

RODRIGUEZ FA. Physiological testing of swimmers and water polo players in Spain. In: Miyashita M, Mutoh Y, Richardson AB (Eds.), Medicine and Science in Aquatic Sports. *Medicine and Sport Science* Karger, Basel, vol 39, 1994.

RODRIGUEZ FA (submitted). *Oxygen uptake and blood lactate accumulation during front crawl swimming in competitive swimmers and water polo players.*

RODRIGUEZ FA (submitted). *Maximal oxygen uptake and cardiorespiratory response during a maximal 400-m swimming test, running and cycling in competitive swimmers.*

RODRIGUEZ FA (submitted). *Aerobic and anaerobic energy expenditure in the metabolic evaluation of competitive swimmers and water polo players.*

STROMME SB, INGJER F, and MEEN HD. Assessment of maximal aerobic power in specifically trained athletes. *J AppI Physiol* 42:833-837, 1977.

THEVELEIN X, DALY D, and PERSYN U. Measurement of total energy use in the evaluation of competitive swimmers. In: Bachi N, Prakop L, Suckaert R (Eds.), *Current Topics in Sports Medicine.* Urban & Schwartzenberg, Wien, pp. 668-676, 1984.

TOUSSAINT HM, and HOLLANDER AP. Mechanics and energetics of trout crawl swimming. In: Miyashita M, Mutoh Y, Richardson AH (Eds.), *Medicine und Science in Aquatic Sports*. Medicine and Sport Science. Karger, Basel, vol 39: 1994.

TROUP JP, HOLLANDER AP, BONE M, TRAPPE S, BARZDUKAS AP. Performance related difference in the anaerobic contribution of competitive freestyle swimmers. In: MacLaren D, Reilly T, Lees A (Eds.), *Biomechantcs and Medicine in Swimming.* Swimming science VI. E & FN Spon, London, 1992.