ASSESSING GROSS EFFICIENCY AND PROPELLING EFFICIENCY IN SWIMMING

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Determining the efficiency (and the economy) of a movement is a primary goal for those interested in understanding, and possibly improving, human locomotion and/or sport's performance. This goal is particularly difficult to achieve in swimming where different "efficiencies" could be computed based on the partitioning of mechanical power output into its useful and non useful components as well as because of the difficulties in measuring the forces a swimmer can exert in water. In this paper the "possible range" of overall (gross) and propelling efficiency values for swimming humans is estimated and discussed.

KEY WORDS: front crawl, propulsion, swimming performance

INTRODUCTION: The only efficiency that can be calculated in swimming with a certain degree of accuracy is drag efficiency (η_D) for it just requires measures of drag (hydrodynamic resistance) and energy expenditure: $\eta_D = W'_D / E'$, where W'_D is the mechanical power output needed to overcome drag forces and E' is metabolic power input. Even if the different methods developed so far to determine (active and/or passive) drag are quite debated in the literature (e. g. Wilson & Thorp, 2003; Toussaint, Roos & Kolmogorov, 2004; Havriluk, 2007; Zamparo, Gatta, Capelli & Pendergast, 2009; Zamparo, Capelli & Pendergast, 2011), they consistently indicate that less than 10% of metabolic power input can be transformed into useful mechanical power output (η_D = 0.03-0.09) (e. g. Holmér, 1972; Pendergast, di Prampero, Craig Jr, Wilson & Rennie, 1977; Kolmogorov & Duplisheva, 1992; Toussaint, Roos & Kolmogorov, 2004; Zamparo, Pendergast, Mollendorf, Termin & Minetti, 2005).

Even more debated are the methods utilized in the literature to calculate overall (gross) and propelling efficiency and the range of their values is even larger than in the case of η_D. The values of η_O (= W'_T / E', where W'_T is total mechanical power output) reported in the literature range from 0.1 to 0.2 (Toussaint, Knops, De Groot & Hollander, 1990; Zamparo et al., 2005) and the values of η_P (W'_D / W'_T) range from 0.2 to 0.8 (Martin, Yeater & White, 1981; Toussaint, Beleen, Rodenburg, Sargeant, De Groot, Hollander & van Ingen Schenau, 1988; Zamparo et al., 2005; Zamparo, 2006; Figueiredo, Zamparo, Sousa, Vilas-Boas & Fernandes, 2011). Particularly for η_P the need to decrease the uncertainty due to the wide range of values reported in the literature is strong since this parameter is a major determinant of performance and hence of great interest for sport scientist and coaches.

METHODS AND RESULTS: Propelling efficiency can be calculated based on values of drag efficiency provided that overall (gross) efficiency is known ($\eta_O = \eta_D/\eta_P$). As indicated in Table 1, by assuming different values of η_O (from 0.10 to 0.30) the possible range of estimated η_P values turns out to be "rather wide" (0.10-0.90) indicating that from 10 to 90% of W'_T can be utilized for propulsion during swimming. One way to reduce this uncertainty is to define a "reasonable range" of η_O values, at least from a theoretical point of view.

DISCUSSION: In cycling, where W'_T is easily measurable with proper ergometers: η_O = 0.25-0.30 (e. g. similar to the values expected from the thermodynamics of muscle contraction at optimal contraction speed, Wooledge, Curtin & Homsher, 1985). Similar values should be expected for all forms of "locomotion" in which no recoil of elastic energy takes place and for which total power output can be accurately assessed; in these conditions, values of η_O lower than 0.25-0.30 are measured only when muscles are working far from the optimal range of their force-length and/or force-speed relationship.

Table 1
Changes in propelling efficiency (η_P) estimates for different values of overall efficiency (η_O) and of drag efficiency (η_D). $\eta_O = \eta_D/\eta_P$.

η_O	η_D (min)	η_D (max)	η_P (min)	η_P (max)
0.10	0.03	0.09	0.30	0.90
0.15	0.03	0.09	0.20	0.60
0.20	0.03	0.09	0.15	0.45
0.25	0.03	0.09	0.12	0.36
0.30	0.03	0.09	0.10	0.30

The effect of an "unfavourable muscle length" on η_O is quite small: when cycling in the prone or supine position the efficiency is 92 - 97% that of cycling upright (Abbott & Wilson, 1995). Muscle efficiency is also a function of the v/v_{max} ratio (velocity of shortening / maximal velocity of shortening) and peaks at about the same shortening speed that gives maximal power production (e. g. Reggiani, Potme, Bottinelli, Canepari, Pellegrino & Stiener, 1997). Since muscle fibre types are characterized by different values of v_{max}, muscle efficiency depends also on the composition of fibres (the slow type fibres being more efficient that the fast type ones) and on their recruitment (e. g. Reggiani et al. 1997). 60 cycles /min (1 Hz) has been suggested as the frequency maximizing efficiency for Type I fibres in cycling (Sargeant & Jones 1995) and arm stroke frequency is not far from this value (34-67 cycles/min: in the four strokes over the 50-800 m distances, in male and female swimmers, as reported by Maglischo, 2003). Therefore, the effect of an "unfavourable contraction speed", as well as that of an "unfavourable muscle length" on η_O in swimming seems rather small.

A final consideration, debated in the literature, regards the possible difference in the efficiency of arm vs. leg exercise: due to the smaller mass involved (arm cranking vs. cycling) the "overall" efficiency of arm exercise was reported to be lower to that of leg exercise (e. g. Pendergast, 1989). However, this is not the case of swimming since large muscle masses (not only the upper limbs) are involved in this mode of locomotion. Moreover, as indicated by Hagerman (2000), the values of η_O reported in the literature for rowing (mainly, but not only, upper body exercise) can be as high as 0.24 (in elite oarsman during a simulated 2000 m race on a rowing ergometer).

On the basis of these considerations it could be concluded that: i) η_O values of about 0.20-0.25 could be determined also for "simulated swimming" if a proper ergometer could be devised; and ii) the "rather low" values of overall (gross) swimming efficiency reported in the literature so far can not be attributed to non-optimal muscle efficiency during swimming but, rather, to an incomplete computation of all work components/energy losses.

On this line of reasoning, according to data reported in Table 1, it necessarily follows that, for η_O values of about 0.20-0.25, η_P could be at most 0.36-0.45 (and the minimum values of about 0.12-0.15): e. g. less than half of total power output can be transformed into power useful for propulsion in swimming humans. These seem quite reasonable estimates since humans are not suited for locomotion in water; in comparison swimming cetaceans are characterized by values of η_P ranging from 0.75 to 0.90 (Fish 1998). Recent studies of computational fluid dynamics (von Loebbecke, Mittal, Fish & Mark, 2009) are even more "restrictive" indicating a range of propulsive efficiency of the underwater dolphin kick in humans (a way more efficient method to move in water than the arm stroke) of 0.11 - 0.29 (compared to 0.56 for cetaceans).

FINAL CONSIDERATIONS: Data of η_p reported in Table 1 represent the "average propelling efficiency" as it can be calculated during a complete swimming cycle. Since unsteady forces are exerted in swimming, when this parameter is calculated in a particular phase of the swimming cycle (e. g. during the propulsive phase) its values could be as much as twice than the average ones. This seems indeed one of the reasons why so different values of propelling efficiency of the arm stroke have been reported in the literature so far.

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