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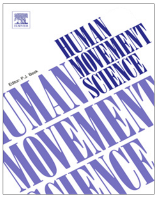

Planimetric frontal area in the four swimming strokes: Implications for drag, energetics and speed

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ABSTRACT

The purpose of this study was to use the planimetric method to determine frontal area (Ap) throughout the stroke cycle in the four swimming strokes as well as during "streamlined leg kicking". The minimum Ap values in all strokes are similar to those assessed during "streamlined leg kicking" (about 0.13 m^2). Active drag ($Da = 1/2\, \rho\, C_d\, Ap\, v^2$) was then calculated/estimated based on the average Ap values, as calculated for a full cycle in each condition. Da is the lowest in the "streamlined leg kicking" condition ($Da = 19.5 v^2$, e.g., similar to the values of passive drag reported in the literature), is similar in front crawl ($Da = 30.0 v^2$), backstroke ($Da = 26.9 v^2$) and butterfly ($Da = 28.5 v^2$) and is the largest in the breaststroke ($Da = 37.5 v^2$).

Based on the C vs. v relationships reported in the literature for the four strokes it is then possible to estimate drag efficiency: for a speed of 1.5 $m\,s^{-1}$, it ranges from 0.035–0.038 (breaststroke and backstroke, respectively) to 0.052–0.058 (butterfly and front crawl, respectively). This study is the first to establish Ap values throughout the swimming cycle for all swimming strokes and these findings have implications for active drag estimates, for the energetics of swimming and for swimming speed.

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1. Introduction

In all forms of human locomotion the speed could be increased either by increasing the propulsive forces or by decreasing the resistive forces. In aquatic locomotion the major resistive force is that of water (hydrodynamic resistance or drag): it is therefore of pivotal importance to measure/estimate this parameter.

Whereas there is quite an agreement in the literature on how measuring drag in passive conditions, where the “non swimming subject” is towed at the water surface at a given speed (Gatta, Cortesi, & Di Michele, 2012; Gatta, Zamparo, & Cortesi, 2013; Havriluk, 2005) the problem of quantifying active drag (during actual swimming) is far to be solved and, indeed, in the swimming literature there is quite a debate on how to tackle this problem (for a discussion on this point see, as an example: Havriluk, 2005, 2007; Toussaint, Paulien, Roos, & Kolmogorov, 2004; Wilson & Thorp, 2003; Zamparo, Capelli, & Pendergast, 2011; Zamparo, Gatta, Pendergast, & Capelli, 2009). For instance, the values of active drag (front crawl) have been reported to be 2–3 times larger than those of passive drag (e.g., di Prampero, Pendergast, Wilson, & Rennie, 1974; Zamparo et al., 2009) but also to be equal or even lower than those assessed in “passive conditions” (e.g., Kolmogorov & Duplisheva, 1992; Toussaint et al., 1988).

Hydrodynamic resistance has three components: pressure (or form) drag, friction drag and wave drag and the former is considered to be the major determinant of drag at moderate swimming speeds (below 1.4 m s^{-1}) (e.g., Pendergast et al., 2005; Wilson & Thorp, 2003). In turn, pressure drag (D_{pr}) can be calculated according to the following equation:

$$D_{\mathrm{pr}} = \frac{1}{2}\rho C_{\mathrm{d}} A v^2 \tag{1}$$

where ρ is water density, C_{d} is the drag coefficient, A is the “reference area” and v is the swimming speed. This equation is applicable to an object with a “stable configuration” that moves in water at “constant speed” (e.g., with given values of A and v) as it is the case during passive drag measurements. This is, of course, not the case during actual swimming, when the swimmer experiences continuous changes of speed and “configuration” (e.g., A and v are not constant). However, a small step forward in the understanding of the resistances a swimmer encounters could be that of estimating drag based on the average values of A (and v) as measured during a swimming cycle. Eq. (1) clearly indicates that, *ceteris paribus*, an increase in A determines an increase in D_{pr} and hence of total hydrodynamic resistance. Measuring A could therefore allow to determine whether there are differences between passive and active drag (as pointed out by Zamparo et al., 2009) as well as whether there are differences in active drag among the four swimming strokes. Indeed, the majority of the active drag estimates reported so far in the literature refer to the front crawl (e.g., di Prampero et al., 1974; Toussaint et al., 1988) and no data are available regarding the other strokes, but at maximal speeds (e.g., with the method proposed by Kolmogorov & Duplisheva, 1992).

1.1. Methods to measure A in “passive conditions”

Measuring A is not an easy task and, in the literature, several methods have been proposed to estimate this parameter. According to Vogel (1994) the term A can be defined in several ways: (1) A is the wetted area: the total surface exposed to flow (streamlined bodies at low Reynolds numbers); (2) A is the frontal area/cross-sectional area: the projected area of the body into a plane normal to the direction of flow (non streamlined bodies, high and medium Reynolds numbers); (3) A is the plan form area (profile area), like wetted area this parameter is independent of orientation with respect to flow (this method is generally used with lift producing airfoils); A can be calculated as the 2/3 of body volume (this method is used for airships where volume is proportional to lift). Although different authors have applied these different definitions to calculate A and hence to estimate drag (for a review see Havriluk, 2005), a swimmer is not a streamlined body, moves at medium to high Reynolds numbers (Mollendorf, Termin, Oppenheim, & Pendergast, 2004) and is mainly propelled by drag (rather than lift) forces; thus frontal area/cross-sectional area seems to be the most reasonable “area of choice”.