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Short Communication

The optimum finger spacing in human swimming

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ABSTRACT

Competitive swimmers spread fingers during the propulsive stroke. Due to the inherent inefficiency of human swimming, the question is: does this strategy enhance performance or is it just a more comfortable hand posture? Here we show, through computational fluid dynamics (CFD) of a 3D model of the hand, that an optimal finger spacing (12°, roughly corresponding to the resting hand posture) increases the drag coefficient (+8.8%), which is 'functionally equivalent' to a greater hand palm area, thus a lower stroke frequency can produce the same thrust, with benefits to muscle, hydraulic and propulsive efficiencies. CFD, through flow visualization, provides an explanation for the increased drag associated with the optimum finger spacing.

Swimming, as opposed to running (Bramble and Lieberman, 2004), was not optimized during human evolution: we use the least sophisticated means of propulsion in water, called oars-like drag-powered swimming, with our musculo-skeletal system working at a very low efficiency (Zamparo et al., 2005). Competitive swimmers today, regardless of stroke style, spread their fingers a finite amount (Fig. 1) even though the overall hand surface area, expected to determine most of the drag/thrust, does not change. Here we show, through computational fluid dynamics (CFD) of a 3D model of the hand, that this strategy enhances performance. There is an optimal spacing (roughly corresponding to the resting spread of fingers) at which the drag coefficient is 8.8% higher than the 'wide open' and the 'fully closed' hand. Virtual flow visualization provides an explanation of the 'functionally equivalent' increase of hand palm area, based on vortices generated behind the hand. This swimming technique, which corresponds to the use of fins in the lower limbs, potentially produces either (a) a higher thrust or (b) the same thrust by accelerating more water at a lower speed, which increases the propelling efficiency (Zamparo et al., 2002).

Humans pay a price for the terrestrial specialization of their locomotion: of the forms of aquatic locomotion available including water jetting, hydrofoils for lift-based swimming, and oar-like paddling, only the last propulsion method is viable. While not as penalized as in horses with their thin appendages, human swimming is severely limited by the localization of most of the engine (71% of total muscle mass) in the non-propelling lower limbs (Nindl et al., 2002), and by a reduced surface of the available 'oars' (i.e. upper limbs, responsible of 88% of total thrust (Hollander et al., 1988)). The paddling surface (A, m^2) is important because: (a) it contributes to the drag ($=1/2 \cdot \rho \cdot A \cdot v^2 \cdot C_D$, where ρ is water density, v (m/s) is the oar speed and C_D is the drag coefficient, which mainly depends on the 3D shape of the object), and (b) the propelling (Froude) efficiency increases if the same thrust is obtained by accelerating a larger amount of water to a lower speed (Alexander, 2003).

Also, similar to the advantage brought by fins to the lower limbs (Zamparo et al., 2005), an increase in A and/or in C_D could increase: (a) muscle efficiency, since contraction can occur at a slower speed, and (b) hydraulic efficiency, related to the energy required to move the propulsive machinery, because of the reduced mechanical internal work associated with a lower stroke frequency for the same thrust (Minetti, 2004).

In competitive swimming, no passive tool is allowed to enhance performance; however, athletes are very frequently observed (and trained) to spread their fingers during a stroke (Fig. 1). If finger spacing has no link to enhanced performance, it seems unlikely that it would be used so frequently in competition for the only purpose of a more comfortable hand posture. Therefore, we hypothesize that, because of the complex hydrodynamics related to the 3D shape of the hand, an intermediate finger spacing (between the closed and the widest ones) could be associated to an increased 'functional' paddling surface or a higher coefficient of drag, providing swimmers with additional thrust and greater overall efficiency (i.e. the product of the three quoted efficiencies). A recent study of the effect of thumb position during a stroke (Marinho et al., 2009) found an increase in the lift coefficient and a decrease in drag coefficient when the thumb was fully abducted (90°). However, they investigated three thumb positions, 0°, 45°, and 90°, with the other fingers kept close to each

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Fig. 1. Underwater photographs of competitive swimmers showing the fingers spread adopted during the stroke.

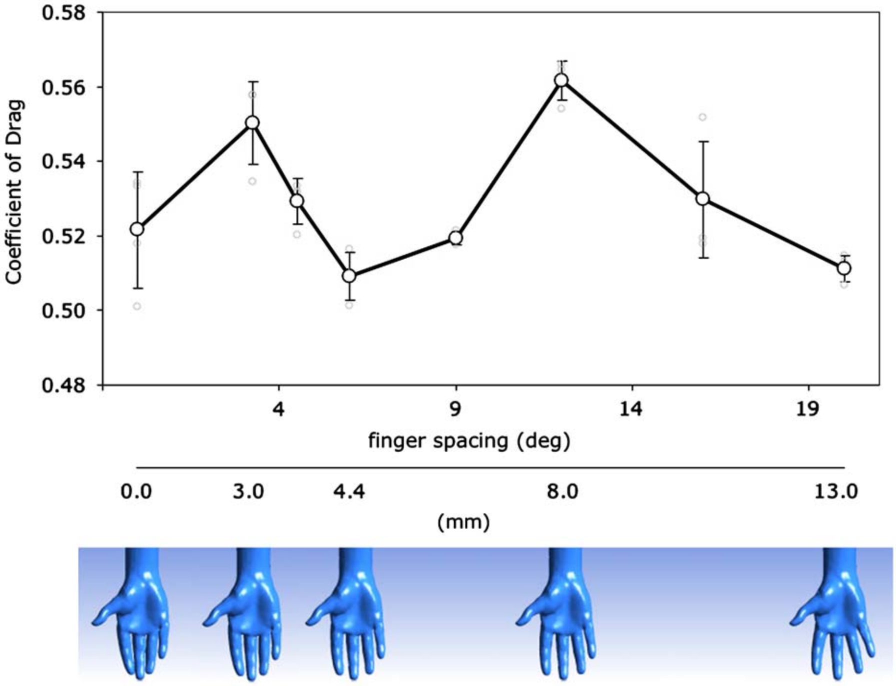

Fig. 2. The upper graph represents the hand drag coefficients vs. different finger spacings, obtained by computation fluid dynamics simulations. Circles and vertical bars show average and SD values, respectively, calculated when pooling all the four investigated speeds.

other and did not consider the effect of a small angle. Other studies in the past (Remmonds and Bartlett, 1981; Sidelnik and Young, 2006), using physical hand models with 2–4 fingers spreads in a wind tunnel and a water flume, suggest that a higher drag could be obtained at intermediate finger spacing and conclude that more finger positions should be investigated and that flow visualization could explain the drag increase.

We chose 8 finger spacings of a 3D mesh of the hand (34,038 triangular surface elements and 650,000 tetrahedral cells) and exposed them to 4 'virtual' water flows via computational fluid dynamics (CFD) simulations with a perpendicular angle of attack (additional details in the methodological notes on the CAD/CFD process section). The estimated C_D, shown in Fig. 2, turned out to be speed independent with a maximum at a finger spacing of 12° (or 8 mm inter-digit distance at mid finger). Such optimum spacing implies an 8.8% higher C_D with respect to a wide-open and fully-closed hand, corresponding to an equivalent increase of 'functional' surface area, and an extra thrust (at a speed of 2.5 m/s as typical of competitive swimming (Maglischo, 2003)) of 3.1 N.

CFD flow visualization (Fig. 3) suggests that the determinants of the optimum finger spacing are the size of the wake region and the magnitude/direction of vortices generated on the dorsal side of the hand.

At the closest and widest finger spacings (leftmost and rightmost panels in Fig. 3, respectively), the wake region is

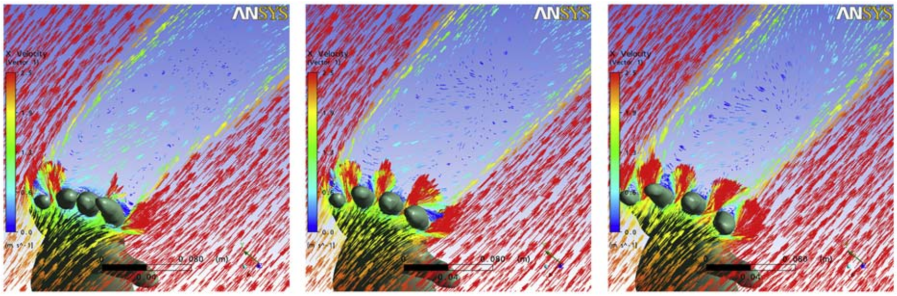

Fig. 3. Flow visualization on a horizontal plane located at mid-finger level, at a water speed of 2.5 m/s, at the closest (left), optimum (middle) and widest (right) finger spacing.

smaller than in optimal spacing (mid panel in Fig. 3), where about +20% of area is observed. Such a wake region behind the hand indicates that, at this finger spacing, the greatest amount of energy is extracted from the flow, which translates into a larger pressure differential between the two sides of the hand and, as a consequence, the highest propulsion.

Also, large vortices develop at the closest finger spacing, resulting in a strong back flow increasing the pressure on the dorsal surface of the hand, thus decreasing the pressure differential on the hand and the overall pressure drag.

At the optimal spacing, water jets produced between the fingers prevent the formation of the vortex and contribute, via a reduced backflow toward the dorsal side of the hand, to create a stagnation region with the consequent increase in the drag force.

Muscle physiology and swimming biomechanics predict metabolic advantages from the optimum finger spacing, which could be assessed by appropriate, although complex, experiments. It is fortunate that the (absolute) optimum spacing appears to correspond to the ‘natural’ resting posture of fingers. This will make less use of lumbricales and interossei, which only assist the flexor digitorum muscles in other hand postures and seem not to be crucial to propulsion.

Conflict of interest

None.

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Appendix 1. Supporting Information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jbiomech.2009.06.012.

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