

Drag Characteristics of Competitive Swimming Children and Adults

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The aims of this study were to compare drag in swimming children and adults, quantify technique using the technique drag index (TDI), and use the Froude number (Fr) to study whether children or adults reach hull speed at maximal velocity (v_{\max}). Active and passive drag was measured by the perturbation method and a velocity decay method, respectively, including 9 children aged 11.7 ± 0.8 and 13 adults aged 21.4 ± 3.7 . The children had significantly lower active (k_{AD}) and passive drag factor (k_{PD}) compared with the adults. TDI (k_{AD}/k_{PD}) could not detect any differences in swimming technique between the two groups, owing to the adults swimming maximally at a higher Fr, increasing the wave drag component, and masking the effect of better technique. The children were found not to reach hull speed at v_{\max} , and their Fr were 0.37 ± 0.01 vs. the adults 0.42 ± 0.01 , indicating adults' larger wave-making component of resistance at v_{\max} compared with children. Fr is proposed as an evaluation tool for competitive swimmers.

Keywords: front crawl, drag, Froude number, Reynolds number, wave drag, swimming technique

Drag in swimming is influenced by velocity, shape, size, and the frontal surface area, and approximates the general pressure drag equations:

$$F_d = \frac{1}{2} \cdot d \cdot FSA \cdot CD \cdot v^2 \quad (1)$$

$$F_d = k \cdot v^2 \quad (2)$$

where F_d is drag force, d is density of water, FSA is the projected frontal surface area, CD is coefficient of drag (changing owing to shape, orientation, and Reynolds number), v is velocity, and k is drag factor. Gliding passively through the water, the swimmer experiences passive drag (PD) caused mainly by the shape, velocity, and size of his or her body. Active drag (AD) is defined as the sum of all drag forces during swimming. Most studies on active and passive drag with swimmers include only adults.

Arguing that the drag during swimming consists of the passive drag and the additional or reduced drag caused by swimming movements, the ratio of active to passive drag factors (k_{AD} and k_{PD}) is an index of swimming technique. This assumption is a proposed model to scale active drag during swimming; it could prove useful when exploring the technical characteristics of a swimmer because drag is normalized to factors such as frontal surface area and passive body shape. The ratio of active drag to passive drag factors is called the *technique drag index* (TDI) and was first suggested by Kolmogorov and Duplisheva (1992). If two swimmers with similar passive drag

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were to be compared, the one with lower active drag can be said to have better technique. Swimming with lower drag at any given velocity reduces the cost of swimming, and the movements do not contribute to excessive or unnecessary drag. Similarly to studies on running economy, in which children run with greater vertical movements of their center of mass compared with experienced adult runners (Ariens et al., 1997), it is hypothesized that less experienced swimmers will have an increased TDI as a result of unnecessary and unrefined movements.

In general, it was found that active drag during freestyle swimming was approximately twice as high as passive drag (TDI = 2), using the $\dot{V}O_2$ extrapolation method for measuring active drag (di Prampero et al., 1974). Later, using the measurement of active drag system (MAD), it was found that active drag was in the same order of magnitude as passive drag, (TDI = 1) (van der Vaart et al., 1987). Another paper, using the velocity perturbation method reported TDIs of top-level freestyle swimmers at 0.5–1.5 (Kolmogorov & Duplisheva, 1992). Only adult swimmers were used in these studies. Little information exists on the drag characteristics of children.

From the growth versus drag study (Toussaint et al., 1990), the 11% height and 36% weight increase after a 2.5-year growth period of 13-year-olds did not change the active drag. Extrapolating these results to a larger age span, children are expected to have the same active drag factor (k_{AD}) as adults, but this has not yet been reported. However, scaling drag to size and velocity yielding the coefficient of active drag, CD_{AD} , this was found to be significantly lower after growth. Related to their size, these swimmers experienced less active drag after growth.

A study investigating active drag of both genders and different performance levels included swimmers from 10 years of age (Kolmogorov et al., 1997). The results showed that swimmers of less ability had less absolute active drag. If we correct for the higher velocity of the better performers, the active drag factor (k_{AD}) was 10 N·m⁻¹ (children) versus 27 for the adults in this study. No clear differences were found when comparing the coefficient of drag (CD_{AD}) values with those of adult swimmers— CD_{AD} for male adults being 0.30 and for male children 0.25. These authors concluded that no difference in CD_{AD} was present between the different performance levels, which should mean that

the higher absolute resistance for adults compared with children was due to higher velocities and a larger size. Other information on drag phenomena in swimming children is scarce.

$$Re = \frac{v \cdot BL}{\nu_i} \quad (3)$$

$$Fr = \frac{v}{\sqrt{g \cdot BL}} \quad (4)$$

The dimensionless hydrodynamical scaling factor Reynolds number (Re) (Equation 3) and Froude number (Fr) (Equation 4) are used for scaling in the ship building industry. The Reynolds number characterizes the state of water flow and is determined by the velocity (v), characteristic length (body length [BL] is used in this study), and the kinematic viscosity of water (ν_i) (Vogel, 1996). The wave-making resistance of a swimmer depends on the Froude number, which is determined by v , the length of the hull (BL), and the acceleration of gravity (g) (Vogel, 1996).

For objects traveling at the surface at increasing velocities, the formation of waves will increase the cost of propulsion sharply. Hull speed is a critical velocity, wherein the wake wavelength equals hull length, and is represented by a Froude number of 0.42 (Vogel, 1996). Above the hull speed, the vessel must climb over the bow wave by hydroplaning to increase speed further. By checking the Froude number of swimmers, it is possible to test whether swimmers use their full potential when considered as displacement vessels.

In the drag versus growth study, the Froude number at a submaximal velocity decreased after growth, indicating that the taller swimmers create less wave-making drag (Toussaint et al., 1990). However, at maximal swimming speed, no one seems to have investigated the Froude number in swimming children. Whether they are swimming at their optimal level, that is, at a Froude number of ≥ 0.42 , is not known.

The aim of this article is to (a) compare drag factors and drag coefficients in children and adults; (b) quantify the differences in swimming technique using the technique drag index in children and adults; and (c) use the Froude number as a means of checking whether children, compared with adults, use their full potential as displacement vessels at maximal velocity.

Methods

The subjects included nine male children, mean age 11.7 ± 0.8 years, and 13 male adults, mean age 21.4 ± 3.7 years; all provided written consent after they were informed of the risks and nature of the study. The Regional Committee for Medical Research Ethics approved the study. Body lengths were measured as standing height with a folding ruler and were 1.50 ± 0.06 and 1.85 ± 0.06 m ($p < 0.01$) for children and adults, respectively, and race performance for 50-m freestyle was 33.7 ± 2.9 and 24.5 ± 0.6 s ($p < 0.01$) respectively. Subjects were included in the study on the basis of being among the best swimmers in their national age group cohort. Two children were excluded from the study because of problems of complying with the data collection methods.

Test Protocol

After a warm-up, including sprints and practicing of procedures, the subjects were filmed during 2×25 -m maximal front crawl (3-min rest interval), one freely and one towing a perturbation buoy. Additionally, two separate trials were filmed consisting of push off and passive prone surface glide to a stop, arms above the head. One underwater video camera (50 Hz) moving with the direction and the velocity of the swimmer recorded a sagittal plane view. A baseline rope with markers every 2.0 m, placed 1.5 m below the swimmer, served as a calibrating measure and reference. Three consecutive stroke cycles were manually digitized using Kinex software (Tallinn, Estonia). The swimmers had a marker at the hip representing their center of mass. The swimming velocity (v) was determined as the horizontal velocity of the hip marker over the three strokes.

Active Drag Measurements

Active drag was calculated from the difference between the swimming velocities with and without towing the perturbation buoy. To ensure similar (maximal) power output for the two sprints, the swimmers were instructed to perform maximally at both trials. Active drag is calculated as (Kolmogorov & Duplisheva, 1992):

$$AD_{\max} = \frac{F_b \cdot v_2 \cdot v_1^2}{v_1^3 - v_2^3} \quad (5)$$

where AD_{\max} is active drag at maximal velocity, F_b is the resistance of the perturbation buoy, and v_1 and v_2 are the swimming velocities without and with the perturbation device, respectively. The drag of the perturbation buoy was calculated from the manufacturer's calibration of the buoy-drag characteristics (k_b) and its velocity: $F_b = k_b \cdot v_2^2$. The same buoy was used for both adults and children, the difference in velocity between free swimming and perturbed state was 9% and 16%, respectively (F_b representing 22% and 44% of active drag, respectively). Originally for this measurement method, the perturbed velocity should be within 10% of the free velocity (Kolmogorov & Duplisheva, 1992). However, it seems that the exact limit of perturbation level was not determined experimentally, and is only a recommendation. Swimming technique was not changed during the perturbed trial, and this supports the use of the relatively larger perturbation for the children. Stroke rate was measured during the two trials to verify whether swimming technique was changed during the perturbed swim. Neither the adults (52.0 ± 5.0 vs. 52.3 ± 5.0 strokes/min) nor the children (53.3 ± 4.0 vs. 52.0 ± 3.7 strokes/min) had any significantly different stroke rates for free swimming compared with perturbed swimming, respectively. To compare with passive drag factor (k_{PD}), Equation 2 was used to calculate the k_{AD} factor as the ratio of AD_{\max} to v_1^2 .

Passive Drag Measurements

The acceleration acting on the swimmer gliding passively can be expressed by Equation 6, where a is acceleration, k_{PD} is passive drag factor, m_v is virtual mass of the subject, and v is velocity. The velocity is then expressed as Equation 7 and 8. The gliding velocity decay was measured by digitizing the hip point from underwater video every 0.5 s for 4–6 s. A Matlab routine (MathWorks, Inc, Natick, MA) using the function “fminsearch” and the least sum of squares was run through the velocity data and estimated the parameters v_0 and k_{AD} in Equation 8. The lowest value of the trials was chosen to represent the passive drag most accurately.

$$a = -\frac{k_{PD}}{m_v} v^2 \quad (6)$$

$$v = \int a dt = \int \frac{k_{PD} v^2}{m_v} dt = \frac{k_{PD}}{m_v} \int v^2 dt \quad (7)$$

$$v(t) = \frac{1}{\frac{1}{v_0} + \frac{k_{PD}}{m_v} \cdot t} = \frac{v_0}{\frac{k_{PD}}{m_v} v_0 t + 1} \quad (8)$$

This method of estimating the passive drag phenomenon was suggested by Klauck and Daniel (1976), and later by Mollendorf et al. (2004); however, these authors did not take added mass into account. When an object accelerates in a fluid, it experiences drag forces and the forces needed to accelerate some mass of fluid backward. According to Vogel (1996), one can think of this force as an additional mass moving with the object. The virtual mass (m_v) is the sum of the mass of the subject and the added mass and is the correct mass to use in our inverse dynamic gliding test, taking care of both the drag forces and the acceleration reaction (see Vogel, pp. 362–364 [1996]). Klauck (1999) found the added mass by means of a towing device to be approximately 30–70 kg on juvenile swimmers. The added mass coefficient (C_a) in this study was in the range of 0.47 to 1.1. No other studies on added mass for swimmers seem to exist. To estimate the added mass, we used a conservative added mass coefficient in the lower range from the Klauck study (1999), namely, a C_a of 0.5. Using this and the volume (V) of the swimmer, we calculated added mass as $m_a = C_a \cdot V \cdot d$. (Vogel, 1996). The volume of the swimmers was found using underwater weighing, as previously described (Kjendlie et al., 2004). Accounting for added mass resulted in a $34 \pm 0.2\%$ higher passive drag force.

Calculations and Statistics

The technique drag index (TDI) was calculated according to Equation 9. Active and passive coefficients of drag (CD_{AD} and CD_{PD}) were found by using Equation 1. For simplification, CD values are assumed not to vary with Reynolds number. This simplification is reasonable because the Re numbers are approximately 2.7×10^6 . Frontal surface area (FSA) was estimated using Clarys's prediction (Clarys, 1979), according to Equation 10, where BM and BL are body mass and body length. This equation was derived from a mixed sample population aged 18–21 (i.e., not directly

validated on children). There are, however, reasons to believe that the method is valid also for children of 12 years of age. Anthropometrical measurements of the subjects showed, for example, that the shoulder widths (measured by subtracting $2 \times$ arm length from arm span) related to body length were similar between adults and children, 13 ± 2 and $11 \pm 5\%$ respectively ($p = 0.38$), and thus that the children's width measurements related to body length are similar to adults.

$$TDI = \frac{k_{AD}}{k_{PD}} \quad (9)$$

$$FSA = \frac{6.93BM + 3.50BL - 377.2}{10000} \quad (10)$$

$$BSA = 0.0235 \cdot BL^{0.42246} \cdot BM^{0.51456} \quad (11)$$

Reynolds (Re) and Froude numbers (Fr) were calculated according to Equations 3 and 4, respectively, with the kinematic viscosity of water (ν_i) of $8.6 \times 10^7 \text{ m}^2 \cdot \text{s}^{-1}$ at 26°C . The two groups were compared for Fr and Re at maximal velocity and an unscaled submaximal velocity of $1.25 \text{ m} \cdot \text{s}^{-1}$. This velocity was chosen for ease of comparison with a previous study (Toussaint et al., 1990).

Body surface area (BSA) was estimated from BL and BM , using Equation 11 (Gehan & George, 1970). This equation was found to explain more than 99% of the variation in surface area among 401 observations, including children. A significance level of minimum 0.05 was accepted and a two-sample t test was used for group comparisons. The post hoc calculated statistical power for the active drag parameter was 0.79, and for the passive drag it was 0.99.

Results

The active drag measurements showed that the adults had significantly higher values of maximal velocity, active drag at maximal velocity, active drag factor (k_{AD}), and active drag factor normalized to body length compared with the children (Table 1). There was no difference between the two groups regarding the active drag coefficient (CD_{AD}). Looking at the adult group, the k_{AD} showed a relatively large SD , owing to three subjects having a k_{AD} value of more than 1.5 times the group average. There were no such outliers for the children.

Table 1 Mean \pm SD of Active Drag Data for Adults and Children

	v_{\max}^a ($\text{m}\cdot\text{s}^{-1}$)	AD_{\max}^b (N)	k_{AD}^c ($\text{kg}\cdot\text{m}^{-1}$)	$k_{AD}\cdot BL^{-1d}$ (kg)	CD_{AD}^e
Adults	1.79	106.1	33.0	17.7	0.84
	± 0.05	± 67.7	± 20.2	± 10.6	± 0.46
Children	1.42	28.5	14.0	9.3	0.66
	± 0.12	± 8.8	± 3.3	± 2.1	± 0.14
$p <$	0.001	0.01	0.01	0.05	0.28 (NS)

^aMaximal velocity.^bActive drag at v_{\max} .^cActive drag factor.^dActive drag factor normalized for body length (kg).^eActive drag coefficient.

The adults had significantly higher passive drag factor (k_{PD}), higher k_{PD} normalized for body length, and lower passive drag coefficient (CD_{PD}) compared with the children (see Table 2). The Pearson product–moment correlation between the two passive drag trials was $r = 0.85$, and a coefficient of variation of 9%, owing to variations in performing the free gliding test. Only the lowest value from the two trials was used in further analysis. The mean \pm SD regression coefficients between the fitted and actual velocity data were $r^2 = 0.98 \pm 0.01$ and $r^2 = 0.98 \pm 0.03$ for the children and adults, respectively.

The technique drag index (Table 2) did not show any statistical differences between the two groups. However, a tendency for the adults to have a higher value is present (NS). For Froude and Reynolds numbers at maximal velocity, adults had significantly higher values (Table 3). In addition, the results in this table show that at $1.25 \text{ m}\cdot\text{s}^{-1}$ adults had lower Froude and Reynolds numbers compared with the children.

Discussion

The main finding of this study is that men have significantly higher parameters of drag than boys. This is due to the larger size of the men because the CD_{AD} did not differ. The presented AD_{\max} (28.5 N) (at $v_{\max} = 1.4 \text{ m}\cdot\text{s}^{-1}$) for the children is close (22% lower) to values reported previously for a mixed group of 13-year-old swimmers with similar maximal velocity ($1.37 \text{ m}\cdot\text{s}^{-1}$) of 37.0 N (Toussaint et al.,

Table 2 Mean \pm SD Passive Drag and Technique Drag Index for Adults and Children

	BSA ^a (m^2)	k_{PD}^b ($\text{kg}\cdot\text{m}^{-1}$)	$k_{PD}\cdot BL^{-1c}$ (kg)	CD_{PD}^d	$k_{AD}\cdot k_{PD}^{-1e}$
Adults	2.01	28.7	15.5	0.74	1.15
	± 0.11	± 3.2	1.5	0.07	0.60
Children	1.31	20.2	13.3	0.94	0.70
	± 0.11	± 3.0	1.6	0.07	0.18
$p <$	0.001	0.001	0.01	0.001	0.06 (NS)

^aBody surface area.^bPassive drag factor.^cDrag factor normalized for body length.^dPassive drag coefficient.^eTechnique drag index, $TDI = (k_{AD} \cdot k_{PD}^{-1})$.**Table 3 Mean \pm SD Froude (Fr) and Reynolds (Re) Numbers for Adults and Children at $v = 1.25 \text{ m}\cdot\text{s}^{-1}$ and v_{\max}**

	Fr $1.25 \text{ m}\cdot\text{s}^{-1}$	Fr v_{\max}	Re $1.25 \text{ m}\cdot\text{s}^{-1}$	Re v_{\max}
Adults	0.29	0.42	2.7×10^6	3.9×10^6
	± 0.01	± 0.01	$\pm 8.4 \times 10^4$	$\pm 1.9 \times 10^5$
Children	0.33	0.37	2.2×10^6	2.5×10^6
	± 0.01	± 0.01	$\pm 9.5 \times 10^4$	$\pm 2.4 \times 10^5$
$p <$	0.001	0.001	0.001	0.001

1990). The two groups of children show surprisingly similar active drag values when the 20% difference of measurement methods is considered (Toussaint et al., 2004). This difference may partly be due to the MAD method's use of only arm strokes whereas the perturbation method includes leg kicking as well. However, the two methods were found to measure the same phenomenon, and the perturbation method is thus both reliable (Kolmogorov & Duplisheva, 1992) and valid (Toussaint et al., 2004). As the adults have higher swimming velocity at maximal sprint, the active drag is, as expected, higher than for children. Comparing active drag factors (k_{AD}), adults still have significantly higher values than the children, about twice in magnitude. However, the k_{AD} is not adjusted for body size. When dividing k_{AD} by body length (BL), adults still have about twice the $k_{AD}\cdot BL^{-1}$ as children.

The CD_{AD} is k_{AD} adjusted for frontal surface area. The presented CD_{AD} results for adults are higher

than previously reported, both when compared with the perturbation method ($CD_{AD} = 0.28 \pm 0.09$) (Kolmogorov & Duplisheva, 1992), and compared with the MAD system $CD_{AD} = 0.64 \pm 0.09$ (Toussaint et al., 1988). These differences may be due to several factors. First, the study of Kolmogorov and Duplisheva used another method of calculation of frontal surface area, and this method has been found to overestimate *FSA* by 100% (Cappaert & Gordon, 1998). Therefore they underestimate the CD_{AD} value compared with the method for finding *FSA* used in the current study. Secondly, the MAD method has shown to measure higher drag values (approx. 20%) than the perturbation method (Toussaint et al., 2004). Thirdly, real differences in active drag between the groups may be present. Furthermore, for the children, comparing CD_{AD} values with the growth versus drag study, the values do not seem to differ, $CD_{AD} = 0.64$ vs. 0.66 , respectively. Looking at CD_{AD} , there were no statistically significant difference between adults and children. This confirms the results of Kolmogorov et al. (1997), who found that CD_{AD} values were not different between experienced and inexperienced swimmers. When corrected for velocity and frontal surface area, drag does not differ between the two groups.

The results of passive drag measurements are in accordance with the active drag data, adults have higher absolute and body length-adjusted k_{pd} than children. However, CD_{pd} was significantly lower in adults than in the children, unlike the case for active drag. This may indicate either that the adults have learned a better glide position or that their body shape (i.e., accounting for size) causes less passive drag.

The other main finding from the current study is that the TDI was not statistically different between children and adults. The hypothesis of children's higher TDI value could not be supported. The numbers show even a tendency for the children to have a lower TDI, which is unexpected. The reason for this may lie in the level of maximal velocity the subjects achieved. Even though all subjects were tested at maximal velocity, the discussion below will reveal that the children had a lower wave-making resistance, and the children did not reach their hull speed. This probably makes their active drag lower than if their velocity would have reached a level represented by $Fr = 0.42$, thereby reducing the TDI and making the children's technique look better than if compared

at the same relative velocities. From these results, it seems that the TDI is not suited as a parameter for evaluating technique, as previously suggested (Kolmogorov & Duplisheva, 1992), unless compared at equal Froude numbers. Comparisons of TDIs at unequal Froude numbers would include not only technical factors; for instance, high power output would mean a higher Froude number and a greater wave-making component of resistance.

Several aspects of technique might alter active drag either by influencing size, such as length and *FSA* or influencing the shape or *CD*. Empirical studies connecting technical solutions of swimming movements to active drag are scarce. Therefore, explaining the individual variations in TDI is difficult. Lateral sway increases the projected *FSA* and may be the result of excessive lateral movements of the underwater stroke, a lateral recovery, or a lack of a streamlined body posture. Furthermore, the kicking action might contribute to increase of drag if the kick is too deep; alternatively, leg kicking done correctly might help to reduce active torque (body angle with the horizontal) (Yanai, 2001), thereby reducing *FSA*. It is even suggested that the kicking action might help reduce wave drag by disruption of the pressure field at the rear of the swimmer (Toussaint, 2006). By manipulating with arm stroke-coordination (see Chollet et al., 2000, for details), swimmers could adjust their hull length by having one arm more or less time in front of their body. Increase of the characteristic length at any given velocity will reduce *Fr* number and wave-drag contribution (Vogel, 1996).

The Froude number (*Fr*) is known to represent a criterion for wave-making resistance (Toussaint et al., 1990). At a velocity of $1.25 \text{ m}\cdot\text{s}^{-1}$, which is closer to the maximal velocity for the children compared with the adults, the Froude number was significantly less for the adults than for the children. Their longer *BL* will reduce the wave-making resistance at any absolute velocity, which indicates that the pressure drag component is greater relative to their total drag. The longitudinal study on drag in children growing 0.15 m over a period of 2.5 years supports this finding. In this study, authors found that after growth, total drag values remained unchanged, but the Froude number was reduced and Reynolds number was increased after the growth period (Toussaint et al., 1990). In contrast to the present results, they also found that CD_{AD} changed, being smaller

after growth. Differences in study design between the current study (cross-sectional) and the growth versus drag study (longitudinal) may be an explanation for the diverging findings. In a cross-sectional study, there is a possibility that the subjects of the two groups may represent the population differently. The subjects in the current study were at different performance levels owing to age and experience; however, both groups represented swimmers at the top level for their age group. This was done to ensure that subjects were as equal as possible, except for age and experience level.

The Froude number achieved by the adults was 0.42 during maximal sprint, identical with the Froude number suggested by Larsen et al. (1981) as the maximal attainable for human swimmers or for nonplanning swimmers in general (Vogel, 1996). Using competition analysis it is possible to calculate Fr for international top swimmers. The top-level swimmer Alexander Popov in a 50-m freestyle race will have Fr 0.49 (BL being 2.01 m and $v = 2.19 \text{ m}\cdot\text{s}^{-1}$; competition analysis data from www.swim.ee). It seems odd that some swimmers attain higher velocities than hull speeds. However, the way Fr is calculated here is with the use of body length (= height) as characteristic length. During front crawl swimming, there are certain phases in the stroke in which the characteristic length is longer than BL, at hand entry and arm stretch in the beginning of the arm pulling phase. Thus, the true Fr is lower in these phases. This opens for discussion of which hull length to use for swimmers and for the possibility that expert swimmers, by using superior technical solutions, achieve Fr greater than 0.42. The children's Fr at v_{max} was 0.37, which according to Larsen et al. (1981) means that they have not yet reached their potential maximal velocity in the water considered as displacement ships. The different Fr of the two groups could mean that their wave drag has a different influence on the total drag at maximal velocity, such that the adults encounter relatively more wave drag than the children. Using the data from Pelayo et al. (1997), who investigated grammar school children for maximal freestyle velocity and anthropometrical measurements, Froude numbers for noncompetitive swimming children is calculated. For males 11 years of age, Fr = 0.20, and, for 17-year-olds, Fr = 0.26. Compared with our data, and compared with international levels, these values are even lower, indicating that the possible attainable

velocity in the water is far from being reached, and that the relative wave-making resistance is lower.

Results and discussion from the current study regard men and boys. The most important drag-related difference between males and females is body composition. It is known that females in general have a higher fat content and different distribution than males and that their floating torque is less (Zamparo et al., 1996); this would affect drag differences between genders in adults. Before puberty, the differences in shape and body tissue composition between boys and girls are less pronounced (Tanner, 1978) and hence drag characteristics are less gender sensitive at these ages. Furthermore, the results for children are limited to the ages of 11 years. For younger children, little information exists on drag, and should be a topic for future research.

To conclude, the results of the current study show that adults have higher absolute active and passive drag factors, and higher active and passive drag factors per unit of body length. The technique drag index could not detect any differences in swimming technique between the two groups, probably due to the effects of adults swimming maximally at a higher relative velocity (higher Fr), thus increasing the wave drag component and thus masking the hypothetical effect of better technique. The children were found not to reach their hull speed at maximal swimming. This is indicating that they, when corrected for size by using Fr, still have not reached maximal attainable velocity in the water, viewed as displacement hulls. As size was found to be an important part of drag, whereas shape or CD values of children and adults were not different, coaches and competitive swimmers are advised to calculate Fr at maximal velocity and use it as an easily accessible evaluation tool. In this way, drag characteristics are scaled for size and the progress of the swimmers can be evaluated regardless of their physical size.

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