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Load-velocity profile and active drag in young female swimmers: an age group comparison

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ABSTRACT

Purpose: The present study aimed to establish differences in load-velocity profiling, the active drag (AD) and the drag coefficient (Cd) between three age groups of female swimmers. **Methods:** Thirty-three swimmers (11, 13 or 16 years old) were recruited. The individual load-velocity profile was determined for the four competitive swimming strokes. The maximal velocity (V0) and load (L0), L0 normalized by the mass (L0% BM), AD and Cd were compared between the groups. A two-way ANOVA and correlation analysis were conducted. **Results:** Compared with younger counterparts, 16-year-old swimmers generally had larger V0, L0 and AD, which was particularly evident when comparing them with 11-year-old ($P \leq 0.052$). The exception was breaststroke where no differences were observed in L0 and AD, while Cd was smaller in 16-year-old than 11-year-old ($P = 0.03$). There was a negative correlation between Cd and V0 for all groups in backstroke ($P \leq 0.038$) and for the 11-year-old and 13-year-old in breaststroke ($P \leq 0.022$) and front crawl ($P \leq 0.010$). For the 16-year-old, large correlations with V0 were observed for L0, L0% BM and AD ($P \leq 0.010$) in breaststroke and for L0 and AD with V0 in front crawl ($P \leq 0.042$). In butterfly, large negative correlations with V0 were observed in the 13-year-old for all parameters ($P \leq 0.027$). **Conclusions**: Greater propulsive force is likely the factor that differentiates the oldest age group from the younger groups, except for breaststroke where a lower Cd (implying a better technique) is evident in the oldest group.

Keywords: swimming, semi-tethered, strength, velocity, technique

In competitive swimming, the goal of the swimmer is to travel a given distance as fast as possible.[1] Two main forces determine swimming performance, namely the propulsive force generated by the swimmer and the resistive force of the water which retards the swimmer during movements (active drag: AD).[2,3] To achieve the highest swimming performance, the propulsive force should be maximized, whereas AD should be minimized. AD is affected by several factors such as the swimmer's technique, body surface area, and swimming velocity. For instance, it is known that AD exponentially increases when increasing the swimming velocity. This means that it might lead to misinterpretation of the swimmer's performance when using AD (without normalizing it by the velocity) as a swimming performance parameter.[4] To better understand the hydrodynamic profile of an athlete, it is useful to use the drag coefficient (Cd), which is a dimensionless parameter that accounts for body surface area and the exponential relationship between drag and swimming velocity.[4,5] It is currently not possible to directly quantify AD. Thus, several indirect methods have been used to estimate it, e.g., by assisted or resisted swimming protocols.[6–8]

The resisted swimming has also been recently used for the load-velocity profile as a performance assessment tool in sprint swimming in adult athletes. The load-velocity profile is a widely used method to estimate maximal performance in multiple sports such as sprint running and strength exercises.[9–15] In general, there is a strong negative linear relationship between the load the exercise is performed with and the achieved velocity. This allows predicting the maximal load (where mathematically the velocity is zero: L0) and the maximal velocity (where mathematically the load is zero: V0).[14,16,17] Moreover, the investigation of load-velocity profiles in sprint swimming showed that it was a reliable and useful tool for estimating the maximal sprint swimming performance in athletes.[16,18] Furthermore, a strong relationship between the slope (steepness of the regression line) and AD was observed in front crawl swimming.[19] This means that, for example, if swimmers have a large L0 and a flatter slope in the load-velocity profile, the swimmers have the ability to generate large propulsive force at zero velocity but they are not able to utilize this ability to generate a fast velocity due to a large AD.[19] The load-velocity profile is a useful tool to estimate maximal performance, monitor athletes over time and objectively define training intensity to enhance performance; however, most studies focus on the investigation of the load-velocity profile in adult athletes.[16,18,20,21]

In many countries, participation in swimming competitions begins at an early age and is popular among girls and boys.[22] Until the age of 10 years, a slight difference between females and males can be found where females achieve better results than males.[23,24] It is known that puberty influences athletic development in each gender differently. According to Dormehl et al.[25], puberty in females begins at approximately 8 to 10 years of age. During maturation, mental status, as well as physiological and biomechanical properties, undergo rapid changes.[26–28] The rise of estrogen concentration initiates breast development, the onset of menstruation and an increase in body fat. The individuals gain a rapid growth spurt and the extremities grow faster than the trunk. Furthermore, changes in the central nervous system are well documented.[29,30] These rapid changes during maturation likely influence swimming performance in young females since the anthropometric characteristics of a swimmer contribute to individual performance. Previous investigations suggested that limb length, body fat and frontal surface area are important factors in swimming, e.g., elite swimmers tend to have longer arms, a larger hand surface and lower body fat compared to the normal population which positively contribute to better sprint swimming performance.[31–33]

The morphological changes (i.e., breast development, rapid growth rate) during sexual maturation likely affect swimming performance. The growth spurt, especially of the extremities, can positively affect swimming performance, whereas the increase in body fat during female maturation and the change of body surface due to breast development may be a disadvantage in the context of sprint swimming performance.[34–38] However, the effect of growth on swimming performance is very complex during female maturation.[36]

Although swimming competition begins at an early age, most researchers focus on the load-velocity profile in adult population and less is known about youth swimming. Furthermore, it is known that there are sex-specific effects on sports performance which should be considered. Therefore, the aim of this study was to investigate the difference of swimming specific performance parameters, namely L0, L0 normalized to body mass (L0% BM), V0, AD and Cd, in three different age groups of young female swimmers in the four competitive swimming strokes. The findings should provide a better understanding in regards to swimming strategies used by young female swimmers whether it is more important to generate large propulsive force or minimize the water resistance to achieve high swimming performance.

Methods

Subjects

Thirty-three competitive female swimmers from three different age groups: eleven 11-year-old (mean ± SD, body mass 48.9 ± 5.9 kg, height 160.0 ± 6.4 cm, BMI 19.0 ± 1.4, World Aquatics [WA] points for 200 m individual medley 305.9 ± 20.8); eleven 13-year-old (mean ± SD, body mass 50.3 ± 6.9 kg, height 162.5 ± 7.8 cm, BMI 19.0 ± 1.3, 200 m IM 464.4 ± 34.3 WA points) and eleven 16-year-old (mean ± SD, body mass 60.8 ± 5.4 kg, height 167.2 ± 5.5 cm, BMI 21.7 ± 1.3, 200 m IM 535.7 ± 78.4 WA points); volunteered to participate in the present study. The inclusion criteria were: female swimmer ranked in the qualification for the regional age group championship and no injuries or illnesses at the time of testing. Participants and their legal guardians were given a detailed oral and written explanation of the aims, procedures, benefits and potential risks associated with participation in the study. A health history questionnaire including details on training activity level, sickness and injuries was completed prior to participation. Eligible participants and their legal guardians provided written informed consent before participation in the study. All participants were trained for the individual medley (IM). The study was approved by the local ethical committee and the National Center for Research Data and conducted in accordance with the Declaration of Helsinki.

Design

This cross-sectional study investigated the differences in V0 L0, L0% BM, AD and Cd between the three age groups in backstroke, breaststroke, butterfly and front crawl. Further, the relationships of L0, L0% BM and AD with V0 were analyzed.

Methodology

Measurements were conducted on two separate days (two swimming strokes per day) in order to minimize the number of trials and to avoid fatigue which could influence the investigated variables. After measuring body mass and height, the 11-year-old swimmers performed a standardized warm-up, including kicking, pulling, sprinting and technique/drill exercises of about 45 minutes in the water since they were not as experienced as the older age groups. The 13-year-old and 16-year-old swimmers performed their individual pre-competition warm-up routine (typically for 45 minutes). After 20 minutes of recovery,[39] the swimmers performed three 25 m semi-tethered swimming trials of two strokes in a randomized order on each day of testing. The swimmers were instructed to perform with three different loads for each stroke with maximal effort. The external loads were individually selected to ensure that each swimmer could complete all trials. The three loads were typically selected from 1-3 kg for

11-year-old and 1-5 kg for 13-year-old and 16-year-old swimmers. In order to attempt full recovery between each trial, recovery time was ~6 min.[40]

To provide the isotonic resistance for the semi-tethered swimming trials, a portable robotic resistance device, 1080 Sprint, (1080 Motion, Lidingö, Sweden), featuring a servo motor (2000 RPM OMRON G5 Series Motor; OMRON Corp., Kyoto, Japan), was used. The motor was attached to a fiber cord that was wrapped around a carbon-fiber spool and attached around the swimmer`s pelvis with an S11875BLTa swim belt (NZ Manufacturing, Tallmadage, OH, USA). To avoid the cord disturbing the lower limb movements of the swimmer, the device was fixed on the starting block which was 1.0 m above the water surface (Figure 1). Temporal velocity data were collected from the integrated software by the manufacturer, version 3.9.8, at a sampling frequency of 333 Hz.

For analyzing the load-velocity profile from the semi-tethered swimming test, velocity data from a 5 m range (10-15 m of the pool) was extracted. The absolute velocity was adjusted by the following equation to obtain the horizontal component of the velocity measured by the device.

$$\mathrm{V_{adj}} = \mathrm{V} \times \cos\left[\sin^{-1}\left(\frac{1.00}{\mathrm{L_w}}\right)\right],$$

where V represents the velocity before and V_{adj} after adjustment, 1.00 is the height (m) from the water surface to the point where the wire is stretched from the device, and L_w is the length of the wire (m) between the machine and the swimmer. The mean V_{adj} was plotted as a function of the external load and a linear regression line was established based on the load-velocity plot. The mean V_{adj} was used for analysis because it has been suggested to produce more accurate load-velocity profiles than maximum velocity.[41] To predict V0 and L0, the intercepts of the regression line with the horizontal and vertical axes were obtained. Further, L0 was normalized with the individual body weight of each participant to obtain L0% BM.

Figure 1 around here

In addition, the velocity perturbation method was used to calculate AD. V0, mean force and velocity data of a semi-tethered swimming trial were used under the assumption that the power output of a swimmer is equal between free-swimming and swimming with external load. The following formula was used:

$$\mathrm{AD} = \frac{\mathrm{F} \times \mathrm{VL} \times \mathrm{V0}^2}{\mathrm{V0}^3 - \mathrm{VL}^3}$$

The mean tethered force (F) was measured at the trial with the external load, the maximal swimming velocity (V0) was estimated using the load-velocity profile and VL is the mean swimming velocity with the defined external load. F and VL were obtained from the trial with the second lightest load, which was based on the rationale that the use of the lightest load for AD calculation would generate considerable random errors.[8]

The drag coefficient was calculated using the following formula:

$$\mathrm{Cd} = \frac{2 \times \mathrm{AD}}{\rho \times \mathrm{A} \times \mathrm{V}^2},$$

where ρ represents the mass density of the water, and A is the surface area of the swimmer's body.[4,5] The surface area of the body was calculated using the formula established by Gehan and George.[42,43]

$$A = 0.0235 \times height^{0.4246} \times weight^{0.51456}$$

Statistical analysis

The Shapiro-Wilk test confirmed normal distribution for L0, L0% BM, V0 and AD. A two-way ANOVA was used to compare the obtained vartiables between age groups in each stroke (within-participants effect: four strokes; between-participants effect: age groups). This was based on a statistical power calculation using G*Power (version 3.1.9.7; Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany; http://www.gpower.hhu.de/),[44] which detected that a combination of 33 participants and four repeated measures is sufficient to ensure high statistical power (minimum 85% and maximum over 95%) to detect a medium effect size when the correlation among repeated measures is higher than medium ($r = 0.5$). Since the stroke effect is out of scope in this study, it will not be elaborated on in the discussion. For the post hoc comparison, Tukey's HSD test was used for L0, L0% BM, V0 and AD. Since Cd was not normally distributed, the Wilcoxon sum exact test with Holm-Bonferroni correction was used. Further, the within-group correlations of L0, L0% BM and AD with V0 were calculated using Pearson's correlation coefficient to get insight into differences in within-group trends between the 11-, 13-, and 16-year-old swimmers. For the correlation between Cd and V0, Spearman's correlation coefficient was used. The threshold values representing small, medium, large, very large and extremely large were defined as 0.1, 0.3, 0.5, 0.7 and 0.9.[45] In addition, the mean coefficient of determination (R^2_{LV}) of the individual load-velocity profiles was calculated. All statistical analyses were conducted using Statistic Package for Social Science (SPSS) version 26 (IBM Corp. Armonk, NY, USA) and R version 4.1.2. The level of significance was set at $P < 0.05$.

Results

In backstroke, no significant correlation of L0, L0% BM and AD with V0 was found, while medium negative correlations between Cd and V0 were observed in all three age groups. In breaststroke, large correlations between V0 and L0, L0% BM and AD were observed only in the 16-year-old athletes. However, regarding the correlation of Cd with V0, medium to large negative correlations were found in the 11-year-old and 13-year-old swimmers but not in the 16-year-old athletes. No correlations were shown in butterfly in the 11-year-old and 16-year-old swimmers, while medium to large negative correlations with V0 were found in the 13-year-old athletes in all investigated parameters. In front crawl, there were medium correlations of L0 and AD with V0 in the 16-year-old females. Large negative correlations of Cd with V0 were observed in the 11-year-old and 13-year-old athletes.

Table 1 around here

The results of the two-way ANOVA are presented in Table 2. Significant age effects were observed in L0, V0, AD and Cd but not in L0% BM (Table 2). As mentioned in the method section, the effect of stroke is out of scope in this study and thus is not further elaborated in the results or discussion section.

Table 2 around here

The post-hoc Tukey HSD test showed that in backstroke, the 16-year-old swimmers had 0.2 m/s faster V0 (P = 0.003) and 2.9 kg larger L0 (P = 0.004) than the 11-year-old and 2.2 kg larger (P = 0.041) than the 13-year-old swimmers. Despite non-significant, the difference between 11- and 16-year-old swimmers in backstroke AD was close to alpha-level (P = 0.052). In breaststroke, the 16-year-old athletes were 0.2 m/s faster than the 11-year-old swimmers (P = 0.005) and the Cd was different (smaller in 16-year-old swimmers) between these two age groups (P = 0.034). In butterfly, the 13-year-old swimmers had 0.2 m/s (P = 0.024) and the 16-year-old athletes had 0.2 m/s ($P \leq 0.001$) faster V0 than the 11-year-old females. The 13-year-old athletes exhibited 2.5 kg (P = 0.025) greater L0 than their younger counterparts and the 16-year-old swimmers had 4.5 kg ($P \leq 0.001$) larger L0 than the 11-year-old athletes. Moreover, the AD was 17.8 N ($P \leq 0.001$) larger in the oldest females compared to the 11-year-old swimmers. In front crawl, the 16-year-old swimmers were 0.2 m/s ($P \leq 0.001$) faster and the L0 was 3.7 kg ($P \leq 0.001$) larger than in the youngest age group. Furthermore, the 13-year-old swimmers had 0.1 m/s (P = 0.040) faster V0 than the 11-year-old females and had 2.1 kg (P = 0.020) smaller L0 than the oldest age group. In addition, the AD of the 16-year-old atheltes was 14.3 N ($P \leq 0.001$) larger compared to the 11-year-old and 8.9 N (P = 0.036) larger compared to the 13-year-old females. The results are presented in Figure 2.

Figure 2 around here

In addition, R^2_{LV} values ranged from 0.996 ± 0.008 in backstroke for 11-year-old to 1.000 ± 0.000 in butterfly for 13-year-old female swimmers (Table 3).

Table 3 around here

Discussion

In this study, variables obtained from a semi-tethered swimming proptocol were compared together with correlation coefficients between three different age groups (11-year-old, 13-year-old and 16-year-old) female swimmers. The individual load-velocity profile was used to assess the L0 and V0 that the swimmer can generate in the four competitive swimming strokes. Moreover, the individual L0 was normalized to the individual body mass to minimize the body mass effect. Furthermore, the AD was calculated using the velocity perturbation method together with Cd to assess the hydrodynamic profile of the athletes. The high R^2_{LV} values demonstrated that the relationship between the load and velocoity during the semi-tethered swimming protocol clearly had a linear relationship, supporting the rationale of estimating V0 and L0 from a linear regression line.

In backstroke, the results of the correlation analysis showed a medium negative correlation between V0 and Cd in all three age groups but no significant correlation between V0 and L0, L0% BM and AD. This indicates that swimmers who have a more efficient technique to reduce water resistance and consequently had a lower Cd value achieved higher velocities. Under the assumption of L0 being largely related to the swimmer's propulsive force, the ability to generate large propulsive force seemed to be less important to achieve fast swimming speed when focusing on the within-group trend. Furthermore, between-group comparisons demonstrated somewhat different results. The effect of age on the investigated parameters showed that the oldest swimmers achieved 0.2 m/s faster swimming speed and also showed a greater L0, implying a greater ability to produce the propulsive force, than the 11-year-old and 13-year-old athletes (+2.9 kg and +2.2 kg, respectively). Given that the older group of swimmers achieved faster V0 and their body size was larger than the younger groups, one would expect that their AD should also be larger compared with their younger counterparts; however, this was not the case. Nevertheless, this result should be treated with caution as the difference between 11- vs 16-year-old groups in AD was very close to alpha-level ($P = 0.052$), meaning that the non-significance might have been due to Type-II error. Given that the Cd was very similar between the groups ($P > 0.8$), it is reasonable to conclude that the 16-year-old athletes probably had better abilities to generate propulsive force compared with the younger groups, which resulted in a faster swimming velocity.

In breaststroke, L0, L0% BM and AD had large correlations with V0 in the oldest swimmers, but those correlations were not observed in the two younger age groups. Contrary, medium to large negative correlations between Cd and V0 were detected in the 11-year-old and 13-year-old athletes, but this was not observed in the oldest swimmers. The positive correlations between V0 and L0, as well as V0 and AD, imply that the 16-year-old athletes relied more on the generation of large propulsive force to achieve fast velocity rather than reduction of the drag. In contrast, for the younger age groups, efficient technical skills to minimize the drag seemed important, given the negative correlation between Cd and V0. For the group comparisons, the 16-year-old swimmers were 0.2 m/s faster than their younger counterparts and significantly lower Cd values were observed in the oldest athletes compared with the youngest swimmers. Therefore, it was probable that the oldest group had advantages based on a better skill from a perspective of hydrodynamic profile compared with the 11-year-old females.

In front crawl, medium correlations of L0 and AD with V0 were observed in the 16-year-old swimmers but not between L0% BM and V0 or between Cd and V0. However, only Cd and V0 had large negative correlations in the 11-year-old and 13-year-old swimmers. Therefore, similar to breaststroke, when focusing on within-group variations, swimmers probably relied on a good hydrodynamic profile to achieve a fast swimming speed in young age groups, whereas the generation of a large propulsive force is more related to the speed in the oldest group. In front crawl, the 16-year-old swimmers had 0.2 m/s faster V0 and 3.7 kg larger L0 than the 11-year-old females. Moreover, the 13-year-old athletes were 0.1 m/s faster than the youngest group, and they had a 2.1 kg smaller L0 than the 16-year-old athletes. Furthermore, AD of the 16-year-old swimmers was 13.4 N and 8.9 N larger than that of the 11-year-old and 13-year-old athletes, respectively. AD is largely influenced by swimming velocity and anthropometry, such as the shape and size of the body. Therefore, the increase in AD together with age was reasonable as both the velocity and anthropometric factors (height and weight) increased with age. Nonetheless, this also reflects that 16-year-old swimmers are required to generate a greater propulsive force because the magnitude of the propulsive force and drag should be equal to maintain a given swimming velocity according to Newton's second law of motion. Considering this result and the between-group differences in L0, propulsive force is likely a factor that differentiates the swimming velocity of the 16-year-old athletes from the 13-year- and 11-year-old females.

In butterfly, no significant correlation was observed in any of the investigated parameters in the 11-year-old and 16-year-old athletes. However, in the 16-year-old group, correlations of V0 with AD and L0 were close to alpha-level ($P = 0.073$ and 0.055, respectively). As noted above, these results might have been due to Type II error. Given that both AD and L0 are force-related variables and the correlation between Cd and V0 was far from the alpha-level in this particular group (*P* = 0.43), it is still a possibility that the ability to generate a large propulsive force is important in this particular age group. Interestingly, medium to large negative correlations with V0 were observed in all investigated parameters in the 13-year-old athletes. This implies that the faster swimmers tend to have a smaller magnitude of the propulsive force and AD, even though the AD is influenced by the body size and swimming velocity as mentioned above. This means that faster swimmers in the 13-year-old group were particularly good at achieving a fast swimming speed by minimizing AD, which was also evident in the negative correlation between Cd and V0, where the correlation coefficient was extremely large (*r* = -0.877). The between-group analyses showed that, compared with the 11-year-old swimmers, the 16-year-old athletes reached 0.2 m/s faster V0 and 4.5 kg larger L0 and the 13-year-old had 0.2 m/s faster V0 and 2.5 kg larger L0. No differences in L0 and V0 were observed between the 13-year-old and 16-year-old swimmers. The AD in the 16-year-old swimmers was 17.8 N larger than in the 11-year-old athletes. Similar to front crawl, the AD increased with increasing age which could be caused by the increased velocity and the change in anthropometric factors, which consequently means the propulsive force likely contributed to the difference in the swimming velocity between the groups. Again, this was also supported by the difference in L0 between the 16-year-old group and the others.

It should be emphasized that the present study focused only on young female swimmers, and the results would likely be different in young males. During the maturation stage, female athletes experience many anthropometrical changes, such as an increase in fat tissues and a widening of the hip and breast development[46] – all of which would likely affect the body surface area as well as the shape of the body to a great extent. Given the impact of torso morphology on the drag,[47] the negative impact of the growth on the AD drag might be larger in females than males. Moreover, it should be noted that there was a greater variation in the WA points in the 16-year-old swimmers. This could affect some of the present study's results, particularly those of the correlation analysis, meaning that different trends among the groups observed in this study could partly be due to the different skill variations in the three groups. Nevertheless, the between-group differences in the WA point variation were likely due to the nature of swimmers' performance development. Many 11-years old swimmers do not have a long history of competition experience and training history, and therefore, a small variation in the swimmer's level can be expected. Therefore, it is reasonable that the level variation can be much greater in older swimmers due a wider range of their competition and training histories. In fact, it is clear from the national database of the swimming federation, where the present study's participants belong (Medley.no: https://medley.no/default.aspx), that the WA point of all 11-year-old swimmers of the nation has a much smaller variation (SD = 61.5) than that of all 16-year-old swimmers (SD = 110.4). In other words, the difference in the WA point variation depending on the age groups was, if not all, a true representation of the whole population where the samples were extracted from. Finally, it should be emphasized that Cd obtained in the present study might have been overestimated. The equation used in this study was a common one to calculate Cd in swimming, which assumes that the drag is proportional to the square of the velocity. However, it should be noted that this equation is valid only for a steady-flow condition. When swimming actively, the flow around the body is highly unstable and it is known that the drag is proportional to up to the cube of the velocity in front crawl. There is currently no study that investigates the relationship between AD and swimming velocity in the other three strokes, but it is highly likely that the drag increases with more than the square of the velocity. The approach with the steady-state equation was still useful to normalize the drag based on swimmer's body size and velocity in the current study, however, causions should be taken when attempting to use the present study's Cd results in any purposes.

Practical Applications

The results of the present investigation highlight the important practical message to coaches and swimmers. The primary message is that performance determinants within a particular age group and factors that differentiate the performance between age groups are not necessarily the same, meaning that coaches should carefully consider the training for swimmers depending on the goals (i.e. short-term goals to be fast in a particular age group at present or long-term goals to be good in a future age group). For example, in backstroke, good technical skills seemed to be very important for short-term development in all age groups, while together with the growth (long-term development), coaches and athletes should also focus on propulsive force generation. The importance of the technical skills is also the case in breaststroke and front crawl for the 11-year-old and 13-year-old group, but in the 16-year-old group, also the ability the generate propulsive force likely plays an important role. In butterfly, especially for the 13-year-old swimmers, the focus of coaches should be on enhancing technical skills to reduce the water resistance. Similar to backstroke, the propulsive force generation should be focused for long-term performance development in butterfly and front crawl, while in breaststroke, it is likely that the long-term focus should primarily be the technical skill.

Conclusions

Generally, 16-year-old swimmers are faster than the younger age groups due to large L0 and AD, which implies their ability to generate a greater propulsive force. The exception is breaststroke where older swimmers can swim faster due to a lower Cd that suggests a better technical skill compared with younger swimmers. When focusing on within-group trends, there are different variations. The medium to large negative correlation between Cd and V0 in the 11-year-old and 13-year-old swimmers indicates that these swimmers relied on a good hydrodynamic profile to achieve fast swimming speed in backstroke, breaststroke, front crawl and especially the 13-year-old swimmers in butterfly. In contrast, for the 16-year-old swimmers, the ability to generate propulsive force is important, particularly in breaststroke and front crawl.

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Figure captions

Figure 1: Experimental set-up for semi-tethered swimming to obtain load-velocity profiles.

Figure 2: Results of the Tukey`s HSD test of V0, L0, L0% BM, AD and Cd.

Table 1: Results of the correlation analysis (Pearson correlation for L0% BM, L0 and AD with V0; Spearman correlation for Cd with V0)

Backstroke		Correlation of V0 with:			
		L0% BM	**L0**	**AD**	**Cd**
11 yrs (n=11)	*r*-value	-0.298	-0.349	-0.353	-0.674
	P-value	0.373	0.292	0.287	0.023*
13 yrs (n=11)	*r*-value	0.044	0.389	0.511	-0.629
	P-value	0.898	0.237	0.108	0.038*
16 yrs (n=11)	*r*-value	0.226	0.350	0.223	-0.669
	P-value	0.504	0.291	0.510	0.024*
Breaststroke		Correlation of V0 with:			
		L0% BM	**L0**	**AD**	**Cd**
11 yrs (n=11)	*r*-value	-0.566	-0.505	-0.466	-0.745
	P-value	0.070	0.113	0.148	0.012*
13 yrs (n=11)	*r*-value	-0.196	-0.172	-0.132	-0.676
	P-value	0.564	0.614	0.699	0.022*
16 yrs (n=11)	*r*-value	0.733	0.737	0.748	-0.089
	P-value	0.010**	0.010**	0.008**	0.796
Butterfly		Correlation of V0 with:			
		L0% BM	**L0**	**AD**	**Cd**
11 yrs (n=11)	*r*-value	0.241	0.479	0.449	-0.509
	P-value	0.475	0.136	0.166	0.114
13 yrs (n=11)	*r*-value	-0.662	-0.747	-0.757	-0.877
	P-value	0.027*	0.008**	0.007**	0.000**
16 yrs (n=11)	*r*-value	0.403	0.592	0.561	-0.263
	P-value	0.219	0.055	0.073	0.434
Front Crawl		Correlation of V0 with:			
		L0% BM	**L0**	**AD**	**Cd**
11 yrs (n=11)	*r*-value	-0.254	0.003	0.085	-0.748
	P-value	0.452	0.993	0.804	0.008**
13 yrs (n=11)	*r*-value	-0.143	0.012	-0.111	-0.735
	P-value	0.675	0.972	0.745	0.010**
16 yrs (n=11)	*r*-value	-0.135	0.620	0.623	-0.534
	P-value	0.693	0.042*	0.041*	0.091

*Correlation is significant at the < 0.05 level; **correlation is significant at the 0.01 level.

Abbreviations: L0, maximal load; L0% BM, maximal load normalized to body mass; V0, maximal velocity; AD, active drag; Cd, drag coefficient.

Table 2: Two-way ANOVA (within-participants effect: four strokes; between-participant effect: age groups)

		F-value	*P*-value	Eta^2
ANOVA L0	Age	9.06	<0.001**	0.246
	Stroke	13.93	<0.001	0.176
	Age x Stroke	1.62	0.182	0.047
ANOVAL0% BM	Age	2.32	0.116	0.061
	Stroke	15.34	<0.001	0.229
	Age x Stroke	2.2	0.08	0.078
ANOVA V0	Age	17.43	<0.001**	0.348
	Stroke	59.98	<0.001	0.52
	Age x Stroke	0.66	0.676	0.023
ANOVA AD	Age	5.87	0.007**	0.178
	Stroke	11.2	<0.001	0.143
	Age x Stroke	1.7	0.159	0.048
ANOVA Cd	Age	4.05	0.028*	0.061
	Stroke	27.16	<0.001	0.408
	Age x Stroke	1.78	0.171	0.083

*Correlation is significant at the < 0.05 level; **correlation is significant at the 0.01 level.

Abbreviations: L0, maximal load; L0% BM, maximal load normalized to body mass; V0, maximal velocity; AD, active drag; Cd, drag coefficient.

Table 3: Goodness of fit of the individual load-velocity profiles

Goodness of fit (R^2_{LV})	11 yrs (n=11)	13 yrs (n=11)	16 yrs (n=11)
Backstroke	0.996 ± 0.008	0.998 ± 0.002	0.999 ±0.003
Breaststroke	0.999 ± 0.001	0.998 ± 0.004	1.000 ± 0.001
Butterfly	0.998 ± 0.004	1.000 ± 0.000	0.999 ± 0.001
Front crawl	0.999 ± 0.003	0.996 ± 0.007	0.998 ± 0.006

Abbreviations: R^2_{LV}; the goodness of fit of the individual load-velocity profile.

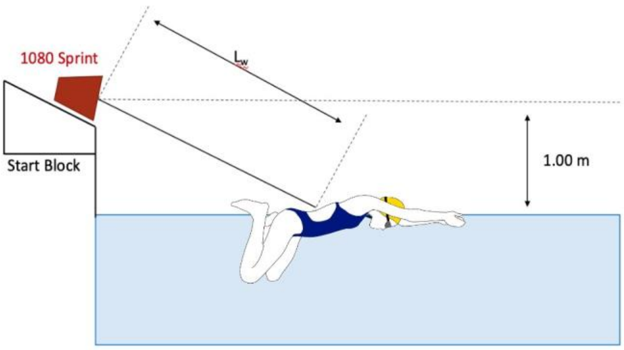

Figure 3: Experimental set-up for semi-tethered swimming to obtain load-velocity profiles.

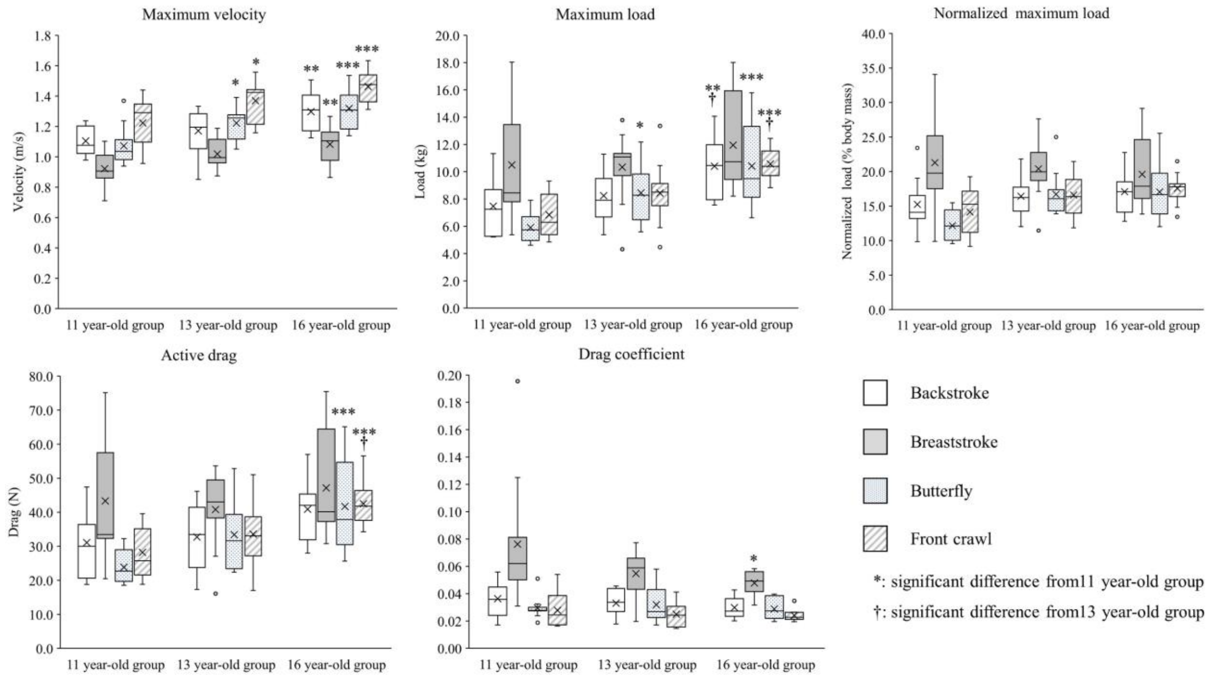

Figure 4: Results of the Tukey`s HSD test of V0, L0, L0% BM, AD and Cd.