Acta of Bioengineering and Biomechanics
Vol. 7, No. 2, 2005

Experimental assessment of the drag coefficient during butterfly swimming in hydraulic flume

R. TAÏAR*, W. BERTUCCI, TH. LETELLIER, I. BENKEMIS

Laboratory for Analysis of Mechanical Constraints (LACM), UFRSTAPS,
University of REIMS, France

Y. TOSHEV

Institute of Mechanics and Biomechanics, Bulgarian Academy of Sciences, Sofia, Bulgaria

A body when moving in a fluid is to withstand drag that is proportional to the drag coefficient, the frontal surface area, and the square of the body velocity relative to the fluid velocity (VOGEL [14]). The aim of our study was to determine the relationships between the drag coefficient (*CD*) and the Reynolds number (*Re*) for a high-level swimmer.

In TAÏAR et al. [12], three most propulsive butterfly positions have been defined: the end of the external sweep (beginning of the cycle), the end of the internal sweep (middle of the cycle), and the end of the thrust (end of the cycle). These three positions were reproduced using real-size mannequins articulated in real-velocity conditions. Experiments have been done in the large-scale hydraulic flume of the University of Nantes.

Two types of the curves *CD* (*Re*) were obtained: for the "best swimmer" and for "other swimmers". Following the swimming of the ex-word champion Pankratov during the World Championship in Rome (1994) the mannequin representing the "best swimmer" has been positioned similarly to the ex-world champion at the beginning, in the middle and at the end of cycle. The body positions of Pankratov have been obtained using the image analysis software Schleihauf™4.0. In order to obtain the curves *CD* (*Re*) representing "other swimmers", the body positions of lower-level swimmers have been used at the beginning, in the middle and at the end of swimming cycle. The two types of curves show well the gap between the techniques of the "best swimmer" and "other swimmers".

Our study shows the importance of the body position during the swimming cycle to minimizing the drug and to assuring better propulsion, i.e. better performance. The results show that the most effective swimmers optimise the body positions in order to reduce the frontal surface and therefore to minimize the drag.

Keys words: biomechanics, swimming, drag, Reynolds number

* Corresponging author: UFRSTAPS, Chemin des Rouliers, Bâtiment 5 ter, BP 1036, 51687 Reims cedex 2, tel: (33) 06-77-94-46-28, fax: (33) 03-26-91-38-06, e-mail: redha.taiar@univ-reims.fr

1. Introduction

A great energy of a swimmer is spent in the water in overcoming the resistance to advancement (KOLMOGOROV et al. [5]). In order to decrease the resistance to the swimmer movement, the relations between various hydrodynamics variables were studied.

Drag is an important parameter to be minimised for increasing the swimming performance, nevertheless only a few authors have tried to accurately analyse the swimmer's body drag. It can be divided into the passive drag and the active drag. The former is the water resistance to the object in a static posture, and the latter is the water resistance related to the swimming motion (CLARYS et al. [2]).

A body when moving in a fluid is to withstand drag that is proportional to the drag coefficient, the frontal surface area and the square of the body velocity relative to the fluid velocity (VOGEL [14]). The magnitude of the drag force (*FD*) for a swimmer is given by:

$$FD = \frac{1}{2} CD\rho SV^2, \tag{1}$$

where: V is the speed of the swimmer and ρ is the freshwater density; S is the front surface area of the swimmer's body in a free stream direction, and CD is called the drag coefficient (depending of the body morphology). From equation (1) we obtain the magnitude of the drag coefficient CD:

$$CD = \frac{2FD}{S\rho V^2}. \tag{2}$$

The direction of the drag force (*FD*) is opposite to the direction of the velocity of the swimmer. It is known that for geometrically similar bodies, which have the same orientation to the free stream direction, the dimensionless drag coefficient (*CD*) depends exclusively on the Reynolds number (*Re*) which expresses the ratio between inertial forces and viscous force around a submerged body. The magnitude of *Re* is given by:

$$Re = \frac{LV}{\nu}, \tag{3}$$

where: L(m) is the body length and ν(m^2/s) is the kinematic viscosity of the fluid. The Reynolds number is a dimensionless factor that describes the interaction between an object and the medium through which the object is moving. It depends on the shape of the object, its speed, and the properties of the medium. Theoretically, when *Re* values increase, *CD* values decrease up to a critical value of *Re* above which *CD* values remain stable (VOGEL [14]). At a given *Re*, the smaller the *CD* of a body, the more hydrodynamic it is. It is to note that *CD* differences between two bodies at high *Re* are mainly due to shape differences.

More precisely, we can distinguish three types of drags: frictional drag, pressure drag and wave drag. The first and the second depend on the Reynolds number, the third

depends on the Froude number (*Fr*), being the dimensionless ratio between the velocity *V* and the square root from the product of the gravity *g* and the characteristic body length *L*:

$$Fr = \frac{V}{\sqrt{gL}} . \tag{4}$$

In swimming conditions, it is very difficult to measure different drags which the body in motion has to withstand. Only the pressure drag or wave drag can be measured. This problem is due to the dissimilarity of the Reynolds and the Froude numbers.

Our present study is to complement the paper by TAÏAR et al. [11]. The aim was to determine the relationships between movements, hydrodynamics and performance of butterfly swimmers. In the present study, we investigated experimentally the relation between the drag coefficient and high values of the Reynolds number using mannequin whose anthropomentry is similar to an average international swimmer's anthropometry. The mannequin was carried over a large-scale hydraulic flume with different velocities corresponding to the velocities of real swimmers.

It is important for us to note that this study is oriented only to the aquatic phase of the swimmer cycle because of an increasing complexity due to interface problems. This approximation should introduce limited errors because in butterfly swimming the aquatic phase represents the main part of the swimmer's propulsion.

2. Material and methods

2.1. Kinematic study

For the kinematic study we used the method described by TAÏAR et al. [11]. The three-dimensional coordinates of the swimmer's hip during butterfly swimming at the World Championship in Rome, 1994, we measured and collected.

2.2. Determination of the most propulsive positions during a butterfly swimming cycle

Using a kinematic approach (TAÏAR et al. [11], [12]) and the kinematic analysis software Schleihauif™ 4.0 (SCHLEIHAUF R.E. [8]), the comparison of the distance covered between two successive positions allowed us to define the three most propulsive positions, i.e. the positions for which the distance covered was the longest. The selected positions were: (a) the end of the external sweep (beginning of the cycle); (b) the end of the internal sweep (middle of the cycle); (3) the end of the thrust (end of the cycle).

It was found interesting that compared to swimmers of lower level performance, the ex-world champion Denis Pankratov (Russia) did not demonstrate the same

instantaneous positions at the cycle moments defined above. Thus, in order to quantify the energy gain (or loss) induced by these different positions, we determined their *CD* in different flow conditions (i.e., different *Re*). The three different key positions of the world champion and those of a swimmer of mean-level performance during these championships were reproduced on articulated mannequin (figure 4) using the numerous body angles given by the image analysis software Schleihauf™4.0. In order to reproduce more adequately the hydrodynamical conditions, 187 cm long mannequin with anthropometry similar to an average international swimmer's anthropometry was used. The range of experimental velocities from 1.4 to 2.1 $m \cdot s^{-1}$ corresponded well to the real range of the butterfly swimming velocities from regional to the top international levels. Six different positions of the butterfly swimming extracted from kinematics study were analysed – three of them as defined above and the other three corresponding to the positions obtained for the ex-world champion Denis Pankratov.

2.3. The hydraulic flume and the drag measurement

2.3.1. Description of a large-scale hydraulic flume

Experiments were done in a large-scale hydraulic flume of the University of Nantes with the following principal characteristics:

- Dimensions: 71 m length, 4.97 m width; 3 m depth (figure 1).

Fig. 1. General view of the hydraulic flume of the University of Nantes (France)

Fig. 2. The mobile carriage in the hydraulic flume.
The mannequin has been fixed below the carriage and then 50 m carried on

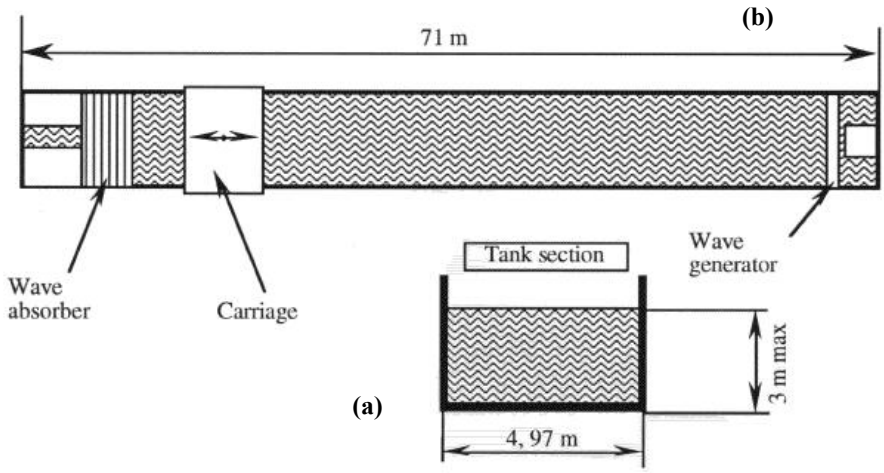

Fig. 3. Schematic presentation of the hydraulic flume and the carriage (a); the tank section of the hydraulic flume (b)

- Carriage with adjustable velocity between 0.5 and 5 m/s with fluctuations less than 0.1% (figure 2).
- Acceleration and deceleration adjustable from 0 to 1 m/s^2 with fluctuations less than 0.001 m/s^2.
- Rectangular tank containing chlorine fresh water (figure 3).

2.3.2. Instrumentation

The sophisticated measuring system supporting the hydraulic flume enabled us to quantify very precisely the following parameters:

- The magnitude of the drag force (*FD*) of the mannequin during motion.
- The Reynolds number (*Re*) at different velocities using equation (3).
- The sinkage (the submergence of the mannequin).
- The trim (the degree to which the mannequin is levelled in relation to a fixed point such as the horizon, the difference between the depth in water at the front and back of the mannequin is also taken into account).

2.3.3. Drug measurement

As mentioned above in order to reproduce more adequately the hydrodynamical conditions, the articulated mannequins whose anthropometry was similar to the average international swimmer's anthropometry were used at the experimental velocities ranging from 1.4 to 2.1 m·s^{-1} which corresponded well to the velocities of real swimmers from regional to the top international levels.

Fig. 4. A specially designed mannequin in preparation

The mannequin was fixed at its center-of-gravity by the means of a steel stem (figures 4 and 5). Previously balanced mannequin (figure 5) was carried over 50 meters at velocities from 1.4 to 2.1 $m \cdot s^{-1}$ (figure 6), covering the scale from regional to international levels. This experiment was repeated six times with six different postures of the mannequin obtained from the kinematics study. The mannequin was placed parallel to the main flow at the water tunnel centre with the head at the depth where velocity was previously measured. The force measured during the experiment represents the magnitude of the drag force (*FD*) for the mannequin in the motion direction. The lift force has not been measured because it has no direct influence on the drag value.

Fig. 5. The previously balanced mannequin immersed in the hydraulic flume

Fig. 6. The immersed mannequin mounted on the mobile carriage during experiments. The mannequin is dressed only to illustrate the possibility of studying the drag from the viewpoint of different sport ware. This problem is out of the aim of the present study

2.3.4. Measurements and error evaluation

A thin stem was chosen in order to minimise its influence and to avoid modification of the flow. Each measurement was made after the time of water stabilisation. Water temperature was measuerd in order to be used in the calculation of the viscosity. Each experiment was recorded, and the force values (*FD*) were selected for the middle part of the channel where the speed variation of the carriage approximated to zero. Mean averages and standard deviations were obtained. The values of the mannequin drag coefficients (*CD*) were calculated using equation (2) where the frontal surface area *S* of

the swimmer's body was measured using the image analysis method described in TAÏAR et al. [12].

3. Results

3.1. Relation between the drag coefficient (*CD*) and the Reynolds number (*Re*)

The shape of the curve *CD* (*Re*) has already been observed for simple geometrical objects (sphere or disk) and for fishes (VOGEL [13]). In the present study, the force values *FD* were obtained experimentally and the *CD* were calculated using equation (2). The values of Reynolds number were also obtained experimentally at different velocities using equation (3).

A set of six curves *CD* (*Re*) was obtained and the results recorded in all phases of the swimming cycle studied (beginning of the cycle, middle of cycle and end of cycle) show that the *CD* decreases with an increase in the value of the Reynolds number (figure 7).

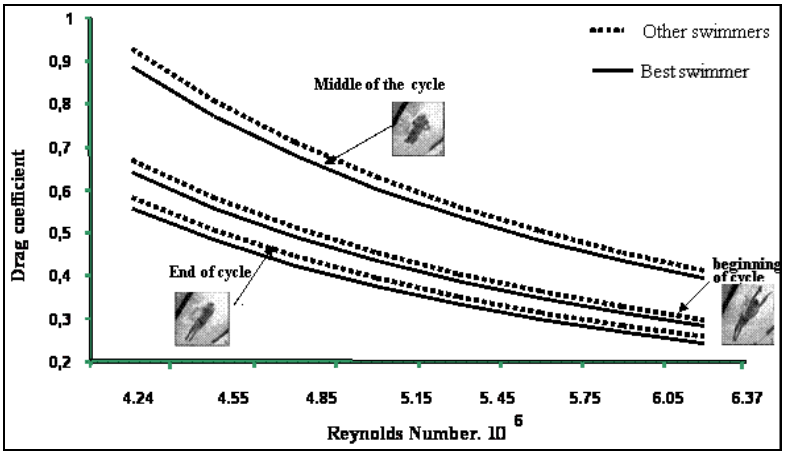

Fig. 7. Relation between the drag coefficient and the Reynolds number in three selected positions (beginning, middle and end of cycle) and on two different swimming levels: "the best swimmer" and "other swimmers"

Two types of curves were obtained – "the best swimmer" and "other swimmers" (figure 7). During the measurements at the World Championship at Rome (1994) the "best swimmer", ex-world champion Pankratov, demonstrated the best streamline compared to other swimmers. He was characterised by the least resistance along the cycle relative to other swimmers. As is well known, the drag coefficient *CD* can be

reduced by a lower frontal surface area *S* and that is why the Pankratov's lower limbs were less bent, his upper limbs were more lengthened at the beginning of the cycle and his head was less raised at the end of cycle. Following the swimming of Pankratov, the mannequin representing "the best swimmer" has been positioned similarly to the ex-world champion at the beginning, in the middle and at the end of the cycle.

The two types of curves show well the gap between the techniques of the ex-world champion ("the best swimmer") and "other swimmers". Otherwise this gap is more important in the range of the Reynolds number between $4.24 \cdot 10^6$ and $4.85 \cdot 10^6$ than in the range of the Reynolds number between $5.15 \cdot 10^6$ and $6.37 \cdot 10^6$.

It is to note that for a given swimmer and for the equivalent *Re* values, the *CD* is more important at the end of the internal sweep (the middle of the cycle) than at the beginning of the cycle (the end of the external sweep) and in the last position of the thrust (the end of the cycle). In the middle of the cycle, the upper limbs are in a vertical plane, perpendicular to the swimmer's displacement, generating a high drag coefficient *CD* due to an increase in the frontal surface area *S*. The drag is lower in the least propulsive positions of the swimming cycle (at the beginning and at the end of cycle). In these two positions, the upper and the lower limbs are globally in the alignment of the trunk due to every swimmer's search for a streamlined position.

4. Discussion

The relation between the drag coefficient and the Reynolds number is in general complicated. The curves representing *CD* as a function of *Re* have already been obtained in the previous studies into simple geometric bodies (HOERNER [4]) and a major role of a streamline capacity at the time of fish locomotion was also evoked (WEBB [15], BLAKE, [1], SAGNES [7]).

The relation between the drag coefficient and the Reynolds number obtained for a swimmer is represented by a curve very similar to those obtained for a cylinder (GUYON at al. [3]) and for a sphere (RHYMING [6]). At high values of the Reynolds number the drag force (*FD*) (proportional to the frontal surface area and the squared velocity) is a major one. The drag coefficient (*CD*) is inversely proportional to these parameters (VOGEL [14]) and does not change much at the large Reynolds numbers which explains the attenuation of the slope angle of a curve (RHYMING [6]).

In swimming, very few similar studies have been mentioned. This is because of a large variability of parameters taken into account during the swimming and the difficulties in measuring experimentally the drag forces of a swimmer in real swimming conditions. The studies already published do not take into account the different swimming styles (butterfly, backstroke, breaststroke or freestyle) nor the changes of the body positions. Different body positions change the shape of an immersed body and therefore the frontal surface area, i.e. the change of the body positions, determines the drag variations during the swimming cycle.

In our study based on the hydrodynamics laws, real-size mannequins articulated in real velocity conditions have been used. Experiments have been carried out in a large-scale hydraulic flume of the University of Nantes. Two types of curves *CD* (*Re*) were plotted – "the best swimmer" and "other swimmers" (figure 7). The results obtained show that for the two types of curves the drag coefficients (*CD*) depend on the positions adopted by the mannequin, i.e. the *CD* are different at a given *Re* and in a given phase of the swimming cycle. Some significant differences have been observed between "the best swimmer" (ex-world champion) and "other swimmers". The mannequin positioned similarly to the ex-world champion (at the beginning, in the middle and at the end of cycle) was always characterized by lower *CD* values than "other swimmers", including the least impulsive phases (the beginning and the end of the cycle). The drag reduction corresponds in this case to a reduction of the frontal surface area *S*. SHEEHAN and LAUGHRIN [10] indicated also that the most important shape drag factor is the frontal surface area of the body.

The frontal surface area is not the only parameter taken into account in the performance, but the results for the mannequin representing the ex-world champion showed the big influence of the swimming positions minimizing the drag during the principal phases of the swimming cycle. These results lead to the conclusion that both the high-level and the lower-level swimmers could improve their performance not only increasing their impulsive forces but also correcting their body positions during the cycle aiming to minimize the drag.

5. Conclusion

The performance of swimmers depends on the control of the drag and other forces acting on the immersed body during swimming. To study the drag control it is important to find the relation between the drag coefficient and the Reynolds number in real swimming conditions. The experiments for the present study have been done in a large-scale hydraulic flume of the University of Nantes using a specially designed mannequin similar to the average international swimmer's anthropometry articulated in real velocity conditions. Two types of curves *CD* (*Re*) were obtained: for "the best swimmer" and for "other swimmers". Following the swimming of the ex-word champion Pankratov during the World Championship in Rome (1994) the mannequin representing "the best swimmer" has been positioned similarly to the ex-world champion at the beginning, in the middle and at the end of the cycle. The body positions of Pankratov have been obtained using the image analysis software Schleihauf™4.0. To obtain the curves *CD* (*Re*) for "other swimmers", body positions of lower-level swimmers have been used at the beginning, in the middle and at the end of the swimming cycle. The two types of curves show well the gap between the techniques of "the best swimmer" and "other swimmers". Our study shows the importance of the body position during the swimming cycle for minimizing the drug and for assuring better propulsion, i.e. better performance.

The results show that the most effective swimmers optimise the body positions in order to reduce the frontal surface and therefore to minimize the drag.

Our study assesses the importance of the body position during the swimming cycle showing that the most effective swimmers optimise the propulsion/resistance report while adopting some different position during the swimming cycle. It also permits us to understand how to minimize the drag and thus to decrease the energy losses due to non-optimal positions during the cycle. We can conclude that both the high-level and the lower-level swimmers could improve their performance optimizing their body positions during the cycle which allows them to minimize the drag.

References

[1] BLAKE R.W., *Fish locomotion*, University Press, 1983, Cambridge, 208 p.

[2] CLARYS J.P., *Human morphology and hydrodynamics*, [in:] *International series on sport sciences swimming III*, edited by Juris Terauds and E. Wendy Bedinfield, University Park Press, Baltimore, 1979.

[3] GUYON E., HULIN J.P., PETIT L., *Hydrodynamics physique*, CNRS, Paris, 1991, p. 506.

[4] HOERNER S.F., *Résistance à l'avancement dans des fluides*, Traduit par Henry F.M., eds Gauthier Villars, Paris, 1965, 471 p.

[5] KOLMOGOROV S.V., RUMYANTSEVA O.A., GORDON B.J., CAPPAERT J.M., *Hydrodynamic characteristics of competitive swimmers of different genders and performance levels*, J. Applied. Biomechanics, 1997, **13**, 88–97.

[6] RHYMING I.L., *Dynamique des fluides*, Presses polytechniques romandes, Lausanne, 1985, 448 p.

[7] SAGNES. P., *Un outils de prise de données sur une image numérisée et son utilité dans les études relatives aux poisson: exemple d'une application concrète en morphométrie*, Bull. Fr. Pêche Piscic, 1995, 339, 131–137.

[8] SCHLEIHAUF R.E., *Kinematic analysis software for three dimensional data handbook* (KA Software, Version 4.0), 1994.

[9] SCHLICHTING H., GERSTEN K., *Boundary-Layer Theory*, 8th revised and enlarged edition, Springer-Verlag, Berlin, 2000.

[10] SHEEHAN D., LAUGHRIN D.M., *Device for quantitative measurement of hydrodynamic drag on swimmers*, Journal of Swimming Reasearch, 1992, **8**, 30–33.

[11] TAÏAR R., SAGNES P., HENRY C., DUFOUR A.B., ROUARD A.H., *Hydrodynamics optimization in butterfly swimming: position, drag coefficient and performance*, Journal of Biomechanics, 1999, **32**, 803–810.

[12] TAÏAR R., ROUARD A., TOSHEV Y., *Performance modelling of butterfly swimmers: links between morphometric, kinematic and hydrodynamic variables*, Acta of Bioengineering and Biomechanics, 2004, 6, 2, 77–88.

[13] VOGEL S., *Life in moving fluids. The physical biology of flow*, Willard Grant Press, Boston, 1981, 352 p.

[14] VOGEL S., *Life moving fluids*, 2nd edn., Princeton, New Jersey, 1994, Princeton University.

[15] WEBB P.W., *Hydrodynamics and energetics of fish propulsion*, Bull. Fish Res. Board Can., 1975, 190, 1–160.

Sformatowane: Punktory i numeracja