A BIOMECHANICAL APPROACH TO DRAG FORCE AND HYDRODYNAMIC COEFFICIENT ASSESSMENTS

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A fundamental theoretical analysis for estimation of kinematic and kinetic characteristics of swimmers was developed. The purpose of the study was to present a simple method for data collection, to establish simple formulae for determining the swimmers characteristics and to evaluate the validity and accuracy of the model estimation against the other methods such as; direct measurements; Measurement of Active Drag, and added drag provided by hydrodynamic body. The active drag force was estimated during maximal swimming in front crawl but the method can also be applied for other strokes. The swimmers performed three 10-meter trials with enough rest in between and with zero initial velocity over which average velocity was calculated. By this method the maximum speed of swimmers in 10m swim could also be estimated. The swimmers began to swim from still position after whistling, and stopped swimming at the end of 10m again by whistling, and kept gliding until still position. The time of 10m swim and the glided distance were measured with reasonable precision and then used in the established formulae for determining the velocity, acceleration, and drag force. One of the elite swimmers was requested to perform swimming with different speeds in order to achieve different characteristic curves for proposed model.

KEY WORDS: kinematics, kinetics, mechanical formulae, swimmer characteristics.

INTRODUCTION: Since the human body, like the shape of ship, presents an additional difficulty in the sense that it moves in the boundary plane between two media: water and air, whereby changes in flow also cause changes in the level of the boundary plane (waves). In other words, the problems are much more complex than those of a body moving in a single medium. If we add to these problems the uneven and poorly streamlined shape of the human body plus its possibility for self-propulsion, then the problems seem endless.

Resistance and propulsive forces that human body either undergoes and/or originates can be measured directly; the resistance can be derived from the propulsive force and vice versa and is always a function of the velocity. The forces of man's hydrodynamic locomotion can also be described in terms of mathematical analyses of the body's shape and movement (Seireg and Baz, 1971; Miyashita, 1974; Francis and Dean, 1975; Jensen and Blanksby, 1975). The complicated procedures of these studies deviate, however, from the direct hydrodynamic considerations of this discussion. Also, their results are still hypothetical and have not been tested against the actual hydrodynamic forces. Early measurements involved indirect calculations of active resistance with additional drag loaded onto the swimmer (Clarys, 1979; di Prampero et al.,1974; Pendergast et al.,1978; Rennie et al., 1975). In the study of the hydrodynamic resistance of a moving human body, two types of resistance must be considered. Passive resistance, that is the amount of water resistance that a body experiences in an unchanged posture, during passive towing or during exposure to water flow in a water flume and when performing gliding without movements, while active resistance is the water resistance associated with the swimming motion.

METHODS: Three distinct cases have been considered, where the water resistance may be considered as proportional to: velocity, V, to squared velocity, V^2, and to both. In all cases the subjects were requested to swim a 10-m distance, from eggbeater position, after surveyor's alarm, as fast as they could. They have also been instructed how to cease swimming at the end of the 10-m swim again by the surveyor's alarm (whistling), and glide as far as they could.

The differential equation for the first case can be written as;

$$FP1-C1V=M.dV/dt \qquad (1)$$

Where FP is the propulsive force and C1 is the hydrodynamic coefficient to be determined. At limit speed (the maximum speed attained by swimmer), V=VL, the acceleration becomes zero then (1) becomes;

$$FP1=C1VL1 \quad (2)$$

Inserting (2) into (1) and integrating we get (Shahbazi and Sanders, 2002);

$$V=VL1\ (1-Exp(-C1t/M)) \quad (3)$$

This equation shows that the swimmer's speed is progressing exponentially, FP can be given as;

$$FP1=C1V(1+ExpC1t/M)) \quad (4)$$

In gliding phase, the swimmer is not applying any propulsive force, FP=0, (1) becomes;

$$-C1V=M.dV/dt \quad (5)$$

Integrating (5) yields the glided distance X and finally the C1 as;

$$C1=2MV/(X+Vt) \quad (6)$$

For the two other cases the differential equations can be written as followings;

$$FP2-C2V^2=M\ dV/dt \quad (7)$$

$$FP3-(C1V+C2V^2)=M\ dV/dt \quad (8)$$

At maximum speed ;

$$FP2=C2V^2L2 \quad (9)$$

$$FP3=(C1VL3+C2V^2L3) \quad (10)$$

The solution of these two differential equations yields for C2 and VL (Shahbazi and Sanders, 2002);

$$C2=M/X \quad (11)$$

$$VL2=0.5\{V+v(V^2+4MV/C2t))\} \quad (12)$$

$$VL3=0.5\{C1/C2+v(\ C1/C2)^2\ +(4MV)/C2t))\} \quad (13)$$

Substituting (12) and (13) in (9) and (10), the propulsive forces can easily be achieved.
The swimmers accelerations in three cases can be given by (Shahbazi and Sanders 2002);

$$a1=(C1VL1/M)(Exp-(2C1t/M)) \quad (14)$$

$$a2=(4C2VL2^2/M)(Exp-(2C2VL2\ t/M)) \quad (15)$$

$$a3=((C1VL3\ +C2VL3^2)/M)(Exp-(C1+C2VL3)\ t/M)) \quad (16)$$

RESULTS AND DISCUSSION: A mathematical study allowed defining formulae in different approaches. The simple measurements of time of 10-m swim and the glided distance were necessary to be used in these formulae, in order to achieve the variations of velocity, acceleration and hydrodynamic force.

In Table 1, subject No. 1, is the lightest subject in present study, has bigger values of mean and maximum velocities in first and second approaches and has still reasonably high value in the third approach. His hydrodynamic force is also high in three approaches. Subject No. 5, who is 10 Kg heavier, has shown smaller mean, maximum and hydrodynamic force magnitudes in all approaches. This means that the subject's mass is an important factor in hydrodynamic characteristics computations. No researchers have reported the possible effects of mass in their estimation of hydrodynamic forces.

In Table 2, the characteristics of a selected elite subject in different speeds are shown. He was requested to perform different types of swimming such as; legs only, hands only and both together and with and without fins and paddles. The subject was able to swim with different speeds, 0.9 to 1.84 ms?^{1}, as mean velocities. We can notice that in all three approaches the higher the speed is, the higher are the values of hydrodynamic force and the hydrodynamic coefficient C1. On the contrary, the values of hydrodynamic coefficient C2, decrease with the increase of the speed.

In Figure 1, the variations of velocities in different approaches are presented. In first approach (series 1), the swimmer actually reaches to his maximum speed after 17 seconds. This means that the swimmers in 10m swim will never reach to their maximum speed. In second approach the swimmer reaches to his maximum speed actually after 6 seconds, but the value of maximum speed seems to be high, such that the curve of first approach will never reach it. In third approach, the swimmer reaches to his maximum speed after 7 seconds. The magnitude of the maximum speed is such that the curve of first approach can finally be reached. This means that the swimmer's maximum speed is definitely VL3 , and is certainly reached by third approach in shorter time.

In Figure 2, the variation of accelerations relative to time is presented. As can be seen in second and third approaches the swimmer swims with uniform velocity where according to the Newton's first law, he experiences no horizontal force, that is, the propulsive force equals the resistive hydrodynamic force. On the contrary, in first approach, the swimmer needs more time to reach his maximum speed. Second approach represents an incredibly big force for starting (4.5 x 79=355.5N), while in the third approach the starting force is about (1.5 x 79=118.5 N) which seems to be reasonable, and can be expected as explosive force from swimmer.

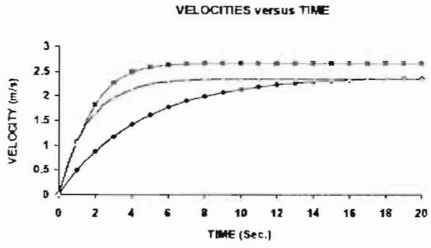
In Figure 3, the variation of hydrodynamic coefficients, C1 and C2 is presented.

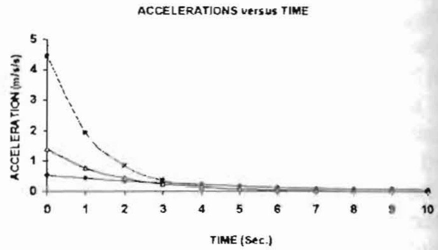
Table 1 Subjects characteristics values ± SD.

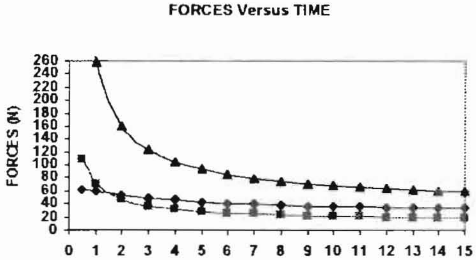
Subjects No.	Body Mass (Kg)	Time of- 10m Swim (Sec.)	Gliding Dist. (m)	Mean-Velocity (ms^{-1})	VL1 (ms^{-1})	VL2 (ms^{-1})	VL3 (ms^{-1})	C1 $(N.S.Kg^{-1})$	C2 $N.S^2.Kg^{-2}$	FP1 (N)	FP2 (N)	FP3 (N)
1	71.3	6.24	5.79	1.60	2.06	2.26	1.94	14.47	12.31	29.73	62.92	74.50
		0.03	0.34	0.01	0.01	0.03	0.48	0.33	0.70	0.59	2.20	0.43
2	72.5	6.25	5.74	1.60	2.06	2.25	1.93	14.75	12.63	30.23	64.15	75.50
		0.06	0.38	0.02	0.03	0.04	0.42	0.33	0.90	0.67	2.25	1.74
3	74.8	6.37	6.60	1.57	2.02	2.25	1.97	14.52	12.14	29.34	61.10	75.57
		0.10	0.28	0.02	0.04	0.05	0.30	0.17	0.55	0.64	1.18	2.57
4	79.0	6.72	5.98	1.49	1.92	2.12	1.84	14.7	13.20	28.18	59.10	71.58
		0.24	0.44	0.06	0.08	0.11	0.14	0.17	0.94	1.50	2.12	5.98
5	81.8	6.74	5.74	1.48	1.90	2.09	1.79	15.42	14.25	29.30	62.17	73.17
		0.14	0.36	0.03	0.04	0.05	0.06	0.48	0.90	1.32	3.33	3.16

Table 2 Characteristics of a selected swimmer ± SD.

Type of Swimm-Ing	Boy Mass (Kg)	Time of- 10m Swim (Sec.)	Gliding Dist. (m)	Mean-Velocity (ms^{-1})	VL1 (ms^{-1})	VL2 (ms^{-1})	VL3 (ms^{-1})	C1 $(N.S.Kg^{-1})$	C2 $N.S^2.Kg^{-2}$	FP1 (N)	FP2 (N)	FP3 (N)
Legs-	79	10.97	4.56	0.91	1.14	1.22	0.96	9.90	17.36	11.30	25.90	25.60
Only		0.03	0.24	0.02	0.01	0.02	0.33	0.28	0.46	0.47	2.12	0.23
Legs +	79	9.09	5.10	1.10	1.32	1.44	1.30	11.10	15.32	19.80	31.90	38.80
Fins		0.06	0.30	0.04	0.02	0.03	0.34	0.23	0.62	0.67	2.05	1.58
Hands-	79	7.86	5.71	1.27	1.63	1.79	1.53	12.79	13.48	20.82	44.25	51.87
Only		0.10	0.22	0.02	0.04	0.04	0.25	0.15	0.45	0.52	1.07	2.17
Hands+	79	7.20	6.25	1.38	1.81	2.03	1.82	13.02	12.25	23.73	48.25	62.46
Paddles		0.24	0.35	0.03	0.06	0.09	0.13	0.14	0.63	1.32	2.03	4.93
Both	79	6.72	6.15	1.48	1.91	2.12	1.87	14.72	13.20	28.20	59.10	71.58
(L & H)		0.14	0.28	0.04	0.03	0.03	0.06	0.28	0.90	1.22	3.13	2.86
Both +	79	5.60	6.48	1.78	2.31	2.58	2.30	17.11	12.20	39.60	81.36	103.90
Fins		0.24	0.34	0.05	0.06	0.10	0.11	0.14	0.76	1.38	2.04	4.98
Both +	79	5.34	6.34	1.84	2.38	2.66	2.34	17.84	12.50	46.52	87.89	110.40
(Fi+Pa)		0.14	0.26	0.03	0.03	0.04	0.04	0.38	0.75	1.22	2.53	2.16







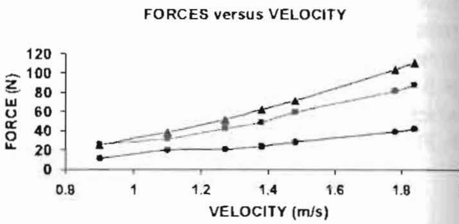
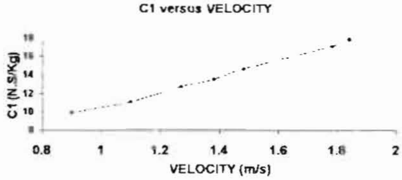
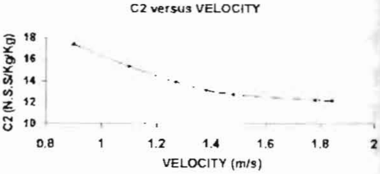


Figure 2 (a&b): The variations of force with time and velocity in different cases.

Figure 1 (a&b): The variations of velocity and acceleration with time for selected swimmer.





CONCLUSION: The comparison of three cases revealed that the third case should be presented as reliable method. However, current information and empirical evidence indicate that third approach can produce results compared, at some stand, to the results reported by researchers with different methods. Although there are a number of reasons, which can account for superiority of third case, a major problem deals with mechanical specificity. Three Dimensional Analysis should produce a more precise result with its complexity. The present study offers inexpensive, reliable, not complicated and very easy to use method.

Acknowledgement

First author would like to thank Stelios Psycharakis and Chris Connaboy, the PhD students, for their effective help in data collecting, and is grateful to Tehran University Research Council for the financial support provided.