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EXPERIMENTAL INVESTIGATION OF THE PROPULSIVE FORCE IN TETHERED SWIMMING OF CROWL STROKE

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Abstract: *This paper presents an experimental investigation to determine the drag force in tethered swimming of crawl stroke swimming and to establish its magnitude in the propulsion of child and adult subjects. In the experiment it was chosen to study the propulsive force of swimmers using a variety of swimming devices (hand paddle, snorkeling flippers), the force being measured experimentally with a force sensor measurement system and data acquisition system.*
The obtained parameters were compared between the subjects of two groups, one of adults and one of children. The effects of swimming devices on the maximum amplitude and average value of the drag force in tethered swimming, were determined for the subjects of the two groups.
Key words: *tethered swimming, drag force, portable objects measurement system.*

1. INTRODUCTION

Swimming is a complex and fascinating discipline, where every detail counts in the race to excellence, with numerous factors contributing to the optimization of sports performance.

It is obvious that propulsion, and the estimation of propulsive and drag force, became an important determinant of performance in crowl swimming stroke [1].

In an attempt to monitor specific targets for swimming performance, tethered swimming has been found to be a useful tool for measurements [2].

Tethered swimming increases the possibilities to measure the maximum drag force which, in theory, corresponds to the propulsive force that a swimmer can produce to overcome water resistance at maximum freestyle swimming speed [3,4].

Wilke & Madsen [5], stated that, for short swimming distances, the role of the maximum drag force in tethered swimming is overwhelming, but this is reduced for long distances, where the endurance force plays the major role.

Yeater et al [3] studied the relationship between swimming speed and average maximum swimming force in front crawl stroke, obtaining a high correlation only for the front crawl. Subsequently, knowing that there was a statistically significant relationship between the mentioned parameters, further studies in this technique were conducted, mainly involving short distance tests [6].

Competitive swimming performance is determined by multiple parameters, including muscle strength during swimming [7] and swimming technique [8].

One method of monitoring multifactor parameters is to use a force sensor to record the anchoring forces exerted during tethered swimming.

Tethered swimming is considered to be an accurate, valid and reliable measure of muscle capacity and oxygen consumption, similar to those observed in freestyle swimming, although small kinematic changes have been observed.

In theory, the maximum force corresponds to the drag and propulsive force that a swimmer must produce to overcome water resistance at maximum freestyle swimming speed [9]. Therefore, experiments involving tethered swimming have examined a wide variety of

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force parameters. For example, sprint speed has been found to be significantly correlated with maximum drag force [9], or the average of maximum forces. However, Taylor et al. [10], found that only average force is a reliable parameter to estimate swimming performance for swimmers grouped into age-classified classes.

In studying the biomechanics of swimming, a fundamental objective is to determine the propulsive force developed by the swimmer and the opposing resistance force, and their relationship with the technique and performance of the swimmer. Obtaining the magnitude of these forces during freestyle swimming is difficult, as the locomotion mechanisms and environment conditions become extremely complex when moving through water.

To overcome this complexity, various experimental and analytical techniques have been developed.

The method of tethering the swimmer to the edge of the pool and measuring the force in the cable is the most commonly used.

In these experiments, the measurement system was mounted on the cable and the subject was instructed to swim at maximum effort. The experiments showed that the anchoring force decreased to zero during freestyle swimming as the speed increased.

The study conducted by Yeater et al [3], focused on the determination of forces in fully tethered swimming in three swimming strokes performed by competitive swimmers.

In the 1980s, in addition to the tethered swimming experiments, several experimental studies were carried out to determine water resistance forces and swimming resistance coefficients.

In the paper published in the early 1990s, Duplisheva et al. [11] presented a hydrodynamic equipment used for measuring the active resistance in the front crawl stroke. The relationships between the measured values of power produced by the swimmer, active resistance, hydrodynamic resistance, hydrodynamic force coefficient and maximum swimming speed, were determined.

Validation of experimental results and theoretical analysis was possible in the late 1990s with the development of numerical analysis programs. Berger et al. [12] continued their research on propulsive forces in front crawl freestyle swimming by performing a comparison of the average water-resistance forces obtained from measurements with the parameters resulting from three-dimensional kinematic analysis. It was found that the two methods, experimental and theoretical, gave comparable results.

Biomechanical characteristics are important determinants for analyzing swimming performance, fundamental in understanding propulsion mechanics in the highly specific hydrodynamic environment. Analysis of the values and variation of the forces generated by swimmers must be a priority in the research of their training, as propulsive force is fundamental to competitive success.

For this purpose, tethered swimming has been one of the most widely used methods throughout the research, allowing substantial associations between force in tethered swimming and swimming performance in sprint events.

In addition, taking into account hydrodynamic and inertial limitations, swimmers should be as symmetric as possible.

Analyzing symmetry in swimming, Carvalho et al [13], observed that asymmetry in water seems to be more related to technical constraints than to muscular imbalances, but the swimmers who generated higher propulsive forces in the aquatic environment were those with higher values of measured experimental forces on land.

Thus, tethered swimming and isokinetic assessments are useful for evaluating muscle asymmetry in terms of assessing the relationship between the propulsive force and performances.

There is a direct relationship between the forces generated in isokinetic swimming and tethered swimming for both front and back crawl swimming style.

Coaches and swimmers can use isokinetic swimming and tethered swimming to determine muscle imbalances and swimming technique, as well as to track training-induced imbalances or those that occur between swimming seasons.

It is considered that the first 10 swim cycles should be sufficient to define the pattern of the symmetry index during a tied swim cycle at a full test.

The propulsive force asymmetries in tethered swimming, were analyzed in 2019 by dos Santos, K.B et al [14]. This group of researchers found that propulsion forces decreased during the test, but the asymmetries did not change during the test.

Mode and frequency of breathing did not influence asymmetry, but the best-performing swimmers were more symmetrical than the poorest performers. The study suggests that future research should investigate strategies to reduce swimming asymmetry in order to improve performance.

In the study [15], the effects for different hand paddles surface sizes on the force-time curve during freestyle swimming were investigated.

It was concluded that medium, large and very large paddle sizes significantly influence the force-time curve during swimming and that these changes are directly proportional to the size of the paddle. Therefore, these sizes may be useful for force development in the water during training.

The aim of the research by Gourgoulis, V., et al [16] was to study the effect of hand paddles on the angle of attack, rebound angles and other kinematic characteristics of the hand during crawl swimming.

Hand paddles increase the propulsion surface area of the hand and so the swimmer has to push a larger mass of water with each swimming stroke, and the hands have to overcome greater resistance.

Monteil and Rouard [17], reported a 10% increase in underwater traction duration when using 264 cm^2 hand paddles, while Payton and Lauder [18], using much larger paddles (480 cm^2), reported a 22% increase.

In the study [18], only large paddles (264 cm^2) caused a statistically significant increase of 9.5% in the total underwater traction duration.

The study by Koga, D. et al [19] investigated the relationship between hand kinematics, hydrodynamic pressure distribution and hand drag force when swimming crawl style at maximum speed.

When comparing the absolute values of the average pressure on the palmar and dorsal side of the hand, it was observed that the average pressure on the dorsal side was significantly higher than on the palmar side and had a larger effect on freestyle swimming.

It was also observed that a higher hand speed leads to a significant decrease in pressure on the dorsal side which leads to an increase in the propulsive force of the hand improving the average swimming speed.

This paper aims a comparative analysis of the swimming drag force, related to BMI, between 6 subjects divided into two groups: a group of 3 adults and a group of 3 children.

The drag forces are measured with a force sensor measurement system and data acquisition system, and the swimmers swam in the pool in a tethered swimming system.

Related the drag force to BMI reduces the importance of the anthropometric parameters that differentiate the two groups of swimmers.

2. MATERIALS AND METHODS

2.1 Subjects measured

The tethered swimming drag force was measured and analyzed for 6 swimmers (3 adult subjects and 3children subjects).

The anthropometric parameters of subjects are presented in Table 1 and Table 2 (age in years, height in meters, weight in kilograms and BMI-Body Mass Index in Kg/m^2).

Table 1

Anthropometric parameters for the group of 3 adult subjects

Code	Age	Height	Weight	BMI
A1	17	1.65	59	21.67
A2	47	1.87	90	25.74
A3	47	1.75	70	22.86
average	37.00	1.76	73.00	23.42
SD	17.32	0.11	15.72	2.09

Table 2

Anthropometric parameters for the group of 3 child subjects

Code	Age	Height	Weight	BMI
C1	9	1.42	37	18.35
C2	9	1.30	36	21.30
C3	9	1.34	27	15.04
average	9	1.35	33.33	18.23
SD	0	0.06	5.51	3.13

The measurements were carried out in the freshwater swimming pool of the sports complex of the Craiova Water Park City Hall, from April to May 2024. All participants were trained on the testing protocol, and the written consent to participate in the experiment was received.

The adult subjects are not beginners in swimming, but have different levels of training, thus:

- A1 is medium trained in swimming;
- A2 has a very good level of training in swimming;
- A3 is very well trained (swimming coach).

The child subjects are not beginners in swimming, they attend the local swimming school, train 3 times a week and have taken the first three places in regional competitions; they have different levels of training.

The two groups of swimmers do not form two compact groups of due to the very different anthropometric parameters (Table 1 and Table 2) and due to the different level of training in swimming technique.

The analysis of the propulsive force in tethered swimming was focused to highlight a known fact from competitive practice: the very high ability to propel one's own body, specific to a child swimmer and which is noticeably reduced in adult swimmers.

2.1 Measurement system and measurement technique

MGCplus measuring system - Data acquisition, is part of the equipment of the Faculty of Mechanics in Craiova and consists of:
-*S-shaped* force transducer with force measuring range from 10N to 1 kN, accuracy class 0.02;
-Modular data acquisition system with 128 channels in one housing.

Fig. 1. Positioning and sequence of elements in the measuring system at the Water Parc-Craiova swimming pool

Each study participant was strapped with a flexible belt around the abdominal region and swam in the center lane of the pool (fig.1 and fig.2).

Fig. 2. Adult subject in maximum drag force in tethered swimming in the measuring moment at the Water Parc-Craiova swimming pool

The belt was attached by a metal carabiner to a parachute suspension cable made of Kevlar with a very low coefficient of elasticity to prevent deformation of the attachment system and the introduction of measurement errors.

The entire system was anchored to a rigid system in the pool structure construction.

For each study participant, drag force was measured in 3 situations:

-freestyle with no aditional swimming devices;

-freestyle swimming with rigid hand paddles;

-freestyle with an appropriately sized, snorkeling device;

Subjects swam for a minimum of 10 strokes (aprox 13 seconds), in tethered swimming, while being strapped to the measurement system.

Using the software associated with the data acquisition system, drag forces were measured.

The first maximum value of each drag force, for all participants, was the moment of shock (when the force sensor's cable was extended); this value does not represent the swimmer's drag force, but was used to set as the zero the moment for all measurements.

3. RESULTS

The measurements were performed over a time interval of 12.5s, representing 2500 mesured frames (referenced on the horizontal axis of the graphs), and the forces were measured in N.

Before plotting, the raw data, measured with the MGCplus system, were processed by filtering with the Butterworth Filter (specific for human measurements).

3.1 Drag force variation in adult subjects

The graphical representations of the drag force for the swimmers, aim to highlight the frequency of arm strokes in free swimming, the maximum value of the drag force and to rank the swimmers in terms of drag force. Fig. 3 highlights the minimum force value for each of the 3 adult swimmers at a given time, in a zoom window.

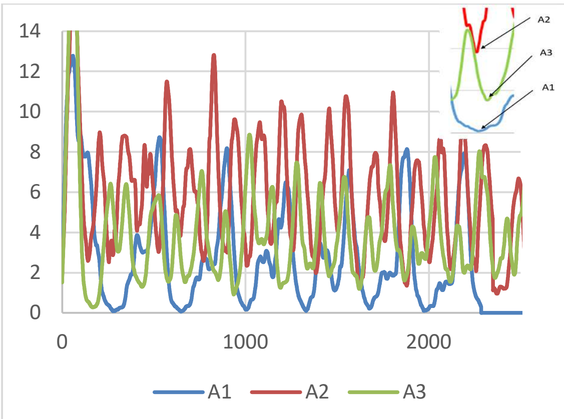

Fig. 3. Variation of drag force related to BMI in freestyle tethered swimming without hand-held devices, in adult subjects (A1, A2, A3) and a zoom window showing the minimum value of the 3 swimmers' drag force

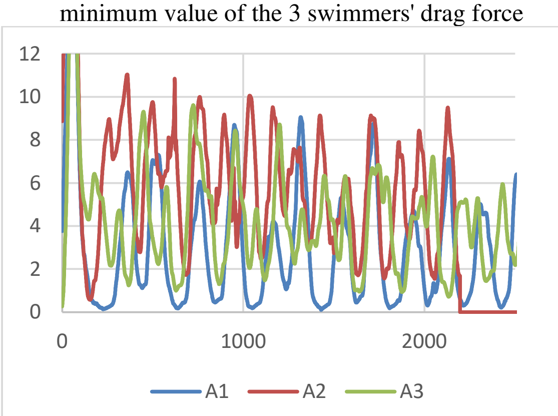

Fig. 4. Variation of drag force related to BMI in freestyle tethered swimming, with hand-paddles, in adult subjects (A1, A2, A3)

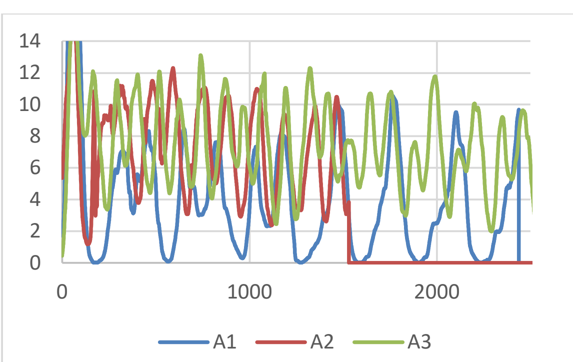

Fig. 5. Variation of drag force related to BMI in freestyle tethered swimming, with snorkeling fins, in adult subjects (A1, A2, A3)

3.2 Drag force variation in child subjects

Figure 6 highlights the minimum force value for each of the 3 children swimmers at a given time, in a zoom window.

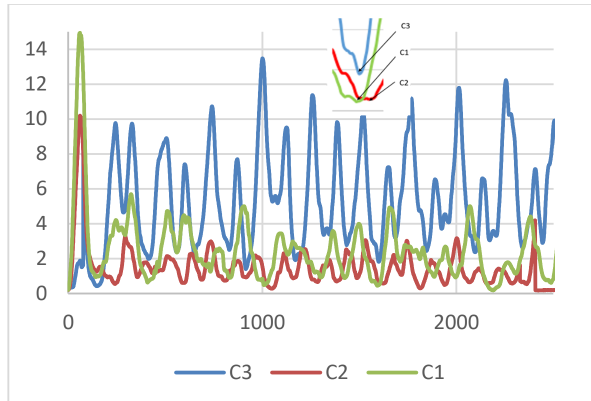

Fig. 6. Variation of drag force related to BMI in freestyle tethered swimming without hand-held devices, in child subjects (C1, C2, C3) and a zoom window showing the minimum value of the 3 swimmers' drag force

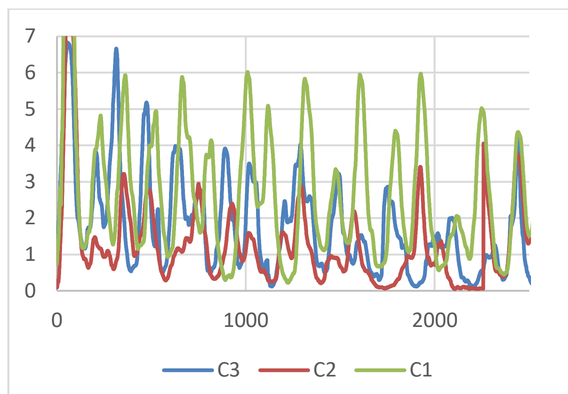

Fig. 7. Variation of drag force related to BMI in freestyle tethered swimming, with hand-paddles, in child subjects (C1, C2, C3)

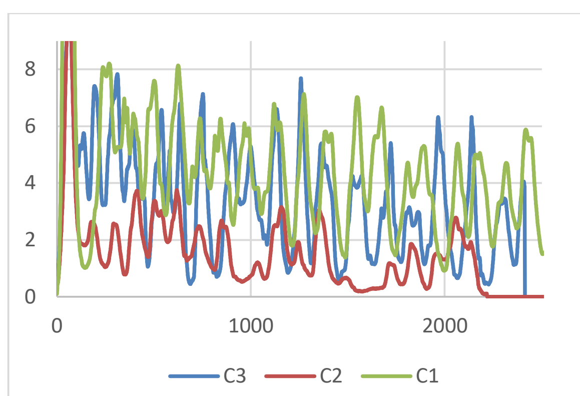

Fig. 8. Variation of drag force related to BMI in freestyle tethered swimming, with snorkeling fins, in child subjects (C1, C2, C3)

3.3 Comparisons between the variation of the drag force of the adult with the drag force of the child subjects

From the previous graphical representations it was observed that the adult swimmer A2 and the child swimmer C3 have the best results in terms of the parameters tracked (frequency of breaststroke movement and maximum value of the drag force, relative to BMI) of the two groups measured. The following figures are a graphical comparison of these parameters for adult A2 and child C3.

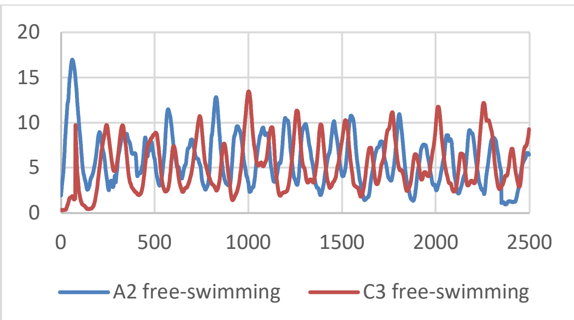

Fig. 9. Variation in free-swimming, of the drag force in tethered swimming, in relation to BMI, comparison between adults A2 and children C3

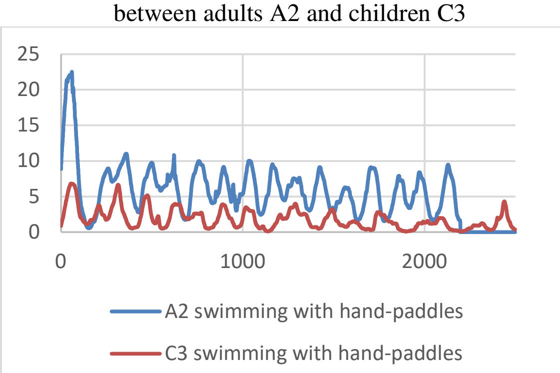

Fig. 10. Variation in free-swimming with hand-paddles, of the drag force in tethered swimming, in relation to BMI, comparison between adults A2 and children C3

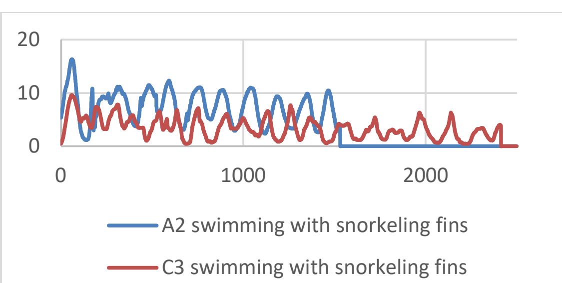

Fig. 11. Variation in free-swimming with snorkeling fins, of the drag force in tethered swimming, in relation to BMI, comparison between adults A2 and children C3

4. DISCUSSIONS

Analyzing the variation of the drag force in tethered swimming, in relation to the BMI, for the group of three adult subjects (A1-A3), in crawl stroke without hand paddle devices (Fig.3) it can be observed that the maximum forces were recorded in subject A2 (swimming champion), and the values with a relatively high degree of symmetry were recorded in subject A3 (swimming teacher).

The same analysis, but with hand-paddles (Fig.4, 5), it can be seen that the maximum force were recorded for subject A3, but in relation to BMI, the three adult subjects (who were measured unitarily using the same swimming devices (hand-paddles and snorkeling fins), performed close in performance.

As can be seen in the graphs in Fig. 3, 4 and 5, the minimum value of the drag force of swimmer A1 (17 years old and inexperienced swimmer) reaches 0, while in swimmers A2 and A3, the minimum value of the same force does not reach zero. Advanced swimmers A2 and A3 (47 year old-former champion swimmer and 47 year old-swimming teacher, respectively), have a much higher frequency of breaststroke movements (~1.6Hz) than swimmer A1 (~0.6Hz). This large difference in the frequency of breaststroke movements is combined with the synchronization of the movements of the lower limbs and the specific inertia of the swimmer's body (which is not rigidly connected in the aquatic environment, except by the wire by which it is connected to the force sensor).

Thus, the three adult swimmers have different values for minimum propulsive force (figure 3-the zoom window)

Analyzing the variation of the drag force in tethered swimming, in relation to the BMI, for the group of three child subjects, the subject C3 was advantaged by the calculus, having a very low body mass index (15Kg/m^2, compared to 18.35 Kg/m^2, and 21.30 Kg/m^2 in C1, respectively C2). That is why subject C3 was able to obtain values of the drag force in tethered swimming without hand-paddles devices, about 3 times higher than the other child subjects (Fig.6).

In Fig. 6-8, we observe that the frequency of breaststroke movements is comparable for the three swimmers (C1~1.3Hz, C2~1.6Hz, C3~1.6Hz), but the maximum value of the drag force is very different. This difference, combined with the specific inertia of the swimmer's body, determines different values for minimum propulsive force (figure 6-the zoom window).

In tethered swimming with hand-paddles devices (Fig.7-8), the difference between the three child subjects is diminished, the top place being taken by subject C1, who seems to have more experience in using handheld devices.

From the comparative analysis of the variation of the drag forces in relation to BMI between the adult A2 and child C3, the following results were obtained:

- In swimming without hand-held devices, the variation of the drag forces related to the BMI of child C3 is comparable to that of adult A2 (Fig. 9);
- In swimming with hand-held devices, the drag forces, relative to BMI, of child are lower than those of adult (Fig. 10-11);

5. CONCLUSIONS

The technique of measuring the propulsive force in tethered swimming can be a useful method in evaluating the effects of training in competitive children swimmers.

The child swimmer subject (C3), in free swimming style, without handheld devices, achieved a higher variation in the parameter of the stroke force/BMI than the adult swimmer subject (A2).

However, the child subject C3 performed worse than the adult subject A2 in the tests with hand paddles and snorkeling fins, possibily duet o less experience with these devices.

By measuring the propulsive force, coaches can directly assess a swimmer's ability to generate speed more efficiently. This allows for evaluating and adjusting training program sif necessary. Additionally, coaces can gauge how well children apply the learned techniques to maximize movement efficiency. An efficient swimmer utilizes their body optimally to generate propulsion with minimal effort. Furthermore, measuring propulsive force can provide insight into child's potential to excel in specific swimming styles or distances, guiding them toward specialization in that style.

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Investigarea experimentală a forței de propulsie în înotul legat al înotătorului de tip crawl

Această lucrare prezintă o investigație experimentală pentru a determina forța de rezistență și pentru a stabili unii parametri pentru a evalua magnitudinea acesteia în propulsia subiecților copii și adulți. În cadrul experimentului s-a ales să se studieze forța de rezistență a înotătorilor raportată la IMC, folosind o serie de obiecte portabile (handheld-uri, lame de înot), forța fiind măsurată experimental cu un sistem de măsurare cu senzori de forță și un sistem de achiziție de date. Parametrii obținuți au fost comparați între subiecții din două grupuri: unul de adulți-A2 și unul de copii-C3. Au fost comparate, de asemenea, efectele obiectelor portabile asupra amplitudinii maxime în înot legat pentru cei doi subiecți.

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