Invited Editorial

Proposal of a deterministic model to explain swimming performance

Tiago M. Barbosa[a], Mario J. Costa[b], Daniel A. Marinho[c]

a - National Institute of Education, Nanyang Technological University, Singapore

b - Polytechnic Institute of Guarda, Portugal

c - University of Beira Interior, Covilhã, Portugal

Abstract

International Journal of Swimming Kinetics 2(1) : 1-54, 2013. Swimming is one of the most challenging sports to investigate. Since long, swimming practitioners base their decisions in scientific evidences. It is known that several scientific domains have a significant role in the swimming performance, such as the “Biomechanics”, “Physiology”, “Anthropometrics”, “Motor Control” and “Muscle strength and conditioning”. The nowadays trend in swimming research is the “Interdisciplinary assessment”, which is related to the “holistic approach”. In Sport Sciences, and especially in Biomechanics, a re-new interest also emerged in the last few years for the design and development of deterministic models. Merging both concepts (i.e., “holistic thinking” and “deterministic models”) there is a chance to expand a deterministic model for competitive swimming, including several other scientific domains besides the Biomechanics. With this it is possible to have a deeper understanding of the variables that determine swimming and how they interplay to enhance performance. The aim of this paper was two-folds: (i) to make a revision and an update of the state of the art about the relationships between swimming biomechanics with performance, energetics, anthropometrics, motor control, muscle strength and conditioning; (ii) to design the deterministic model of such relationships.

Keywords : aquatic locomotion, energetics, kinematics, hydrodynamics, muscle strength, EMG, anthropometrics

Corresponding author:

Tiago M. Barbosa

Physical Education & Sports Science Academic Group

National Institute of Education

NIE5-03-32, 1 Nanyang Walk, Singapore 637616

Phone: (65) 6790-3774. Fax: (65) 6896-9260

E-mail: tiago.barbosa@nie.edu.sq

1. Introduction

Swimming is one of the most challenging sports to investigate. Human beings are not specially prepared to propel themselves in aquatic environment as happens with several other specimens. Even so, competitive swimming is one of the most popular sports around the world. Both facts lead clubs and nations to keep a tight competition and willing to enhance their athletes' performances as much as possible.

Since long, but specially starting in the seventies, swimming practitioners (i.e., coaches, athletes, etc.) base their decisions in scientific evidences. The turnover to a more science-based practice is related to a couple of milestones. The organization, for the first time, in 1971, of the "International Symposium on Biomechanics in Swimming, water polo and diving" (known nowadays as "Biomechanics and Medicine in Swimming"). This is a scientific meeting held every 4-year that gathers all main research groups dedicated to this sport and is supported by UNESCO. The release of the textbook "Swimming: Science and technique" from Counsilman (Counsilman, 1968). The textbook was a best-seller and one of the first attempts to explain the swimming techniques and training procedures according to empirical data.

Nowadays a solid and large scientific community investigates competitive swimming, delivering useful information to practitioners. It is known that several scientific domains have a significant role in the swimming performance, such as the "Biomechanics", "Physiology", "Anthropometrics", "Motor Control" and "Muscle strength and conditioning". Over the years every now and then some of these domains were more "main stream" than others. For instance, there was a high interest for "Hydrodynamics" in the early 80s, for "Biochemistry" in the late 80s and in "Anthropometrics" in the early 90s (Barosa et al., 2010a). Since 2006, the trend in swimming research is the "Interdisciplinary assessment" (Vilas-Boas, 2010; Barbosa et al., 2010a). This "Interdisciplinary assessment" is based on the "holistic approach". This can be defined as the interplay of several scientific domains and how those variables determine a given outcome (for the case, the swimming performance). This approach is widely accepted in scientific fields such as Human Sciences (e.g. Anthropology), Social Sciences (e.g., Management & Business and Economics), Health Sciences (e.g. Medicine) and Basic Sciences (e.g. Physics and Biology).

In Sport Sciences, and especially in Biomechanics, a re-new interest also emerged in the last few years for the design and development of deterministic models. A deterministic model is a modeling paradigm that determines the relationships between a movement outcome measure and the biomechanical factors that produce such a measure (Chow and Knudson, 2011). A block diagram is often used to provide an overview of the relationships. Merging both concepts (i.e., "holistic thinking" and "deterministic models") there is a chance to expand a deterministic model for competitive swimming, including not only biomechanical variables, but as well, variables from other scientific domains. With this it is possible to have a deeper understanding of the variables that determine swimming and how they interplay to enhance performance. Some research groups call to this a

"Biophysical" approach. Previous works suggested the relationships between some scientific domains with swimming performance (Barbosa et al., 2010b; Barbosa, 2012). Figure 1 presents a proposal of relationship between some of those domains.

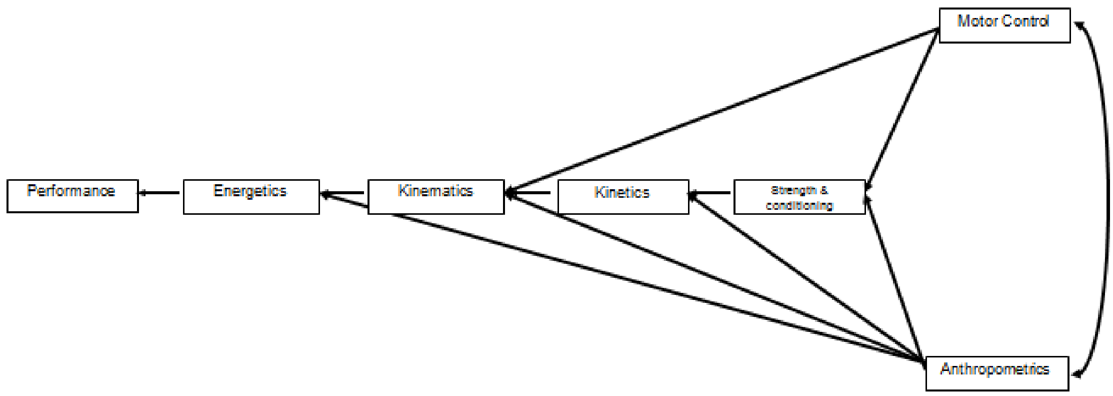

Figure 1: The scientific domains included in a deterministic model for competitive swimming.

The aim of this paper was two-fold: (i) to make a revision and an update of the state of the art about the relationships between swimming biomechanics with performance, anthropometrics, motor control, muscle strength and conditioning; (ii) to design the deterministic model of such relationships. Searches were done in several data bases (e.g., Index Medicus, MEDLINE, Science Citation Index, Scopus, SPORTDiscus) and in our departmental files (Physical Education and Sport Science Academic Group at the National Institute of Education, Nanyang Technological University), including conference proceedings (e.g., Biomechanics and Medicine in Swimming, Symposium of the International Society of Biomechanics in Sports, Medicine and Science in Aquatic Sports, International Scientific Conference of Aquatic Space Activities). Several keywords (e.g., biomechanics, kinematics, kinetics, energetics, physiology, performance, swimming, anthropometrics, motor control, inter-limb coordination, electromyography, neuromuscular, muscle strength, muscle power) with multiple combinations were used in the search strategy.

2. Relationship between swimming biomechanics and performance

2.1. Relationship between swimming performance and energetics

Research evidence has reported that energetics is one of the domains with higher influence in swimming performance (Barbosa et al., 2010b). The two energetic variables often cited in the literature due to its relationship with the swimming performance are the energy expenditure and the energy cost.

The total energy expenditure ($\dot{E}_{tot}$) represents the energy input in the biological system and should be used to produce external mechanical work (Winter, 2009). $\dot{E}_{tot}$ can be computed based on the contribution of all energetic pathways:

$$\dot{E}_{tot} = \sum_{i=1}^{3} A_i \tag{1}$$

Where $\dot{E}_{tot}$ represents total energy expenditure, A_i represents a given energetic pathway. The A_i includes the aerobic, anaerobic lactic and anaerobic alactic pathways (di Prampero et al., 1974; Zamparo et al., 2011; Figueiredo et al., 2011):

$$\dot{E}_{tot} = Aer + An_{lac} + An_{alac} \tag{2}$$

Where $\dot{E}_{tot}$ represents total energy expenditure, *Aer* represents aerobic contribution, An_{lac} represents anaerobic lactic contribution and An_{alac} represents anaerobic alactic contribution. The *Aer* contribution is measured with net oxygen up-take (i.e. difference between the value measured at the end of the task and the rest value):

$$Aer = VO_2 net \quad (3)$$

The An_{lac} contribution is estimated with the VO_2 equivalents ($\alpha.\delta^{1}$ = 2.7 $mlO_2.kg^{-1}.mmol^{-1}$) of net blood lactate approach (di Prameproi et al., 1978; Thevelin et al., 1984):

$$An_{lac} = (\alpha \cdot \delta^{-1}) \cdot \left[La^{-}\right] net \quad (4)$$

Where $\alpha.\delta^{1}$ represents the constant value to convert lactate units in oxygen uptake units and $[La^{-et\ al}net$ represents the blood lactate net corrected for body mass (difference between the value measured in the end of the task and the rest value). And the An_{alac} contribution is estimated based on the phosphocreatine concentration as (Binzoni et al., 1992; Zamparo et al., 2011; Figueiredo et al., 2011):

$$An_{alac} = PCr(1 - e^{-1/t}) \cdot BM \quad (5)$$

Where PCr is the phosphocreatine concentration at rest (18.5 $mmol \cdot kg^{-1}$ as proposed by Zamparo et al., 2011), t (s) is the duration of the exercise, τ is the time constant of PCr splitting at work onset [23.4 s, as proposed by Binzoni et al. (1992) and used by Figueiredo et al., (2011)] and BM is the swimmer's body mass. The energy derived from the utilization of the PCr stores (AnAl) is estimated assuming that, in the transition from rest to exhaustion, the PCr concentration decreases by 18.5 $mM \cdot kg^{-1}$ muscle (wet weight) in a maximally active muscle mass [e.g. assuming it corresponds to 30% of body mass (Zamparo et al., 2011)]. AnAl can be then expressed in kJ assuming a P/O_2 ratio of 6.25 and an energy equivalent of 0.468 kJ $mmol^{-1}$ (Capelli et al., 1998; Zamparo et al.;, 2011; Figueiredo et al. 2011).

Even so, several concerns are often addressed by some researchers about the partial contribution of the An_{alac} to the $\dot{E}_{tot}$ in exercise bouts longer than 1 to 2 minutes of duration, as happens in most swimming events (Capelli et al., 1998; Rodriguez, 1999). In this sense, equation 2 can be simplified, removing An_{alac}, and combining equations 3 and 4 stays as:

$$\dot{E}_{tot} = VO_2 net + (\alpha \cdot \delta^{-1}) \cdot \left[La^-\right] net \qquad (6)$$

Energy cost (C) is defined as an inverse of the biological system efficiency, being related to mechanical efficiency and to mechanical work:

$$C = \frac{w_{tot}}{\eta_o} \qquad (7)$$

Where C represents the energy cost, w_{tot} represents total mechanical work per unit of distance and η_o represents overall efficiency. The C can also be defined as the total energy expenditure required to place the body over a given unit of distance (Schmidt-Nielsen, 1972; di Prampero, 1986) and computed as:

$$C = \frac{\dot{E}_{tot}}{v} \quad (8)$$

Where v represents the swimming velocity, $\dot{E}_{tot}$ represents the total energy expenditure corrected for body mass and C represents the energy cost.

Several experimental studies were conducted in swimming in order to discriminate athlete's competitive levels based on this reasoning. From descendent order, for a given swim velocity the higher $\dot{E}_{tot}$ belongs to breaststroke followed by butterfly stroke, backstroke and front crawl, respectively (Barbosa et al., 2006a). The partial contribution of each energetic pathway for the 200m freestyle event was 65.9% (*Aer*), 13.6% (An_{lac}), and 20.4% (An_{alac}) (Figueiredo et al., 2011). The partial contribution of each one of the 3 pathways changes according to the swimming event, being higher the contribution of *Aer* to long-distance races and of An_{lac} as well as of An_{alac} to short-distance ones (Capelli et al., 1998). It was verified that high-level swimmers had a lower C than lower-level counterparts (Fernandes et al., 2006). Plus, comparing national level versus international level swimmers, there were slight differences across both cohort groups (Costa et al., 2012).

2.2. Relationship between energetics and swimming biomechanics

2.2.1. Kinematics

The goal of competitive swimming is to travel the event distance at the maximal velocity since the performance is assessed by the time spent to cover that same distance:

$$t(v1,v2)_{min} = \frac{d(t2)-d(t1)}{v(t2)-v(t1)} \quad (9)$$

Where *t* is the time, *v* is the swimming velocity, *d* is the displacement. Swimming is a periodic movement performing synchronized actions from the limbs and the trunk. Linear velocity of cyclic or periodic movements can be measured as:

$$\bar{v} = 2 \cdot \pi \cdot r \cdot \frac{1}{P} \quad (10)$$

Where *v* represents mean linear velocity, *r* the radius and *P* the period (time spent to make a full revolution). For the case of human periodic movements, equation 10 can be slightly changed to:

$$\bar{v} = SL \cdot SF \quad (11)$$

Where *v* represents the mean swimming velocity, *SL* the stroke length, and *SF* the stroke frequency. The three kinematical variables from equation 11 are considered for most biomechanical assessments of swimming techniques. Besides these, there are a couple of other variables computed on regular basis to estimate the swimming efficiency based on the *v*, *SL* and/or *SF*, such as the stroke index (SI) (Costill et al., 1985):

$$SI = SL \cdot \bar{v} \quad (12)$$

Where *SI* represents the stroke index, *SL* the stroke length and v the swimming velocity. It is considered that a swimmer that is able to achieve a given velocity with a higher SL instead of SF will be more efficient. And the propelling efficiency (ηp) (Zamparo et al., 2005):

$$\eta_p = \left[\left(\frac{v \cdot 0.9}{2\pi . \cdot SF \cdot l}\right) . \frac{2}{\pi}\right] \cdot 100 \tag{13}$$

Where *v* represents the swimming velocity, *SF* the stroke frequency, and *l* the arm's length. Equation 13 is an adaptation of a previous theoretical work from Martin et al. (1981) using the Froude efficiency concept:

$$\eta_p = \frac{v^2}{u^2} \tag{14}$$

Where *ηp* represents the propelling efficiency, *v* the body's velocity and *u* the tangential hand's velocity. Increasing the *v* (assuming that propulsive force increases with drag force) the *ηp* should remain constant. However, a decrease of *ηp* might indicate less efficient propulsion, since a higher *u* will be necessary for produce thrust.

Besides these variables for an "overall" assessment of the swimmers' kinematics (i.e. *v*, *SF* and *SL*) and efficiency (*SI* and *ηp*) some other variables are selected to a more deep understanding of the biomechanical behavior. Body velocity (considering it as a simplification of external mechanical work) depends from *SF* and *SL* as reported in equation 11. On the other hand, *SF* and *SL* depend, respectively, from the partial duration and partial distance covered within each stroke cycle phase:

$$SF = \sum_{i=1}^{n} \frac{1}{t_i} \qquad (15)$$

Where *SF* represents the stroke frequency and t_i the duration of each partial phase of the stroke cycle (the number of phases in each stroke cycle depends from the swimming technique being analyzed); While:

$$SL = \sum_{i=1}^{n} d_i \qquad (15)$$

Where *SL* represents the stroke length and d_i the distance traveled by the body in each partial phase of the stroke cycle (the number of phases in each stroke cycle depends from the swimming technique being analyzed). Moreover, t_i and d_i depend from the limb's actions (i.e., limb's trajectory and limb's velocity) in each phase (Barbosa et al., 2011).

The assessment of the intra-cyclic variation of the velocity (dv) within a stroke cycle is another approach to make an overall mechanics' assessment and estimation of the swimming efficiency. Swimmers do not move at uniform movement (i.e., $v_i = v_o$; a = o). The variations in the limb's and trunk actions lead to v variations, within every stroke cycle (Barbosa et al., 2010b):

$$v = v_0 + \Delta v(t) \tag{16}$$

Where v represents the instantaneous velocity, v_0 the velocity at the beginning of the stroke cycle, Δv is the change of the velocity with the stroke cycle and t the time. The swimmer's Δv happens in the three components of the velocity Cartesians axis (horizontal, vertical and lateral) (Psycharakis et al., 2010; Figueiredo et al., 2012). However, the most informative for researchers and practitioners seem to be the horizontal Δv (also known as dv). A theoretical comparison between the mechanical work performed while swimming at constant v and with dv is described as (Nigg, 1983):

$$\frac{w_d}{w_{d-\text{constan}}} = 1 + \frac{3}{T}\int_0^T \left[\frac{\Delta v(t)}{v_0}\right] dt + \frac{3}{T}\int_0^T \left[\frac{\Delta v(t)}{v_0}\right]^2 dt + \frac{1}{T}\int_0^T \left[\frac{\Delta v(t)}{v_0}\right]^3 dt \tag{17}$$

Where w_d is the mechanical work, $v(t)$ is the swimming velocity at a given time, v_0 is the swimming velocity at the beginning of the stroke cycle and T is the total duration of the stroke cycle. Within the stroke cycle, v changes (~10%) produce an additional work demand (~3%) (Nigg, 1983). This suggests that dv can be considered as an appropriate estimation of the C and the swimming efficiency.

2.2.2. Kinetics

As reported in equation 16 swimmers present a uniform accelerated movement. Therefore, the Δv, considering a given period of time, defines the acceleration ($a = \Delta v/t$). This variable is dependent upon the applied resultant mechanical force and the inertial term of Newton's law:

$$a = \frac{F}{m} \quad (17)$$

Where *F* represents the applied resulted mechanical force, *m* the mass and *a* the acceleration. Meanwhile, the *F* is the result of the vector adding of propulsive forces and drag forces, which have two opposed forces:

$$a = \frac{Fp + D}{m} \quad (18)$$

Where *Fp* represents the sum of all components of the propulsive forces involved and *D* the sum of all components of the drag force. In this sense, the swimming kinematics is dependent from the interplay between *Fp* and *D*.

Effective propelling force can be defined as the component of the total propulsive force acting in the direction of moving. This force is produced due to the interaction of the swimmer with the water to overcome hydrodynamic drag forces resisting forward motion. Thus, it is a hydrodynamic force with the same direction of the movement but opposite to *D*. There are several mechanisms responsible to produce propelling forces, although some of them seemed to be more efficient than others (Marinho et al., 2010). Propelling forces can be gathered in two main cluster groups. The ones produced from steady- and unsteady-flows. Propulsive drag and lift forces are among the steady-flow propelling forces and quantified as:

$$D_p = \frac{1}{2} \cdot \rho \cdot v^2 \cdot S \cdot C_D \quad (19)$$

and

$$L = \frac{1}{2} \cdot \rho \cdot v^2 \cdot S \cdot C_L \qquad (20)$$

Where D_p represents the drag force, L the lift force, ρ the fluid density, v represents the swimming velocity, S represents the projection surface of the propelling segment, C_D represents the drag coefficient and C_L represents the drag coefficient. It is known that:

$$D_p \perp L \qquad (21)$$

The D_p is a force in the movement direction, while L is perpendicular to the movement. On top of that, the relative contribution of D_p and L to overall propulsion is one of the most discussed issues in swimming hydrodynamics research (Marinho et al., 2010; 2011). Mixed results have been reported for the role of each one to overall propulsion. Further studies should be carry out to clear this out. So, effective propelling force is the component of the resultant vector in the displacement direction:

$$Fp = D_p + L \cdot cos\,\alpha \qquad (22)$$

Where D_p represents the drag force, L the lift force and α the absolute angle of the resultant vector in the displacement direction (i.e., horizontal axis). Propulsion is produced mainly by the arms' actions (Hollander et al., 1988; Descholdt et al., 1999). Nevertheless, leg's propulsion should not be disregarded and to the best of our knowledge little is known about the leg's propulsion. Therefore, future studies under this field should also be addressed (Marinho et al., 2010). As a speculation, probably this is because leg's actions (especially at front crawl, backstroke and butterfly stroke) might be strongly related to unsteady-flows mechanics. Indeed, those mechanics should be deeply investigated (Sanders, 1999; Bisxler and Riewald, 2002). There is a trend for, under a limb's acceleration condition, the measured values for propulsive forces be higher (Sato and Hino, 2002; Rouboa et al., 2006). Unsteady flow conditions are also related to a vortex or intermittent jet-flow. The orientation of the jet-flow relative to swimming direction determines the contribution to thrusting the body (Ungerechts and Klauck, 2010). The vortex circulation value when assuming that a pair of vortices observed in the flow field is a vortex ring can be calculated as (Kamata et al., 2006):

$$\Gamma = \int \omega \cdot ds \qquad (23)$$

Where ω represents the vorticity and ds indicates the unit area. Moreover, the induced velocity by the vortex ring is calculated using the formula and applying the law of Biot-Savart (Kamata et al., 2006):

$$v_0 = \frac{\Gamma}{2 \cdot R} \qquad (24)$$

Where v_0 represents the induced velocity, Γ the circulation of vortex ring and R the vortex ring radius.

Drag force (D) represents the resistance to move forward in a fluid environment. It can be expressed by Newton's friction equation:

$$D = \frac{1}{2} \cdot \rho \cdot v^2 \cdot S \cdot C_D \tag{25}$$

Where D represents the drag force, ρ is the fluid density, v is the swimming velocity, S is the projection surface of the swimmer and C_D is the drag coefficient (changing owning to shape, orientation and Reynolds number). The total drag force is the sum of the all drag components (Toussaint et al., 2006):

$$D = D_f + D_p + D_w \tag{26}$$

D represents the swimmer's total drag force, D_f is the swimmer's friction drag component, D_p is the swimmer's pressure drag component and D_w is the swimmer's wave drag component. Skin-friction drag is attributed to the forces tending to slow the water flowing along the body surface of the swimmer. Pressure drag is caused by the pressure differential between the front and the rear of the swimmer. Wave drag is due to the displacement of the swimmer at the water surfaces, which catches and compresses water, leading to the formation of surface waves. Wave drag can be neglected when a swimmer is at least 0.60m deep (i.e., ~1.8 chest depths) (Lytlle et al., 1999; Vennel et al., 2006). Friction drag represents roughly 5%, pressure drag 80% and wave drag 15%, displacing at 1.0 m/s. At higher velocities (2.0 m/s), friction drag represents 3%, pressure drag 57% and wave drag 40% (Toussaint et al., 2000). Partial contribution of each drag component to total drag depends from several issues such as (Marinho et al., 2009): (i) swim or gliding velocity; (ii) underwater dolphin kicking after start and turn; (iii) body position while gliding and swimming; (iv) drafting.

Another mechanical force that plays an important role in swimming is buoyancy. Buoyancy has a vertical and upright direction, opposite to the body's weight and is quantified as:

$$B = \rho \cdot g \cdot V \quad (27)$$

Where B represents the buoyancy force, ρ is the density of the water, g is the gravitational acceleration and V is the volume of the displaced body of the liquid. During static vertical buoyancy the swimmer is in a fluid mechanics statics equilibrium, where the net forces acting must be:

$$\sum F_i = 0 \quad (28)$$

Being considered as F_i:

$$W + B = 0 \quad (29)$$

Where W represents the body weight force and B is the buoyancy force. So:

$$(BM \cdot g) + (\rho \cdot g \cdot V) = 0 \quad (30)$$

Where BM represents the body mass, g is the gravitational acceleration, ρ is the fluid density and V the fluid volume. If the swimmer's buoyancy force exceeds its weight, he will "rise" in the water and emerge. If the swimmer's weight exceeds its buoyancy he will sink. Therefore, higher buoyancy might allow a higher position at water surface. So, the assessment of the buoyancy can be used to analyze the swimmers' hydrostatic profile (Barbosa et al., 2012).

Based on these theoretical assumptions, a number of research investigations were performed in swimming. The research performed demonstrated increases of *v* imposes increases in $\dot{E}_{tot}$ (because the VO_2 and the $[La^-]$ increases) (Barbosa et al., 2005; 2006a; 2006b). However, an increase of the *v*, based on the *SL*, decreases the *C* and increase the swim efficiency (e.g., higher *SI*, *ηp* and lower *dv*) (Barbosa et al., 2008a). The increase of the v_{limbs} lead to an increase of the *v* (Barbosa et al., 2008b). The v is even more enhanced if the swimmer knows how to maximize v_{limbs} in the most propulsive phases within the stroke cycle (Barbosa et al., 2008b). The increase of the v_{limbs} is related to *Fp* (D_p, *L* and jet-vortex) (Schleihauf et al., 1988). Meanwhile, *v* also depends from *D*, which should be minimized adopting a more streamlined body position, whenever the rules allow being at a depth higher than 0.60m (Vilas-Boas et al., 2010). However, since most of the time the swimmer is at water surface, higher buoyancy can be an advantage (Yanai, 2001).

3. Relationship between swimming biomechanics and anthropometrics

3.1. Relationship between swimming kinematics and anthropometrics

Anthropometrics assessment included on regular basis the measurement of lengths (e.g., height, arm span, limbs' lengths, segment's diameters, etc), areas (e.g., body surface area, hand's area, feet area), volumes and masses (e.g., body mass, body volume, lean mass, fat mass). Several anthropometrical features were related to the swimmer's biomechanics.

One of the first interests was to relate the height with the arm span (*AS*). It is known that swimmers should have a high AS. Practitioners suggest that a ratio of 1/1.03 should exist between the height and the AS (i.e. *AS* should be ~3% higher than the height). However, to the best of our knowledge there is no empirical data supporting it. A notable and pioneer research about these relationships was developed by Grimston and Hay (1986). In such paper it was reported the positive influence of the limb's lengths, including the *AS*, in the *SL*. And therefore, indirectly *AS* is related to *v*, according to equation 11. On the same way, *AS* is also related to the ηp, as suggested in equation 13. Several others replicated this kind of studies but in other swimming techniques, race events, genders, ages and with larger samples sizes with a higher statistical power (Pelayo et al., 1996; 1997; Tella et al., 2003).

As described in equations 3 to 5 some energetics outputs depend from the body mass (BM). A higher *BM* imposes a higher number of active muscle masses (i.e., larger and higher number of cells and tissues) and therefore a higher energy production in any of the three energetic pathways. So, to be able an inter-subject and across a time-frame an intra-subject comparison, those variables are normalized to BM.

There are also a few evidences of significant relationships between other anthropometric features and the swimmer's biomechanics and even his/her energetics profile (Chatard et al., 1992; Kjendlie et al., 2004; Kjendlie and Stallman, 2010). Comparing two cohort groups based on the arm span, it was observed that the group with longer arm's length had the lowest *C* (Chatard et al., 1992).

Swim economy outcomes can also be scaled for a length (e.g., body length), body area (e.g., body surface area) or allometry. For instance, in such cases, gender differences turn out to disappear or decrease significantly (Ratel and Poujade, 2009). The explanation for this variation in the swim economy as a function of scaling factors for body size is not clear, although morphological, biomechanical and energetic variables have been suggested by others (Kjendlie et al., 2004; 2010). Figure 1 suggests that energetics depends from kinematics and anthropometrics, thus it can be speculated that anthropometrics affects directly energetics but also indirectly through the kinematical behavior.

Another issue to perform a kinematical assessment is the best anatomical landmark to be selected. Most times the decision is to choose between the head/vertex, the hip or the centre of mass. Notably the head/vertex is used as reference point to perform a race analysis (Arellano, 2000; Jesus et al., 2011). Hip is mainly used during race analysis or training session (Leblanc et al., 2007; Barbosa et al., 2013). The centre of mass is mainly selected during training session or control and evaluation session (Barbosa et al., 2003; Figueiredo et al., 2009). To simplify, the Cartesian position in the plane (i.e. 2D) of the total centre of mass (CM) of a body is defined as:

$$CM \rightarrow (x; y) \qquad (31)$$

Both *xx* and *yy* coordinates are determined according to the position of the partial CM of each segment of the multi-system body (i.e. segments' relative locations) and its partial masses:

$$X_{CM} = \frac{\sum_{i=1}^{n} x_i \cdot m_i}{\sum_{i=1}^{n} m_i} \qquad (32)$$

and,

$$Y_{CM} = \frac{\sum_{i=1}^{n} y_i \cdot m_i}{\sum_{i=1}^{n} m_i} \qquad (33)$$

Where *xi* and *yi* represent the positions of the partial *CM* of each segment and *mi* the partial masses. Swimming is a locomotion technique characterized by the movement of the limbs, trunk and head. So, the location of the *CM* within a stroke cycle might not be at a fixed position. On the other hand, both the head/vertex and the hip have fixed locations, no matter the segment's range of motion. So, it is questionable the head/vertex and the hip deliver data as valid and as accurate as the *CM*. Indeed, there is a solid body of knowledge stating that, in competitive swimming, there is a fairly moderate-large bias assessing a fixed-point kinematics (Barbosa et al., 2003; Figueiredo et al., 2009; Psycharakis et al., 2009). There is a

0.1 s (i.e. ~10%) time-delay (Barbosa et al., 2003), a 7% and 3% bias, respectively for forward velocity and displacement (Fernandes et al., 2012) in the hip's vs CM's assessment.

3.2. Relationship between swimming kinetics and anthropometrics

Mechanical equilibrium when immersed in water at null velocity depends from the annulations of all forces as reported in equation 29. Stable equilibrium is characterized by the action line of the Weight force when is at the same vertical projection of the buoyancy force. While weight force depends from Newton's second law of motions (W = m.g), buoyancy is according to Archimedes principle (B = ρ.g.V) (equation 30). The floating capacity (i.e., mechanical relationship between *W* and *B*) in a biological body is determined by anthropometric characteristics. This includes tissue density (more fat mass, leading to less density), lung volume, relative limb's position and water density (Seifert et al., 2010a).

Another variable of interest is the "passive floating torque". While in the prone position, at null velocity, besides the external forces *B* and *W* there are acting as well a couple of torques from those same forces. The stable equilibrium includes not only the condition described in equation 29 but also that:

$$\sum_{i=1}^{n} m_o F_i = 0 \qquad (35)$$

I.e.

$$m_o W + m_o B = 0 \quad (36)$$

and

$$W \cdot l_w \cdot sin\alpha + B \cdot l_B \cdot sin\alpha = 0 \quad (37)$$

Where m_o represents the torque rotating in the axis, *W* the weight, *B* the buoyancy, l_w the arm of the weight force (i.e. CM to feet distance) and l_B the arm of the buoyancy force (i.e. volume centre/geometric centre to feet distance). Both torques acts in the same angular direction (i.e. clockwise), creating a force binary. The passive floating torque is to be linked to the *C*. A better static floating position is related to a lower *C* (Zamparo et al., 1996; Kjendlie et al., 2004). Differences in the floating torque are due to differences in body length. Taller subjects have a higher distance between the centre of volume and the CM. A lower total body fat also plays a role, since it increases the body density and decreases the *B*. All this will help induce less streamlined position swimming and, thus increases the *S* and the *D*.

Equations 19, 20 and 23 suggest that propelling forces are related to surface areas. Some empirical data verified that larger propelling areas mean a higher propelling efficiency (Toussaint et al., 1991; Gourgoulis et al., 2008) and other were not able to do so (Zamparo, 2006; Morais et al., 2012). Appropriate hand's orientation (i.e., attack and pitch angles) on stroking has a role enhancing thrust. Moreover, a couple of studies did not report significant associations between surface area and swimming efficiency, in fairly young swimmers. Probably the level of expertise is a variable to control, as some of the subjects assessed might not perform an appropriate hand's orientation although having different hand surface area among them.

Furthermore, several other areas have to be considered when assessing the *D*. Equation 25 suggests that the *S*, defined as the projection surface of the swimmer, has to be took into account. For some researches, *S* is computed as the trunk transverse surface area. Trunk transverse surface can be measured in water or in land, with the swimmer at the hydrodynamic position with a planimeter technique (e.g., on screen measure area software of 2D digital images, body scan) or estimated from anthropometrical variables including height and *BM* (Clarys, 1979):

$$S = 6.9256 \cdot BM + 3.5043 \cdot H - 377.156 \qquad (38)$$

Or, including chest diameters and perimeters for males and females, respectively (Morais et al., 2011):

$$S_{male} = 6.662 \cdot CP + 17.019 \cdot CSD - 210.708 \qquad (39)$$

$$S_{female} = 7.002 \cdot CP + 15.382 \cdot CSD - 255.70 \qquad (40)$$

Where *S* is the trunk transverse area, *CP* is chest perimeter and *CSD* is chest sagital diameter. However, since a floating torque phenomenon exists, as discussed previously, other researchers compute the "Projection frontal area", including not only the S but also the frontal area due to the sink of the legs (Mollendorf et al., 2004):

$$PFA = S \cdot cos\,\alpha + \frac{BSA}{2} \cdot sin\,\alpha \quad (41)$$

Where PFA represents the projection surface area, S the trunk transverse area and BSA the body surface area estimated as (Shuter and Aslani, 2000):

$$BSA = 71.84 \cdot BM^{0.425} \cdot H^{0.725} \quad (42)$$

Discussing equation 26 it was highlighted that whenever a body travels in a fluid environment it catches and drag for a while fluid particles. The water around the swimmer that is set in motion can be considered as an "added mass" (m_a). I.e., it is the water that a swimmer has to accelerate in addition to his/her BM during the dv. The m_a is expressed as (Vogel, 1994):

$$m_a = C_a \cdot V \cdot \rho \quad (43)$$

Where m_a represents the added mass, Ca is the added mass coefficient, V the body volume of the swimmer and ρ the water density. Relative m_a for boys, women and men were respectively 26.8%, 13.67% and 26.8% of the BM (Caspersen et al., 2010). Roughly it can be stated that the m_a in human swimmers, in extended gliding position, is approximately 25% of the subjects' BM and should be considered in further kinetics and even kinematics analysis.

The Strouhal number (S_t) is another variable to be discussed. Fluid mechanics defines *St* as a dimensionless number describing oscillating flow mechanisms:

$$S_t = \frac{f \cdot l}{v} \tag{44}$$

Where S_t represents the Strouhal number, *f* is the frequency of the vortex shedding, *l* is the body' length and *v* is the velocity of the fluid. *St* is known to govern a series of vortex growth and shedding regimes for airfoils undergoing pitching and heaving motions, including animals (Taylor et al., 2003) and therefore, swimmers (Arellano et al., 2003; Hochstein and Blickhan, 2011). Notably, this number is used for the analysis of underwater ondulatory kick and butterfly stroke. Even so, based on equation 44 it seems that taller subjects have a clear advantage.

4. Relationship between swimming biomechanics and motor control

4.1. Relationship between inter-limb coordination, swimming biomechanics and other scientific fields

Swimming is typically a human movement involving the coordination of several segments that are acting at the same time to propel the swimmer forward. For a long time, the segments' synchronization assessment was made qualitatively. E.g., visual inspection of the arm's actions while swimming front crawl to determine if the swimmer was performing an inter-arm catch-up, semi catch-up or power-stroke synchronization (Maglischo, 1993). In the 2000s there was a shift to quantify such inter-limb coordination. The nature of the inter-limb coordination is quantified using concepts and principles of dynamical theory, with especial reference to some findings about bimanual, walking-running and lower-upper limb tasks (Seifert and Chollet, 2008). At the start, Chollet et al. (2000) established an index of coordination that quantifies the time lag between the propulsion of one arm and that of the second arm. I.e., the index roughly quantified the three types of synchronization described by Maglischo (1993) and others. Nowadays, it is possible to quantify the inter-limb coordination in all four swimming techniques. The inter-limb coordination assesses the time gaps quantifying the arm-arm coordination in front crawl and backstroke and the arms-legs coordination in the breaststroke and butterfly strokes. To measure the index of coordination (IdC) it is consider the four arm-stroke phases (entry- phase A, pull- phase B, push- phase C and recovery- phase D) of the left and right arm, respectively (Chollet et al., 2000):

$$IdC_{left\_arm} = \left(\frac{t_{end\_phaseC\_left\_arm} - t_{end\_phaseB\_rigth\_arm}}{t_{stroke\_cycle}} \right) \cdot 100 \quad (45)$$

and,

$$IdC_{left\_arm} = \left(\frac{t_{end\_phaseC\_rigth\_arm} - t_{end\_phaseB\_left\_arm}}{t_{stroke\_cycle}} \right) \cdot 100 \quad (46)$$

therefore,

$$IdC = \frac{IdC_{left\_arm} + IdC_{left\_arm}}{2} \quad (47)$$

Where *IdC* is the index of coordination and t is the time of each phase or the full stroke. When: (i) *IdC* < 0 %, the arm's coordination is called "catch-up" because there is a lag time between the propulsive phases of the two arms; (ii) *IdC* = 0%, the propulsive phase of one arm started at the time the other arm finished and is called "opposition" and; (iii) *IdC* > 0 %, the propulsive phase of both arms overlapped and the coordination is called "superposition". Total time gap (TTG) is used to measure inter-limbs (i.e. arms vs legs) coordination in Breaststroke and Butterfly stroke (Seifert et al., 2008):

$$TTG = \left(\frac{t_{end\_arms} - t_{beginning\_legs}}{t_{stroke\_cycle}} \right) \cdot 100 \qquad (47)$$

Where *TTG* represents the total time gap and *t* is the time of each limb's action or the full stroke. So, coordination is defined by the total time gap between arms and legs (i.e., which is the sum of the different time gaps between arm and leg actions).

Both *IdC* and *TTG* are influenced by several constrains, including (Seifert, 2010): (i) environmental (e.g., drag force); (ii) task (e.g., swim velocity) and; (iii) organismic (e.g., anthropometrics). Those constrains are linked to the scientific fields reported in figure 1. With decreasing *v*, swimmers tend to adopt a decrease *IdC* (Seifert et al., 2010b; Schinitzler et al., 2008) or TTG (Seifert et al., 2008; Chollet et al., 2004). However, high-level swimmers have a high and more stable *IdC* (Seifert et al., 2007) or a lower *TTG* (Seifert et al., 2008; Chollet et al., 2004). As expected, a high *v* leads to a high *D*, leading to high *IdC* (Seifert et al., 2010c). Similarly, with increasing drag, significant increases in the *IdC* were reported (Schnitzler et al., 2011). Plus, it was reported a link between energetics-biomechanics-motor control. Results showed that the increase in *C* was correlated to an increase in the *IdC* and *SF*, and a decrease in *SL* (Komar et al., 2012; Figueiredo et al., 2013a). Plus, the *IdC* and *ηp* are also inversely correlated (Figueiredo et al., 2013a). Those differences among competitive levels, as happens as well between genders, seem to be related to anthropometrics (Seifert et al., 2004; 2008) and muscle strength, being the later one discussed in another sub-section.

4.2. Relationship between neuro-muscular activation, swimming biomechanics and other scientific fields

Another approach to understand the swimmer's motor control is using the neuro-muscular activity. Since the early 1960s has been done some research about the swimming neuromuscular activity. However, for a long time such research was mostly qualitative, replicating in some way the pioneer study of Ikai et al. (1694). Indeed, the basis for the swimming stroke descriptions popularized in some swimming textbooks including the one from Counsilman ()1968 was based on the qualitative description of the swimmer's electromyography (EMG) data from Ikai et al. (1964). In the 80s EMG assessment became more "quantifiable". But it seems than it was in the late 2000s that the quantification of EMG became a regular-basis practice in competitive swimming research. Even so, EMG body of research in competitive swimming is much lower than other land-based sports and even aquatic activities (e.g., aquatic walking, head-out aquatic exercises, hydrotherapy).

EMG assessment is made based in the time or frequency (i.e. spectral) domains. Time-domain included the assessment of variables, such as the average amplitude of the signal, the root mean square and the EMG integrated, respectively (Cram et al., 1998; Winter, 2009):

$$avgEMG = \frac{1}{2}\sum_{1}^{s} fs \qquad (48)$$

$$\mathrm{R}MS = I\{|m(t)|\} = \frac{1}{T}\left[\int_{t}^{t+T} |\,\mathrm{m}^2(\mathrm{t})\,|\,\mathrm{dt}\right]^{1/2} \quad (49)$$

$$\mathrm{iEMG} = I\{|m(t)|\} = \frac{1}{T}\int_{t}^{t+T} |\,\mathrm{m}(\mathrm{t})\,|\,\mathrm{dt} \quad (50)$$

Where *avgEMG* represent the average amplitude of the signal and *fs* the value of the EMG at a given moment, *RMS* is the root mean square, *iEMG* is the EMG integrated.

During most of the 60s, 70s and 80s the framework was to know which muscles presented a higher and lower activation patter throughout a stroke cycle. At front crawl, the *latissimus dorsi* muscle seems to be one of the most actives (Clarys, 1979; Bankoff and Vitti, 1978) besides the *triceps brachii, bicepcs brachii* muscle and *pectoralis major* (Clarys, 1979; Birrer, 1986; Nuber et al., 1986). Plus, the best swimmers, at the same relative effort, had a greater *v*, lower EMG activity and more selective recruitment (Rouard and Billat, 1990). For the time being, interestingly no research deeply assessed the breaststroke EMG, because it can be expected a high activity from lower limbs muscle as well.

Another topic of interest was to relate EMG with kinematics (e.g., *SL, SR, v*) and energetics (e.g., $[La^-]$, VO_2) (Rouard and Clarys, 1995; Caty et al., 2006; Aujouannet et al., 2206, Stiern et al., 2011). It seems that a higher *SF* or *v* lead to an increase of the EMG activation (Cabri et al., 1988); since a higher number of fast-twitch fibers are stimulated (Vitasalo et all., 1988). In a more deep assessment, relating EMG with limb's kinematics, e.g., at front crawl, the downsweep was the phase with the lower activity, while the upsweep had the highest (Rouard and Clarys, 1995). Once again at front crawl, several others reported similar data in the following decades, e.g., the *triceps brachii* is the most activate muscle during the push phase, the *bicepcs brachii* and *pectoralis major* during the pull phase and the *upper trapezius* in the recovery (Figueiredo et al, 2013b). Meanwhile, some interest also existed relating EMG with hydrodynamic variables (Clarys, 1985).

For spectral domain, the most selected variables are the median of frequency and the Fast Fourier transformation, respectively (Cram et al., 1998; Winter, 2009):

$$MF = \mu_{1/2} \quad (51)$$

$$x(t) = A + \sum_{1}^{n} \left[B_n \cos(f_n.t) + C_n sen(f_n.t) \right] \quad (52)$$

Where MF represents the median of the frequency, μ is the set of values. Even so, new spectral indices have been proposed and considered to be valid, reliable and more sensitive than those traditionally used for competitive swimming (Clarys, 1985; Figueiredo et al., 2010). Probably this is a debate that is still starting among the swimming research community and new highlight will be delivered in a near future.

Spectral analysis in swimming is used to study muscle fatigue and its relationship to limb's kinematics. EMG spectrum of several muscles shifted toward lower frequency after a maximal swimming bout (Aujouannet et al., 2006; Stirn et al., 2010) as it happens in other aquatic and land-based human movement.

Interestingly, increasing distance of a 200m freestyle event, the incapacity to sustain the *v* in the last laps was coincident with the increase of the fatigue indexes for several muscles (i.e., *flexor carpi radialis, biceps brachii, triceps brachii, pectoralis major, upper trapezius, rectus femoris and biceps femori*s) (Figueiredo et al., 2010).

5. Relationship between muscle strength and conditioning, swimming biomechanics and other scientific fields

5.1. Dry-land muscle strength and conditioning

As it happens to most of the competitive sports, muscle strength and conditioning is one important component of the athlete's fitness. Swimmers include almost on daily-basis dry-land training sessions in their training routines. Dry-land muscle strength and conditioning has two major goals: (i) to improve the athlete's fitness level and; (ii) to prevent muscle-skeletal injuries. Further discussion will be focusing only the relationship between the muscle strength and conditioning to swimming biomechanics and remain scientific fields (i.e., athlete's fitness level). The discussion of the injury prevention goes beyond the aim of the paper.

Upper-body muscular strength has demonstrated to be well correlated with v (Sharp et al., 1982; Costill et al., 1986; Hawley et al., 1992; Tanaka and Swensen, 1998; Aspenes et al., 2009). So, dry-land strength and conditioning training increases maximal power through an overload of the main muscles (as discussed in sub-section 4.2.) used in swimming (Tanaka et al., 1993).

Nevertheless, relationships and associations between dry-land strength and swimming performance are not always strong because: (i) dry-land strength does not relate directly with performance, but with other scientific fields, that in some how link to it (e.g., motor control, anthropometrics, biomechanics); (ii) not all muscles and/or measurement tests used are sensitive; (iii) there is a transfer issue between dry-land and aquatic-based strength.

There are some debate about the relationship between dry-land strength and swimming performance. Several papers found a weak-moderate relationship and even a non-significant one (Johnson et al., 1993; Crowe et al., 1999; Garrido et al., 2010). The weak-moderate relationship might have two reasons: (i) these studies evaluated the maximum load during maximum repetitions, which is more related to maximum force than with explosive force (Gonzalez-Badillo and Sanchez-Medina, 2010). To most swimming events, explosive force is the most important (Toussaint, 2007) to travel as quick as possible a given distance within 1-2 minutes; (ii) as suggested by some preliminary deterministic models for competitive swimming and even some empirical data, dry-land strength does not relate directly to performance. As suggested in figure 1, strength and conditioning seems to be in one extremity of the deterministic model, while the performance is in the opposite one. In the middle there are several scientific fields playing a role on it and being mediators of the performance-strength relationship. It was found out a 20 to 40% improvement on muscle strength after a strength program, but only 4.4 to 2.1% improvements in the performance (Strass, 1988). Other found similar strength improvements, but with no significant changes in performance (Trappe and Pearson, 1994).

In the last few years some evidences emerged of significant relationships between muscle strength and conditioning to performance (Girold et al., 2007; Aspenes et al., 2009; Garrido et al., 2010). However, those studies assessed young swimmers and not adult/elite ones, so some precaution should be considered.

Another topic to be discussed is the test's sensitivity: (i) dry-land strength tests should mimic as much as possible the limb's action and the muscles being activated while swimming; (ii) muscle tension should be as close as possible from the one that happens on water. Several strength testes used in dry-land assessments are not probably valid because they unable the replication of the swimming movement. Basic tests such as the squat jump, bench press, Lat pull down are not specific enough of the limb's actions. Another good example is the handgrip that is used on regular basis for talents identification (Geladas et al., 2005; Silva et al., 2007). This is an outcome mostly phenotype related (Frederiksen et al., 2002) and less to trainability. Handgrip is an isometric test, which does not have a significant transfer to dynamical tensions happening during swimming. Indeed a weak-moderate relationship was verified between handgrip test and swimming performance for most swimming techniques (Garrido et al., 2012). To overcome this limitation, some researchers select a more specific dry-land test with the biokinetic swim bench. Some authors reported strong relationships between muscle power in this apparatus and swimming performance (Sharp et al., 1982). Even so, it has to be considered that biokinetics swim bench only uses the arms, without lower limbs' actions and body roll. Some research groups dedicate a lot of their attention to this topic, highlighting these same results (Swain, 1996; 1997).

5.2. Aquatic-based muscle strength and conditioning

As addressed properly in the previous sub-section, one question raised is if the dry-land strength and conditioning can be transferred to aquatic strength. Some researchers questioned if such transfers can be positive and strong or not (Tanaka et al., 1993). Aquatic strength, i.e. propulsive strength, is measured on regular basis with tethered swimming (Morouco et al., 2011).

Tethered swimming corresponds to the propelling force that a swimmer must produce to overcome the water resistance at maximum free swim velocity (Dopsaj et al., 2003; Morouco et al., 2011). This technique is being used since the early 70s (Magel, 1970). It allows the measurement of the exerted forces, representing an individual Force-time curve chart during the bout. This approach seems to be more specific than dry-land strength (Kjendlie and Thorsvald, 2006). Because it implies the use of all body structure in a similar way to the form used in free swimming and it is performed in aquatic environment (Costill et al., 1986; Dopsaj et al., 2003).

Most common variables to be analyzed from the individual F(t) curves are: peak maximum force (Christensen and Smith, 1987; Keskinen et al., 1989), average of maximum force (Yeater et al., 1981; Fomitchenko, 1999), average force (Ria et al., 1990; Morouco et al., 2011), minimum force (Dopsaj et al., 2003), impulse (Dopsaj et al., 2001) and fatigue index (Morouco et al., 2012).

Tethered swimming is highly related to maximum velocity, namely in front crawl (Costill et al., 1986; Christensen and Smith, 1987; Keskinen et al., 1989; Fomitchenko, 1999). There are also evidences of a strong relationship between propulsive force with short-distance performances in all four swimming techniques (Keskinen et al., 1989; Morouco et al., 2011; Dopsaj et al., 2001; Cortesi et al., 2010).

Plus it has some connections to aerobic (Pessoa-Filho et al., 2008) and anaerobic (Morouco et al., 2012; Ogonowska et al., 2009) energetic pathways. The aerobic or anaerobic assessment with tethered swim depends from the bout's time and intensity. The analysis of the decline in the force exerted may suggest a greater predisposition for short- or long-distance events (Stager et al., 2005).

It was verified that tethered swim (i.e. critical force) was associated to maximal lactate steady-state (Ikute et al., 1996; Pessoa-Filho et al., 2008; Papoti et al., 2009). Similar data was reported for net blood lactate concentrations between 100m free swimming and tethered swimming with equal duration (Thanopoulos et al., 2010). The maximum peak force output (in the first 10s) was pointed as an index of the maximum rate of phosphagens catabolism and the average force of the 30s bout represents the anaerobic capacity, associated with the glycolytic metabolism (Soares et al., 2010). Tethered forces were also highly correlated with power obtained in Wingate arm cranking test (Ogonowska et al., 2009).

Even so, some further limitations should be addressed to tethered swimming: (i) there is a change in the stroke kinematics (Maglischo et al., 1984; Psycharakis et al., 2011); (ii) the fluid mechanics around stationary subject is not the same as happens in free swim; (iii) while kicking, feet may touch the cable, creating some bias, overestimating data.

6. Conclusions

From what was discussed in the previous sections, it is possible to attempt an overall description of the relationships reported. The deterministic model of those relationships is presented in figure 2. Figure 2 is an expansion of figure 1, including the scientific domains, the main variables included in each one of them and the links.

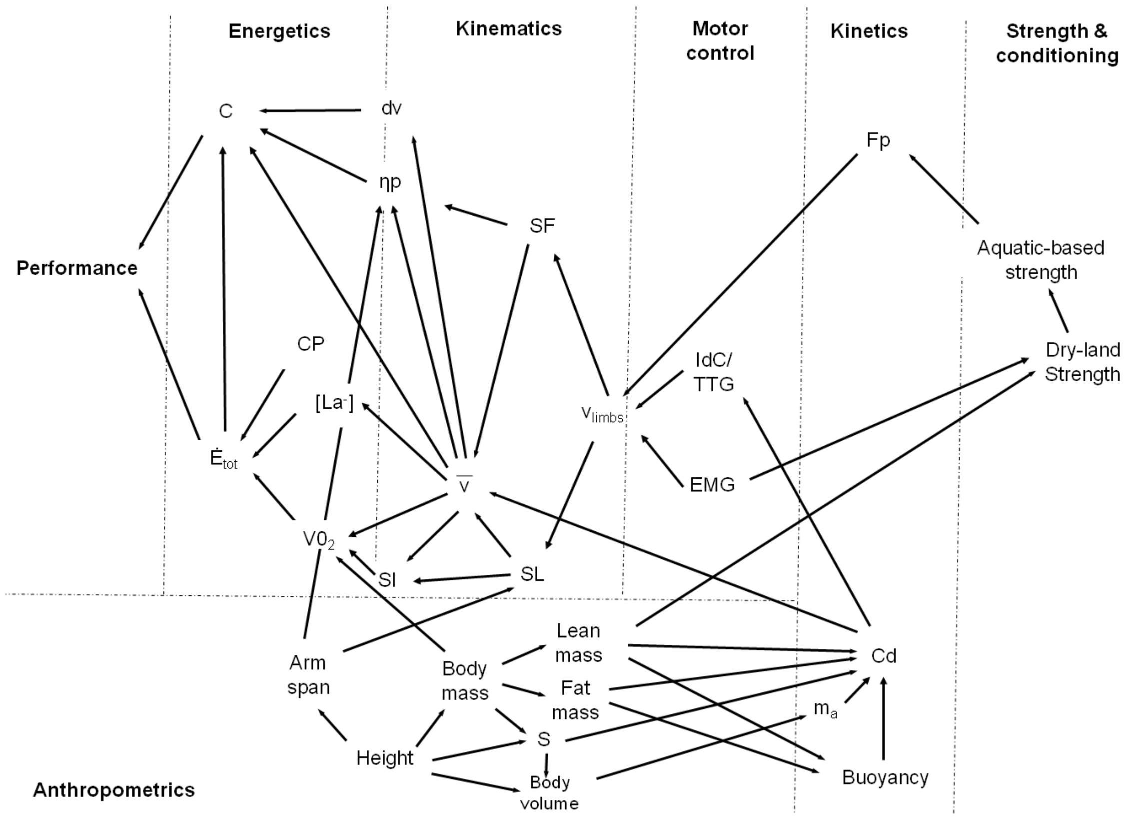

Figure 2: The designed deterministic model for competitive swimming, including the scientific domains and its variables, according to the state of the art. C – energy cost; $\dot{E}_{tot}$ - energy expenditure; CP – phosphocreatine; [La-] – blood lactate; VO_2 – oxygen up-take; ηp – propelling efficiency; SI – stroke index; dv – intra-cyclic variation of the horizontal velocity of the center of mass; SF – stroke frequency; SL – stroke length; v – mean swimming velocity; v_{limbs} – limb's velocity; IdC - index of coordination; TTG – total time gap; EMG – electromyography; S –body surface areas; m_a – added water mass; Fp – propulsive force; Cd – Drag coefficient.

It seems that there is no single path to enhance the performance. Each swimmer can select a given path, different from a counter partner to achieve the same performance. Even so, inter-individual variability in the selected path seems to be higher for non-expert (i.e. regional level) and elite (i.e., international level) swimmers, while it is lower for expert swimmers (i.e. national level) (Seifert et al., 2011). Based on this, it seems that probably the most efficient way to enhance the performance (e.g., shift from a non-expert to expert level) is to improve inter-limb coordination with concomitant increase of the dry-land muscle strength (through a better intra- and inter-muscular activation and a slight increase of lean mass) and be able to transfer such strength to aquatic-based strength. This will increase the limb's velocity and improve its synchronization. Both increases the SL and therefore the v. The increase of the v, through the SL instead of the SF increases the swim efficiency (i.e., increases the ηp and SI; decreases the dv and C) and therefore the swimming performance. This is a path and/or strategy based on the improvement of the biological system efficiency to enhance the swimming performance. This is also typically used with young swimmers. But for these ones, the tracking of other anthropometrical features (e.g., height, arm span, surface areas) are also taken into account. Subjects taller, with higher arm span have advantage in decrease drag force and increasing SL. Plus, higher propelling surface areas, including hands and feet might increase the thrust.

In a near future, research should: (i) add new scientific domains to the model (e.g., Genetics, biological maturation for the case of young athletes); (ii) development of confirmatory models (i.e. assessment of this theoretical relationships with structural equation modeling); (iii) attempt to predict performance based on the model design, quantifying the partial contribution of each domain and variable for the final outcome.

It can be addressed as conclusions: (i) swimming performance depends, respectively, from energetics, kinematics, kinetic, strength and conditioning, motor control, and also anthropometrics; (ii) some variables have a direct effect in the performance, while others have an indirect effect; (iii) there are several paths and strategies that can be selected to achieve a given performance; (iv) there is a higher variability in the paths and strategies selected in non-expert and in elite swimmers than in expert counterparts.

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