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Review

Energetics and biomechanics as determining factors of swimming performance: Updating the state of the art

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Abstract

The biophysical determinants related to swimming performance are one of the most attractive topics within swimming science. The aim of this paper was to do an update of the "state of art" about the interplay between performance, energetic and biomechanics in competitive swimming. Throughout the manuscript some recent highlights are described: (i) the relationship between swimmer's segmental kinematics (segmental velocities, stroke length, stroke frequency, stroke index and coordination index) and his center of mass kinematics (swimming velocity and speed fluctuation); (ii) the relationships between energetic (energy expenditure and energy cost) and swimmer's kinematics; and (iii) the prediction of swimming performance derived from above mentioned parameters.

Keywords: Swimming; Energy cost; Kinematics; Motor coordination; Performance

Contents

1. Introduction

The goal of a competitive swimmer is to travel a given distance with the minimum time. With that aim, the swimmer must be animated to his maximal velocity, which can be expressed as[1,2]:

$$v_{\max} = \frac{\dot{E}_{tot\text{-}max}}{C} \quad (1)$$

where $v_{\max}$ represents maximal swimming velocity ($m\,s^{-1}$), $\dot{E}_{tot\text{-}max}$ maximal total energy expenditure corrected for body mass ($ml\ O_2\ kg^{-1}\ min^{-1}$) and C energy cost ($J\ kg^{-1}\ m^{-1}$). C is converted into the SI units since 1 ml O_2 is equivalent to 20.1 J.[2] The maximal total energy expenditure can be com-

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puted based on the contribution of the aerobic, anaerobic lactic and anaerobic alactic systems. However, in competitive swimming, the contribution rate of the anaerobic alactic system is quite low, once the majority of the events have lastly more than 1 min.[3] Therefore, the main energetic resources come from the other two systems and can be calculated as[2,4]:

$$\dot{E}_{tot} = VO_2net + (\alpha \cdot \delta^{-1}) \cdot [\mathrm{La}^-]\,net \quad (2)$$

where $\dot{E}_{tot}$ represents maximal total energy expenditure corrected for body mass, VO_2net the net oxygen uptake corrected for body mass (difference between the value measured at the end of the task and the rest value), $\alpha \cdot \delta^{-1}$ the constant value to convert lactate units in oxygen uptake units and $[\mathrm{La}^-]net$ the blood lactate net corrected for body mass (difference between the value measured in the end of the task and the rest value). The $\alpha \cdot \delta^{-1}$ parameter, used as VO_2 equivalents, is assumed as being 2.7 ml O_2 kg^{-1} mmol^{-1} in competitive swimming. The 2.7 value of $\alpha \cdot \delta^{-1}$ is valid for venous[4] and arterial[5] blood collections.

The C is defined as the total energy expenditure required to displace the body over a given unit of distance.[6–8] C is related to mechanical efficiency and to mechanical work:

$$C = \frac{w_{tot}}{\eta_o} \quad (3)$$

where C represents energy cost, w_{tot} total mechanical work per unit of distance and η_o overall efficiency. A fraction of the total mechanical work has to be used to accelerate and decelerate the limbs with respect to the center of mass (internal mechanical work) and another fraction is wasted to accelerate water (transfer of kinetics energy into water). Propulsive efficiency assumes an important role and is given as[1,9]:

$$\eta_p = \frac{w_d}{w_{tot}} \quad (4)$$

where η_p represents propulsive efficiency, w_{tot} total mechanical work and w_d mechanical work to overcome drag force.

Eq. (4) can be detailed as[10]:

$$\eta_p = \frac{w_d}{w_d + w_k} \quad (5)$$

where w_d represents mechanical work used beneficially to overcome drag, w_k mechanical work lost in giving water a kinetic energy change. Using the MAD-system, η_p can be measured as[10]:

$$\eta_p = \frac{v^3 free}{v^3 MAD} \quad (6)$$

Recently it was reported η_p close to 0.65–0.81 range (mean of 0.73) for expert swimmers having a sprint v of 1.64 m s^{-1}.[11] Meanwhile, highly trained triathletes have lower η_p (mean of 0.44 ± 0.03).[12]

Combining Eqs. (3) and (4):

$$C = \left(\frac{w_{tot}}{\eta_p}\right) \eta_o^{-1} \quad (7)$$

Therefore, the swimmer's technical ability (the subject propelling efficiency plus the capability to overcome drag) and the overall efficiency affect strongly the C at a given v.[1]

One of the main goals of Sports Biomechanics is to characterise the motor pattern of practitioners and to improve its efficiency in order to enhance performance. In competitive swimming, performance is related to the energetic profile of the swimmer (Eq. (2)) and his technique level (Eq. (5)). It is clear there exist significant relationships between the bioenergetical profile, biomechanical characteristics and swimming performance. The intervention in such constrains in order to improve performance is defined as a "biophysical intervention".

The aim of this paper was to perform an update of the "state of the art" about the relationships between performance, energetics and biomechanics in competitive swimming. The purpose was to describe as much as possible the relationships in all four competitive strokes. It must be stressed that the percentage of citations throughout the manuscript, according to swim strokes evaluated, is somewhat proportional to the one existing in the literature.

2. Relationships between segmental kinematics and center of mass kinematics

A competitive swimmer tries to travel a given distance as fast as possible. So, mean swimming velocity is the best measure for swimming performance[13,14]:

$$\bar{v} = SL \cdot SF \quad (8)$$

where v represents mean swimming velocity, SL stroke length and SF stroke frequency.

The relationship between SL, SF, v and performance according to the event swam (race distance and stroke technique) is one of the major points of interests in biomechanical research. For a given distance and gender, Freestyle is the fastest stroke, followed by Butterfly, Backstroke and Breaststroke.[14–16] Throughout an event, the decrease of v is related to the decrease of SL in all swim strokes.[14,17] So, if a swimmer does not have a long SL, there is less latitude for "shorting" it and a great dependence on SF to swim faster.[13] Regarding the spatial–temporal parameters in 100 m[18,19] and in the 200 m[19] distances, at Freestyle high-level swimmers presented higher and more stable data throughout the race. Nevertheless, an intra-individual $SF - v$ curve is adopted.[14]

For inter-lap change, both genders demonstrated a "zig-zag" pattern for SF, but more pronounced in male swimmers.[20] SF achieved the maximum during the last lap in both genders.[20] However, SF variability was lower in Front Crawl than in Backstroke and in Olympic swimmers than in national level swimmers.[21]

Comparing race distances, ranging from 100 m to 1500 m[13,14] or swim paces from 50 m to 200 m[22] and from

50 m to 400 m,[23] in longer events, all stroke parameters had a tendency to decrease. When evaluating lower distance ranges (100 m versus 200 m) some researchers described contradictory results. Chollet et al.[24] showed that in high-level swimmers, in the four swim strokes, *SF* decreased from 100 m to 200 m, but *SL* did not changed between the event in Backstroke and Front Crawl. *SL* decreased from 100 m to 200 m in Butterfly, while increased in Breaststroke.[24] According to competitive level, for a given event, high-level swimmers present increased v and *SL* than lower-level swimmers.[14–16,22,23]

Increases or decreases in v are determined by combined increases or decreases in *SF* and *SL*, respectively.[2,11,14,25] Experimental data reported polynomial relationships between v and *SF*, as well as, between v and *SL*.[2,26–28] Moreover, partial correlations between v and *SF* controlling the effect of the *SL* and between v and *SL* controlling the effect of *SF* were positive and significant in all swimming strokes.[2] The non-linear relationship may have two explanations: (i) the decline in v and the changes in *SF* and *SL* combination, reflects the development of local fatigue, leading to a reduction in mechanical power output and thereby both v and *SF* decrease[11,29]; (ii) neuromuscular activation of several muscles in a multi-segment and multi-joint movement, as it is the case of swimming, follows the force–velocity relationship pattern for a single joint system. In this sense, in order to achieve a given output, an optimal number of motor units must be recruited.[30] Indeed, for every combination of participant and form of locomotion considered, the relationships of *SF* versus v and *SL* versus v had the same basic characteristics.[31]

High stroke index (*SI*) values were strongly associated with a low *C*.[32] In this sense, *SI* can also be used as overall swimming efficiency estimation. *SI* is computed as:

$$SI = SL \cdot \bar{v} \tag{9}$$

Predictability of VO_2max at Freestyle increased significantly when *SI* was included in the multiple regression analysis of a 386.8 m swim.[32] *SI* was higher in international level swimmers than in national level ones in all swim strokes.[33] Freestyle has the highest *SI*, followed by Backstroke, Butterfly and Breaststroke.[33] *SI* decreased from longer to shorter events.[33] In all events, *SI* is higher in male than female swimmers, independently of their competitive level.[33] Nevertheless, *C* and *SI* are dependent from v. Statistically this is considered as a multicolinearity phenomena, imposing some limitations to *SI* interpretation.[29]

The study of the intra-cyclic variation of the horizontal velocity of the center of mass (*dV*) within a stroke cycle is a feasible way to analyse the overall swimmers mechanics. *dV* analysis allows the: (i) identification of critical events in different phases of the cycle; (ii) collection of relevant data for practitioners; and (iii) the discrimination of swimmer's competitive level. *dV* can be computed as:

$$dV = \frac{\sqrt{\sum_i (v_i - \bar{v})^2 F_i / n}}{\sum_i v_i F_i / n} 100 \tag{10}$$

where *dV* represents intra-cyclic variation of the horizontal velocity of the center of mass, v mean swimming velocity, v_i instant swimming velocity, F_i absolute frequency and n is the number of observations.

Comparing the *dV* between the four strokes, Butterfly and Breaststroke present a higher variation than Freestyle and Backstroke when measured with mechanical methods[34] or image-digitise methods.[35] Swim strokes with higher intra-cyclic variations of mechanical body impulse also have higher *dV*. Females generally had a lower *dV* than male swimmers.[36,37] Gender differences are related to anthropometric parameters and mechanical power output.[37]

The relationship between *dV* and v is a conflicting issue among researchers: (i) there is no interplay between *dV* and v[37,38]; (ii) decreases of the *dV* are associated with v increases[36,39,40]; (iii) increases of the *dV* are associated with the acceleration capacity of elite swimmers[22]; and (iv) a better adjustment of 2nd order polynomial function is considered, where increasing v promoted a *dV* increasing up to a given value and then a decrease.[35] It can be hypothesised that the positive relationship may be frequent in shorter events, while negative ones happen in longer events. However, the non-linear relationship is also described in regular bases for human terrestrial locomotion techniques.[41]

The v is also influenced by mode of inter-limb coordination (arm-stroke phases, legs and breathing). Inter-limb coordination is assessed by the time gap between the: (i) propulsion of the two arms, in alternated strokes, and is called as index of coordination (*IdC*)[18,42]; (ii) arm and leg propulsion, in simultaneous strokes and is defined as total time gap (*TTG*).[23]

For Freestyle and Backstroke, when *IdC* is: (i) lower than 0%, is called “catch-up”; (ii) equal to 0%, is called “opposition”; and (iii) higher than 0%, is called “superposition”. For Breaststroke and Butterfly stroke, arm–leg coordination is defined by the *TTG* (which is the sum of the different time gaps between arm and leg actions). A recent study showed that the change between v and coordination also followed a polynomial relationship as other stroke parameters.[28]

IdC/*TTG* is influenced by: (i) environmental constraints, e.g., active drag and v[38,43]; (ii) task constraints, e.g., pace or *SF* imposed, goal, instruction or rules of the task[43,44]; and (iii) organismic constraints, e.g., the swimmers speciality,[43,44] competitive level,[43,44] anthropometric or disability characteristics[43–45] and gender.[18,43,46]

For elite swimmers, high active drag at high v induces a high *IdC*. With decreasing v, swimmers tend to adopt a lower *IdC* (catch-up coordination) or higher *TTG*.[18,23,37,47] High-level swimmers are characterised by high and more stable *IdC* (superposition coordination) or lower *TTG*.[18,23,43,47] Compared according to race paces, elite men showed higher

IdC than elite women.[23,37] When compared according to v, elite men have a greater catch-up coordination than elite women.[46] These differences are the result of anthropometric and muscular power differences between genders. According to race distance, *IdC* increases and *TTG* decreases with shorter events.[23,37,47] Relating *IdC* or *TTG* with *dV*, it was verified that there is no significant change in the last one with increasing swim pace.[22,37,38] It seems that adaptations of propulsive phase duration and *IdC* ensure *dV* stability.

Another approach is to understand the influence of the segmental kinematics and coordination with v and *dV*. The segmental variables that better predict the *dV* of butterfliers were mainly those related to the end of the underwater path of the arm-stroke[48,49] and the second downbeat.[49] The last phase of the underwater path with a high hand's velocity and the second downbeat are important to reduce the *dV* and increase the v. There are no published data for the remaining swimming strokes about this issue.

Another issue related to motor pattern of the limbs is the different forms of propulsive forces during steady flow (drag and lift forces) and unsteady flows (vortex). Antero-posterior patters are related to a higher contribution of propulsive drag to overall propulsion. Diagonal patters are related to a higher contribution of the lift force to overall propulsion. Nowadays, most of the relevant research about this issue is done based in: (i) experimental methods, e.g., "particle image velocimetry"[50] or (ii) numerical methods, e.g., "computer fluid dynamics".[51]

3. Relationships between energetics and swimmer's kinematics

It is consensual in the literature that $\dot{E}_{tot}$ increases with increasing v.[7,8,29,35,52–54] For a given v, and by this order, the Butterfly and the Breaststroke were the least economical strokes, the Backstroke and the Freestyle being the most economical ones.[52] However, in a recent paper for all the selected velocities, Freestyle was the most economic stroke, followed by Backstroke, Butterfly and Breaststroke.[53] An obvious distinction between alternated and simultaneous techniques is clear. This is related with the higher variation of the swimmer's impulse along the stroke cycle in each technique. Higher intra-cyclic variations of the impulse induce an additional mechanical work and, consequently, higher $\dot{E}_{tot}$.

The main question is related to the type of relationship that is established between $\dot{E}_{tot}$ and v. Some authors suggested a linear relationship[8,29,35,53,54] while others a non-linear one.[55]

Drag force is a major determinant of the *C* in swimming.[27] At constant v, the swimmer is submitted to drag force described as[56]:

$$D = Kv^2 \quad (11)$$

where *D* represents drag force, *K* a drag factor (including several other variables from fluid mechanics) and v swimming velocity. To overcome the drag force, swimmer must generate a certain amount of work per stroke (w_d):

$$w_d = D \cdot SL = K \cdot v^2 \cdot SL \quad (12)$$

The rate at which this work is produced by the swimmer equals the power necessary to overcome drag (Pd), so[11]:

$$P_d = w_d SF \quad (13)$$

Combining Eqs. (12) and (13):

$$P_d = K \cdot v^2 \cdot SL \cdot SF = K \cdot v^3 \quad (14)$$

So, the theoretically expected relationship should be cubic, once energy output run in parallel with power, and power is a function of the velocity cubed.[55]

However, several manuscripts reported a better adjustment when linear approaches were employed.[8,29,35,53,54] The explanation for this fact can be: (i) an increasing efficiency with increasing v up to a given value[35]; (ii) the small range of v analysed. Performing an infinitesimal analysis of a non-linear function in a reduced range of velocities, the linear approach fits better[8]; and (iii) the limited number of subjects evaluated.

It is reported on a regular basis that *C* increases with increasing *SF*.[2,29,57] At Backstroke, Breaststroke and Butterfly stroke, increases in *SF* were associated with increases in *C*, even when controlling v.[2] It was suggested that, a significant relationship between *SF* and η_p exists since[57]:

$$\eta_p = \left(\frac{v \cdot 0.9}{2\pi \cdot SF \cdot l} \right) \frac{2}{\pi} \quad (15)$$

where η_p represents propulsive efficiency, v swimming velocity, *SF* stroke frequency and l shoulder to hand average distance. It must be stressed that Eq. (15) can only be applied to estimate η_p in Front Crawl. This equation was obtained by modeling the arm-stroke as a paddle wheel motion, an assumption that cannot be applied to the remaining swimming techniques. Indeed, the first authors which have presented this calculation were Martin et al.[58] They have proposed a simplified calculation of the hand speed, considering the arm as a rigid segment (ignoring the elbow flexion) and having a constant underwater hand speed (ignoring the glide and catch phase).

A theoretical relationship between *C* and η_p, with *SL* is also considered[59]:

$$SL = \sqrt[3]{\frac{\eta_p \cdot w}{D \cdot SF^2}} \quad (16)$$

where *SL* represents stroke length, η_p propulsive efficiency, w mechanical work per stroke cycle, *D* drag force and *SF* stroke frequency. Nevertheless, it is not evident from experimental data that the decrease in *C* is associated with increasing *SL*.[2,7,8,57]

Another studied issue is the dependence of *C* from *dV*. If a swimmer would be able to displace with a uniform movement:

$$v = v_0 = \text{constant} \quad (17)$$

According to Eq. (14), in that case the mechanical work performed by a swimmer within every stroke is:

$$w_d = K \cdot v^3 \cdot T = w \ \text{constant} \quad (18)$$

where w_d represents mechanical work, K drag factor, v swimming velocity and T duration of a stroke cycle. Theoretically, more economical swimmers have a constant dV. However, the swimmer does not displace at a constant v. The variations in the arms, legs and trunk actions lead to v variations, within every stroke cycle:

$$v = v_0 + \Delta v(t) \quad (19)$$

In such case, the w_d can be described as a combination of Eqs. (14) and (19):

$$w_d = \int_0^T K\,[v_0 + \Delta v(t)^3]dt \quad (20)$$

A comparison between the mechanical work performed while swimming at constant v and swimming with fluctuating v is described as[60]:

$$\frac{w_d}{w_{d-\text{constant}}} = 1 + \frac{3}{T}\int_0^T \left[\frac{\Delta v(t)}{v_0}\right] dt + \frac{3}{T}\int_0^T \left[\frac{\Delta v(t)}{v_0}\right]^2 dt + \frac{1}{T}\int_0^T \left[\frac{\Delta v(t)}{v_0}\right]^3 dt \quad (21)$$

Eq. (18) shows that every change in v results in a mechanical work per stroke increase. Moreover, theoretically, changes in v of 10%, within a stroke cycle, results in an additional work demand of about 3%.[60] A higher dV leads to an increase in C in order to overcome inertia and drag force.[60,61] Whereas these movements are necessary to displace the swimmer forward, they include elements, which add up to the necessary mechanical work done by himself, affecting swimming efficiency.[61,62]

From experimental data, it can also be concluded that a higher C is related with high dV in all swimming strokes.[8,35,53,63,64] A couple of studies did not observe significant relationships at Freestyle at slow v[63] and at Breaststroke.[35] However, when partial correlations between C and dV, controlling the effect of the v, were computed, significant relationships were obtained for all techniques.[35] The non-significant relationships described above can be explained by: (i) the protocols used to assess biomechanics and energetics were applied in different moments[63]; (ii) the relationship was established between the C and the hip and not the center of mass dV's[63]; and (iii) the effect of v, which also interplays with dV, was not taken in account.[35,63] However, comprehensive knowledge about this relationship with other competitive level rather than national and/or international level swimmers is rare.

At this moment one pilot study with a single female swimmer of high-level related C with IdC at Freestyle. IdC and C were correlated with a very high-level.[65] With increasing swim pace, IdC switched from "catch-up coordination" to "opposition coordination" when reaching near the VO_2max. Nevertheless, such relationship should be evaluated in different swim strokes, with larger samples and with different competitive levels.

4. Predicting swimming performance from energetics and swimmer's kinematics

In elite swimmers, SL[18,22,44,64] and η_p[12] are higher and active drag[27] is lower when compared to other competitive levels. This can be related to a significant relationship between η_p, mechanical work per stroke cycle, drag force and stroke mechanics,[11] as described in Eq. (13).

The kinematics of elite swimmers is quite different from other competitive levels. Elite butterfliers presented a lower angle between trunk and horizontal plane; Elite backstroke's and freestylers have a symmetrical body roll; Elite breaststrokers have appropriate timing for arms and legs recovery; Elite freestylers have higher elbow position during the catch.[66]

For a given event, high-level swimmers present an increased v and SL than lower-level swimmers.[14–16,22,23] SI is also higher in international swimmers than in national level.[33] Empirical data and speculations are made that elite swimmers have a lower dV.[35,36] High-level swimmers are characterised by high and more stable IdC (superposition coordination) for alternated[18,43,44] and lower TTG for simultaneous strokes.[23,43,47]

High-level swimmers have a better capacity to maximise their energy input ($\dot{E}_{tot-max}$, VO_2max, [La$^-$] production, minimal velocity at VO_2max) than lower-level swimmers.[54] Moreover, high-level swimmers are more economical and efficient (C slope, C at a given v, η_p) than lower-level swimmers.[12,54] All this data is related to Freestyle and it seems that comprehensive knowledge to remain strokes is non-existent.

Another possibility is to develop statistical models that are able to identify the best predictors of swimming performance.[67] It is consensual that elite swimmers are more economical for a given v.[54] Several authors reported that peak VO_2 or VO_2max was the best performance predictor.[32,63] It was verified that for the 386.8 m distance the best predictors were the SL and the VO_2max corrected for lean mass.[32]

It is a recent approach to solve complex problems such as performance modeling. E.g., modeling the 400 m Freestyle performance in young male swimmers the estimation error was $7 \pm 7.8\%$ and for the 200 m Medley performance $1.7 \pm 13.3\%$.[68]

The purpose of cluster analysis is to discover a system of organising observations, for instance, subjects according to swimming performance. This is done based on the fact that members of the groups share properties in common (e.g.,

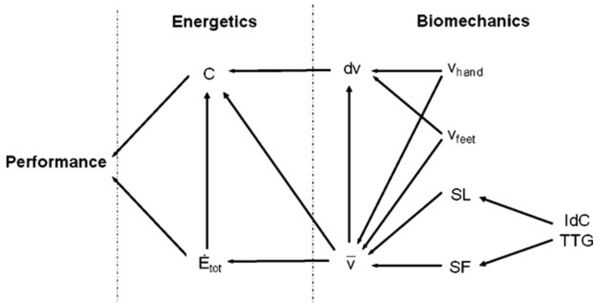

Fig. 1. The relationships between energetics, biomechanics and performance in competitive swimming. *C*: energy cost; $\dot{E}_{tot}$: energy expenditure; *dV*: intra-cyclic variation of the horizontal velocity of the center of mass; *IdC*: index of coordination; *TTG*: total time gap; *SF*: stroke frequency; *SL*: stroke length; v: mean swimming velocity; v_{hand}: hand's velocity; v_{feet}: feet's velocity.

energetic profile, biomechanics behaviour or inter-limb coordination strategies). The closest described in the literature is a research about inter-individual variability to determine different profiles for similar or different performances.[69]

5. Conclusion

The development of biomechanical models explaining the relationships established between the variables here presented can be a feasible way to promote technical evaluation, with relevant information for practitioners. From what was discussed in the previous sections, it is possible to attempt a description of the relationships between all of them (Fig. 1). Swimming performance is dependent from the energetic profile and this one from the biomechanical behaviour. C and $\dot{E}_{tot}$ have a moderate–good prediction capacity of swimming performance. On the other hand, those variables are dependent from the swimmer's technical level. An overall quantification of the swimmer's technical level can be done examining his v or *dV*. Both of them are the balanced result from propulsive and drag forces. The v and *dV* behaviour is the direct and indirect result from stroke mechanics and segmental velocities. Finally, these last ones are related to motor control phenomena as inter-limb coordination, quantified with *TTG* and *IdC*. So, the physiologic, motor control or biomechanical knowledge and approaches, once isolated, are not sufficient for enhancement swimming performance. Individual adaptations based on interacting constraints should have more emphasis in order to understand performance.

Nevertheless, important steps must be taken in the future to understand more deeply those relationships, e.g.: (i) the development of studies about swimming performance and bioenergetical profile in a large scale, including swimmers of different competitive levels, swimming techniques and gender; (ii) to explore deeply the interplay between *dV*, *IdC*/*TTG* and v in a range of speeds as large as possible; (iii) to understand the relationships between *SF* and *SL* with segmental kinematics; (iv) to bring new highlights about the role of neuromuscular activity in the segmental kinematics; (v) to perform meta-analysis about performance, energetics and biomechanics; (vi) to study the interplay between performance, energetics and biomechanics based on longitudinal data; and (vii) analyse individual adaptations instead of pooled data to understand swimming performance according to interacting constraints.

As practical implications, it can be concluded that: (i) swimming performance is strongly related to energetic profile and this one to technical level; (ii) high-level swimmers are more economical; (iii) lower speed fluctuation, higher stroke length and superposition arm's coordination are important to increase swimming economy at given swimming velocity; and (iv) high segmental velocities in the most propulsive phases of the stroke cycle and lower drag force in the less propulsive ones are determinants of higher swimming velocity and lower speed fluctuation.

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References

1. Zamparo P. Effects of age and gender on the propelling efficiency of the arm stroke. *Eur J Appl Physiol* 2006;**97**:52–8.
2. Barbosa TM, Fernandes RJ, Keskinen KL, et al. The influence of stroke mechanics into energy cost of elite swimmers. *Eur J Appl Physiol* 2008;**103**:139–49.
3. Rodríguez F. Cardiorespiratory and metabolic fiel testing in swimming and water polo: from physiological concepts to practical methods. In: Keskinen K, Komi P, Hollander AP, editors. *Biomechanics and medicine in swimming VIII*. Jyväskylä: Gummerus Printing; 1999. p. 219–26.
4. di Prampero P, Pendergast D, Wilson D, et al. Blood lactic acid concentrations in high velocity swimming. In: Eriksson B, Furberg B, editors. *Swimming medicine IV*. Baltimore: University Park Press; 1978. p. 249–61.
5. Thevelein X, Daly D, Persyn U. Measurement of total energy use in the evaluation of competitive swimmers. In: Bachl N, Prakup L, Suckert R, editors. *Current topics in sports medicine*. Wien: Urban & Schawarzenerg; 1984. p. 668–76.
6. Schmidt-Nielsen K. Locomotion: energy cost of swimming, flying and running. *Science* 1972;**177**:222–8.
7. Pendergast D, Zamparo P, di Prampero D, et al. Energy balance of human locomotion in water. *Eur J Appl Physiol* 2003;**90**:377–86.
8. Barbosa TM, Keskinen KL, Fernandes RJ, et al. Energy cost and intracyclic variations of the velocity of the centre of mass in butterfly stroke. *Eur J Appl Physiol* 2005;**93**:519–23.
9. Webb P. The swimming energetics of trout. Oxygen consumption and swimming efficiency. *J Exp Biol* 1971;**55**:521–40.
10. Toussaint HM, Truijens MJ. Biomechanical aspects of peak performance in human swimming. *Anim Biol* 2005;**55**:17–40.
11. Toussaint H, Carol A, Kranenborg H, Truijens M. Effect of fatigue on stroking characteristics in an arms-only 100-m front-crawl race. *Med Sci Sports Exerc* 2006;**38**:1635–42.
12. Toussaint H. Differences in propelling efficiency between competitive and triathlon swimmers. *Med Sci Sports Exerc* 1990;**22**:409–15.

13. Craig A, Pendergast D. Relationships of stroke rate, distance per stroke and velocity in competitive swimming. *Med Sci Sports Exerc* 1979;**11**:278–83.
14. Craig A, Skehan P, Pawelczyk J, et al. Velocity, stroke rate and distance per stroke during elite swimming competition. *Med Sci Sports Exerc* 1985;**17**:625–34.
15. Kennedy P, Brown P, Chengalur S, et al. Analysis of male and female olympic swimmers in the 100-meter events. *J Sports Biomech* 1990;**6**:187–97.
16. Chengalur S, Brown P. An analysis of male and female olympic swimmers in the 200 m events. *Can J Spt Sci* 1992;**17**:104–9.
17. Hay J, Guimarães A. A quantitative look at swimming biomechanics. *Swimming Tech* 1983;**20**:11–7.
18. Seifert L, Chollet D, Chatard JC. Kinematic change during a 100-m front crawl: effects of performance level and gender. *Med Sci Sports Exerc* 2007;**39**:1784–93.
19. Sidney M, Delhaye B, Baillon M, et al. Stroke frequency evolution during 100 m and 200 m events front crawl swimming. In: Keskinen K, Komi P, Hollander AP, editors. *Biomechanics and medicine in swimming VIII*. Jyväskylä: Gummerus Printing; 1999. p. 71–5.
20. Letzelter H, Freitag W. Stroke length and stroke frequency variations in men's and women's 100m freestyle swimming. In: Hollander AP, Huijing PA, de Groot G, editors. *Biomechanics and medicine in swimming*. Illinois: Human Kinetics Publishers; 1983. p. 315–22.
21. Hellard P, Dekerle J, Avalos M, et al. Kinematic measures and stroke rate variability in elite female 200-m swimmers in the four swimming techniques: Athens 2004 Olympic semi-finalists and French National 2004 Championship semi-finalists. *J Sports Sci* 2008;**26**:35–46.
22. Leblanc H, Seifert L, Tourny-Chollet C, et al. Intra-cyclic distance per stroke phase, velocity fluctuation and acceleration time ratio of a breaststroker's hip: a comparison between elite and non elite swimmers at different race paces. *Int J Sports Med* 2007;**28**:140–7.
23. Seifert L, Boulesteix L, Chollet D, et al. Differences in spatial–temporal parameters and arm-leg coordination in butterfly stroke as a function of race pace, skill and gender. *Hum Mov Sci* 2008;**27**:96–111.
24. Chollet D, Pelayo P, Tourney C, et al. Comparative analysis of 100 m and 200 m events in the four strokes in top level swimmers. *J Hum Mov Studies* 1996;**31**:25–37.
25. Kjendlie PL, Haljand R, Fjortoft O, et al. Stroke frequency strategies of international and national swimmers in 100-m races. In: Vilas-Boas JP, Alves F, Marques A, editors. *Biomechanics and medicine in swimming X, Suppl. 2*. Porto: Portuguese Journal of Sport Science; 2006. p. 52–4.
26. Keskinen KL, Komi PV. The stroking characteristics in four different exercises in freestyle swimming. In: de Groot G, Hollander AP, Huijing P, van Ingen Schenau G, editors. *Biomechanics XI-B*. Amsterdam: Free University Press; 1988. p. 839–43.
27. Pendergast DR, Capelli C, Craig AB, et al. Biophysics in swimming. In: Vilas-Boas JP, Alves F, Marques A, editors. *Biomechanics and medicine in swimming X, Suppl. 2*. Porto: Portuguese Journal of Sport Science; 2006. p. 185–9.
28. Seifert L, Chollet D. Modelling spatial–temporal and coordinative parameters in swimming. *J Sci Med Sport* 2008. Epub ahead of print.
29. Barbosa TM, Keskinen KL, Fernandes RJ, et al. Relationship between energetic, stroke determinants and velocity in butterfly stroke. *Int J Sports Med* 2005;**26**:841–6.
30. Cabri J, Annemans L, Clarys J, et al. The relation of stroke frequency, force and EMG in front crawl tethered swimming. In: Ungerechts B, Wilke K, Reischle K, editors. *Swimming science V*. Illinois: Human Kinetics Books; 1988. p. 183–9.
31. Hay J. Cycle rate, length, and speed of progression in human locomotion. *J Appl Biomech* 2002;**18**:257–70.
32. Costill D, Kovaleski J, Porter D, et al. Energy expenditure during front crawl swimming: predicting success in middle-distance events. *Int J Sports Med* 1985;**6**:266–70.
33. Sánchez J, Arellano R. Stroke index values according to level, gender, swimming style and event race distance. In: Gianikellis K, editor. *Proceedings of the XXth international symposium on biomechanics in sports*. Cáceres: Universidad de Extremadura; 2002. p. 56–9.
34. Craig AB, Termin B, Pendergast DR. Simultaneous recordings of velocity and video during swimming. In: Vilas-Boas JP, Alves F, Marques A, editors. *Biomechanics and medicine in swimming X, Suppl. 2*. Porto: Portuguese Journal of Sports Sciences; 2006. p. 32–5.
35. Barbosa TM, Lima F, Portela A, et al. Relationships between energy cost, swimming velocity and speed fluctuation in competitive swimming strokes. In: Vilas-Boas JP, Alves F, Marques A, editors. *Biomechanics and medicine in swimming X, Suppl. 2*. Porto: Portuguese Journal of Sports Sciences; 2006. p. 28–9.
36. Manley P, Atha J. Intra-stroke velocity fluctuations in paces breaststroke swimming. In: MacLaren D, Reilly T, Lees A, editors. *Biomechanics and medicine in swimming VI*. London: E & FN Spon; 1992. p. 151–60.
37. Schnitzler C, Seifert L, Ernwein V, et al. Arm coordination adaptations assessment in swimming. *Int J Sports Med* 2008;**29**:480–6.
38. Seifert L, Toussaint H, Schnitzler C, et al. Effect of velocity increase on arm coordination, active drag and intra-cyclic velocity variations in front crawl. In: Nomura T, Ungerechts B, editors. *1st international scientific conference of aquatic space activities*. Tsukuba: University of Tsukuba; 2008. p. 254–9.
39. Togashi T, Nomura T. A biomechanical analysis of the swimmer using the butterfly stroke. In: MacLaren D, Reilly T, Lees A, editors. *Biomechanics and medicine in swimming VI*. London: E & FN Spon; 1992. p. 87–91.
40. Takagi H, Sugimoto S, Nishijima N, et al. Differences in stroke phases, arm–leg coordination and velocity fluctuation due to event, gender and performance level in breaststroke. *Sports Biomech* 2004;**3**:15–27.
41. Minetti A. The three modes of terrestrial locomotion. In: Nigg B, MacIntosh B, Mester J, editors. *Biomechanics and biology of movement*. Illinois: Human Kinetics; 2000. p. 67–78.
42. Chollet D, Chalies S, Chatard JC. A new index of coordination for the crawl: description and usefulness. *Int J Sports Med* 2000;**21**:54–9.
43. Seifert L, Chollet D. Inter-lib coordination and contrains in swimming: a review. In: Beaulieu NP, editor. *Physical activity and children: new research*. New York: Nova Science Publishers; 2008. p. 65–93.
44. Seifert L, Chollet D, Rouard A. Swimming constrains and arm coordination. *Hum Mov Sci* 2007;**26**:68–86.
45. Satkunskiene D, Schega L, Kunze K, et al. Coordination in arm movements during crawl stroke with locomotor disability. *Hum Mov Sci* 2005;**24**:54–65.
46. Seifert L, Boulesteix L, Chollet D. Effect of gender on the adaptation of arm coordination in front crawl. *Int J Sports Med* 2004;**25**:217–23.
47. Chollet D, Seifert L, Leblanc H, et al. Evaluation of arm–leg coordination in flat breaststroke. *Int J Sports Med* 2004;**25**:486–95.
48. Silva AJ, Alves F. Determinant factors to variation in Butterfly velocity. In: Sanders R, Hong Y, editors. *Applied proceedings of the XVIII international symposium on biomechanics in sports–swimming*. Edinburgh: Faculty of Education of the University of Edinburgh; 2000. p. 73–4.
49. Barbosa TM, Fernandes RJ, Morouço P, et al. Predicting the intra-cyclic variation of the velocity of the centre of mass from segmental velocities in Butterfly stroke: a pilot study. *J Sports Sci Med* 2008;**7**:201–9.
50. Kamata E, Miwa T, Matsuuchi K, et al. Analysis of sculling propulsion mechanism using two-components particle image velocimetry. In: Vilas-Boas JP, Alves F, Marques A, editors. *Biomechanics and medicine in swimming X, Suppl. 2*. Porto: Portuguese Journal of Sports Sciences; 2006. p. 50–2.
51. Rouboa A, Silva A, Leal L, et al. The effect of swimmer's hand/forearm acceleration on propulsive forces generation using computational fluid dynamics. *J Biomech* 2006;**39**:1239–48.
52. Holmér I. Physiology of swimming man. *Acta Phys Scand* 1974;**407**:1–55.
53. Barbosa TM, Fernandes RJ, Keskinen KL, et al. Evaluation of the energy expenditure in competitive swimming strokes. *Int J Sports Med* 2006;**27**:894–9.
54. Fernandes RJ, Billat V, Cruz A, et al. Does net energy of swimming affect time to exhaustion at the individual's maximal

oxygen consumption velocity? *J Sports Med Phys Fitness* 2006;**46**: 373–80.

55. Wakayoshi K, D'Acquisto J, Cappaert JM, et al. Relationship between oxygen uptake, stroke rate and swimming velocity in competitive swimming. *Int J Sports Med* 1995;**16**:19–23.
56. Toussaint H, Roos P, Kolmogorov S. The determination of drag in front crawl swimming. *J Biomech* 2004;**37**:1655–63.
57. Zamparo P, Pendergast D, Mollendorf J, et al. An energy balance of front crawl. *Eur J Appl Physiol* 2005;**94**:134–44.
58. Martin RB, Yeater RA, White MK. A simple analytical model for the crawl stroke. *J Biomech* 1981;**14**:539–48.
59. Toussaint H, Hollander AP. Mechanics and energetics of front crawl swimming. In: Miyashita M, Mutoh Y, Anderson AB, editors. *Medicine and science in aquatic sports*. Basel: Karger; 1994. p. 107–16.
60. Nigg B. Selected methodology in biomechanics with respect to swimming. In: Hollander AP, Huijing P, de Groot G, editors. *Biomechanics and medicine in swimming*. Illinois: Human Kinetics Books; 1983. p. 72–80.
61. Costill D, Lee G, D'Acquisto L. Video-computer assisted analysis of swimming technique. *J Swimming Res* 1987;**3**:5–9.
62. Kornecki S, Bober T. Extreme velocities of a swimming cycle as a technique criterion. In: Eriksson B, Furberg B, editors. *Swimming medicine IV*. Baltimore: University Park Press; 1978. p. 402–7.
63. Alves F, Gomes-Pereira J, Pereira F. Determinants of energy cost of front crawl and backstroke swimming and competitive performance. In: Troup JP, Hollander AP, Strasse D, Trappe SW, Cappaert JM, Trappe TA, editors. *Biomechanics and medicine in swimming VII*. London: E & FN Spon; 1996. p. 185–92.
64. Vilas-Boas JP. Speed fluctuations and energy cost of different breaststroke techniques. In: Troup JP, Hollander AP, Strasse D, Trappe SW, Cappaert JM, Trappe TA, editors. *Biomechanics and medicine in swimming VII*. London: E & FN Spon; 1996. p. 167–71.
65. Morais P, Vilas-Boas JP, Seifert L, et al. Relationship between energy cost and the index of coordination in front crawl—a pilot study. *J Sport Sci* 2008;**26**:11.
66. Cappaert J. Biomechanics of swimming analysed by three-dimensional techniques. In: Keskinen K, Komi P, Hollander AP, editors. *Biomechanics and medicine in swimming VIII*. Jyväskylä: Gummerus Printing; 1999. p. 141–5.
67. Chatard JC, Lavoie JM, Lacour J. Analysis of determinants of swimming economy in front crawl. *Eur J Appl Physiol* 1990;**61**:88–92.
68. Silva AJ, Costa AM, Oliveira PM, et al. The use of neural network technology to model swimming performance. *J Sports Sci Med* 2007;**6**:117–25.
69. Button C, Davids K, Schollhorn W. Coordination profiling of movement systems. In: Davids K, Bennett S, Newel Kl, editors. *Movement system variability*. Illinois: Human Kinetics Publishers; 2006. p. 133–52.