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Breaststroke swimmers moderate internal work increases toward the highest stroke frequencies

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ABSTRACT

A model to predict the mechanical internal work of breaststroke swimming was designed. It allowed us to explore the frequency–internal work relationship in aquatic locomotion. Its accuracy was checked against internal work values calculated from kinematic sequences of eight participants swimming at three different self-chosen paces. Model predictions closely matched experimental data (0.58 ± 0.07 vs $0.59 \pm 0.05 \text{ J kg}^{-1} \text{ m}^{-1}$; $t(23) = -0.30$, $P = 0.77$), which was reflected in a slope of the major axis regression between measured and predicted total internal work whose 95% confidence intervals included the value of 1 ($\beta = 0.84$, $[0.61, 1.07]$, $N = 24$). The model shed light on swimmers ability to moderate the increase in internal work at high stroke frequencies. This strategy of energy minimization has never been observed before in humans, but is present in quadrupedal and octopodal animal locomotion. This was achieved through a reduced angular excursion of the heaviest segments ($7.2 \pm 2.9^\circ$ and $3.6 \pm 1.5^\circ$ for the thighs and trunk, respectively, $P < 0.05$) in favor of the lightest ones ($8.8 \pm 2.3^\circ$ and $7.4 \pm 1.0^\circ$ for the shanks and forearms, respectively, $P < 0.05$). A deeper understanding of the energy flow between the body segments and the environment is required to ascertain the possible dependency between internal and external work. This will prove essential to better understand swimming mechanical cost determinants and power generation in aquatic movements.

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1. Introduction

While the external work (W_{ext}) refers to the work required to accelerate the body center of mass (BCOM), the internal work (W_{int}) reflects the work needed to accelerate a segment relative to the BCOM. Calculation of W_{int} is paramount to physiologists and biomechanicists. Not only does it provide a measure of internal exertion, but also allows an in-depth examination of the efficiency cascade of locomotion and the limit of the musculoskeletal system. For instance, remarkably deep insights have been gained into terrestrial gaits, unveiling the mechanical determinants of step frequency (Cavagna and Franzetti, 1986), cost of transport (Formenti et al., 2005; Minetti et al., 1994a, 1993), and gait control (Minetti et al., 1994b). It also proved clinically useful in the study of pathological gait, providing a new understanding of the role of segmental impairments in the resulting decreased economy

(Detrembleur et al., 2003), and offering treatment directives in rehabilitation programs (McGibbon et al., 2001).

Despite its scientific relevance on land, such an approach remains poorly explored in human aquatic locomotion. To our knowledge, only Zamparo et al. (2002, 2006, 2005) computed the internal power (i.e., the amount of internal work done per unit of time) while kicking the leg and swimming the front crawl. They found out that arm stroke internal power was rather small, contrary to the leg that occupied a great fraction (80–85%) of the total internal power. This finding was of great value since it provided a quantitative mechanical explanation of the suboptimal hydraulic efficiency of front crawl swimming (Zamparo et al., 2005).

It is striking to note how often studying the front crawl is preferred to the breaststroke in studies of aquatic locomotion. Yet breaststroke, although much less economical, possesses unique features (e.g., locomotion mainly powered by the synchronous action of the lower limbs, erecting trunk, glide phase) that are likely to make the situation quite different compared to front crawl. It can thus serve as an interesting basis to broaden our understanding of aquatic movement performance.

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The first aim of the present study was to provide a simple predictive equation to estimate the mechanical internal work of breaststroke swimming, and to check its accuracy against internal work values measured from kinematic sequences captured at various stroke frequencies. In a second step, it allowed us to explore the frequency–internal work relationship in swimming, and contrast aquatic vs terrestrial locomotion.

2. Material and methods

2.1. Internal work predictive equation

From the 2D analysis of Minetti (1998), mechanical internal work (in $\text{J kg}^{-1} \text{m}^{-1}$) during terrestrial locomotion can be predicted by the following equation:

$$W_{\text{int}} = qvf, \quad (1)$$

where q reflects the inertial properties of the moving segments, v is the average progression speed (m s^{-1}) and f the stride frequency (Hz). Later, Zamparo et al. (2002) rightly related the term v when front crawl kicking to the speed of the vertical movements of the legs. Here a similar formalism was adopted for the breaststroke distinguishing the upper and lower body anteroposterior motions. The choice to stick to a 2D approach was justified on several grounds: (1) unpublished results of internal work partitioning from our group revealed the preponderance of the work done in the sagittal plane, notably along the anteroposterior axis; (2) 3D terms would introduce more complex equations; the goal was to keep the model simple; (3) extremities can intuitively be conceived as sliding back and forth along an axis parallel to the surface. For the sake of simplicity this resembles two slider–crank mechanisms, which convert rotatory into reciprocating motion (Fig. 1): pistons (limb extremities) are animated from the center of the crankshaft (hip joint) through the cranks (thighs and trunk) and the connecting rods (lower legs and arms). Building on that analogy, the term v for the lower body motion was taken as

$$v = 2x_{\text{lo}} \frac{f}{d_{\text{lo}}}, \quad (2)$$

given:

$$d_{\text{lo}} = 1 - t_{\text{glide,lo}}f, \quad (3)$$

where x_{lo} is the anteroposterior distance covered by the feet during half a cycle; $t_{\text{glide,lo}}$, the time the lower body spent gliding. The duty factor d_{lo} therefore expressed the fraction of the cycle duration during which the lower body is in motion relative to the BCOM. Without that correction, v would be greatly underestimated as leg glide—during which no W_{int} is done since legs do not move relative to the BCOM—would be included in the calculation. From Eqs. (2) and (3), the internal work done by the lower body is now written:

$$W_{\text{int,lo}} = 2q_{\text{lo}}x_{\text{lo}} \frac{f^2}{d_{\text{lo}}}. \quad (4)$$

Likewise, the internal work done by the upper body is given by:

$$W_{\text{int,up}} = 2q_{\text{up}}x_{\text{up}} \frac{f^2}{d_{\text{up}}} \quad (5)$$

and

$$d_{\text{up}} = 1 - t_{\text{glide,up}}f, \quad (6)$$

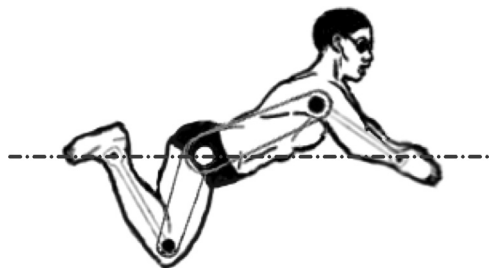


Fig. 1. A breaststroke swimmer modeled as two slider–crank mechanisms. Extremities are sliding back and forth along an axis (dash line) parallel to the surface, and animated from the center of the crankshaft (hip joint) through the cranks (thighs and trunk) and the connecting rods (lower legs and arms).

where x_{up} refers to the anteroposterior displacement of the hands during half a cycle, and $t_{\text{glide,up}}$ is the time the upper body spent gliding. Total internal work was calculated as the sum of $W_{\text{int,lo}}$ and $W_{\text{int,up}}$. To isolate q_{lo} and q_{up} , Eqs. (4) and (5) can be rearranged as

$$q_{\text{lo}} = \frac{W_{\text{int,lo}}}{2x_{\text{lo}} \frac{f^2}{d_{\text{lo}}}} \quad (7)$$

and

$$q_{\text{up}} = \frac{W_{\text{int,up}}}{2x_{\text{up}} \frac{f^2}{d_{\text{up}}}}. \quad (8)$$

2.2. Participants and experimental validation protocol

Eight elite Norwegian swimmers, four females (19.3 ± 6.1 years; 1.69 ± 0.04 m; 65.6 ± 5.2 kg) and four males (25.0 ± 3.1 years; 1.90 ± 0.03 m; 88.0 ± 2.5 kg) volunteered to participate in this study. Before participation, they signed informed consent forms approved by the Norwegian national ethics committee. Tests took place in a 25-m indoor swimming pool. After a 15-min warm-up consisting of low- to moderate-intensity aerobic swimming, each participant swam three 25-m breaststroke laps at different self-chosen paces and stroke frequencies interspersed with 2-min rest periods.

2.3. Kinematic analysis

Kinematic data were obtained by tracking 3D marker positions using the motion capture technique (Qualisys Track Manager 2.6, Qualisys, Gothenburg, Sweden). Ten cameras (Oqus 3 and 4 series, 100 Hz) were placed in waterproof cases, six of them mounted just below the water surface and four standing on tripods at the bottom of the pool. They were calibrated using a wand with two markers (inter-point distance 749.5 mm), moved in a volume of about 37.5 m^3 , 10 m (X; pointing horizontally and in the sense of forward motion) \times 2.5 m (Y; horizontally and laterally towards the left of the swimmer) \times 1.5 m (Z; vertically and dorsally) so that each camera covered at least 800–1000 points. The root mean square reconstruction error for position was 1.6 mm.

The body was modeled as 13 rigid segments (feet, shanks, thighs, hands, forearms, upper arms, and trunk) according to de Leva (1996). Twenty-seven retro-reflective markers—19 mm in diameter, developed to suit underwater usage—were thus positioned on each body side as follows: acromion, lateral epicondyle, great trochanter, lateral femoral condyle, calcaneus, lateral malleolus, first and fifth metatarsophalangeal joint, a three-marker cluster on the hand (dorsal wrist, second and fifth metacarpophalangeal joints). To later reconstruct segment six degrees of freedom, four additional four-marker clusters were placed laterally on the forearm, upper arm, thigh and shank according to the directions provided by Cappozzo et al. (1997).

MATLAB R2013a (The MathWorks, Inc. Natick, MA, USA) was used for data processing. Marker coordinates were filtered using the singular spectrum analysis (Alonso et al., 2005): the fourth main components were retained for signals reconstruction and a window length of $l/10$ was chosen, with l being the length of the time series (Ishimura and Sakurai, 2012). One stroke cycle per participant was analyzed in the middle of the pool when swimming speed is stabilized. A cycle was defined between two consecutive starting backward movements of the heels. Respective segment masses, center of mass (COM) locations and moments of inertia were estimated for both male and females from de Leva's (1996) anthropometric tables. The coordinates of the BCOM were determined for each frame from the masses and the instantaneous positions of each of the 13 segments COMs.

2.4. Mechanical internal work calculation

BCOM velocity was calculated as the first derivative of its position with respect to time. The linear velocity of the COM of each segment relative to the BCOM was obtained in the same way, from differentiation of the difference between the absolute coordinates of segment COM and those of the BCOM. Each set of axes was made orthonormal (correcting unit floating axes by two successive cross-products), and defined a local, right-handed reference frame centered on the segment COM (Cappozzo et al., 2005). Segment 3D orientation in space was represented by unit quaternions (a way to parameterize rigid body attitude that does not suffer from singularities, unlike traditional Euler angles), and angular velocity components derived from quaternion rates (Diebel, 2006). At a later stage, segment angles were projected onto the sagittal plane, the minimum and maximum values determined, and the angular excursion calculated.

The internal energy level (E_{int}) of a system of n segments of mass m at instant t can be expressed as

$$E_{\text{int}}(t) = \sum_{i=1}^n \left(\underbrace{\frac{1}{2} m_i (v_{xti}^2 + v_{yti}^2 + v_{zti}^2)}_{E_{k,t}} + \underbrace{\frac{1}{2} (I_{xi} \omega_{xti}^2 + I_{yi} \omega_{yti}^2 + I_{zi} \omega_{zti}^2)}_{E_{k,r}} \right) \quad (9)$$

where v is the linear velocity of the COM of the i th segment relative to the BCOM; ω and I , the angular velocity and moment of inertia of the i th segment around the principal axes (x , longitudinal axis; y , transverse axis; z , sagittal axis). The first term of the sum refers to the translational kinetic energy, while the second yields the rotational kinetic energy (respectively, $E_{k,t}$ and $E_{k,r}$).

In order to yield realistic internal work values, kinetic energy transfers should be included in the analysis (Willems et al., 1995). Accordingly, kinetic energy curves were summed among adjacent segments within a same limb only in order to exclude energy transfers through the BCOM from one limb to another that are not likely to occur. Increments in the resulting traces were then summed, and yielded the positive work to accelerate the segments relative to the BCOM. The total internal work W_{int} was expressed as J per kg of body mass and unit distance (m) traveled, a customary unit for the mechanical cost of locomotion.

2.5. Statistical analysis

STATA 12 (StataCorp, Inc., College Station, TX, USA) was used for all analyses, and the critical significance level set at 0.05. Data are expressed as means \pm SD. Normal Gaussian distribution was checked for all variables by the Shapiro–Wilk test prior to analysis. The mean measured internal work was compared with the mean predicted internal work using the Student's paired t -test. Whether the theoretical predictions and the measurements deviated from identity was assessed with a major axis regression. The model was considered perfectly accurate if the 95% confidence interval of the slope β of the major axis included a value of 1 (Rayner, 1985). Differences in angular excursion between the lowest and highest frequencies were tested for a statistical difference from 0 using one-sample t -tests.

3. Results

Stroke frequencies measured in the present study ranged from 0.50 to 0.77 Hz, corresponding to swimming speeds within the interval 0.82–1.18 m s⁻¹. Increased stroke frequency was associated with enhanced swimming speed (females: $r(10)=0.92$, $P<0.001$; males: $r(10)=0.84$, $P=0.006$). Values of internal work predicted by the model were remarkably close to the experimental data (0.58 ± 0.07 vs 0.59 ± 0.05 J kg⁻¹ m⁻¹; $t(23)=-0.30$, $P=0.77$; Fig. 2). This was reflected in a slope of the major axis regression between measured and predicted total internal work whose 95% confidence intervals included the value of 1 ($\beta=0.84$, [0.61, 1.07], $N=24$). Internal work increased linearly as stroke frequency rose (Fig. 3, upper panel). Neither duty factors d_{lo} and d_{up} ($r(22)=-0.03$, $P=0.90$; $r(22)=-0.05$, $P=0.82$, respectively; Fig. 3, second panel) nor limbs anteroposterior displacement x_{lo} and x_{up} correlated with stroke frequency ($r(22)=-0.06$, $P=0.77$; r

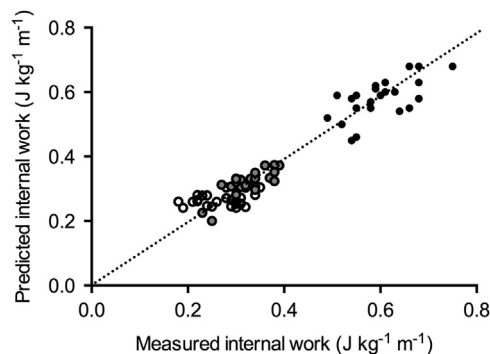


Fig. 2. Predicted against measured mechanical internal work. The dotted line is the identity line. The major axis computed for the full body predictions is not represented. Dots are individual internal work values computed from 24 kinematic sequences at various speed and frequencies (white: upper body; gray: lower body; filled: full body).

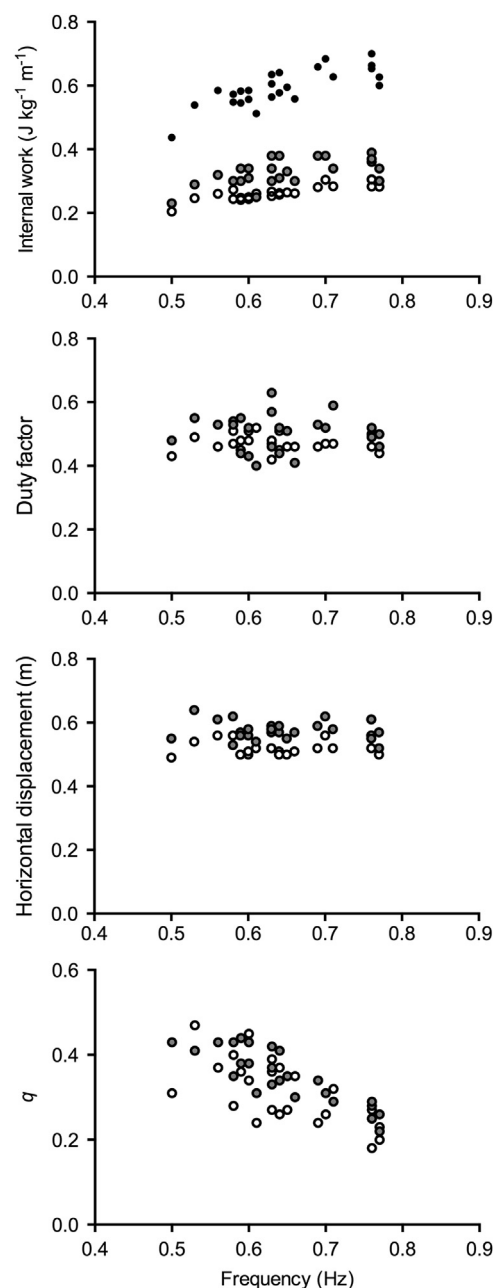


Fig. 3. The upper panel displays the measured internal work as a function of stroke frequency. The second panel reports the duty cycle values for upper and lower body. The third panel illustrates the horizontal displacements of upper and lower body, and the lower panel shows the parameter q —reflecting the inertial properties of the moving segments—obtained from (Eqs. (7) and (8)). Dot colors are as in Fig. 2.

(22)=0.08, $P=0.55$, respectively; Fig. 3, third panel), whereas q_{lo} and q_{up} correlated negatively with stroke frequency ($r(22)=-0.86$, $P<0.001$; $r(22)=-0.68$, $P<0.001$, respectively; Fig. 3, lower panel).

All segments but the upper arm exhibited significant differences in angular excursion between the laps swum at the highest frequency and those at the lowest (Fig. 4). Angular excursion was significantly increased at the shank ($8.8 \pm 2.3^\circ$, $P=0.007$) and at the forearm ($7.4 \pm 1.0^\circ$, $P=0.038$). Conversely, angular excursion was reduced at the thigh ($7.2 \pm 2.9^\circ$, $P=0.041$) and at the trunk ($3.6 \pm 1.5^\circ$, $P=0.048$).

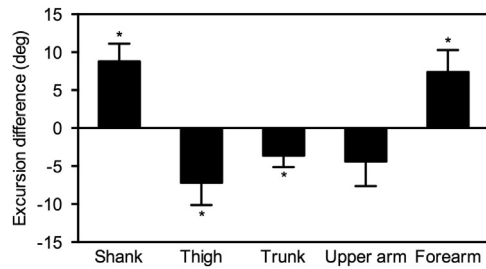


Fig. 4. Differences in segment angular excursion between the highest and lowest stroke frequencies (mean \pm SD). Positive values indicate an increased sweep angle in the vertical plane, and vice versa. Constant horizontal displacements of upper and lower body were achieved, toward the highest frequencies, through a reduction of angular excursion of the heaviest segments (thighs and trunk) in favor of the lightest ones (shanks and forearms). * Significantly different from 0 ($P < 0.05$).

4. Discussion

Our 2D model was straightforward, yet accurate in predicting changes in 3D breaststroke swimming internal work. These successful predictions suggest that motion along the mediolateral axis can safely be disregarded; the sagittal plane alone provided satisfactory information. Furthermore, modeling upper and lower body motions as two piston mechanisms was a sound approach to capture breaststroke dynamics. Linear velocities of the extremities in both breaststroke and slider–crank systems rightly reflect the speed at which the whole chain is animated. As such, hand and feet motions along the anteroposterior axis are good markers of W_{int} done during aquatic locomotion.

Our results revealed that upper and lower body had equal and constant duty cycles, and similar downward trends in the parameter q . The model can hence be made simpler setting $d_{\text{lo}} = d_{\text{up}} = 0.5$ and $q = q_{\text{lo}} = q_{\text{up}}$, and writes: $W_{\text{int}} = 4qf^2(x_{\text{lo}} + x_{\text{up}})$. The sum of the upper and lower body anteroposterior displacement being invariant (1.07 ± 0.02 m; see Fig. 3, third panel), replacing now gives: $W_{\text{int}} = 4.28qf^2$. Regressing q against f , we obtain $q = -0.72f + 0.81$, which, fed back into the previous equation, yields: $W_{\text{int}} = -3.08f^3 + 3.47f^2$. This latter model tended to slightly underestimate measured internal work (0.58 ± 0.05 vs 0.60 ± 0.07 , $t(23) = -0.41$, $P = 0.69$), with major axis slope 95% confidence intervals excluding 1 though ($\beta = 0.61$, $[0.42, 0.81]$, $N = 24$). More importantly, however, as the model only requires the input of stroke frequency (which can be readily measured), it remained entirely satisfactory whenever underwater camera set-up is unavailable.

The compound term q accounts for limb geometry and inertial properties (Minetti, 1998; Nardello et al., 2011). Here this parameter was found to decline as the stroke frequency (and the swimming speed) increased. According to Minetti (1998), a decrease in q conveys the ability to minimize the locomotion mechanical work by reducing the moment needed to rotate the limbs. This capacity has never been observed before in humans, q being constant in walking, running (Minetti, 1998; Nardello et al., 2011) and cycling (Minetti et al., 2001). However, it exists in horses (Minetti, 1998) and spiders (Biancardi et al., 2011). Quadrupeds and octopods essentially contrast with bipeds in that they display higher stability and more versatile locomotor repertoire. While human limb geometry is constrained either during the walking and running stance phase or by the crank length while pedaling, horses passing from walk to trot show remarkable changes in limb geometry (Minetti, 1998). Likewise, spiders exhibit distinct limb motion patterns between low and high stride frequencies (Biancardi et al., 2011). Breaststroke swimmers therefore resemble, from the point of view of locomotion dynamics, quadrupeds demonstrating different gaits. The aquatic environment, lacking

solid support unlike on land, provides additional freedom in limb movement. In breaststroke, a trade-off could exist between ‘grouping’ the lower body segments near the BCOM before the kick (possibly lessening W_{int}) and the higher hydrodynamic resistance that this would entail.

Hogan (1985) advanced that the central nervous system may alter the inertial behavior of a multi-joint limb by changing its configuration in space, thanks to additional degrees of freedom provided by the kinematic redundancy of the skeletal system. Here we found that all segments but the upper arm had significantly different angular excursions between the highest and the lowest movement frequency. Specifically, the angular excursions of the heaviest segments (thighs and trunk) were reduced with increased frequency, and vice versa for the lightest segments (shanks and forearms). This finding is in agreement with the ‘Knowledge II’ theory of the planning and control of motor action (Rosenbaum et al., 1995). It indeed predicts the apportionment of lower amount of motion by the central nervous system to segments with high inertia, while segments with low inertia would exhibit an increase or a much smaller decrease in angular amplitude. Since the anteroposterior displacement for both upper and lower body was constant regardless of swimming frequency, favoring lighter segments toward the highest frequencies contributed to the decrease in q . Swimmers thus proved able to reduce the moment needed to rotate their limbs through motor reorganization, therefore slowing down the increase in internal work.

An additive, hypothetical mechanism contributing to decrease the internal work needed may rest on the added mass concept from fluid mechanics. As the velocity of a body is changing in water, the rate of change of kinetic energy of the fluid is changing also. This amount of energy is regarded as arising from a mass of fluid added to the mass of the body (Batchelor, 1967). It should be emphasized that this distinct mass of water is rather virtual: in fact, every fluid particle will accelerate to varying degrees as the body moves, the added mass being a weighted integration of this entire mass (Newman, 1999). The body behaves as if it was heavier, and additional mechanical work is required against both the inertia of the body itself and the inertia of the displaced fluid (Brennen, 1982). At the surface—where swimmers actually are—there is no such a simple physical interpretation. Fluid mechanics studies of cylinders oscillating at the surface offer a clear illustration. Under a certain range of oscillation frequencies, free surface deformations have been found to yield decreasing or even negative added masses (Chung, 1977; Frank, 1967). And it is incorrect to interpret a negative added mass as a subtracted mass of water (Falnes, 1983). These surprising findings may be explained on the basis of a standing wave system resonating above the body (Newman et al., 1984). In that ideal case, the wave energy flux is zero; no additional external work is needed to deform the free surface; hence the work to overcome inertia is less. Similar hydrodynamic interference effects might as well occur in breaststroke swimming. Sanders et al. (1998) did not support a posteriorly traveling wave in breaststroke; perhaps counter-propagating waves are created by the oscillating trunk and lower limbs, approaching a resonant system as swimming frequency increases. Reduced added mass by this means would contribute to decrease the work required to accelerate the segments relative to the BCOM.

Our understanding of the relationship between W_{int} and W_{ext} in aquatic locomotion is impeded by the lack of attention being paid to added mass and wave generation. Costs of moving the segments relative to the body center of mass, and of imparting kinetic energy to the water have been regarded in the past as two independent, additive components within the energy cascade in aquatic locomotion (Zamparo et al., 2002). Based on the above, the two might actually be coupled to some extent. In effect, a decelerating segment will generate extra thrust due to the added mass

inertia (Vogel, 1994). Thus, as pointed out by Kautz and Neptune (2002) in cycling, internal energy decreases might ultimately produce positive external work in swimming also.

5. Conclusion

A simple yet accurate predictive equation was devised to estimate the internal work of breaststroke swimming. This is a valuable component of a more comprehensive model including W_{ext} , which would predict the metabolic energy expenditure associated to a given speed and stroke frequency in breaststroke swimming. It shed light on swimmers ability to moderate the increase in W_{int} at the highest stroke frequencies. Such capacity, never observed before in humans, is also present in quadrupedal and octopedal animal locomotion. This was achieved through a reduced angular excursion of the heaviest segments in favor of the lightest ones. Perhaps W_{int} is sensed and triggers such motor responses. A deeper understanding of the energy flow between the body segments and the environment is required to ascertain the possible dependency between W_{int} and W_{ext} . Considering added mass and wave concepts will prove essential to better understand swimming cost determinants and power generation in aquatic movements.

Conflict of interest statement

The authors declare no conflict of interest.

References

- Alonso, F.J., Castillo, J.M.D., Pintado, P., 2005. Application of singular spectrum analysis to the smoothing of raw kinematic signals. *J. Biomech.* 38, 1085–1092.
- Batchelor, G.K., 1967. *An Introduction to Fluid Dynamics*. Cambridge University Press, Cambridge, UK.
- Biancardi, C.M., Fabrica, C.G., Polero, P., Loss, J.F., Minetti, A.E., 2011. Biomechanics of octopedal locomotion: kinematic and kinetic analysis of the spider *Grammostola mollicoma*. *J. Exp. Biol.* 214, 3433–3442.
- Brennen, C.E., 1982. *A Review of Added Mass and Fluid Inertial Forces*. Naval Civil Engineering Laboratory, Port Hueneme, CA (No. CR82.010).
- Cappozzo, A., Cappello, A., Della Croce, U., Pensalfini, F., 1997. Surface-marker cluster design criteria for 3-D bone movement reconstruction. *IEEE Trans. Biomed. Eng.* 44, 1165–1174.
- Cappozzo, A., Della Croce, U., Leardini, A., Chiari, L., 2005. Human movement analysis using stereophotogrammetry. Part 1: theoretical background. *Gait Posture* 21, 186–196.
- Cavagna, G.A., Franzetti, P., 1986. The determinants of the step frequency in walking in humans. *J. Physiol.* 373, 235–242.
- Chung, J.A.F., 1977. Forces on submerged cylinders oscillating near a free surface. *J. Hydronaut.* 11, 100–106.
- de Leva, P., 1996. Adjustments to Zatsiorsky–Seluyanov's segment inertia parameters. *J. Biomech.* 29, 1223–1230.
- Detrembleur, C., Dierick, F., Stoquart, G., Chantreine, F., Lejeune, T., 2003. Energy cost, mechanical work, and efficiency of hemiparetic walking. *Gait Posture* 18, 47–55.
- Diebel, J., 2006. *Representing Attitude: Euler Angles, Unit Quaternions, and Rotation Vectors*. Matrix. Stanford University, Stanford, CA.
- Falnes, J., 1983. *Added-Mass Matrix and Energy Stored in the "Near Field"*. Universitetet i Trondheim, Noregs tekniske høyskole, Institutt for eksperimentalfysikk, Trondheim, Norway.
- Formetti, F., Ardigo, L.P., Minetti, A.E., 2005. Human locomotion on snow: determinants of economy and speed of skiing across the ages. *Proc. Biol. Sci.* 272, 1561–1569.
- Frank, W., 1967. *Oscillation of Cylinders in or Below the Free Surface of Deep Fluids*. Naval Ship Research and Development Center, Washington.
- Hogan, N., 1985. The mechanics of multi-joint posture and movement control. *Biol. Cybern.* 52, 315–331.
- Ishimura, K., Sakurai, S., 2012. Effect of window length when smoothing with singular spectrum analysis technique in running data. In: Bradshaw, E.J., Burnett, A., Hume, P.A. (Eds.), *Proceedings of the XXXth International Conference on Biomechanics in Sports*. Australian Catholic University, Melbourne, Australia, pp. 29–32.
- Kautz, S.A., Neptune, R.R., 2002. Biomechanical determinants of pedaling energetics: internal and external work are not independent. *Exerc. Sport Sci. Rev.* 30, 159–165.
- McGibbon, C.A., McGibbon, C.A., Krebs, D.E., Krebs, D.E., Puniello, M.S., Puniello, M.S., 2001. Mechanical energy analysis identifies compensatory strategies in disabled elders' gait. *J. Biomech.* 34, 481–490.
- Minetti, A.E., 1998. A model equation for the prediction of mechanical internal work of terrestrial locomotion. *J. Biomech.* 31, 463–468.
- Minetti, A.E., Ardigo, L.P., Saibene, F., 1993. Mechanical determinants of gradient walking energetics in man. *J. Physiol.* 472, 725–735.
- Minetti, A.E., Ardigo, L.P., Saibene, F., 1994a. Mechanical determinants of the minimum energy cost of gradient running in humans. *J. Exp. Biol.* 195, 211–225.
- Minetti, A.E., Ardigo, L.P., Saibene, F., 1994b. The transition between walking and running in humans: metabolic and mechanical aspects at different gradients. *Acta Physiol. Scand.* 150, 315–323.
- Minetti, A.E., Pinkerton, J., Zamparo, P., 2001. From bipedalism to bicyclism: evolution in energetics and biomechanics of historic bicycles. *Proc. Biol. Sci.* 268, 1351–1360.
- Nardello, F., Ardigo, L.P., Minetti, A.E., 2011. Measured and predicted mechanical internal work in human locomotion. *Hum. Mov. Sci.* 30, 90–104.
- Newman, J.N., 1999. *Marine Hydrodynamics*, 9 ed. The MIT Press, Cambridge, MA.
- Newman, J.N., Sortland, B., Vinje, T., 1984. Added mass and damping of rectangular bodies close to the free surface. *J. Ship Res.* 28, 219–228.
- Rayner, J.M.V., 1985. Linear relations in biomechanics: the statistics of scaling functions. *J. Zool.* 206, 415–439.
- Rosenbaum, D.A., Loukopoulos, L.D., Meulenbroek, R.G., Vaughan, J., Engelbrecht, S.E., 1995. Planning reaches by evaluating stored postures. *Psychol. Rev.* 102, 28–67.
- Sanders, R.H., Cappaert, J.M., Pease, D.L., 1998. Wave characteristics of olympic breaststroke swimmers. *J. Appl. Biomech.* 14, 40–51.
- Vogel, S., 1994. *Life in Moving Fluids: The Physical Biology of Flow*. Princeton University Press, Princeton, NJ.
- Willems, P.A., Cavagna, G.A., Heglund, N.C., 1995. External, internal and total work in human locomotion. *J. Exp. Biol.* 198, 379–393.
- Zamparo, P., Pendergast, D.R., Mollendorf, J.C., Termin, A.C., Minetti, A.E., 2005. An energy balance of front crawl. *Eur. J. Appl. Physiol.* 94, 134–144.
- Zamparo, P., Pendergast, D.R., Termin, B., Minetti, A.E., 2002. How fins affect the economy and efficiency of human swimming. *J. Exp. Biol.* 205, 2665–2676.
- Zamparo, P., Pendergast, D.R., Termin, A., Minetti, A.E., 2006. Economy and efficiency of swimming at the surface with fins of different size and stiffness. *Eur. J. Appl. Physiol.* 96, 459–470.