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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 ± 0.05 J kg^{-1} 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 octopedal animal locomotion. This was achieved through a reduced angular excursion of the heaviest segments ($7.2 \pm 2.9°$ and $3.6 \pm 1.5°$ for the thighs and trunk, respectively, $P < 0.05$) in favor of the lightest ones ($8.8 \pm 2.3°$ and $7.4 \pm 1.0°$ 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 J kg^{-1} m^{-1}) during terrestrial locomotion can be predicted by the following equation:

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

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

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

given:

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

where x_{lo} is the anteroposterior distance covered by the feet during half a cycle; $t_{glide,lo}$, 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:

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

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

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

and

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

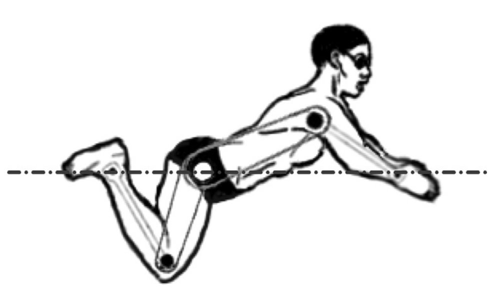

Fig. 1. A breaststroke swimmer modeled as two slider–crank mechanisms. Extremities are sliding back and forth along an axis (dash line) parallel to the surface, and animated from the center of the crankshaft (hip joint) through the cranks (thighs and trunk) and the connecting rods (lower legs and arms).

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

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

and

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

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) × 2.5 m (*Y*; horizontally and laterally towards the left of the swimmer) × 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 *COM*s.

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

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