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Inter-limb coordination and energy cost in swimming

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ABSTRACT

Objectives: This study investigated the relationship between inter-arm coordination and the energy cost of locomotion in front crawl and breaststroke and explored swimmers' flexibility in adapting their motor organization away from their preferred movement pattern.
Design: Nine front-crawlers performed three 300-m in front crawl and 8 breaststrokers performed three 200-m in breaststroke at constant submaximal intensity and with 5-min rests. Each trial was performed randomly in a different coordination pattern: freely chosen, 'maximal glide' and 'minimal glide'. Two underwater cameras videotaped frontal and side views to analyze speed, stroke rate, stroke length and inter-limb coordination.
Methods: In front crawl, inter-arm coordination was quantified by the index of coordination (IdC) and the leg beat kicks were counted. In breaststroke, four time gaps quantified the arm to leg coordination (i.e., time between leg and arm propulsions; time between beginning, 90° flexion and end of arm and leg recoveries). The energy cost of locomotion was calculated from gas exchanges and blood lactate concentration.
Results: In both front crawl and breaststroke, the freely chosen coordination corresponded to glide pattern and showed the lowest energy cost (12.8 and 17.1 J kg^{-1} m^{-1}, respectively). Both front-crawlers and breaststrokers were able to reach 'maximal glide' condition (respectively, +35% and +28%) but not 'minimal glide' condition for front crawl.
Conclusions: The freely chosen pattern appeared more economic because more trained. When coordination was constrained, the swimmers had higher coordination flexibility in breaststroke than in front crawl, suggesting that breaststroke coordination was easier to regulate by changing glide time.

1. Introduction

Can swimmers self-adapt their motor organization, such as inter-limb coordination and movement patterns, to minimize energy cost? Many coaches try to help swimmers develop the most economical race pace in terms of speed, stroke rate and stroke length but few researches explored the link between inter-limb coordination and swimming economy or energy cost.[1–3] As water is 800 times denser than air, finding the most economical inter-limb coordination is a real challenge, especially in breaststroke where arms and legs recoveries are underwater.

Several studies in front crawl have shown that inter-arm coordination changes with speed, from catch-up pattern at distance race paces to opposition or superposition patterns at sprint race paces.[4,5] Similar results were observed in breaststroke, as speed increase led to a shift from glide to continuity or superposition pattern.[6,7] However, individual adaptations occur regarding swim specialty, gender and level of expertise.[8] For instance, some elite front crawl swimmers keep the same inter-arm coordination pattern whatever the swim speed,[9] suggesting, through graded speed tests of 25-m, that several motor coordination pacing strategies are possible. When race pacing strategy was analyzed for front crawl swimming, the values for inter-arm coordination remained stable and close to the superposition pattern through the last three 25-m laps of a 100-m trial in elite swimmers, while coordination changed from catch-up to superposition in less expert swimmers.[10] Thus, one may question whether the coordination pattern for a given speed is fixed and stable or individual and adaptive, and whether swimmers can select and self-adapt their inter-limb coordination economically.

Continuity in the arm propulsive phases in front crawl and continuity in the arm and leg propulsive phases in breaststroke resulted in less intra-cyclic speed variations,[11–13] which may lower the energy cost. In fact, Nigg[14] calculated that a 10% change in the swimming speed within a stroke cycle increased the work

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demand by about 3%, suggesting that minimizing intra-cyclic speed variations lead to a lower energy expenditure. When propulsive continuity in front crawl was assessed through graded speed tests of six 300-m,[2,3] a significant correlation was found between the index of coordination value and the energy cost of locomotion. However, when speed was controlled, the correlation between inter-arm coordination and the energy cost of locomotion was not significant,[1] suggesting that no single inter-arm coordination pattern could be considered as most economical. From there, it remains unclear whether for a given swimming speed (i) a certain pattern of inter-limb coordination is related to the lowest energy cost, which can be spontaneously adopted by the swimmers, and (ii) swimmers can vary their inter-limb coordination in order to minimize the energy cost.

The goal of the present study was to examine how expert swimmers are able to adopt an economic inter-limb pattern of coordination and if they are able to vary this freely chosen coordination pattern (i.e., by gliding between two propulsive actions to their maximal and to their minimal capability) to minimize energy. To attempt this goal, this study assessed the energy cost of the coordination patterns in alternate (front crawl) and simultaneous (breaststroke) strokes for a fixed speed in national level swimmers. It was hypothesized that the freely chosen coordination pattern (i) would have the lowest energy cost in order to save metabolic energy and also because this pattern would be more trained than constrained coordination, (ii) does not correspond to continuity of propulsive actions as coordination emerges from a set of constraints. (iii) It is also hypothesized that breaststroke enables larger adaptation of glide when coordination is constrained than front crawl.

2. Methods

Seventeen Swiss national level swimmers voluntarily participated in this study: 9 front crawl specialists (18.7 ± 4.9 yr, 179.3 ± 3.3 cm, 68.7 ± 6.2 kg, and 275.8 ± 9.3 s for a 400-m front crawl) and 8 breaststroke specialists (18.3 ± 2.1 yr, 180.5 ± 4.4 cm, 66.8 ± 6.4 kg, and 155.5 ± 9.9 s for a 200-m breaststroke). Both groups trained 11.9 ± 3 h week^{-1}, with 29.1 ± 4.4 km week^{-1} of swimming and 4.3 ± 1.3 h week^{-1} of dry-land training. Performance was assessed by the personal time record and expressed in percentage of the world record (by dividing the person's time by the world record time). In our study, the performance level was 80% of the world record. Each participant was informed of the procedures and risks associated with study participation and gave written informed consent prior to participation. This study was performed in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the Faculty of Biology and Medicine, University of Lausanne (protocol #87/10).

After a regular individual warm-up in a 50-m indoor pool, front crawl swimmer performed three 300-m trials at 80% of front crawl 400-m personal best time (target speed of 1.16 m s^{-1}). Each breaststroke specialist performed three 200-m trials at 70% of breaststroke 200-m personal best time (target speed of 0.97 m s^{-1}). This intensity and work duration were selected to enable the swimmers to finish the trials in >3 min 30 s in order to reach a VO_2 steady state. The observation of the breath-by-breath VO_2 responses confirmed a steady state and that there was no development of VO_2 slow component in all trials. This verification was important since prior exercise may speed the VO_2 kinetics and induce a VO_2 slow component in a subsequent bout. Due to the moderate intensity of the trials and the recovery duration, this was not observed in the present study.

The swimmers were asked to swim the first trial using a freely chosen coordination pattern, then trials 2 and 3 in random order to 'maximal glide' and to 'minimal glide' between two propulsive actions. Five minutes rests were allowed between trials. Swimming speed was monitored with an Aquapacer Solo (Challenge and Response, Inverurie, UK). Markers were positioned every 2.5 m along the edge of the pool, and an operator then walked along the deck with a stick immerged in the water to indicate the prescribed swim speed to the swimmer. As in previous studies, the operator used the auditory signal of the Aquapacer in correspondence with the visual markers on the deck to match his walking pace.[3] The swimmers were asked to maintain speed by keeping their heads at the level of the operator's immerged stick with a range <1 m.

Two underwater video cameras (Sony FCB-EX10L, Paris, France) filmed the swimmer from a frontal view, the other from a side view with video frame rate of 50 Hz. They were mixed and genlocked to get the frontal and lateral views on the same screen. The lateral view allowed the calculation of the average speed (v in m s^{-1}), the stroke rate (SR in Hz) and the stroke length (SL = v/SR in m) on three cycles over a 10-m distance (from 10-m to 20-m) using the swimmer's head as the marker. From the video device, front crawl arm stroke was broken into four phases: entry and catch of the hand in the water, pull, push and recovery; and the leg beat kick for one arm stroke was counted.[4,5] In breaststroke, the arm stroke was divided into five phases: glide, outsweep, insweep, first part of the recovery, and second part of the recovery; the leg stroke also comprised five phases: propulsion, insweep, glide, first part of the recovery, and second part of the recovery.[6,7] The duration of each phase was expressed as a percentage of the duration of one arm stroke. The key motor events of the stroke phase were determined every 0.02 s by three independent expert operators measuring with a blind technique, i.e., without knowing the results of the analyses of the two other operators, as previously described.[15]

In front crawl, the index of coordination (IdC) calculated the time gap between the propulsions (pull and push phases) of the two arms as a percentage of the duration of the arm stroke.[4,10] Catch-up pattern was IdC < 0%, opposition pattern was IdC = 0%, and superposition pattern was IdC > 0%.[4,10] In breaststroke, four time gaps (T1, T2, T3, T4) measured time gap between the stroke phases of each pair of limbs: T1 is from the end of leg propulsion to the start of arm outsweep and corresponds to the glide time between legs and arms propulsion. Glide pattern was T1 < 0%, opposition pattern was T1 = 0%, and superposition pattern was T1 > 0%.[6,7] T2, T3 and T4 assess the synchronization between the arm and leg recoveries (for further details[6,7]). Coordination flexibility is computed as the percentage of change between constrained coordination and freely chosen coordination.

During exercise, minute ventilation, oxygen consumption (VO_2) and carbon dioxide production were recorded breath-by-breath by AquaTrainer® snorkel and the K4b^2 telemetric gas exchange system (Cosmed, Roma, Italy), which was calibrated according to the manufacturer's instructions before each test. Ectopic artefacts were manually eliminated and the data were then averaged every 5 s. According to Barbosa et al.,[16] no significant kinematical changes are observed when swimming at maximal intensity in front crawl and breaststroke with the AquaTrainer® snorkel. A capillary blood sample was obtained from the finger no more than 30 s after the end of the steps and analyzed for blood lactate concentration (lactate Pro LT, Arkay Inc., Kyoto, Japan). The samples were also taken at rest and at the end of each condition. The energy cost of locomotion (C in mLO_2 kg^{-1} m^{-1}) was defined as $C = \dot{E} \cdot v^{-1}$ where $\dot{E}$ is the total metabolic energy expenditure (aerobic and anaerobic pathways) expressed in mLO_2 min^{-1} kg^{-1} and v, in m min^{-1}, is the swimming speed at submaximal and maximal intensities.[17] The aerobic part of swimming C (C_{aero}) was equal to the ratio between VO_2net (i.e., the difference between the VO_2 measured during the last min of each swimming stage and its value at rest) and the swimming speed.[17,18] The anaerobic glycolytic net C (C_{anaero}) was estimated using blood