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Inter-individual variability in the upper–lower limb breaststroke coordination

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ABSTRACT

The aim of the present study was to examine inter-individual variability in upper–lower limb breaststroke coordination. First, inter-individual variability was compared between recreational and comparative swimmers. Second, as recreational swimmers revealed more variable inter-limb coordination than competitive swimmers, inter-individual variability was assessed among recreational swimmers to identify coordination profiles. The elbow–knee continuous relative phase (CRP) was used to analyze upper–lower limbs coupling during a breaststroke cycle. Twenty-four recreational and twenty-four competitive swimmers swam 25 m at 80% of their maximal speed. Underwater and aerial side views were mixed and genlocked. Angular position, velocity and CRP were calculated for the knee and elbow joints by digitizing body markers from the side view. The kinematics of three cycles were filtered, averaged and normalized in terms of percentage of total cycle duration. The topography of the mean CRP curve of the recreational swimmers resembled a 'W-shape', whereas an 'inverse U-shape' was seen in the competitive swimmers. However, higher inter-individual variability was observed among the recreational swimmers than among the competitive swimmers (38.1° vs. 19.4° ; $p < .05$), suggesting that several profiles of inter-limb coordination may exist in recreational swimmers. Coordination profiling showed that three clusters could classify the recreational swimmers.

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1. Introduction

Variability has long been considered a dysfunctional aspect of human behavior, representing a degree of noise to be eliminated or reduced with increasing proficiency (Davids, Glazier, Araujo, & Bartlett, 2003; Glazier, Wheat, Pease, & Bartlett, 2006; van Emmerik & van Wegen, 2000). Thus, a high level of expertise would be the capability to reproduce a movement like an automaton. In reality, however, behavioral variability may occur at different levels of the learning and training process. For example, Seifert and Chollet (2008) described two general coordination modes among recreational breaststroke swimmers: (i) the superposition of propulsion and recovery phases (i.e., leg propulsion during the arm recovery and vice versa), hence the upper- and lower-limbs moving sequentially like an “accordion”, and (ii) the superposition of arm and leg propulsions, with the upper- and lower-limbs coupling resembling the movement of “windscreen wipers”.

A similar bimodal coordination regime has been observed during other bimanual coordination tasks, such as finger or wrist movements in either in- or anti-phase coordination, depending on movement frequency (e.g., Kelso, 1984). In contrast, highly skilled breaststroke swimmers seem locked to just one main mode at different speeds, called “continuous” coordination, corresponding to the alternation of the propulsion by the legs and the arms (i.e., one pair of limbs propel while the other pair of limbs glide stretched forward) and synchronization of the recovery phases of the arms and legs (Chollet, Seifert, Leblanc, Boulesteix, & Carter, 2004; Persyn, Hoeven, & Daly, 1979; Seifert, Leblanc, Chollet, & Delignières, 2010). However, as the average propulsion should equal the drag (that depends on the swimming speed squared), the “continuous” coordination of elite breaststroke swimmers is to be understood from the balance of forces and energy conservation principles. In practice, it means that elite breaststrokers adapt their inter-limb coordination by spending more or less time in glide with the body fully extended, which has been described by Maglischo (2003) in terms of three coordination modes: (i) glide coordination in which the body stays fully extended and streamlined before the arm catch, which is usually adopted for the 200-m event; (ii) continuous coordination in which arm propulsion takes over just as leg propulsion is completed, destined for the 100-m event, and (iii) superposition coordination in which the arms start their propulsion before the completion of leg propulsion, typical for the 50-m event.

In a proposed schematic classification of elite, competitive and recreational swimmers, inter-individual variability can be conceived like an “hourglass” shape (Fig. 1), showing that human motor variability is not only an attribute of beginners and is not always detrimental as has been traditionally thought (Bartlett, Wheat, & Robins, 2007; Davids et al., 2003; Glazier et al., 2006; Riley & Turvey, 2002). With the advent of dynamical systems theory, the functional role of variability has been highlighted, as it allows the required flexibility to adapt to a variety of constraints (Bartlett et al., 2007; Newell, 1986). In this context, variability is seen as a mechanism allowing individuals to adapt their movements as a function of organismic, environmental and task constraints (Newell, 1986; Seifert & Chollet, 2008; Seifert, Chollet, & Rouard, 2007). There is not one optimal pattern of coordination to a given motor problem, but several solutions exist, leading to considerable intra- and inter-individual variability (Glazier & Davids, 2009). Variability allows the performer to explore different motor solutions, facilitating the discovery and adoption of individualized optimal patterns of coordination.

In Fig. 1, it is conceived that recreational swimmers would initially show considerable inter-individual variability as they seek an individually appropriate coordination pattern to accommodate the novel constraints of locomoting in water. In order to compete effectively, expert swimmers must undergo a considerable amount of practice and instruction and at this stage of learning inter-individual variability is compressed to a narrower range of movement solutions. Finally, to achieve world class standards of performance elite swimmers must once again explore the environment to optimize their technique with their individual strengths (e.g., physical, anatomical, mental, etc.) in order to gain an advantage over competing swimmers. Hence for this comparatively small group of swimmers one may predict that there is a secondary blooming of inter-individual differences.

Intra- and inter-individual variability exists in several activities and its analysis is important in identifying coordination profiles (Button, Davids, & Schöllhorn, 2006). Cluster analysis is an increasingly common technique for detecting patterns in high dimensional data-sets. One significant

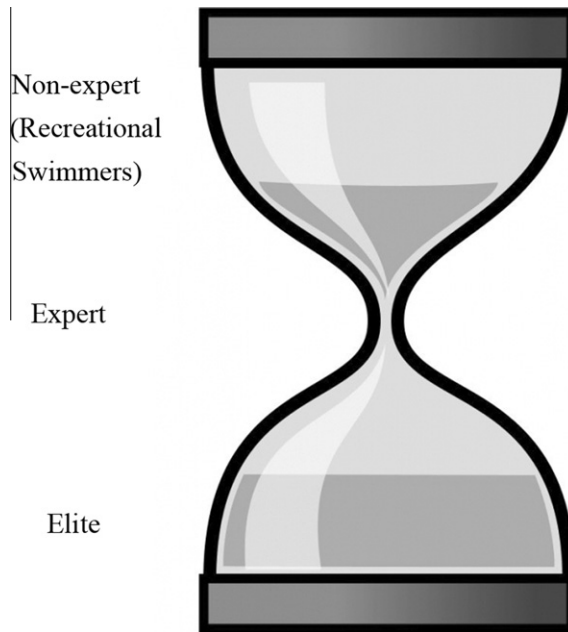


Fig. 1. Schematic representation of amount of variability as a function of expertise.

advantage of movement pattern clustering is that no a priori assumptions about the structure of the dataset are required to identify similar patterns. For example, [Chow, Davids, Button, and Rein \(2008\)](#) employed cluster analysis to detect inter-individual differences of coordination patterns in executing a football shot. [Rein, Button, Davids, and Summers \(2010\)](#) also used cluster analysis to explore differences between performers with different skill levels performing the basketball hook shot. The technique proved particularly sensitive as between 2 and 8 different coordination modes emerged from the participants as they threw from different distances from the basket.

The various behaviors of elite breaststroke swimmers are well documented ([Colman, Persyn, Daly, & Stijnen, 1998](#); [Vilas-Boas, 1996](#)) and the main coordination mode of expert swimmers is well established ([Chollet et al., 2004](#); [Seifert et al., 2010](#)). In contrast, the analysis of the behavior of the recreational swimmers remains largely descriptive ([Seifert & Chollet, 2008](#)) and requires further research. The inter-individual coordination variability of the recreational swimmers could result from (i) organismic constraints (e.g., swimmers could be at a different stage of the learning process), (ii) environmental constraints (e.g., a different perception of the aquatic resistance that the swimmer overcome by kinematics – temporal or spatial – variations), (iii) a different perception of the task constraints (e.g., floating instead of swimming). The aim of this study was to analyze the inter-individual variability of swimmers at different skill levels to test the proposed conceptual “hourglass” model of variability. This study was realized in two steps: (i) Assessment of the inter-individual coordination variability between competitive and recreational swimmers, in order to confirm that the latter exhibit greater inter-individual variability in achieving the task, (ii) Application of a cluster analysis to focus on inter-individual variability among recreational swimmers.

2. Methods

2.1. Participants

Forty-eight female and male swimmers were separated into two groups according to significant differences in their performance level (best time on 50-m: recreational group: 50.77 ± 5.04 s; competitive

group: 35.81 ± 2.43 s), $F(1, 23) = 190.26$, $p < .05$, and swimming skill (respective percentages of world record for the short course on January 1, 2007: recreational group: $54.5 \pm 7.3\%$; competitive group: $78.5 \pm 5.3\%$), $F(1, 23) = 207.57$, $p < .05$. The 24 recreational swimmers were 16.7 ± 1.7 years old, had a body mass of 63.2 ± 8.8 kg and were 168.5 ± 8.9 cm tall. The 24 competitive swimmers were 16.1 ± 1.5 years, 61.8 ± 5.8 kg and 171.0 ± 7.4 cm. The two groups showed no significant differences in age, weight or height. All the swimmers were able to perform a symmetric leg kick and partially or completely immerse their head during the arm extension, as required by the FINA rules. Six markers were placed on the anatomical landmarks of the shoulder, elbow, wrist, hip, knee, ankle on the right side of the body.

2.2. Protocol

The protocol was explained in full to the participants and they provided written consent to participate in the study, which was approved by the university ethics committee before it was conducted. In the case of minors, informed written consent was obtained from the participants and their parents.

One week prior to the experimental trial, the recreational and competitive swimmers swam a preliminary breaststroke trial to establish their maximal speed during a 50-m swim. For the competitive swimmers, the 50-m performance was compared to the best competitive time of the current season and the superior performance was used. The experimental trial consisted of swimming 25 m at 80% of the maximal speed with an in-water start and self-paced by the swimmer to avoid speed variations due to pacing. After each trial, all swimmers were informed of their performances. The swimmers were asked to swim within $\pm 5\%$ of their targeted time. If this was not accomplished, the subject had to repeat the trial. The trial was monitored by two experienced timers who assessed the stroke rate and speed with a stopwatch and a Seiko Base 3-frequency-meter in order to validate each trial.

2.3. Video analysis and stroking parameters (velocity, stroke rate, stroke length)

Two Samsung SC107 digital camcorders were connected via an AV/DV analogical input to two custom-made underwater cameras. One camera filmed the swimmers from a frontal view, the other from a side view (distance 11 m). A third camcorder (Canon Obtura) placed on the pool deck videotaped the swimmers over a distance of 12.5 m (between the 10-m and 22.5-m marks on the pool edges), which enabled us to calculate the average swimming velocity (m s^{-1}) and stroke rate (Hz). Using the average velocity and the stroke rate, the stroke length (m stroke^{-1}) could be calculated:

$$\text{stroke length} = \text{velocity} / \text{stroke rate} \quad (1)$$

Underwater and above-water views were mixed and synchronized for data processing. A flashing light was used to synchronize the pictures. After being digitized, the images of the underwater side view (sagittal plane) were analyzed with Dartfish Prosuite 4.0® software (Atlanta, GA) to assess the elbow and knee angles. The acquisition rate was 66 frames s^{-1} . The underwater cameras had a 500-line definition.

2.4. Arm to leg coordination

Based on a previous study by Seifert et al. (2010), the continuous relative phase (CRP) between the elbow (shoulder–elbow–wrist) and knee (hip–knee–ankle) angles was analyzed from two or three cycles, recorded in the central part of the pool to avoid start and turn effects. These cycles were averaged by normalizing the duration of each cycle in terms of percentages. A cycle began from a position of maximal leg flexion and ended at the return to this position. The curves of elbow and knee angles during an entire cycle were smoothed by a Butterworth low-pass filter (cut-off frequency 6 Hz) by OriginPro 7.5714® software (1991–2003, OriginLab Corporation, Northampton, MA, USA). Following Hamill, Haddad, and Mc Dermott (2000), the data on angular displacements and angular velocities were normalized to the interval $[-1, +1]$ as follows:

$$\text{Angular position : } \theta_{\text{norm}} = \frac{2\theta}{(\theta_{\text{max}} - \theta_{\text{min}})} - \frac{(\theta_{\text{max}} + \theta_{\text{min}})}{(\theta_{\text{max}} - \theta_{\text{min}})} \quad (2)$$

where θ_{max} is the maximum angular position within one complete cycle and θ_{min} is the minimum angular position within one complete cycle.

$$\text{Angular velocity : } \omega_{\text{norm}} = \frac{2\omega}{(\omega_{\text{max}} - \omega_{\text{min}})} - \frac{(\omega_{\text{max}} + \omega_{\text{min}})}{(\omega_{\text{max}} - \omega_{\text{min}})} \quad (3)$$

where ω_{max} is the maximum angular velocity within one complete cycle and ω_{min} is the minimum angular velocity within one complete cycle. Angular velocity was obtained through differentiating displacement data.

Phase angles were calculated using the following formula:

$$\text{Phase angle : } \phi = \tan^{-1}(\omega_{\text{norm}}/\theta_{\text{norm}}) \quad (4)$$

Finally, the continuous relative phase (CRP) for a complete cycle was:

$$\text{CRP} = \text{Elbow phase angle} - \text{Knee phase angle} \quad (5)$$

Theoretically, three coordination modes are possible: synchronization of two actions corresponds to in-phase (0°), lag time between two actions corresponds to out-of-phase which was called anti-phase (180°) when the lag time was full and corresponded to opposite actions. However, following [Bardy, Oullier, Bootsma, and Stoffregen \(2002\)](#), [Diedrich and Warren \(1995\)](#), [Seifert, Delignières, Boulesteix, and Chollet \(2007\)](#) and [Seifert et al. \(2010\)](#), a variation of $\pm 30^\circ$ was accepted in this study for the determination of a coordination mode. Therefore, an in-phase mode was assumed to occur for $-30^\circ < \text{CRP} < 30^\circ$, while the anti-phase mode was assumed to occur for $-180^\circ < \text{CRP} < -150^\circ$ and $150^\circ < \text{CRP} < 180^\circ$. Beyond this step, a coordination mode of intermediate phase was also taken into account.

The time spent in the in-phase mode is indicative of how swimmers synchronize the propulsion of one pair of limbs with the glide of the second pair of limbs, as well as the time spent in glide with the body fully extended. The CRP value at the beginning and end of the cycle indicates the swimmer's capability to keep the arms extended forward while the legs are starting their propulsion from knee flexion. The maximum CRP value is the greatest positive CRP value, which is distinct from the CRP value reached at the beginning and end of the cycle, and it indicates the presence or absence of the glide. The first and second minimum CRP values are the two greatest minimal peaks of the CRP, which again are distinct from the CRP value reached at the beginning and end of the cycle, and it indicates how the arm recovery (elbow extension) and leg recovery (knee flexion) are synchronized.

2.5. Inter-individual coordination variability and profiling

Inter-individual variability in the recreational group and in the competitive group was assessed by the SD of CRP between subjects for each % composing the 100% of the cycle.

Coordination profiling within the recreational swimmers group was established by a cluster hierarchical analysis (CHA), as advised by [Ball and Best \(2007\)](#), [Button et al. \(2006\)](#), and [Rein et al. \(2010\)](#) to classify different participant profiles. For example in swimming, cluster analysis has already been used to classify (i) the characteristics of subject' physical fitness in terms of either critical velocity or anaerobic working capacity in breaststroke ([Abe et al., 2006](#)), (ii) the backstroke start as regards the body segment vector of the swimmers ([Wilson & Howard, 1983](#)).

2.6. Statistical analysis

2.6.1. Differences between recreational and competitive groups

After having checked the normality of the distribution (Ryan Joiner test) and the variance homogeneity (Bartlett test), the dependent variables were compared between competitive and recreational swimmers using two-ways ANOVAs (fixed factor: skill level; random factor: subject). When one of the two previously mentioned conditions to use a parametric test failed, the non-parametric

Kruskal–Wallis test was used. The comparison of the two skill levels was done for (i) the stroking parameters (speed, stroke rate, stroke length), (ii) mean CRP, (iii) intra-cyclic SD of CRP, (iv) time spent in the in-phase mode, (v) CRP at the beginning and the end of the cycle, (vi) maximum peak of CRP values, and (vii) time at which maximum peak of CRP occurred.

2.6.2. Inter-individual coordination variability between recreational and competitive groups

The inter-individual variability of CRP (i.e., SD of CRP between subjects) was compared between the two groups of skill level by paired *t*-test.

2.6.3. Inter-individual coordination profiling

2.6.3.1. Cluster analysis to classify recreational swimmers. As higher inter-individual variability of CRP was expected in the recreational swimmers group; cluster hierarchical analysis (CHA) using the squared Euclidean distance dissimilarity measure and the Ward linkage method was applied to determine several profiles within this group of swimmers. Eleven variables were used to classify the recreational swimmers: mean CRP, intra-cyclic SD of CRP, % of time spent in in-phase mode of coordination, the CRP at the beginning and at the end of the cycle, the maximum peak, the first minimum peak and the second minimum peak of CRP values, the times at which the maximum peak, the first minimum peak and the second minimum peak of CRP occurred. The results of the cluster analysis were described as a dendrogram.

2.6.3.2. Cluster validation. According to Breiman (1996) and Rein et al. (2010), the number of clusters and the classification of the subject in the cluster were validated by means of a bootstrapping procedure (called “bagging” which is applied to dendrogram and machine learning; Breiman, 1996). One bagging procedure corresponds to construct the dendrogram, then to repeat this operation on all subjects – 1 (one excluded at the time) and examine whether obtained classifications are stable or not. For example, if we removed subject 1, we observed if each subject remained in his initial cluster or if he switched from one cluster to another cluster).

Finally, the CRP variables which significantly differentiated the clusters were determined using the Fisher information. Fisher information corresponds to the ratio between inter-cluster and intra-cluster distances:

$$\text{Fisher information} = J_b/J_w \quad (6)$$

Inter-cluster distance (J_b) corresponds to:

$$J_b = \sum_g N_g d^2(\mu_g, \bar{X}) \quad (7)$$

where N_g is the number of element in the cluster g , d is the chosen distance, μ_g is the center of cluster g (i.e., the mean of all points in g), \bar{X} is the center of all the points (i.e., mean of all the points).

Intra-cluster distance (J_w) corresponds to:

$$J_w = \sum_g \sum_{i \in C_g} d^2(x_i, \mu_g) \quad (8)$$

where C_g are the points in cluster g , x_i is the value for each point.

The higher the Fisher information, the more discriminative are the variables. Based on the Fisher information, the cluster analysis was repeated several times, removing each variable one by one. A variable was considered significantly discriminative when the composition of the dendrogram (number of cluster and classification of the subject in the cluster) did not change in comparison to the initial result. All tests were conducted with Minitab 15.1.0.0[®] software (Minitab Inc., Paris, France, 2006) with a conventional significance level of $p < .05$.

3. Results

3.1. Differences between recreational and competitive groups

The competitive swimmers had higher speed, $F(1,23) = 163.57$, $p < .05$ (1.06 ± 0.08 vs. 0.83 ± 0.10 m s⁻¹), and stroke length, $F(1,23) = 46.57$, $p < .05$ (1.83 ± 0.26 vs. 1.51 ± 0.24 m stroke⁻¹) than recreational swimmers, but similar stroke rate (respectively, 0.58 ± 0.08 vs. 0.55 ± 0.08 Hz). The mean CRP curve of the recreational swimmers showed a “W-shape” with two minimal peaks of CRP and one maximal peak of CRP, whereas on average, the competitive swimmers had an “inverse U-shape” with one maximal peak of CRP (Fig. 2). Five variables significantly explained the difference of CRP curve shape between the two groups (Table 1).

3.2. Inter-individual coordination variability

As can be seen in Fig. 2, CRP had a high standard deviation (i.e., inter-individual variability). Furthermore there was greater inter-individual variability across the CRP curves of the 24 swimmers of the recreational group compared to those of the competitive group (Fig. 3). Indeed, the paired *t*-test revealed a significantly greater standard deviation of the CRP curves for the recreational group (the inter-individual standard deviation of CRP averaged through the complete cycle equalled 38.1°) than within the competitive group (the inter-individual standard deviation of CRP averaged over the entire cycle equalled 19.4°) ($p < .05$). Thus, the greater inter-individual variation of the recreational swimmers can be explored more thoroughly by coordination profiling analysis.

3.3. Inter-individual coordination profiling

The dendrogram that enabled us to classify the recreational swimmers in three clusters is shown in Fig. 4: cluster 1 comprised 6 subjects (S): S1, S3, S4, S7, S8, S11; cluster 2 comprised 9 subjects: S2, S10, S13, S14, S15, S16, S18, S19, S23; and cluster 3 comprised also 9 subjects: S5, S6, S9, S12, S17, S20, S21, S22, S24. Cluster 1, called “intermediate coordination”, fell between clusters 2 and 3, showing intermediate values of intra-cyclic coordination variability and time spent in the in-phase mode (Fig. 5a). Cluster 2, the “most variable coordination”, was characterized by the highest intra-cyclic coordination variability, and the most negatives values of CRP at the beginning and end of the curve (Fig. 5b). Cluster 3, called “in-phase coordination”, was characterized by the longest time of the cycle spent in the in-phase mode and by the lowest intra-cyclic coordination variability (Fig. 5c).

The cluster validation using the bagging procedure showed that the cluster composition changed when subjects S1, S4, S5, S7, S11, S16 and S20 were removed leading subjects S6, S21 and S24 to

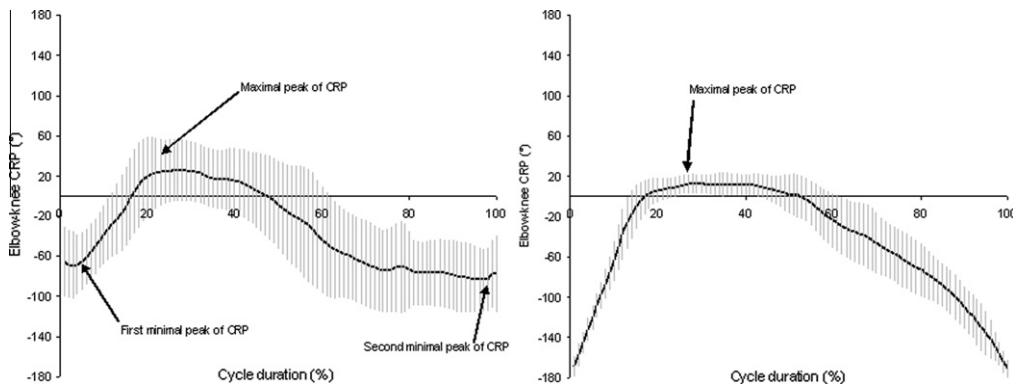


Fig. 2. Continuous relative phase (CRP) between elbow and knee through a complete cycle showing W-shape for the mean (\pm SD) of the recreational swimmers (left panel) in comparison to inverse U-shape for the mean (\pm SD) of the competitive swimmers (right panel).

Table 1

Difference in CRP variables between recreational and competitive swimmers. When homogeneity of variance or/and normal distribution were not verified, ANOVA tests were replaced by the non-parametric Kruskal–Wallis tests. NS means non-significant difference.

Variables	Skill level	Mean	SD	ANOVA	Kruskal–Wallis
CRP beginning	Recreational	−65.4	35.2		$Z = 5.94$ $H = 35.27$
	Competitive	−168.7	10.4		
CRP min1	Recreational	−80.4	26.4		$Z = 3.84$ $H = 14.71$
Timing of CRP min1	Recreational	5.0	5.1		
CRP max	Recreational	45.0	25.4		
	Competitive	20.3	11.6		
Timing of CRP max	Recreational	28.5	11.0	NS	NS
	Competitive	35.0	13.2		
CRP min2	Recreational	−105.1	31.4		
Timing of CRP min2	Recreational	81.2	11.2		
CRP end	Recreational	−77.4	38.5		$Z = 5.92$ $H = 35.02$
	Competitive	−170.7	11.0		
Mean CRP	Recreational	−33.1	25.2	NS	NS
	Competitive	−43.6	10.9		
SD of CRP	Recreational	47.25	14.3		$Z = 2.47$ $H = 6.12$
	Competitive	57.2	7.1		
% Cycle in-phase	Recreational	33.5	18.3	$F(1, 23) = 7.75$	
	Competitive	48.7	11.0		

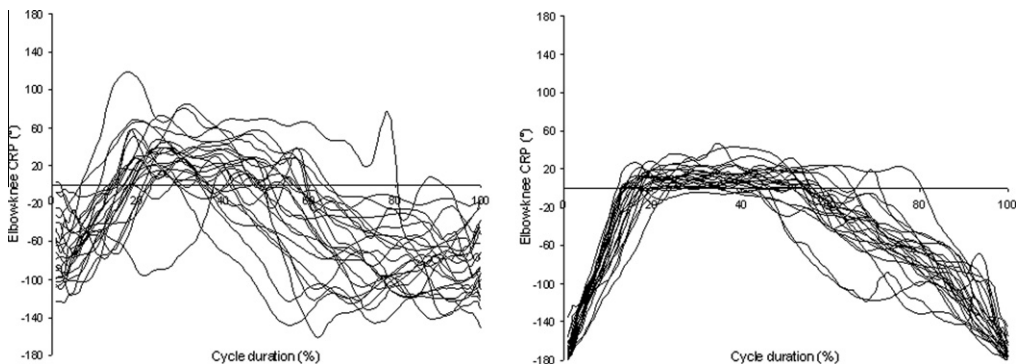


Fig. 3. Continuous relative phase (CRP) between elbow and knee through a complete cycle for the 24 recreational swimmers (left panel) and for the 24 competitive swimmers (right panel).

switch from cluster 3 to cluster 1. Furthermore, the cluster composition did not change when the 17 others subjects were removed one by one.

The Fisher information was used to classify the variables which further differentiated the three clusters; the ranking from the most discriminative to the least discriminative variable was: CRP end, CRP beginning, CRP min2, SD of CRP, mean of CRP, CRP min1, % of time spent in in-phase mode of coordination, CRP max, timing of CRP min1, timing of CRP min2, timing of CRP max (Table 2). However, the bagging procedure showed that when removing each variable one by one, the cluster composition only changed when CRP end, CRP beginning, mean of CRP, % of time spent in the in-phase mode of coordination and CRP max were removed from the analysis; in this last case, only subject S6, S21 and S24 switched from cluster 3 to cluster 1. In summary, the most discriminative variable to

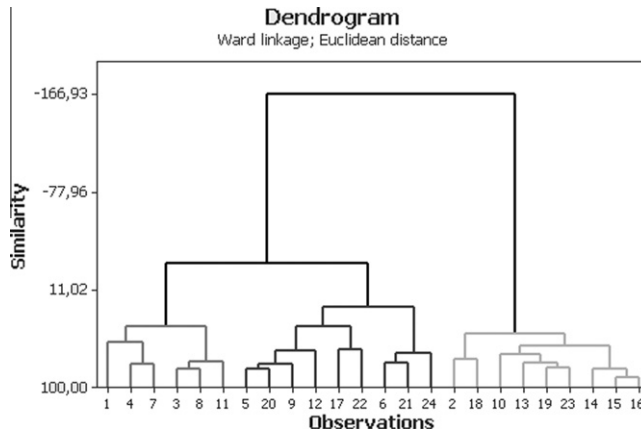


Fig. 4. Dendrogram of the hierarchical cluster analysis (with Ward linkage and Euclidean distance) presenting the classification of the 24 recreational swimmers in three clusters.

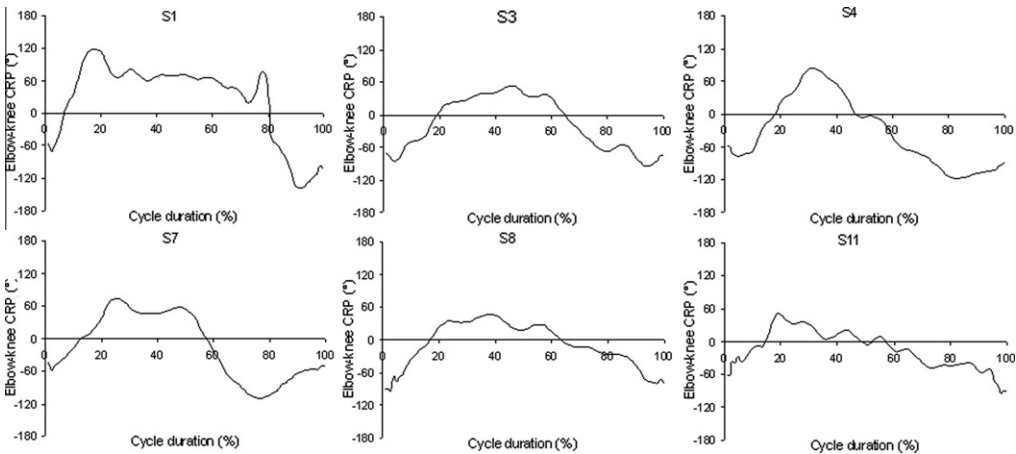


Fig. 5. Continuous relative phase (CRP) between elbow and knee through a complete cycle for the three clusters: 6 swimmers for cluster 1 (5a), 9 swimmers for cluster 2 (5b), 9 swimmers for cluster 3 (5c).

compose the three clusters could be: CRP end, CRP beginning, CRP min 1, CRP min2, CRP max, mean of CRP, SD of CRP, % of time spent in in-phase mode of coordination.

4. Discussion

4.1. Differences between recreational and competitive groups

The analysis of inter-individual variability via CRP curves provided an indication of the mechanical efficiency of the inter-limb coordination of swimmers. The “inverse U-shape” of the CRP curve of the competitive breaststroke swimmers showed an efficient in-phase coordination mode as the only part of the cycle spent within this mode was the glide with the body fully extended, starting at ~20% and finishing at ~60% of the cycle (and varying with swim speed (Chollet et al., 2004; Seifert et al., 2010)). Unlike the recreational swimmers who did not present a glide phase, the longer relative duration of the cycle found for the in-phase mode for the competitive swimmers arose from their time spent in

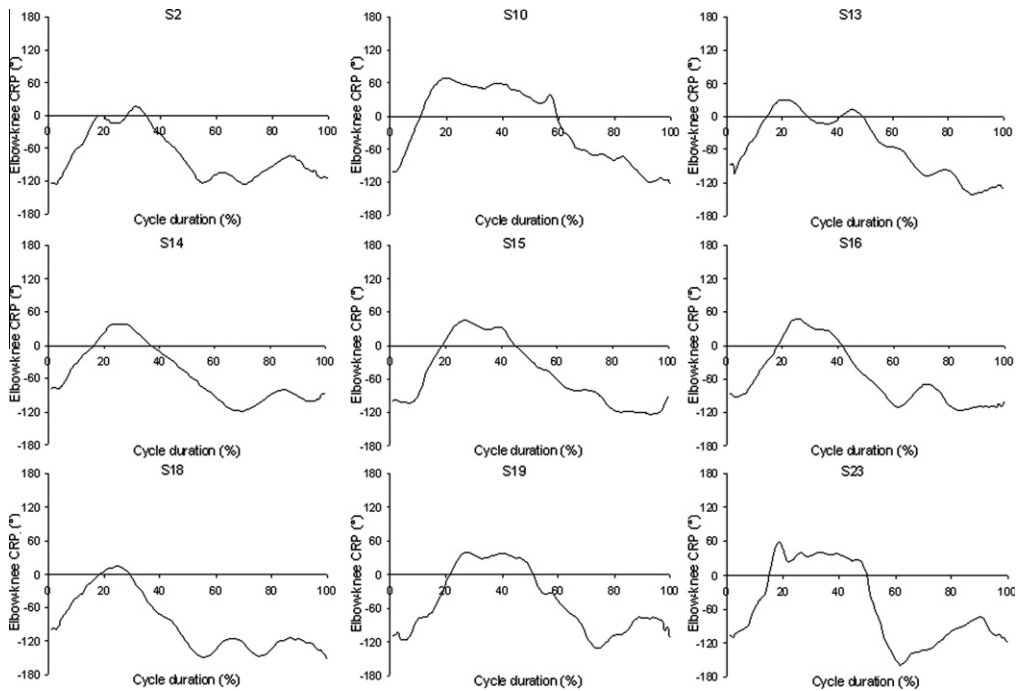


Fig. 5 (continued)

glide with the body in a streamlined position (cf. Leblanc, Seifert, & Chollet, 2009). For the rest of the cycle, the competitive swimmers showed great intra-cyclic variations of CRP (SD of CRP = 57.2°) that came from the out-of-phase mode, notably the combination of intermediate phase and anti-phase elbow–knee coupling: (i) the propulsion of one pair of limbs while the other pair of limbs glided in a hydrodynamic position (i.e., extended), and (ii) synchronization of the recovery of the arms and legs. In summary, this complex motor organization of the competitive swimmers corresponded to four phases in each complete cycle: (i) leg propulsion: the knee passed from maximal flexion at the beginning of the cycle to maximal extension at $\sim 20\%$ of the cycle (which corresponded to maximal peak of CRP) while the arms remained stretched forward; (ii) glide with the body fully extended (at 20–60% of the cycle); (iii) arm propulsion: the elbow passed from maximal extension at 50% of the cycle to maximal flexion at 80% of the cycle while the legs remained extended; (iv) arms and legs recovery: the arms passed from maximal flexion to maximal extension while the legs passed from maximal extension to maximal flexion.

Conversely, as recreational swimmers spent less time in glide with the body fully extended, the time spent in the in-phase mode of coordination (33.5% of the cycle duration) implies their elbow flexion (or extension) occurred at the same time as knee flexion (or extension), therefore the whole body movement resembled an “accordion-like” motion. In other words, the in-phase mode of elbow–knee coordination corresponded to simultaneous homologous muscular activations of the upper- and lower-limbs (Swinnen, Jardin, Meulenbroek, Douskaia, & Hofkens-van den Brandt, 1997). This kind of inter-limb coupling is inefficient as propulsion of one pair of limbs is thwarted by underwater recovery of the other pair of limbs (Tokuyama, Okamoto, & Kumamoto, 1976). The CRP values of the rest of the cycle mostly showed out-of-phase coordination mode with smaller intra-cyclic variations (SD of CRP = 47.2°) than in competitive swimmers. Moreover, the CRP curve looked like a “W-shape” where the two minimal CRP peaks indicated that knee extension had begun before elbow extension had been completely finished (as already remarked by Leblanc et al., 2009; Seifert et al., 2010; Tokuyama et al., 1976).

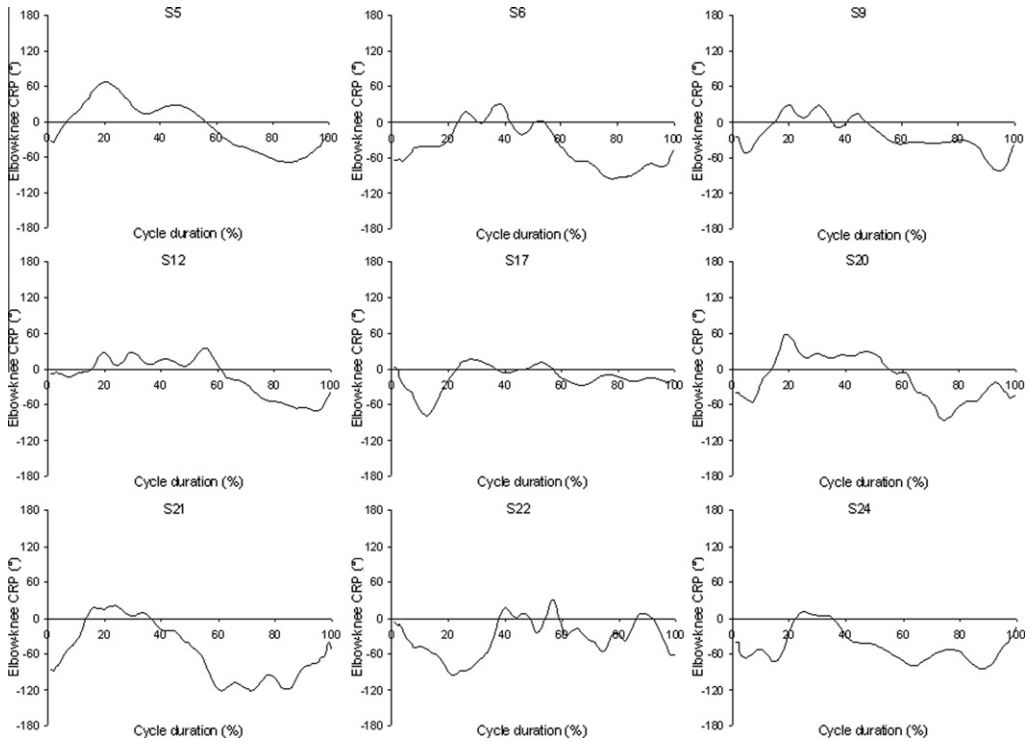


Fig. 5 (continued)

4.2. Inter-individual coordination variability

In this study all competitive swimmers used a “continuous” coordination mode, with more or less time spent in glide with the body fully extended, explaining the small inter-individual variability. Conversely, recreational swimmers did not reach this complex motor organization as they did not (i) glide with the arms and with the legs in extended position and (ii) alternate the propulsion. Therefore their two pairs of limbs always made a continuous flexion–extension movement that led to a partial or complete accordion motion (Seifert & Chollet, 2008), explaining the higher inter-individual variability in recreational than in competitive swimmers (respectively, SD of $CRP = 38.1^\circ$ vs. 19.4°).

4.3. Inter-individual coordination profiling

The higher inter-individual variability of the recreational group confirmed that several swimming style options were used by the less skilled swimmers, despite demonstrating a similar equitable level of performance in terms of speed and stroke length. In fact, the cluster analysis determined three global behaviors among the recreational swimmers, suggesting that swimmers within this group were at different stages in acquiring the expert behavior, and/or perceived differently the task constraint and the aquatic resistance.

Cluster 2 (called “most variable coordination”) was closest to the expert coordination. These swimmers showed the highest intra-cyclic coordination variability that was due to the most negative CRP value at the beginning and at the end of the cycle, the greater CRP value for the first and the second minimal peak of CRP , and for the maximal peak of CRP . These high CRP variations corresponded to the intermediate coordination mode between upper and lower-limbs and could indicate the progress in acquisition of both (i) the alternation between propulsion of one pair of limbs during the glide of

Table 2

Differences in CRP variables between the three clusters: higher is the Fisher information, more discriminative is the variables; notably, for a discriminative variable, inter-cluster distance should be higher than intra-cluster distance, in that case Fisher information >1.

Cluster		CRP beginning	CRP min1	Timing of CRP min1	CRP max	Timing of CRP max	CRP min2	Timing of CRP min2	CRP end	Mean CRP	SD CRP	% In-phase
Cluster 1	Mean	−63.9	−74.4	2.8	71.3	29.8	−105.4	91.0	−81.0	−10.5	53.4	29.0
<i>n</i> = 6	SD	15.1	14.0	1.5	27.7	11.2	20.6	10.3	18.2	19.2	14.9	16.6
Cluster 2	Mean	−98.7	−103.2	3.0	39.8	24.2	−132.2	79.8	−115.0	−54.4	56.4	22.3
<i>n</i> = 9	SD	13.8	13.4	2.1	17.9	4.1	15.2	13.1	20.2	19.0	7.8	7.4
Cluster 3	Mean	−33.2	−61.7	8.6	32.7	32.0	−77.9	86.0	−37.5	−27.1	33.9	47.7
<i>n</i> = 9	SD	28.5	26.3	6.9	18.5	14.8	26.2	12.9	15.9	17.2	8.2	18.9
Inter-cluster distance		18195.6	7525.0	173.7	5712.3	266.9	12520.3	805.8	25673.0	7017.0	2494.3	2925.3
Intra-cluster distance		9103.0	7901.9	430.1	8843.1	2477.7	8629.2	2909.5	6925.2	7107.6	1960.8	4592.6
Fisher information = (inter/intra)		2.0	1.0	0.4	0.6	0.1	1.5	0.3	3.7	1.0	1.3	0.6

the other pair of limbs, and (ii) the synchronization of the upper-limbs recovery with the lower-limbs recovery. For example, Fig. 6 shows that the swimmer S18 of cluster 2 (i) had the capability to produce a high peak of angular velocity during knee extension and elbow flexion, suggesting two distinct propulsions; (ii) glided with the legs extended (from 20% to 40% of the cycle) while arms started to propel; (iii) tried to synchronize their arm and leg recoveries at ~75% of the cycle (as observed in the competitive swimmers, Seifert et al., 2010). Thus, these swimmers perceived the aquatic resistances and tried to overcome them by using Newton's third law (i.e., action in one direction leads to a reaction in the opposite direction) by generating propulsion by accelerating limbs. However, these positive characteristics were counteracted by a slow recovery of the arms that finished during the propulsion of the legs (as the maximal elbow extension occurred at the same time as maximal knee extension, i.e., ~17% of the cycle). To conclude, the coordination of the swimmers of cluster 2 could be characterized by a “partial” superposition of contradictory actions (end of arms recovery during leg propulsion).

The swimmers grouped by cluster 3 (called “in-phase coordination”) showed an upper–lower coordination with less mechanical efficiency as they had the lowest intra-cyclic CRP variability and spent the longest time of the cycle in the in-phase mode. As illustrated in Fig. 7, swimmer S17 of cluster 3 spent 85% of the cycle in the in-phase coordination, meaning that his elbow flexion occurred at the same time as his knee flexion, and elbow extension occurred during knee extension. This coordination mode entails a “freezing” of degrees of freedom (as previously observed for making slalom-like movements on a ski-simulator, Vereijken, van Emmerik, Whiting, & Newell, 1992) and led to the lowest

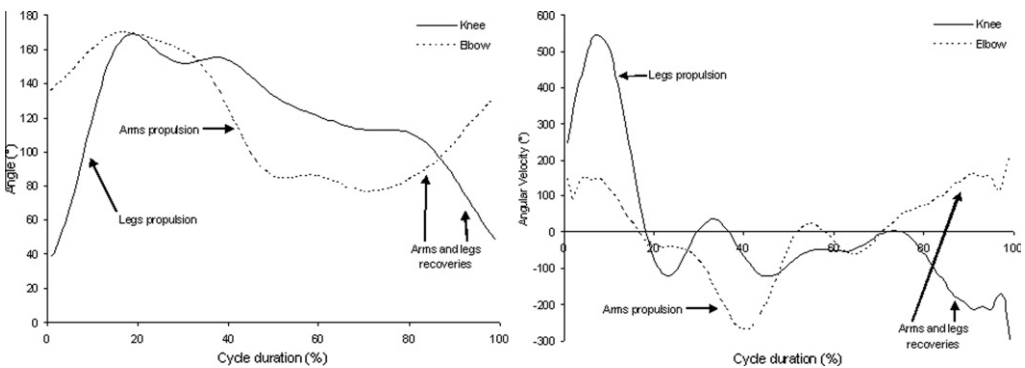


Fig. 6. Knee and elbow angular position (left panel) and angular velocity (right panel) through one complete cycle for the swimmer S18 of cluster 2.

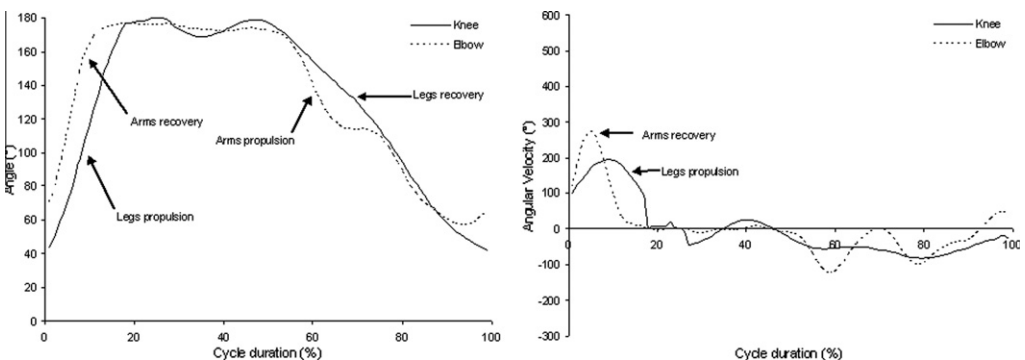


Fig. 7. Knee and elbow angular position (left panel) and angular velocity (right panel) through one complete cycle for the swimmer S17 of cluster 3.

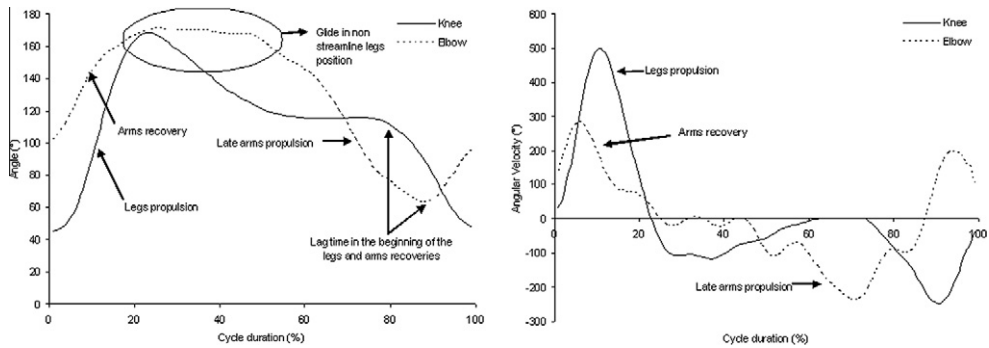


Fig. 8. Knee and elbow angular position (left panel) and angular velocity (right panel) through one complete cycle for the swimmer S3 of cluster 1.

coordination efficiency, as swimmer S17 completely superposed contradictory actions (propulsion of one pair of limbs during recovery of the other pair of limbs, see angular velocity in Fig. 7). Indeed, Fig. 7 shows similar shape and complete temporal superposition of the knee and elbow angular position and angular velocity. The main differences with the other clusters were (i) flexion and extension of each pair of limbs occurred in a homogeneous manner, without providing acceleration for propulsion but following a continuous movement preventing glide; (ii) the arms recovery only started at 93% of the cycle duration and reached 70° of extension when the legs started their propulsion (i.e., beginning of the cycle), whereas the arms recovery of S18 of cluster 2 reached 138° of extension when leg propulsion started (Fig. 6). Thus, for cluster 3, each action of one pair of limbs was completely counteracted by an action of the other pair of limbs, suggesting that these swimmers were in the first stage of breaststroke learning, as they mainly focused on floating (i.e., keeping the body at the water surface by making downward limb movements) instead of propelling forward (i.e., by making backward limb movements). The swimmers of this cluster had to dissociate propulsion from recovery, by including acceleration for propulsion and glide times.

The upper–lower coordination of swimmers within cluster 1 fell between that of clusters 2 and 3. For example, as shown in Fig. 8, swimmer S3 of cluster 1 had (i) a high peak of angular velocity during knee extension (as observed in S18 of cluster 2) but partially counteracted by the arm recoveries which occurred at the same time as leg propulsion (as observed in S17 of cluster 3); (ii) an intermediate value of arm extension (~100°) when leg propulsion started. In fact, the main problem of swimmer S3 of cluster 1 was the late beginning of arm propulsion that occurred at 50% of the cycle and so the late beginning of arms recovery (i.e., at 90% of the cycle) that caused a lag time with the beginning of legs recovery (i.e., at 80% of the cycle). It is due to the too long relative duration (30% of the cycle) spent with the body extended in a non-hydrodynamic position: the legs were extended between 160° and 100° from 20% to 50% of the cycle while the arms glide stretched forward. Previous studies have shown that a glide time could be appropriate in breaststroke, notably at slow speed to minimize active drag (Kolmogorov, Rumyantseva, Gordon, & Cappaert, 1997; Leblanc et al. 2009; Takagi, Sugimoto, Nishijima, & Wilson, 2004); however, the swimmer should adopt a streamlined position with the body fully extended. This intermediate group could be experimenting with Newton's third law, but not in a directly effective fashion as the spatial and temporal organization of the movement showed time gaps detrimental to go forward.

5. Conclusion

The CRP curve of the recreational swimmers showed an W-shape with two minimal peaks of CRP and one maximal peak of CRP, due to superposition of the propulsion of one pair of limbs with the recovery of the other pair of limbs, whereas the competitive swimmers had an inverse U-shape with one maximal peak of CRP, due to propulsions alternation and glide times. Higher inter-individual

variability was observed in recreational swimmers, showing that the superposition of propulsion of one pair of limbs with recovery of the other pair of limbs (i.e., contradictory actions) could be “partial” or “complete”. It came from angular position and velocity differences observed among the three clusters used to classify the recreational swimmers. Although the three clusters of the recreational swimmers reached similar performances, they seemed to be not at the same stage of the learning process and did not perceive the same environmental and task constraint as they exhibited different behaviors. Some recreational swimmers could be just starting to explore Newton's third law while others already exploited aquatic resistances, distinguishing propulsion and recovery, creating acceleration and glide. In other words, some swimmers focused on floating while others organized their inter-limb coordination to propel forward.

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