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Adaptability in swimming pattern: how do swimmers modify propulsive action as a function of speed?

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Abstract

We aimed to examine how participants of different skill level adapt their stroke when asked to swim at different speeds. 20 subjects divided into (a) low- (n=6), (b) medium- (n=8), and (c) high-(n=7) expertise level swam in front crawl at four different swim paces of 60, 70, 85 and 100% of their maximal speed in a swimming flume. Eight force sensors placed on the dominant hand helped to determine kinetic parameters (force impulse over 5sec I^+ ; arm stroke impulse $I^+_{/arm}$, which are calculated on integral of the force-time curve). Stroke frequency (SF), stroke length (SL), stroke index (SI), Index of coordination (IdC), propulsive phase duration both in percentage of total cycle (PrP%) and absolute duration (PrPs) were determined using four underwater cameras. Results showed that those populations clearly differ in SL and SI, both indicators of swim efficiency. Whatever the skill, increase in swim speed is highly correlated with I^+ . However, no clear conclusion could be drawn from the magnitude of kinetic (I^+ , $I^+_{/stroke}$, $F_{average}$, P_{pull} , P_{push}) and coordination (IdC, PrP%, PrPs) parameters, which were similar in magnitude in low- and high-level swimmers. But examination of adaptive strategies showed that if all swimmers increased I^+ by increasing their stroke frequency, medium- and high-level swimmers were capable of reorganizing inter-arm movement coordination patterns to increase $I^+_{/arm}$. This study shows how more skilled swimmers adapt their coordination in a subtle way to get attuned with their environment.

Keywords: motor control, expertise, force, coordination.

List of acronyms

I^+ : force impulse over 5 seconds

$I^+_{/arm}$: force impulse over 1 cycle in the right hand

SF: stroke frequency

F_{pull} : force (in N) developed during pull phase

F_{push} : force (in N) developed during the push phase.

PrPs: absolute time of propulsive phase duration (in s)

PrP%: time of the relative duration of the propulsive phase.

1. Introduction

Complex behaviour arises from the inter-relationship, interaction and interconnectivity of elements within a system and between a system and its environment [4]. The emergence of behaviour in sport has been characterized as an adaptive complex system which depends upon organismic, task, and environmental constraints [2]. Put up simply, moving forward represent the task constraint in swimming. To achieve this goal, propelling actions to overcome drag are produced. Environmental constraints are mostly linked to water physical properties (density and fluidity), which supports propulsion but also generates drag; last, organismic constraints consist in individual biometric characteristics, but also level of expertise. To move forward, swimmers thus generate force impulses with several part of their. If skill level influences drag-speed relationship [10], it is unclear from the literature how it affects force impulse generation.

Mathematically, an impulse is defined as the time integral of the resultant force acting on a body [5]. Over a fixed period of time, the total impulse, I^+ , expressed in Newton.second (N.s), is the integral over time of the total force production (Equation 1)

$$\text{Equation 1: } I^+ = \int_{t_2}^{t_1} F(t)dt \text{ (N.s)}$$

In swimming, speed is produced by a series of propulsive impulses generated by both arms and legs. If we consider swim speed being relatively constant from cycle to cycle, the total impulse I^+ can be considered as being the sum of this discrete impulse (Equation 2):

$$\text{Equation 2: } I^+ = n \times (I_{\text{right arm}}^{+/} + I_{\text{left arm}}^{+/} + I_{\text{right leg}}^{+/} + I_{\text{left leg}}^{+/})$$

n: number of cycle during the period considered

$I_{\text{right arm}}^{+/} + I_{\text{left arm}}^{+/} + I_{\text{right leg}}^{+/} + I_{\text{left leg}}^{+/}$: discrete impulses from arms (right and left) and legs (right and left) during a swim cycle.

If a swimmer wants to increase his/her average swim speed, he/she will have to find ways to increase his total propulsive force impulse (I^+), or decrease his hydrodynamic drag. This goal can be achieved by increasing the frequency of the impulses, or increasing the magnitude of within cycle impulses, or by simultaneously increasing both of these factors. Within cycle, the different impulses (eg: $I_{\text{right arm}}^{+/}$) can be increased either (a) by increasing the amplitude of the force, (b) by increasing the duration of the force, (c) by increasing both amplitude and duration.

Past studies showed that when a swimmer increases his/her speed, an increase in stroke frequency (SF) and a modification in relative duration of propulsive time (in percentage) occurs. But no study so far examined how the magnitude of the within cycle impulses was affected, and if these adaptation were skill-dependent.

In the present study, we aim to provide an insight of swimmers' adaptability as a function of skill level by for the first time recording simultaneously kinematical and kinetical parameters in ecological conditions.

2. Methods:

Twenty male swimmers sub-divided into three distinct categories: low-, medium-, and high-level of expertise participated in the present study (see Table 1).

Table 1: Main characteristics of the participants

Expertise level	Training /week (hours)	Age (years)	Hand surface area (cm ²)	Maximal speed (m.s ⁻¹)	% of world record speed (100m)
Low (n=6)	0.5	32.5±4.0	165±25	1.24±0.05	45.4±3.7
Medium (n=6)	4	27.0±7.5	172±16	1.54±0.1	69.3±4.9
High (n=8)	14	18.7±2.9	159±14	1.82±0.05	82.5±2.6

The swim trials took place in a motorised aquatic flume. Participants had to swim at four individual-specific speeds relative to their maximal speed: v_1 (60%), v_2 (70%), v_3 (85%), v_4 (100%). The kinematic parameters taken into account were: stroke frequency (SF), stroke length (SL), stroke index (SI), propulsive phase duration (PrP%), coordination parameters (IdC). They were determined using the method described by Seifert et al. [7].

To determine force parameter four pairs of mono axial pressure sensors (Kyowa, Tokyo, Japan) were glued to the surface of a glove. Due to technical limitations, only the results from one hand (the dominant one) could be recorded. Total resultant force was then calculated by applying Takagi and Wilson's method [9].

To calculate force impulse, video and force curve were superimposed on a single graphical user interface. The force signal was cropped and reconstructed so that only the force developed during propulsive time determined previously (pull and push phases) was taken into consideration. Force impulse over 5 seconds (I^+) was calculated by numerical integration. The discrete impulse for 6 hand cycle was determined and then averaged to obtain an estimate of the average impulse per hand cycle ($I^+_{/stroke}$). Also, from the force curve, the two main peak forces were determined during pull (F_{pull}) and push (F_{push}) phase, and taken as indicators of the magnitude of the force within the cycle. The absolute duration (PrPs, in seconds) of the propulsive phase of the arm was also measured.

To analyse the data, a series of two-ways ANOVAs for repeated measures [repeated factor: pace] were used to compare the mean values for each variable as a function of pace and expertise level. To detect significant differences, Tukey's post hoc tests were used. The threshold for significance was set at the 0.05 level of confidence. For the statistical analysis, Minitab 15.1 was used.

3. Results

When increasing swim speed, all swimmers increased SF, I^+ and IdC ($p < 0.05$). Swim speed, SL and SI discriminated among skill levels. The IdC was higher in low- and high-skilled level than in medium-level group ($p < 0.05$).

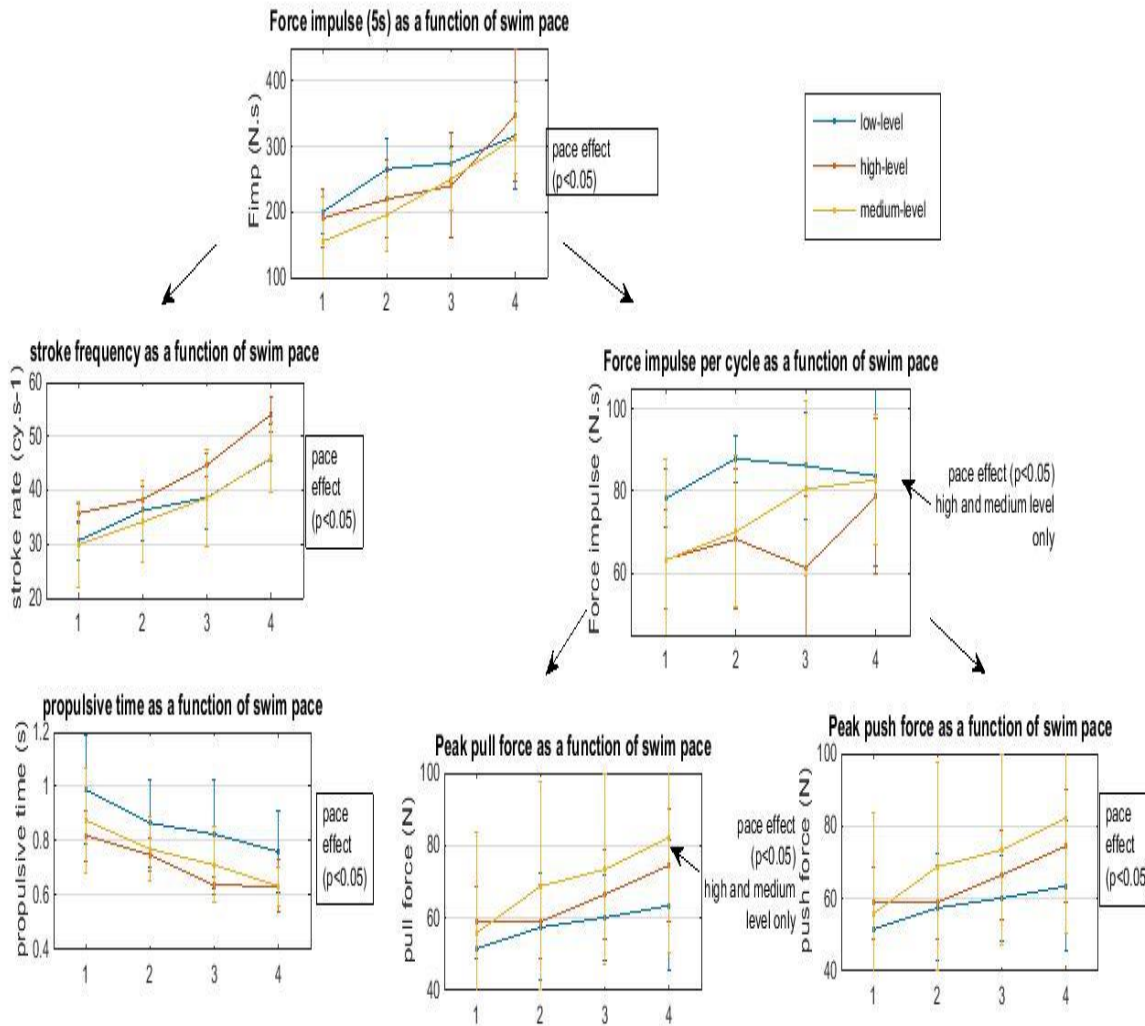


Fig. 1: Force impulse, stroke frequency, force impulse per cycle, propulsive time, peak pull and push forces as a function of pace and skill level.

Figure 1 examines the determinant of I^+ as a function of skill and pace. In all populations, I^+ increases over pace is obtained by a subsequent increase in stroke frequency. However force impulse per cycle ($I^+_{/stroke}$) only increased in medium (63 ± 6.7 vs 83 ± 7.3 N.s, $p < 0.05$) - and high (63 ± 7.2 vs 78 ± 7.2 N.S, $p < 0.05$)-expertise level from pace 1 (slow) to pace 4 (sprint). Absolute propulsive time per stroke (PrPs) decrease of $\sim 24\%$ when swim speed increases in all populations. Only medium- and high-expertise level were capable of increasing both peak pull and peak push forces when increasing swim speed (high level: 58 vs 74N for pull, 69 vs 82 N for push phase; medium level: 55 vs 82 N for the pull phase, 65 vs 97 N or the push phase). This suggests that, for medium and high level swimmers, $I^+_{/stroke}$ is increased by an in the magnitude of the force developed rather than by the propulsive time duration.

4. Discussion

The objective of this study was to examine and compare the motor adaptive behaviour of swimmers with different skill levels when they increase their swim speed. Main results were twofold: first, the magnitude of the total impulse (I^+) generated during 5 sec is not skill

dependent. Second, if I^+ increase with swim speed, only medium- and high-level swimmer are capable of increasing $I^+_{/stroke}$ simultaneously scaling up stroke frequency and discrete impulse.

Propulsive impulses are generated by swimmers to move forward, therefore overcoming drag encountered. In that, better swimmers are characterized by a capacity to produce propulsive impulses of higher magnitude, and/or exhibit lower drag at similar swim speeds [1-10]. Seifert et al. [8] suggested that lower-level swimmer tended to increase swim speed while increasing SF and IdC but not tangential hand speed, which suggested that their hand tended to “slip” through the water. Our data do not support this hypothesis, since the magnitude of the impulses is no different among skill level. Here, only measurement of the force exerted perpendicular to the hand were taken into account. In other words, we did not measure the efficient component of the force, that is, the component used for propulsion. However, both SL and SI, which both are indicators of swim efficiency, strongly differentiate between skill levels. In accordance with Toussaint et al. [10], those data suggest that this is not the capacity to generate high force impulses (I^+) that differentiate among skill level, but rather the capacity to reach high values of propulsive efficiency.

In what concern kinematical adaptations, all swimmers increase their propulsive impulse (I^+) while swimming faster. This was obtained only by increasing SF in low-level swimmers (strategy 1), whereas middle- and high-expertise level increased both SF and $I^+_{/cycle}$ (strategy 3). So despite the fact that all participants increased their SF, IdC, propulsive peaks, and decreased their PrP(s), only middle- and high-expertise level could scale up the magnitude of the force to allow $I^+_{/cycle}$ to increase despite a decrease in PrP(s). Leblanc et al. [3] already observed such phenomenon in breaststroke: whereas expert swimmers were capable of adapting different speeds by modifying the coordinative mode, non-expert only changed speed by altering SF.

Those data suggest that such situation make hard for low-level swimmers to produce efficient component at the highest speeds, and confirms that adaptability is a particularity of expert performance [6]. In accordance with past studies, those findings confirm that expertise is characterized by swim efficiency, but also that adaptability in itself is a key-element into differentiating among skill levels.

However, due to technical limitation, our study was unable to provide a full picture of swimmer’s adaptability. Indeed, only part of the discrete impulses (one hand) could be observed; and as we outlined earlier, the magnitude of the efficient component could only be estimated. But despite those limitations, this study provides a significant breakthrough in the biomechanical measurements in swimming. By using force sensors, we were for the first time able to measure force production in an ecological situation; moreover, combining force and videos helped to determine in a much more precise and objective way the duration of the propulsive time, therefore providing a much more reliable idea of swimmers’ behavioural adaptation with speed. Still, confirmatory studies measuring impulses from other part of the body and that takes into consideration efficient component of the force are necessary.

5. Conclusion

The capacity to exhibit adaptive behaviour in highly constrained environment has often been pointed out to be a characteristic of expert performance in sport. In swimming, actions of experts are mostly dedicated to lower active drag and generate propelling action as efficient as possible. The present study shows that expertise could also be characterised in terms of level of adaptability, that is, more capacity to modify coordination and force production to adequately adapt constraints. In that sense, analysis of expert performance in sport seems to be an adequate paradigm to examine how adaptability is important to characterize complex systems.

6. Scientific Validation

This paper has been unanimously validated in a collaborative review mode with the following reviewers:

- Reviewer 1 Ricardo Fernandes, Faculty of Sport, University of Porto
- Reviewer 2: Carlota Torrents Martins, C University of Lleida (Spain)
- Reviewer 3: Alice Della Penna, CRI, Paris

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