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Ludovic Seifert, Huub Toussaint, Morgan Alberty, Christophe Schnitzler, Didier Chollet. Arm coordination, power, and swim efficiency in national and regional front crawl swimmers. *Human Movement Science*, 2010, 29 (3), pp.426. 10.1016/j.humov.2009.11.003 . hal-00640441

HAL Id: hal-00640441

<https://hal.science/hal-00640441>

Submitted on 12 Nov 2011

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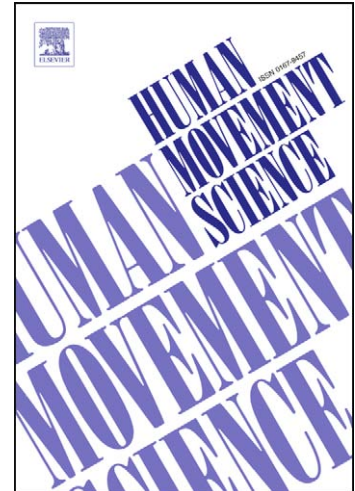
Accepted Manuscript

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PII: S0167-9457(09)00113-4
DOI: [10.1016/j.humov.2009.11.003](https://doi.org/10.1016/j.humov.2009.11.003)
Reference: HUMOV 1191

To appear in: *Human Movement Science*



Please cite this article as: Seifert, L., Toussaint, H., Alberty, M., Schnitzler, C., Chollet, D., Arm coordination, power, and swim efficiency in national and regional front crawl swimmers, *Human Movement Science* (2009), doi: [10.1016/j.humov.2009.11.003](https://doi.org/10.1016/j.humov.2009.11.003)

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Arm coordination, power, and swim efficiency in national and regional front crawl swimmers

Abstract

The effects of skill level on index of arm coordination (IdC), mechanical power output (P_d), and swim efficiency were studied in front crawlers swimming at different speeds. Seven national and seven regional swimmers performed an arms-only intermittent graded speed test on the MAD-system and in a free condition. The MAD-system measured the drag (D) and P_d . Swimming speed (v), stroke rate (SR), stroke length (SL), stroke index (SI), relative entry, pull, push, and recovery phase durations, and IdC were calculated. Swim efficiency was assessed from SI, the coefficient of variation of calculated hip intra-cyclic velocity variations (IVV), and the efficiency of propulsion generation, i.e., the ratio of v^2 to tangential hand speed squared (u^2). Both groups increased propulsive continuity (IdC) and hand speed (u) and applied greater P_d to overcome active drag with speed increases ($p < .05$). This motor organization adaptation was adequate because SI, IVV , and v^2/u^2 were unchanged. National swimmers appeared more efficient, with greater propulsive continuity (IdC) and P_d to reach higher v than regional swimmers ($p < .05$). The regional swimmers exhibited a higher u and lower SI, IVV , and v^2/u^2 compared to national swimmers ($p < .05$), which revealed lower effectiveness to generate propulsion, suggesting that technique is a major determinant of swimming performance.

Key words: biomechanics, motor control, expertise, drag, swimming.

PsycINFO Classification: 2330, 3720

1. Introduction

Swimming is a cyclic form of locomotion in the aquatic environment whereby propulsion is generated to overcome resistive forces. Therefore, the goal for competitive swimmers is to maximize propulsion while minimizing drag, given a finite metabolic capacity. As expressed in Equation 1, swimming speed (v) depends on total energy expenditure rate (\dot{E}), propulsive efficiency (e_p), mechanical efficiency (e_m), and resistive forces (D):

$$v = \dot{E} \cdot e_p \cdot e_m \cdot D^{-1} \quad (\text{Equation 1})$$

In variable swimming movement, the same change in speed (v) considering a given period of time defines the acceleration (a) and is dependent on the applied resultant force (F) and the inertial term of the equation of movement:

$$F = m \cdot a \quad (\text{Equation 2})$$

where F is the resultant force from propulsion (P) and drag (D):

$$P + D = m \cdot a \quad (\text{Equation 3})$$

Thus, variable movement is: (i) the result of a circumstantial prevalence of P or D , or (ii) a consequence of an increased (or reduced) added mass effect during a given swim cycle.

To assess some of the performance characteristics of a swimmer in practice, several stroking parameters are measured (swimming speed, v ; stroke rate, SR ; stroke length, SL ; and stroke index, SI) (Costill et al., 1985; Craig & Pendergast, 1979), where v relates to SR and SL according to Equation 4:

$$v = SR \cdot SL \quad (\text{Equation 4})$$

and SI to v and SL according to Equation 5 (Costill et al., 1985):

$$SI = v \cdot SL \quad (\text{Equation 5})$$

In uniform movement, acceleration is null ($a = 0$ and $v = v_0$), which means $P = D$. Thus, to swim at constant speed, swimmers must overcome the resistive forces of water, i.e., the active drag (D) that increases with speed squared (Toussaint & Truijens, 2005) (Equation 6):

$$D = K \cdot v^2 \quad (\text{Equation 6})$$

where K is a constant of proportionality depending on body size and shape: $K = 0.5 \cdot C_d \cdot A_p \cdot \rho$, C_d is the drag coefficient, A_p is the projected frontal area, and ρ is the density of water.

To overcome this active drag, the swimmer applies a certain amount of work per stroke (W_d) corresponding to the product of SL and drag force (Equation 7):

$$W_d = D \cdot SL \quad (\text{Equation 7})$$

Thus, the mechanical power output to overcome drag (P_d in W) is related to the product of the work generated per stroke and the swimmer's SR (Equation 8):

$$P_d = W_d \cdot SR \quad (\text{Equation 8})$$

Combining Equations 7 and 8:

$$P_d = D \cdot v \quad (\text{Equation 9})$$

While part of the total mechanical power output (P_o) is used beneficially to overcome active drag (P_d), another part is dissipated in the water as kinetic energy when water is accelerated in the process of propulsion generation (P_k) (Toussaint et al., 1988), so total power output P_o equals:

$$P_o = P_k + P_d \quad (\text{Equation 10})$$

The mechanical efficiency (e_m) is calculated as the ratio of the energy equivalence of oxygen uptake to the P_o delivered, while the propulsive efficiency (e_p) quantifies the useful power for body translation (Equation 11) (Lighthill, 1975; Toussaint et al., 1988):

$$e_p = P_d / P_o \quad (\text{Equation 11})$$

Propulsion is generated by the movement of propelling surfaces, e.g., the hands and feet; however, the relative contribution of the feet is much reduced (Deschodt, Arsac, & Rouard, 1999). Wiegand, Wuensch, and Jaehnig (1975) were the first to relate swimming v and hand speed to determine propulsive and resistive phases in the arm stroke; Martin, Yeater, and White (1981) later proposed a model to assess arm stroke efficiency, which was then adapted by Zamparo, Pendergast, Mollendorf, Termin, and Minetti (2005). This model assumes that the arm is a rigid segment of length l rotating at constant angular speed (ω) about the shoulder, which enables the calculation of tangential hand speed (u) (Equations 12 and 13):

$$\omega = 2\pi \cdot SR \quad (\text{Equation 12})$$

$$u = \omega \cdot l \quad (\text{Equation 13})$$

In this model, the efficiency of propulsion generation (e_{pg}) is quantified as the ratio between v and SR, which is directly related to u and calculated over the underwater part of the cycle, corresponding to half of a complete arm cycle (Equation 14):

$$e_{pg} = (v / (2\pi \cdot SR \cdot l)) \cdot (2 / \pi) \quad (\text{Equation 14})$$

The e_{pg} was close to 0.42-0.55 when expert front crawl swimming speed varied from 1 to 1.4 m.s⁻¹ (Zamparo et al., 2005); it did not change with gender but varied with age (0.31 before puberty, 0.38-0.40 at about 20 years, 0.25 at about 40 years) (Zamparo, 2006). Toussaint, Carol, Kranenborg and Truijens (2006) showed that during four 25-m bouts of a 100-m all-out, mechanical power output and hand speed (u) respectively decreased from 200 to 150 W and from 2.14 to 1.91 m.s⁻¹ while the e_{pg} , calculated as the v^2/u^2 ratio, tended to slightly (but not significantly) decrease from 0.63 to 0.60. Performance seemed linked to high hand forces, mechanical power output, and hand speed, and it was found to decrease with fatigue (Toussaint et al., 2006).

The previous calculation of e_{pg} does not take into account the intra-cyclic velocity variation (*IVV*). In fact, the swimming speed is not uniform as the application of propulsive forces in water leads to acceleration and deceleration within the cycle, i.e., of the center of gravity *IVV* (Fujishima & Miyashita, 1999; Miller, 1975; Miyashita, 1971; Nigg, 1983). Therefore, to accurately measure efficiency, an estimation of the extra power output wasted with *IVV* is required (Miller, 1975; Nigg, 1983). Generally, higher *IVV* has been correlated to an increased rate of the energy expenditure of swimming (Alves, Gomes-Pereira, & Pereira, 1996; Barbosa et al., 2005, 2006) caused by a power term related to the acceleration and deceleration of the center of gravity. Notably, Nigg (1983) predicted that a speed change of 10% within a stroke cycle resulted in an additional work demand of about 3%, suggesting that the best solution to increase the capacity to produce propulsive forces while minimizing power output seems to be to reduce *IVV*.

One way to minimize *IVV* would be to organize the inter-limb coordination well, as the propulsive continuity of the two arms in front crawl would permit the swimmer to minimize the deceleration between two propulsions and, therefore, increase swim efficiency. To assess the inter-arm coordination in front crawl swimming, Chollet, Chabies, and Chatard (2000) developed an index of coordination (*IdC*) which quantifies the lag time between the propulsive actions of the two arms. When the swimming speed increased from slow to fast paces, *SR* increased while *SL* decreased, and *IdC* increased to reflect a shift from catch-up (lag time between the propulsions) to a relative superposition (overlap of the propulsions) coordination mode (Chollet et al., 2000; Seifert, Chollet, & Rouard, 2007). Expert swimmers reached

greater v , which could be ascribed to their greater SL and propulsive continuity (greater IdC) than less expert swimmers, both during speed incremental tests (Chollet et al., 2000; Seifert, Chollet, & Rouard, 2007) and 100-m races (Seifert, Chollet, & Chatard, 2007). A study on the effect of fatigue on stroking characteristics revealed that fatigue development induced an increase in SR and IdC to compensate for the reduced capacity to generate a propulsive impulse per stroke. The change in arm coordination allowed a better chain of the propulsive actions and led to more time allotted to propulsion per distance unit. Such motor adaptation ensured that the overall propulsive impulse remained constant, whereas average propulsive force per arm stroke was reduced (Alberdy, Sidney, Pelayo, & Toussaint, 2009). Seifert, Chollet, and Rouard, (2007) postulated that an increase in environmental constraints, notably active drag, would necessitate the increase in IdC. In fact, above a critical speed ($1.8 \text{ m}\cdot\text{s}^{-1}$) and SR (0.83 Hz) (Potdevin et al., 2003; Seifert, Chollet, & Rouard, 2007), superposition coordination was the main motor solution observed. For expert swimmers, the changes in inter-limb coordination appeared efficient because *IVV* did not increase over eight trials of 25-m at increasing speed (Schnitzler, Seifert, Ernwein, & Chollet, 2008). However, this assumption has not yet been supported by published data showing the implied relationships between active drag and inter-limb coordination changes with speed and the efficiency of these changes with regard to the swimmer's skill level.

The aim of the present study was thus to examine how a combined group of national and regional swimmers organized their stroke (i.e., their inter-limb coordination and their power output application) to increase v , and more particularly how the national swimmers changed their coordination when swimming at higher speeds. It was also examined whether, for a given speed, the stroke organization of the national swimmers would be more efficient (the latter assessed by *IVV* and changes in SI and the e_{pg} , i.e., v^2/u^2). It was hypothesized that the increase in speed would lead to greater IdC, mechanical power output, and efficiency for the national swimmers, indicating that their change in coordination was more efficient and enabled them to reach higher v than regional swimmers.

2. Method

2.1. Participants

Fourteen French male swimmers separated into two skill levels volunteered for this study. The first group was composed of seven national swimmers for whom the mean \pm standard deviation of age, body mass, height, arm span, and arm length was: 21.9 ± 4.2 years, 80.7 ± 7.0 kg, 1.86 ± 0.04 m, 1.93 ± 0.07 m, 0.65 ± 0.03 m, respectively. At the time of the experiment, they were training 20.0 ± 1.0 hours per week and had 11.6 ± 2.5 years of practice, which indicates expert skill, according to Ericsson and Lehmann (1996). Their mean performance for the 100-m front crawl in the long pool was 51.3 ± 2.3 s, which corresponds to a national rank and is $90.2 \pm 3.9\%$ of the 2007 world speed record. The second group was composed of seven regional swimmers for whom the mean \pm standard deviation of age, body mass, height, arm span, and arm length was: 21.7 ± 3.1 years, 73.6 ± 9.4 kg, 1.81 ± 0.07 m, 1.84 ± 0.07 m, 0.64 ± 0.02 m, respectively. At the time of the experiment, they were training 9.4 ± 4.3 hours per week and had 8.0 ± 4.3 years of practice. Their mean performance for the 100-m front crawl in the long pool was 56.8 ± 1.9 s, which corresponds to a regional rank and is $81.5 \pm 2.8\%$ of the 2007 world speed record. The protocol, approved by the university ethics committee, was explained to the swimmers, who then gave their written consent to participate.

2.2. Protocol

The swimmers performed two intermittent graded speed tests in randomized order, using an arms-only front crawl stroke (using a pull-buoy): one on the MAD-system (10 bouts of 25-m) and one in the free swimming condition (8 bouts of 25-m), from slow ($\sim 60\%$) to 100% of maximal speed (with an absolute increment of $0.05 \text{ m}\cdot\text{s}^{-1}$, which corresponded to a relative increment of 5% of maximal speed). The bout was self-paced to avoid the speed variations that can arise when the swimmer follows a target. Thus to be sure that the normalized v (expressed in % of maximal speed) on the MAD-system and in the free condition were close for each bout, two more bouts were allowed on the MAD-system as this condition was uncommon for the swimmers. Four minutes of rest were given before the next bout was swum.

a. 2.3. Video analysis in the free condition

Swimmers were video-taped by two underwater video cameras (Sony compact FCB-EX10L, $f = 50$ Hz), with one camera placed to obtain a frontal view and the other to obtain a side view. The frontal

underwater camera was fixed on the edge of the pool, 0.4 m below the water. The side underwater camera was fixed on a trolley and an operator followed the swimmer's head to avoid parallax. Both cameras were connected to a double-entry audio-visual mixer, a video timer, a video recorder, and a monitoring screen to mix and genlock the frontal and side views on the same screen. A third camera mixed with the side view for time synchronization video-taped all trials with a profile view from above.

b. 2.4. Graded speed test on MAD-system

For the graded speed test, the swimmers swam on the MAD-system, which allowed them to push off from fixed pads with each stroke. These push-off pads were attached to a 22-m rod and the distance between them was 1.35 m. The rod was mounted 0.8 m below the water surface and was connected to a force transducer, enabling direct measurement of push-off forces for each stroke. Assuming a constant mean swimming speed, the mean propelling force equals the mean drag force (D in N). Hence, swimming one bout on the system yields one data-point for the speed-drag curve (Toussaint & Truijens, 2005). Using Equation 6, the relationship between drag force and speed was established for each swimmer and thus the individual K factor was determined. The mechanical power output (P_d) was then calculated for each speed, according to Equation 9. Finally, the power output for each swimmer was assessed through the ratio $P_{d\ max}/K$, where $P_{d\ max}$ represents the maximal power output developed at the fastest bout.

c. 2.5. Stroking parameters

The lateral view of the free swimming condition allowed the calculation of the average speed (v_{free} in $\text{m}\cdot\text{s}^{-1}$) over a 10-m distance (from 10-m to 20-m) using the swimmer's head as the marker. Over this distance, a mean period (defined as the time that separates two consecutive entries of the same hand in the water) was determined with the video timer on three consecutive arm stroke cycles (T_{cycle}) taken in the 10-m central part of the pool. An average stroke rate value ($\text{SR}_{\text{free}} = 1/T_{\text{cycle}}$ in Hz) was calculated. The stroke length (SL in m) was calculated from v and SR using Equation 4. The stroke index (SI) was calculated from v and SL according to Equation 5. During the MAD-system condition, the average speed (v_{MAD}) was calculated from the time spent to cover the 18.9-m distance between the second and last pads. The average stroke rate (SR_{MAD}) was calculated from the duration of each stroke, which was the time

separating the push-off between two pads. As has been done previously (Toussaint et al., 2006), the v and SR data were normalized in percentage of the maximal value reached at the fastest bout. Eight of the ten bouts performed on the MAD-system, corresponding to the same intensity of the eight bouts swum in the free swimming condition, were selected. Then the normalized v and SR were compared between the free swimming and MAD-system conditions.

d. 2.6. Coordination of arm movements

In line with Chollet et al. (2000), four arm phases per stroke were determined from the two underwater views recorded in the free condition. *Phase A*: entry and catch of the hand in the water. This corresponded to the time from the hand's entry into the water to the maximal forward coordinate of the hand, which also marked the beginning of its backward movement. *Phase B*: pull. This corresponded to the time from the beginning of the hand's backward movement to the hand's arrival in the vertical plane to the shoulder. This phase was the beginning of propulsion. *Phase C*: push. This corresponded to the time from the hand's position below the shoulder to its release from the water. *Phase D*: recovery. This corresponded to the time from the hand's release from the water to its following entry into the water.

The key motor points of the arm phase were determined every 0.02 s (since $f = 50$ Hz) by three independent operators measuring with a blind technique, i.e., without knowing the results of the analyses of the two other operators, as previously described (Seifert et al., 2006). The three analyses were then compared. When the differences were < 0.04 s, the mean of the analyses was accepted to quantify the key point. When the error was > 0.04 s, the three operators proceeded to a new assessment of the key points. Three strokes were analyzed and the data were then averaged.

The duration of each phase was measured for each arm stroke cycle with an accuracy of 0.02 s (50 Hz) and was expressed as a percentage of the duration of the complete arm stroke cycle. The duration of the propulsive phases was the sum of phases B and C. The duration of the non-propulsive phases was the sum of phases A and D. The duration of a complete arm stroke cycle was the sum of the durations of the propulsive and non-propulsive phases (Equation 15).

$$\text{Duration}_{\text{Complete cycle}} = [(\text{Phase A} + \text{Phase B} + \text{Phase C} + \text{Phase D})_{\text{left arm}} + (\text{Phase A} + \text{Phase B} + \text{Phase C} + \text{Phase D})_{\text{right arm}}] / 2$$

(Equation 15)

The index of coordination (IdC) calculated the time gap between the propulsions of the two arms as a percentage of the duration of the complete arm stroke cycle (Chollet et al., 2000). IdC was the mean of IdC_{left} (Equation 16) and $\text{IdC}_{\text{right}}$ (Equation 17):

$$\text{IdC}_{\text{left}} = [(\text{Time}_{\text{End of phase C for left arm}} - \text{Time}_{\text{Beginning of phase B for right arm}}) \cdot 100] / \text{Duration}_{\text{Complete cycle}}$$

(Equation 16)

$$\text{IdC}_{\text{right}} = [(\text{Time}_{\text{End of phase C right arm}} - \text{Time}_{\text{Beginning of phase B for left arm}}) \cdot 100] / \text{Duration}_{\text{Complete cycle}}$$

(Equation 17)

When IdC was $< 0\%$, the arm coordination was called “catch-up” because there was a lag time between the propulsive phases of the two arms. When the propulsive phase of one arm started at the time the other arm finished its propulsive phase, the coordination was called “opposition” (IdC = 0%). In fact, the opposition coordination for IdC = 0 is theoretical; in practical terms, opposition coordination is accepted for $-1\% < \text{IdC} < 1\%$. When the propulsive phases of the two arms overlapped, the coordination was called “superposition” (IdC $> 0\%$).

e. 2.7. Swim Efficiency

Three indicators of swim efficiency were calculated from the test in free swimming condition: (i) SI (Equation 5), (ii) the coefficient of variation (CV) of the hip intra-cyclic velocity variation (IVV), and (iii) the efficiency of propulsion generation, i.e., the v^2/u^2 ratio.

Concerning IVV, a video-velocity-meter device was used, as previously reported (Schnitzler et al., 2008). The underwater side view was synchronized with a velocity-meter (Fahnenmann 12® 045, Bockenheim, Germany, $f = 50$ Hz). The swimmers were connected to a very stiff cable driving an electromagnetic angular velocity tachometer. The measurements were taken using 30 m of stainless steel light cable coiled around the tachometer and connected at the distal end to a harness belt attached to the swimmer’s waist. This provided a linear velocity measurement of the hip and was relayed into a computer. For each participant, the three strokes of the 10-m central part were averaged. The corresponding time-velocity

curves were filtered with Origin 5.0 software (Microcal Inc., Northampton, England, 1997) with a low-pass filter. The cut-off frequency was set at 6 Hz. The *IVV* was analyzed by calculating its coefficient of variation (*CV*) (Alberty, Sidney, Huot-Marchand, Hespel, & Pelayo, 2005; Alves et al., 1996; Barbosa et al., 2005; Miller, 1975; Schnitzler et al., 2008) obtained from Equation 18:

$$CV = \text{standard deviation} / \text{mean} \quad (\text{Equation 18})$$

where mean is the mean swimming v and standard deviation is the *SD* of the instantaneous swimming v from the three stroke cycles.

The efficiency of propulsion generation was calculated from an adaptation of Equation 10 proposed by Zamparo et al. (2005). Instead of using SR and the total underwater part of the cycle, which includes the non-propulsive entry + catch phase in the calculation, the calculation of the tangential hand speed (u) in the present study considered (Equation 19): (i) the sum of the absolute duration (s) of the propulsive phases B and C, and (ii) the angle of the propulsive phase measured between the arm (wrist-shoulder) and the horizontal axis angle from the beginning of phase B to the end of phase C. Two body marks (wrist and shoulder on the right side) were digitized with Dartfish© software (Dartfish ProSuite4.0, 2005, Switzerland) from the underwater side view to calculate the arm-horizontal axis angle at the beginning of phase B. The angle between the arm and the horizontal axis at the end of the phase C is 0° .

$$u = [\text{angle of the propulsion phase} / (\text{phase B} + \text{phase C})] \cdot l \quad (\text{Equation 19})$$

Then, according to Toussaint et al. (2006), the efficiency of propulsion generation (e_{pg}) of the arm stroke was the v^2/u^2 ratio, assuming that v^2 is proportional to the drag force and u^2 is proportional to the propulsive force. When the swimming speed increased, assuming that propulsive force increases with drag force, the e_{pg} should remain constant. Thus, a decrease in e_{pg} could be indicative of a less effective propulsion “generating pattern” since a relatively higher tangential hand speed is necessary for force generation.

f. 2.8. Statistical analysis

Before using parametric statistics (Minitab 14.10, Minitab, Inc., 2003), the normal distribution (Ryan-Joiner test, equivalent to the Shapiro-Francia test) was checked and the homogeneity of variance (Bartlett test) was controlled for each variable.

For both free swimming and MAD-system conditions, the normalized v and SR were compared between the two skill groups by Student t tests. On the whole population, two-way ANOVA (condition and pace) compared the normalized v and SR between the free swimming and MAD-system conditions for the eight bouts of speed.

Two-way ANOVA (group and speed) analyzed the effect of graded speed on (i) the stroking parameters (v , SR, SL), (ii) the IdC and arm stroke phases, (iii) the swim efficiency (SI, CV, of IVV, u , v^2/u^2), and (iv) D and P_d . When a significant main effect was obtained, a *post hoc* pairwise multiple comparison analysis was performed with the Tukey test to identify differences. Then, the K obtained from Equation 3 and the ratio $P_{d\max}/K$ were compared between the two groups by Student t test.

The relationships between IdC and the other variables, and between v and the other variables, were assessed by Pearson's correlation test, as well as stepwise regression analysis. The variables entered the equation if $F > 4$ and removed if $F < 3.96$. For all tests, the level of significance was set at .05.

3. Results

3.1. Stroking parameters

The Student t test did not show any significant between-group differences for the normalized v and SR in the free swimming and MAD-system conditions. For the whole population, a non-significant difference of $0.6 \pm 2.2\%$ was noted between normalized v_{free} and normalized v_{MAD} , while a significant difference of $15.5 \pm 8.1\%$ was noted between normalized SR_{free} and normalized SR_{MAD} , $F(1, 195) = 468.27$, $p < .05$ (Fig. 1).

<< Insert Fig. 1 >>

The stroking parameters significantly changed with the increase in speed and significantly differed between groups. Indeed, v_{free} , $F(7, 96) = 94.02$, SR_{free} , $F(7, 96) = 1125.67$, v_{MAD} and SR_{MAD} , $F(7, 96) = 74.57$, increased through the eight bouts of speed (all $p < .05$), while SL decreased, $F(7, 96) = 42.68$, $p < .05$ (Fig. 2). For these bouts, the national swimmers had greater v_{free} , $F(1, 96) = 36.44$, SL, $F(1, 96) = 9.74$, v_{MAD} and SR_{MAD} , $F(1, 96) = 30.85$, than the regional swimmers (all $p < .05$) and non-significantly different SR_{free} (Fig. 2).

3.2. Drag and mechanical power output on MAD-system

For both groups, the drag force increased through the bouts of speed, $F(7, 96) = 30.92, p < .05$. This was not the case for the last two bouts where performance was at or near the maximum. The increase in speed led to a significant increase in the mechanical power output through the eight bouts, $F(7, 96) = 39.02, p < .05$. For most of these bouts, greater drag force, $F(1, 96) = 5.77, p < .05$, and $P_d, F(1, 96) = 7.81, p < .05$, were noted for the national swimmers than for the regional swimmers (Fig. 3). Although the Student t test did not show significance difference in K between national ($K = 25.54 \pm 5.11$) and regional swimmers ($K = 28.01 \pm 3.51$), the ratio between $P_{d \max}$ (at the last bout) and K was significantly higher for the national swimmers ($P_{d \max}/K = 8.61 \pm 2.00$) than for the regional swimmers ($P_{d \max}/K = 6.44 \pm 1.10$) ($p < .05$). Apparently the national swimmers were able to produce significantly more power output relative their drag profile than the regional swimmers.

<< Insert Fig. 3 >>

3.3. Coordination of arm movements

For both groups, IdC increased with speed, $F(7, 96) = 51.21, p < .05$, except between the first and second bouts and the seventh and eighth bouts (Fig. 4). The observed changes in IdC were related to the decrease in the relative duration of the entry+catch phase, $F(7, 96) = 49.90, p < .05$, and to the increase in the relative duration of both pull phase, $F(7, 96) = 36.38, p < .05$, and push phase, $F(7, 96) = 21.44, p < .05$ (Fig. 4). The relative duration of the recovery phase did not change significantly with the increase in speed for either group and was close to $26.2 \pm 2.4\%$. The angle of arm propulsion (i.e., angle between the arm and horizontal axis from the beginning of pull phase to the end of push phase) did not change significantly with the increase in speed for either group and was close to $156.1 \pm 4.2^\circ$. The national swimmers had greater IdC, $F(1, 96) = 33.94, p < .05$, that was related to their shorter entry+catch phase, $F(1, 96) = 21.23, p < .05$, and longer push phase, $F(1, 96) = 64.36, p < .05$, which was mostly noted for the last four bouts (Fig. 4).

3.4. Swim Efficiency

The tangential hand speed (u) increased through the eight bouts of speed [$F(7,96) = 35.61$; $p < .05$], except between the last two bouts, while SI, the CV of IVV and v^2/u^2 did not change significantly (Table 1). The national swimmers had greater SI, $F(1, 96) = 28.17$, and v^2/u^2 , $F(1, 96) = 41.00$, smaller u , $F(1, 96) = 7.60$ (all $p < .05$) and non-significantly different CV of IVV (Table 1).

<< Insert Table 1 >>

3.5. Relationships among variables

The results of the Pearson's correlation and stepwise regression tests studying the relationships between IdC and the other variables, and between v and the other variables, are presented in Tables 2 and 3. The stepwise regression showed that SR, v^2/u^2 , drag force, and hand speed explained 95.3% of the IdC changes, while SR, v^2/u^2 and hand speed explained 92.5% of the v changes.

<< Insert Tables 2 and 3 >>

4. Discussion

The first aim of this study was to examine how the combined group of national and regional swimmers organized their stroke to increase v , and more particularly how the national swimmers achieved higher speed. The second aim was to explore the swim efficiency of the stroke organization in relation to the skill level and swimming speed.

4.1. Relevance of the protocol

The MAD-system was used to assess the drag force, and it was assumed that the maximal mechanical power production in the free swimming condition would be similar to the recorded power production on the MAD-system. Therefore, as shown by the normalized v (Fig. 1), all the swimmers were put in situations of equal relative effort when swimming 25-m at their maximal speed on the MAD-system and in free condition (as previously done to study the 100-m event, Toussaint et al., 2006), as well as when

swimming the other bouts at submaximal speed. Only the normalized SR changed between the two conditions, being higher on the MAD-system due to the fixed SL (as previously observed, Toussaint et al., 2006). The scale of the absolute values of v achieved in the free condition was smoothly lower than those observed in the literature (Seifert, Chollet, & Rouard, 2007) and in competition (Haljand, 2007) due to the absence of leg kick in our study.

4.2. Stroke organization according to speed and skill

4.2.1. Drag and mechanical power output on MAD-system

Our results showed an increase in drag force with speed that led both groups to develop higher mechanical power output to overcome higher active drag. However, the national swimmers were able to develop higher mechanical power output and stroke length than the regional swimmers, which enabled them to reach higher swimming speed. This phenomenon was not due to significant differences in overall drag coefficient (drag factor: K), but could be attributed to the capacity of the national swimmers to demonstrate higher propulsive force to overcome higher environmental constraints (i.e., higher drag force). Indeed, the relative power output ($P_{d\ max}/K$) and the absolute power output (P_d) were significantly higher for the national than for the regional swimmers.

4.2.2. Coordination of arm movements

As the speed increased, the temporal organization of the stroke cycle was modified. Correlation and stepwise regression showed that stroke rate is the main predictor of IdC and swimming speed changes (in accordance to Seifert, Chollet, & Rouard, 2007). Indeed, for both groups of swimmers, stroke rate increased by shortening the duration of the catch+entry phase, thus at the expense of the non-propulsive underwater phase (Chollet et al., 2000; Seifert, Chollet, & Rouard, 2007). In other words, both groups of swimmers favored the time dedicated to propulsion (pull + push phases) within the stroke cycle (according to Albery et al., 2009). In whole stroke swimming (arm + leg), superposition coordination appeared as the main solution over a critical speed of $1.8\ \text{m}\cdot\text{s}^{-1}$ and/or a critical stroke rate of $0.83\ \text{Hz}$ (Potdevin et al., 2003; Seifert, Chollet, & Rouard, 2007). With arms only, Figs. 2A and 4A show that for slow speed, the swimmers adopted catch-up coordination (IdC $\sim -18\%$). Then, above a critical speed of $1.6\ \text{m}\cdot\text{s}^{-1}$ opposition coordination was required (IdC $\sim 0\%$), which implies a better chain

of consecutive propulsive actions in both arms. Moreover, the national swimmers demonstrated higher propulsive continuity (i.e., higher IdC) in relation to their higher stroke length, stroke index and higher efficiency of propulsion generation (i.e., higher v^2/u^2 ratio).

4.3. Swim efficiency according to speed and skill

Throughout the eight bouts of 'free' swimming, *IVV* did not significantly change for either group and remained low ($0.12 < CV < 0.16$), while the propulsive continuity of the two arms increased. This indicated that the swimmers were able to adapt their stroke technique to minimize *IVV* and reach higher speed, confirming the results of previous studies in which the *IVV* of national swimmers did not increase with speed ($0.11 < CV \text{ of } IVV < 0.16$) while IdC increased from $-13.2 \pm 4.4\%$ to $-2.7 \pm 0.8\%$ (Schnitzler et al., 2008). The low *IVV* was related to higher propulsive continuity, which ensured low energy cost (Alves et al., 1996, Barbosa et al., 2006). Indeed, through an incremental set of 200-m swims until exhaustion, Barbosa et al. (2006) confirmed that *IVV* is correlated with the energy cost in the four strokes, and particularly in freestyle ($r = 0.62$), suggesting that *IVV* is a relevant indicator of swim efficiency. However, in our rather homogeneous group of swimmers no clear difference was seen in *IVV*.

Although the two groups showed similar low *CV* of *IVV* through the eight bouts, the national swimmers revealed greater propulsive continuity of the two arms than the regional swimmers, suggesting that if the propulsive surface and orientation are correct, a greater IdC could be associated with higher mechanical power output (as shown by the correlation and stepwise regression analyses of Tables 2 and 3).

However, a greater IdC does not automatically ensure efficiency of propulsion generation and high swimming speed because swimmers can slip through the water (Counsilman, 1981) or spend a long time in the propulsive phase due to slow hand speed (Aujouannet, Bonifazi, Hintzy, Vuillerme & Rouard, 2006; Seifert, Chollet, & Chatard (2007). According to hydrodynamic theories of propulsion, the orientation, surface and speed of the body segments involved in propulsion are crucial factors to determine lift and drag force magnitudes. In our study, the motor organization of the two groups appeared adequate in relationship to the given swimming speed because it did not lead to significant changes in SI and the v^2/u^2 ratio through the eight bouts. Nevertheless, the regional swimmers showed higher hand speed (u) for lower swimming speed (v) than the national swimmers, reflecting lower efficiency of

propulsion generation ($v^2/u^2 = 0.15 \pm 0.02$ for regionals vs. 0.19 ± 0.05 for nationals), meaning that regional swimmers have to modify their technique to swim faster. Indeed, whether or not a great hand speed enables a high stroke rate and contributes to swimming speed, the stepwise regression analyses showed that v^2/u^2 appeared as the second main predictor of a high IdC and v . Thus, in agreement with the conclusion of Toussaint (1990), who compared triathletes and swimmers, our results suggested that a relative lack of skill and technique could lead to lower efficiency of propulsion generation. In our study, several proposals could be made to explain the lower u and greater v^2/u^2 ratio of the national swimmers:

(i) The hand speed concerned solely the sagittal plane, so hand sweeps that may have occurred in the frontal plane were missed. The national swimmers might have preferred lift forces that resulted in greater hand sweeps which would enlarge the hand path and explain a lower antero-posterior hand speed (Ichikawa, Shiraki & Nomura, 2008; Matsuuchi, 2008; Schleihauf, Gray & DeRose, 1983). Indeed, using a 3-D analysis of hand trajectories recorded in a flume, Ichikawa et al. (2008) found no significant correlation between swimming speed and either hand speed or the distance covered by the hand during the propulsive phase (considered as the backward displacement of the hand).

(ii) The national swimmers could have used a greater propulsive surface by swimming with higher elbow position during the catch and subsequent propulsive phases. They may also have better oriented their hands to avoid slippage through the water. Indeed, the dropped elbow position has often been observed in less expert swimmers (Arellano, Lopez-Contreras & Sanchez-Molina, 2003), as well as slippage through water (Counsilman, 1981), which would explain the greater hand speed than the national swimmers but the lower SL, SI and v^2/u^2 ratio.

5. Conclusion

For both groups, the increase in speed led them to increase their propulsive continuity and hand speed and to apply greater mechanical power output to overcome the active drag. This adaptation of the motor organization appeared adequate because it did not lead to changes in SI, IVV or the v^2/u^2 ratio through the eight bouts. The national swimmers appeared more efficient (i.e., higher SI and v^2/u^2 ratio) and they also showed greater propulsive continuity (higher IdC). In addition, their higher mechanical power output enabled them to reach higher v . Conversely, the higher hand speed of the regional swimmers may have

reflected hand slippage through the water, suggesting that great hand force and speed need to be associated with a correct path and orientation of the hand.

Acknowledgments

No funding was received for this work. The authors thank Franck Bouzard for the video system assistance and Cathy Carmeni for language editing.

Conflict of interest

The authors have no professional relationships to disclose with companies or manufacturers who will benefit from the results of the present study.

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Fig. 1. Comparison between free swimming (white) and MAD-system (gray) conditions for the normalized v (1A) and the normalized stroke rate (1B) at each speed the mean of the two groups; *: significant difference between the two conditions, $p < .05$.

Fig. 2. Effect of skill level on v_{free} (2A), v_{MAD} (2B), stroke rate_{free} (2C), stroke rate_{MAD} (2D), and stroke length (2E). *: significant difference between national (white) and regional (gray) swimmers, $p < .05$.

Fig. 3. Effect of skill level on drag force (3A) and mechanical power output (3B). *: significant difference between national (white) and regional (gray) swimmers, $p < .05$.

Fig. 4. Effect of skill level on index of coordination (4A). *: significant difference between national (black point) and regional (white point) swimmers, $p < .05$. Effect of skill level on arm stroke phases (4B): entry+catch phase (gray), pull phase (white) and push phase (black). *: significant difference between national (first column) and regional (second column) swimmers, $p < .05$.

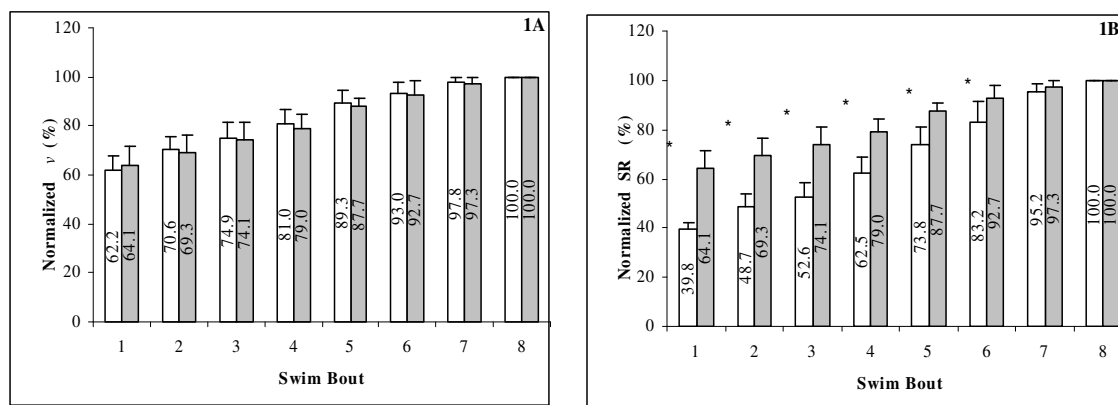


Figure 1. Comparison between free swimming (white) and MAD-system (gray) conditions for the normalized v (1A) and the normalized stroke rate (1B) at each speed the mean of the two groups; *: significant difference between the two conditions, $p < .05$.

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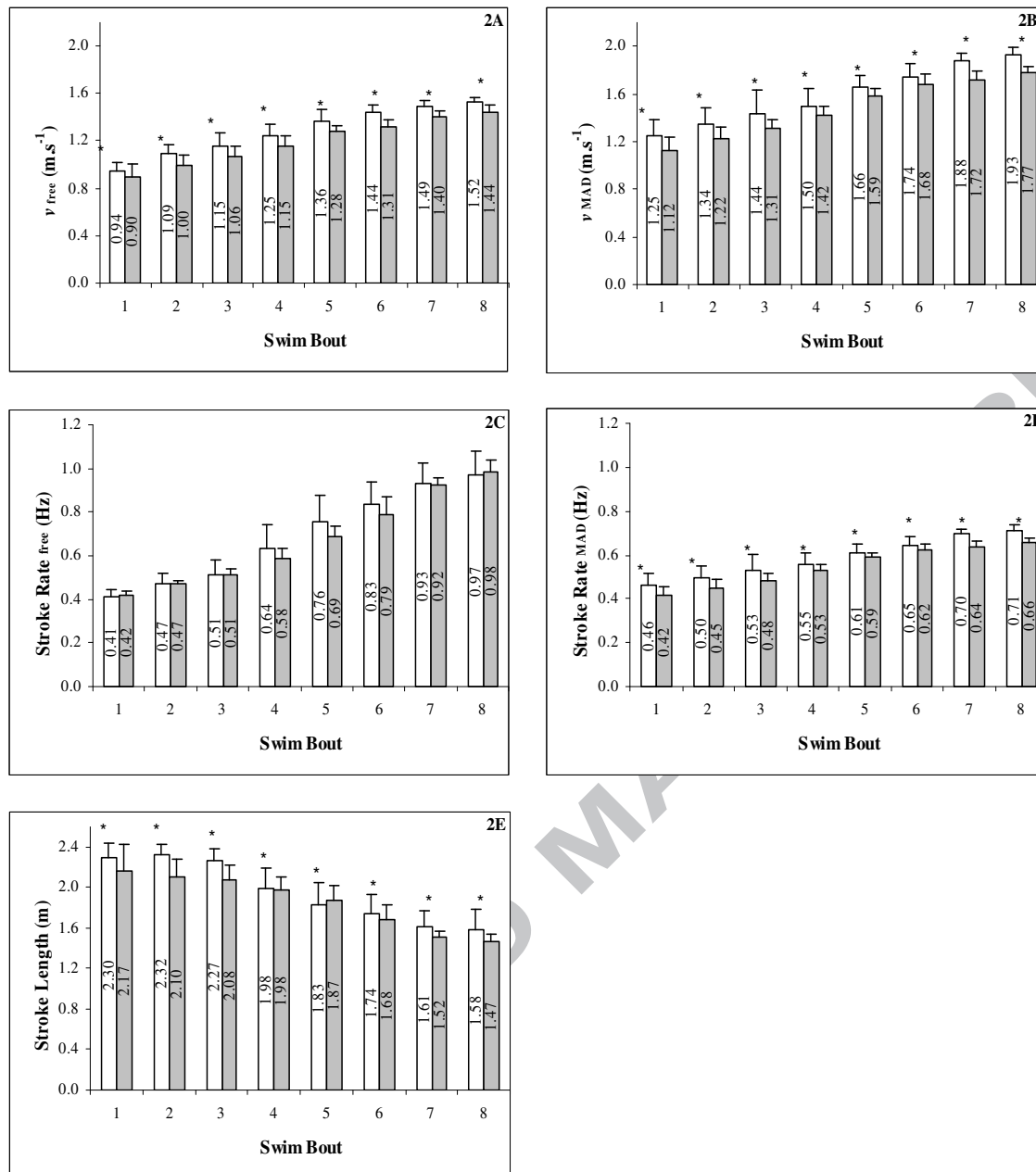


Figure 2. Effect of skill level on v_{free} (2A), v_{MAD} (2B), stroke rate_{free} (2C), stroke rate_{MAD} (2D) and stroke length (2E). *: significant difference between national (white) and regional (gray) swimmers, $p < 0.05$.

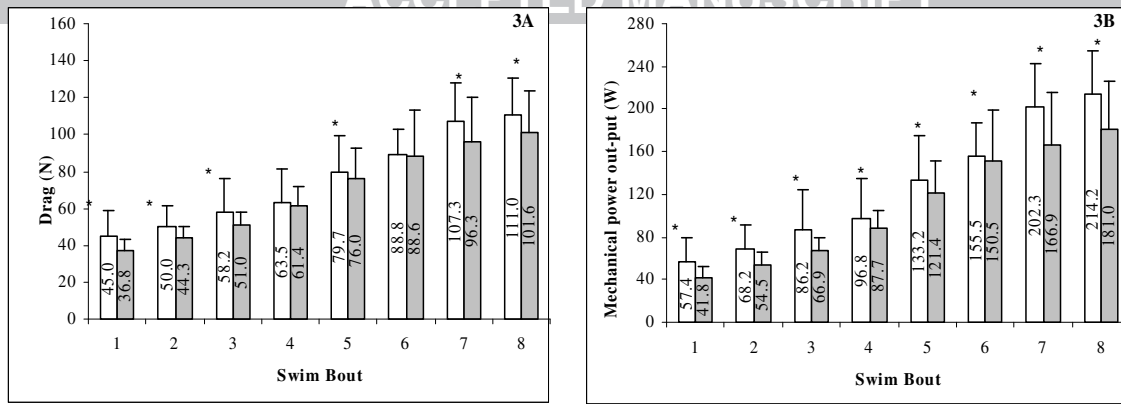


Figure 3. Effect of skill level on drag force (3A) and mechanical power output (3B). *: significant difference between national (white) and regional (gray) swimmers, $p < .05$.

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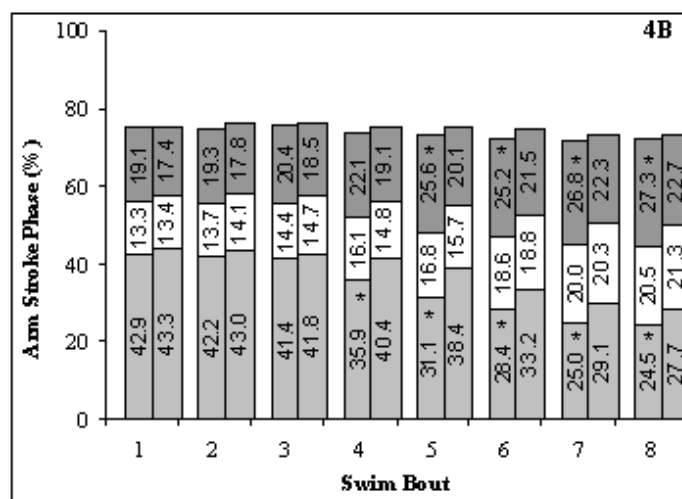
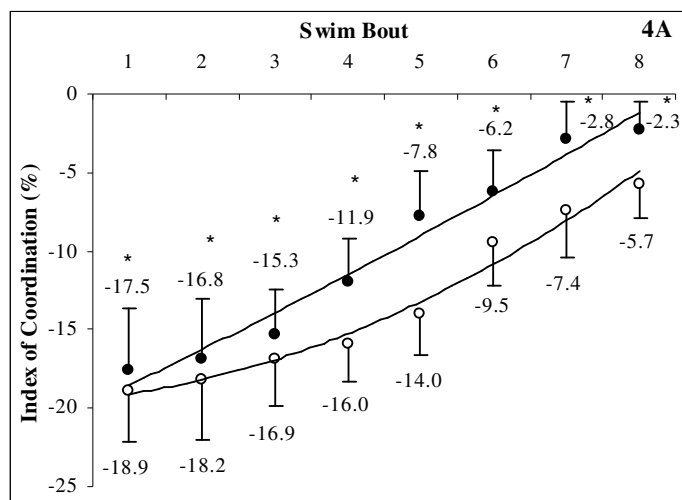


Figure 4. Effect of skill level on index of coordination (4A). *: significant difference between national (black point) and regional (white point) swimmers, $p < 0.05$. Effect of skill level on arm stroke phases (4B): entry+catch phase (gray), pull phase (white) and push phase (black). *: significant difference between national (first column) and regional (second column) swimmers, $p < 0.05$.

Table 1. Effect of skill level on the efficiency parameters: stroke index, swimming speed / hand speed ratio, intra-cyclic velocity variation. *M*: mean, *SD*: standard deviation; *: significant difference with regional swimmers, $p < .05$.

Swim Bout	Stroke Index ($m^2/stroke/s$)				Tangential hand speed (u in $m \cdot s^{-1}$)				Swimming speed / Tangential hand speed (v^2/u^2)				Coefficient of variation of hip intra-cyclic velocity			
	National		Regional		National		Regional		National		Regional		National		Regional	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
1	2.17	0.25	1.97	0.48	2.21	0.31	2.36	0.17	0.19	0.07	0.15	0.03	0.14	0.04	0.15	0.02
2	2.54	0.16	2.10	0.36	2.56	0.30	2.61	0.30	0.19	0.05	0.15	0.02	0.15	0.01	0.15	0.03
3	2.61	0.22	2.22	0.33	2.60	0.34	2.72	0.23	0.20	0.05	0.16	0.02	0.15	0.02	0.14	0.02
4	2.46	0.21	2.28	0.26	2.94	0.42	3.01	0.33	0.18	0.06	0.15	0.02	0.15	0.01	0.13	0.02
5	2.49	0.26	2.40	0.24	3.12	0.43	3.32	0.26	0.19	0.05	0.15	0.02	0.14	0.02	0.13	0.03
6	2.51	0.29	2.20	0.14	3.35	0.36	3.44	0.33	0.19	0.05	0.15	0.02	0.15	0.02	0.12	0.02
7	2.40	0.26	2.13	0.14	3.52	0.39	3.82	0.32	0.18	0.05	0.14	0.01	0.16	0.03	0.14	0.02
8	2.41	0.34	2.11	0.16	3.53	0.42	3.91	0.26	0.19	0.05	0.14	0.01	0.13	0.04	0.14	0.04
<i>M</i>	2.45 *	0.25	2.18	0.26	2.98 *	0.37	3.15	0.27	0.19 *	0.05	0.15	0.02	0.15	0.02	0.14	0.03

Table 2. Significant correlation (r) at $p < 0.05$.

	v_{free}	IdC
v_{free}		0.81
SR_{free}	0.91	0.85
SL	-0.70	-0.77
SI	0.39	0.69
IdC	0.81	
Phase A	-0.83	-0.93
Phase B	0.74	0.88
Phase C	0.71	0.90
Hand speed	0.82	0.55
v^2/u^2	0.79	0.28
Drag	0.76	0.70
Power	0.79	0.74

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Table 3. Summary of the model, included in the stepwise regression, for predictors of IdC and v_{free} .

	Variables	R^2	R^2_{adjusted}	T	p	$Beta$	F	p
IdC	Stroke rate	0.76	0.75	9.76	< 0.01	0.483	(4,51)	< 0.01
	v^2/u^2	0.93	0.92	8.47	< 0.01	45.4	255.92	
	Drag	0.94	0.94	3.10	< 0.01	0.037		
	Hand speed	0.95	0.95	-2.33	0.02	-2.4		
v_{free}	Stroke rate	0.66	0.85	5.44	< 0.01	0.081	(3,52)	< 0.01
	v^2/u^2	0.89	0.88	5.16	< 0.01	1.47	226.11	
	Hand speed	0.93	0.92	7.29	< 0.01	0.195		