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ORIGINAL ARTICLE

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Relative contribution of arms and legs in humans to propulsion in 25-m sprint front-crawl swimming

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Abstract Eight male subjects were asked to swim 25 m at maximal velocity while the use of the arm(s) and legs was alternately restricted. Four situations were examined using one arm (1A), two arms (2A), one arm and two legs (1A2L) and both arms and legs (2A2L, normal swim) for propulsion. A significant mean increase of 10% on maximal velocity was obtained in 1A2L and 2A2L compared to 1A and 2A. A non-significant 4% effect was obtained in 1A. This study focused on the actual contribution of leg kick in the 10% gain in maximal velocity. It was clear that the underwater trajectory of the wrist was modified by the action of the legs (most comparisons $P < 0.001$). Therefore it was thought that the legs enhanced the generated propulsive force by improving the propulsive action of the arm. The arm action was quantified by selecting typical phases from the filmed trajectory of the wrist, namely forward (F), downwards (D) and backwards (B). Although there was a tendency for individual changes in kinematic parameters (F, D and B) to occur with individual changes in velocity when 2A was compared to 2A2L, no relationship was found between the relative changes in F, D and B and relative changes in velocity. This was illustrated by describing the responses of three individuals who could represent three patterns of contribution by legs and arms to propulsion in high speed swimming.

Key words Aquatic locomotion · Maximal velocity · Wrist trajectory · Leg kick effects

Introduction

The highest velocity in human locomotion in water is reached in short-distance freestyle swimming. These high velocities depend on the capacity to generate the highest propulsive force to overcome water resistance or drag. Several authors have suggested that drag may be diminished by improving swimming technique (Schleihauf et al. 1986; Maglischo et al. 1988; Toussaint et al. 1988; Chatard et al. 1990), that is by keeping an optimal gliding position of the body and by improving the respective and complementary actions of legs and arms.

The action of the upper limbs has usually been described in terms of 3-D analysis of the trajectory of the hand underwater (Schleihauf 1979; Maglischo et al. 1986; Monteil 1992; Deschodt et al. 1995). We have recently described which characteristics of the 3-D trajectory are strongly correlated with performance, i.e. swimming velocity, in a population of 60 elite male 100-m swimmers, including the 1994 World Champion (Deschodt et al. 1994). In that study, the maximal forward (F) and maximal downwards (D) coordinates and the amplitude of the slipping backward (B) of the wrist obtained in the saggital plane were the best determining factors of interindividual variations in swimming velocity.

The propulsive efficiency of competitors has been a matter of considerable interest over many decades (Brown et al. 1971; Schleihauf et al. 1983; Maglischo et al. 1988). In 1975, Miyashita (1975) has suggested that “the propulsive force which drives the swimmer forward is created by the swimmer’s arm as they push the water backwards”. Moreover, other studies (Schleihauf 1979; Schleihauf et al. 1983, 1988) have shown that the propulsive force balancing the opposing drag force at maximal velocity depends on the lift force generated by the hand, the forearm and the arm. Miyashita and

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Kanshisa (1979) have reported a significant correlation ($r = 0.71$) between individual isokinetic peak torque of the arms and individual performance in a 100-m freestyle swim. Sharp et al. (1982) have also found a linear relationship ($r = 0.90$) between arm power, using an apparatus specifically designed to mimic the arm action during swimming (Biokinetic Swim Bench) and performance in 25-yard swims.

These findings have suggested implicitly that the leg kick could be relegated to a position of secondary importance for propulsion. In other words, the role of leg kick could be limited to keeping the body in a good position in the water. We have speculated, however, that in addition to a role in keeping equilibrium, the leg kick may also play a large part in the generation of propulsion force during sprint freestyle races. Thus maximal swimming velocities were obtained from our subjects who were instructed either to use or not to use leg kick for propulsion. At the same time to test the influence of the action of the contralateral arm, we imposed situations where either one arm and both legs were moving or one arm without the legs. We expected that these situations would lead not only to differences in the maximal velocity of swimming but also would induce changes in the kinematic parameters associated with the underwater trajectory of the wrist.

Methods

Population

Eight male swimmers who had participated in swimming competitions from regional to national level gave their informed consent to take part in this study. Individual best performances in 100-m freestyle ranged from 54.04 s to 61.02 s, which corresponded to an average velocity of 1.76 (SD 0.15) $m \cdot s^{-1}$.

Experiment procedure

After a standardized warm-up for 5 min consisting in completing a 1 200-m swim within 900 s, the subjects swam all-out for four periods separated by 5 min of active recovery. Each period of exercise consisted in swimming 25 m as fast as possible either using normal front-crawl or front-crawl with restricted movements.

The first 25-m was swum using one arm only (1A) the left one being arbitrarily chosen from among a population in which the right arm was dominant. In this situation, the contribution of the right arm to propulsion, named *contralateral* was neutralized as was that of the lower limbs. The individuals were asked to keep the contralateral arm forward along the body, while the legs were neutralized using a wire around the ankles and a small buoy maintained by the knees. The second 25-m sprint was swum using both arms (2A) but not the legs for propulsion. Here the legs were also neutralized using the wire and a small buoy. The third 25-m sprint was swum using the left arm only and both legs (1A2L) for propulsion, the contralateral arm being kept fixed as above for 1A. Lastly, the fourth 25-m sprint was swum normally, and both arms and both legs (2A2L) contributed to propulsion. For each individual these four periods were arranged in random order.

We believed that a comparison between 1A and 1A2L, and between 2A and 2A2L would allow the influence of using the legs for propulsion to be compared to the influence of using arms only for propulsion. In addition, the comparisons of 1A and 2A, and of 1A2L and 2A2L would provide insights into the contribution to propulsion of the contralateral arm.

Data collection

Two video-camcorders (HI8 EVO 150 TR Sony, NTSC) were used to record the arm stroke during each 25-m sprint. Each camera covered a distance of 8 m of the swim which was located between the 12th and 20th-m of the 25 m. Each video-camcorder was enclosed in a waterproof box (Sony SPK-TRA) fixed at a depth of 0.60 m so that frontal and lateral (left) frames could be obtained. Frames were synchronized using light emitting diodes. The optical angle of each camera was set at 90°, according to the software of Schleihauf (1994). At the end of each experiment, a 1.50-m calibration ruler was filmed at the middle part of the two fields.

Data treatment

Following the software of Schleihauf (1994), the subaquatic views were digitized frame-by-frame and point-by-point between two successive points at which the wrist entered the water. For each frame, the two wrist and hip joints were manually digitized. The trajectories of each joint in the water could be obtained in three dimensions – antero-posterior, transversal and vertical. The trajectories were smoothed with a polynomial function.

The accuracy and reliability of these kinds of analyses have been described in a previous study (Monteil et al. 1996). A test-retest examination of the digitization of the frame obtained from different experimenters was made and showed a high correlation with an error of less than 3%.

Two methods of treatment were employed. In the first wrist trajectories were represented in three-dimensions using the position of the wrist when entering the water as a spatial reference with 0, 0, 0 coordinates. In the second, to compare interindividual strokes, it was necessary to refer the spatial positions to time because the durations of individual cycles (i.e. the number of frames obtained for each stroke) were not identical. In this case the coordinates of each wrist position in a frame were associated with a time corresponding to a given percentage of the total time for the stroke. Averaged spatial stroke representations provided x spatial coordinates with a time step corresponding to x% of the stroke. Coordinates at each x% step were obtained with linear interpolation between the bordering digitized data.

Data analysis

The parameters used for quantitative statistical analysis were:

1. The trajectory of the wrist in the water during each of the four situations
2. The amplitude and duration of the whole stroke and some relevant phases within the stroke which have been described in the literature. Stroke length (SL) is defined as the amplitude of the hip on the antero-posterior axis between the two successive points at which the left wrist entered and then exited the water.

According to previous studies different spatial positions of the wrist could be identified along its trajectory in the water to determine different phases in the aquatic stroke (Schleihauf 1974, 1979; Wiegand et al. 1975; Reischle 1979; Rouard 1987; Hay 1988; Monteil 1992).

Using our previous analysis (Deschodt et al. 1995), a quantitative description of each stroke was obtained from (Fig. 1):

1. On the antero-posterior axis – maximal coordinate that the wrist reached in the forward (F) phase and the horizontal distance covered during the phase moving backwards (B) between F and minimal x coordinate.
2. On the vertical axis – the maximal negative coordinate of the downwards movement (D) of the wrist in the water.

Statistical analysis

To show significant differences between two situation tests on the same population (for example between 1A and 2A), non-para-

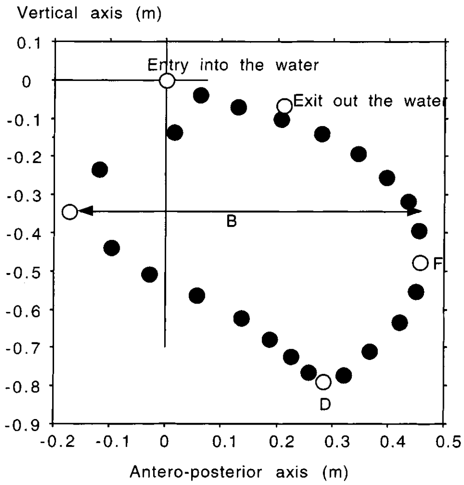

Fig. 1 Example of the trajectory of the wrist underwater. Definition of the maximal co-ordinates of each of the underwater phases in the antero-posterior and vertical axes: *B* amplitude of backward phase, *F* maximal horizontal coordinate, *D* minimal vertical co-ordinate

metric tests (Wilcoxon) were used. Linear regression analyses were used to describe the relationships between different parameters. For all the statistical analyses, the level of significance was set at $P = 0.05$.

Results

The swimming velocity

The averaged swimming velocities in each of the four swimming situations are shown in Table 1. Statistical differences were found between both 1A and 1A2L and 2A and 2A2L, $P < 0.001$. The 1A mean velocity was 92.7 (SD 3.8)% (range 85.5%–98.8%) of 1A2L, and 2A mean velocity 90.7 (SD 4.7)% (range 83.0%–97.1%) of 2A2L (Table 2). These results suggest that, when swimming using legs, a higher velocity by about an average of 10% was achieved, which will be discussed later when considering the role of the legs in propulsion.

However we did not obtain significantly higher swimming velocities, when the situations involving both arms were compared with the corresponding situations with one arm (Table 1). It was also clearly observed (Table 2) that the significant gain in velocity due to the contribution of the leg kick (about 10%) was much higher than the gain due to the contribution of the contralateral arm (about 4%, non significant).

Such comparisons between maximal velocity during swimming are however in sufficient to indicate whether the legs provided the 10% higher velocity by their own propulsive action, or whether the action of the legs led to changes in swimming style, producing changes in efficiency at the level of arm-propulsion. This possibility could be answered by an analysis of the concomitant changes in the trajectory of the wrist underwater.

Table 1 Characteristics of the underwater wrist trajectory *SL* stroke length, *F* forwards, *D* downwards, *B* backwards, *1A* one arm, *2A* two arms, *1A2L* one arm 2 legs, *2A2L* both arms and both legs

	Velocity ($m \cdot s^{-1}$)		Amplitude (m)								Duration							
			SL (m)		F (m)		D (m)		B (m)		SL (s)		F (%)		D (%)		B (%)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1A	1.56	0.15	0.16	0.04	0.35	0.09	−0.90	0.17	−1.21	0.23	0.62	0.04	32.00	6.00	56.00	10.00	75.00	6.2
2A	1.60	0.16	0.15	0.05	0.30	0.09	−0.93	0.19	−0.89	0.15	0.69	0.06	31.00	5.00	56.00	10.00	74.8	7.9
1A2L	1.69	0.13	0.21	0.07	0.70	0.12	−1.00	0.13	−0.89	0.16	0.94	0.05	42.00	8.00	73.00	8.00	74.7	6.89
2A2L	1.76	0.15	0.21	0.07	0.49	0.11	−0.81	0.15	−0.61	0.18	0.85	0.04	40.00	6.00	58.00	10.00	78.02	6.8
Contralateral arm effect																		
1A vs 2A	NS		NS		NS		NS		$P < 0.001$		NS		NS		NS		NS	
1A2L vs 2A2L	$P < 0.05$		NS				$P < 0.001$		$P < 0.001$		NS		NS		NS		NS	
Leg action																		
1A vs 1A2L	$P < 0.001$		$P < 0.01$		$P < 0.001$		NS		$P < 0.001$		$P < 0.001$		$P < 0.001$		$P < 0.001$		NS	
2A vs 2A2L	$P < 0.001$		$P < 0.01$		$P < 0.001$		$P < 0.01$		$P < 0.001$		$P < 0.001$		$P < 0.001$		$P < 0.001$		NS	

Table 2 Relative changes in wrist kinematic parameters and velocity. *SL* stroke length, *F* forwards, *D* downwards, *B* backwards, *1A* one arm, *2A* two arms, *1A2L* one arm 2 legs, *2A2L* both arms and both legs

	Velocity (%)		F (%)		D (%)		B (%)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1A2L vs 1A	+7.34	3.77	+50.06	7.94	+9.60	9.25	−35.80	12.51
2A2L vs 2A	+9.69	4.52	+36.52	18.09	−15.23	11.53	−54.50	34.70

Kinematic analysis of wrist trajectory

In consideration of the results of our previous work (Deschodt et al. 1994), we have assumed for the present study that the saggital view of the trajectory of the underwater wrist provides a reliable representation of the organization of the upper limb for propulsion. For quantification, the trajectory of the wrist underwater has been divided into three relevant phases, F (forward), D (downwards) and B (backwards) selected on the basis of a multifactorial statistical analysis that included the maximal swimming velocity (Deschodt et al. 1994). The amplitudes and durations of each of the selected phases are shown in Table 1.

Statistically significant differences were mostly found for the effect of leg action rather than for the action of the contralateral arm (Table 1). Thus, as was the case with maximal velocity, restricted arm action also showed few significant changes regarding the wrist trajectory. However, a significant contribution by the leg kick on the kinematic parameters was made as indicated by the statistical differences between 1A and 1A2L, and 2A and 2A2L (Table 1). The contribution of the legs was mainly to produce significantly larger SL and F amplitudes, whereas B was significantly smaller. The duration of the arm stroke and the durations of both the F-phase and the D-phase were also longer when the legs were contributing. These observations again raise the question of whether there is a direct role for the leg kick in propulsion or alternatively whether its role is to increase velocity by changing the pattern of the trajectory of the wrist thus allowing the creation of a higher propulsive force.

Although the effect of the action of the contralateral arm was of lesser magnitude on both swimming velocity and wrist trajectory than that observed for leg action, it is noteworthy that a surprisingly large amplitude of F and to a lesser extent of D occurred in 1A2L. This can also be clearly seen in Fig. 2a, where the relationships obtained between swimming velocity and the value of the *F*-coordinate obtained in each situation are illustrated. Figure 2a indicates that:

1. In every situation except 2A2L the larger the value of the individual *F*-coordinate the higher the swimming velocity
2. This was not true when comparing between situations where 1A2L generally provided the largest values of the individual *F*-coordinates which did not correspond to the individual highest individual velocities (Table 1).

In Fig. 2b and c it can be seen that the values of individual D and B coordinates were correlated to individual maximal velocities obtained in almost every situation. As shown in Table 1, the values of D and B were maximized in the normal swimming situation i.e. 2A2L. Since Table 1 indicated that the contribution of the legs, to the wrist trajectory was more significant than the contribution of the contralateral arm, a further analysis of the relative effect of legs on kinematic parameters and velocity was performed.

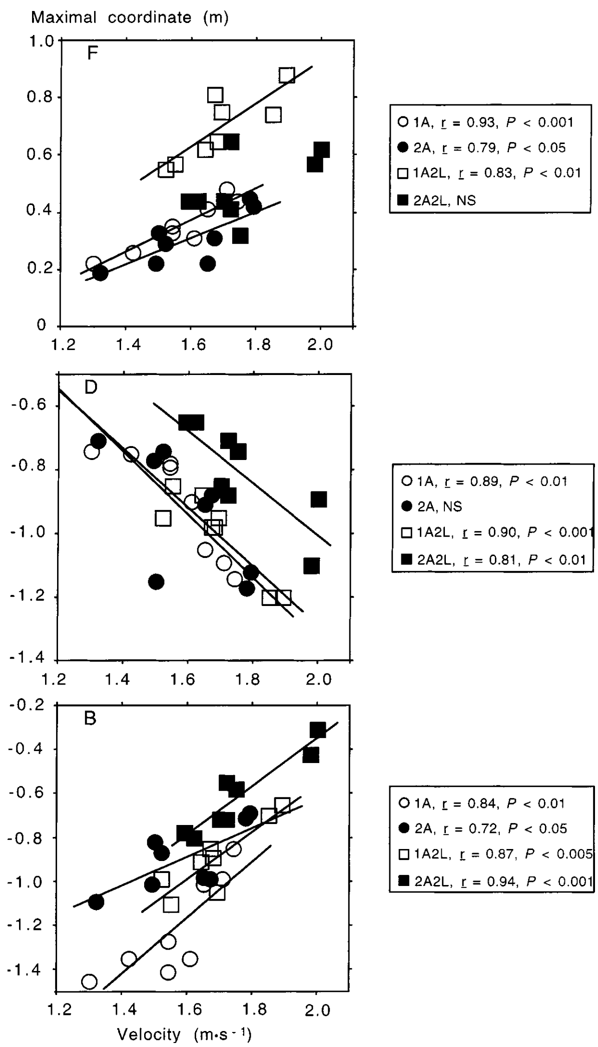

Fig. 2 Relationships between velocity and the maximal coordinate of each phase of the underwater wrist trajectory (*F*, *D* and *B*, see definitions Fig. 1) for the situations *1A*, *2A*, *1A2L* and *2A2L*, see definitions Table 1

Relative changes in wrist trajectory and maximal velocity

In Table 2, relative changes in kinematic parameters of wrist trajectory (δSL/SL, δF/F, δD/D and δB/B, expressed as percentages) were calculated for the situations where the legs contributed to propulsion (1A2L and 2A2L) and situations where they did not (1A and 2A). Table 2 shows that the leg influenced wrist trajectory to a large extent, for example from −54% to +36% between 2A and 2A2L for B and F respectively. Table 2 also suggests that individual responses of the legs in 2A/2A2L were not all in the same general direction as indicated by the large standard deviations which gave coefficients of variation ranging from 50%–76%. We have tested the hypothesis that those individuals who showed the largest relative changes in magnitude of wrist kinematic parameters F, D and B would also show the highest relative increases in velocity. No such relationships were found (Fig. 3).

Nevertheless, the wide range of individual responses did not however obscure the fact that some subjects showed an increase in one of the parameters between 2A and 2A2L (Figs. 4–6), although these responses did not reach conventional levels of statistical significance. The role of the legs as represented by links between data obtained for individuals in 2A and the corresponding data in 2A2L was mostly demonstrated by the fact that the increase in velocity was accompanied by an increase in F, D and B. Individual responses (subjects A, B and C) have been selected for discussion because they illustrate that the magnitude of individual responses varied markedly according to the degree of leg restriction/contribution.

Discussion

The present study was aimed at evaluating the influence on the maximal 25-m freestyle swimming velocity and on

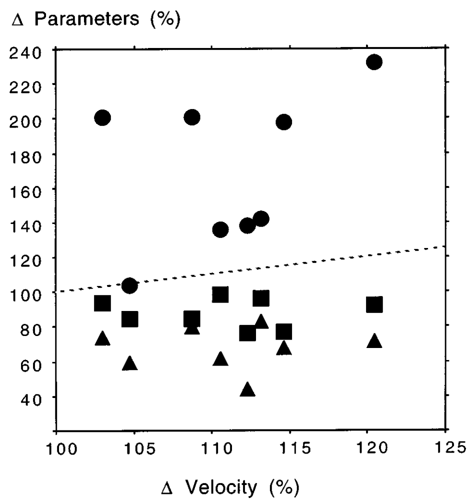

Fig. 3 Relationships between individual relative changes in kinematic parameters (Δ *parameters*, ● Δ *F*, ■ Δ *D*, ▲ Δ *B*, for definitions see Fig. 1) and individual relative changes in velocity (Δ *velocity*)

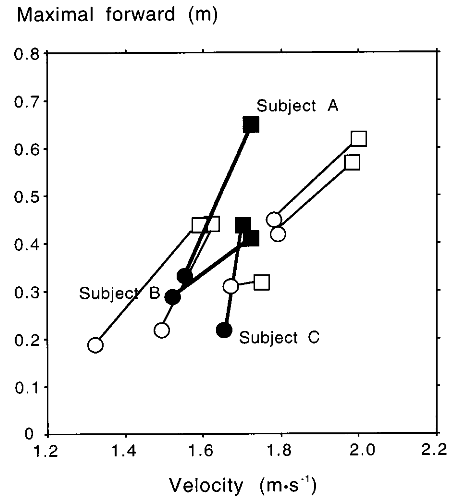

Fig. 4 Ability of individuals to use legs illustrated by linear relationships between maximal forwards coordinates and swimming velocity in two situations (● ○ *2A* and ■ □ 2A2L, for definitions see Table 1)

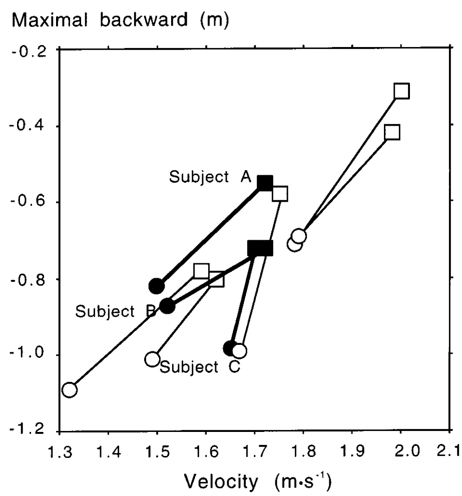

Fig. 5 Ability of individuals to use legs illustrated by linear relationships between maximal backwards coordinates and swimming velocity in two situations (● ○ *2A* and ■ □ *2A2L*, for definitions see Table 1)

the trajectory of the left wrist underwater, of restricting the leg kick and also of restricting the swimming to one arm. This was achieved by making underwater video recordings while the subjects swam all-out in 25-m sprints either using the *normal* front crawl stroke or in situations where the participation of the arms and/or leg was restricted.

The role of legs in maximal swimming velocity

The main finding of the present study was that with the participation of the legs there occurred a significantly higher velocity by 10%, whereas the participation of the contralateral arm produced only a 4% higher velocity

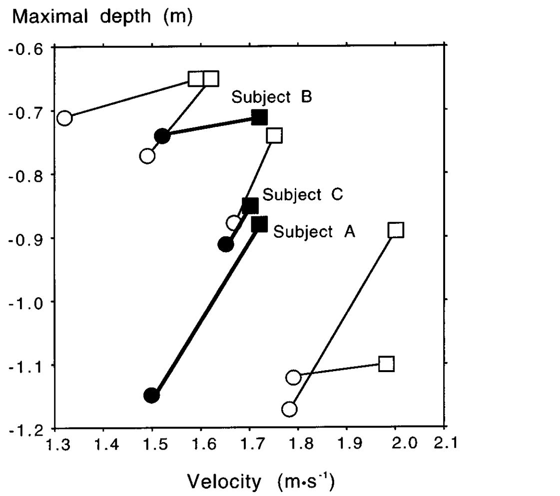

Fig. 6 Ability of individuals to use legs illustrated by linear relationships between maximal vertical coordinates and swimming velocity in two situations (● ○ *2A* and ■ □ *2A2L*)

which was non-significant. In other words in 1A2L, the swimmers reached only 96% of the maximal velocity they attained in 2A2L, whereas in 2A the velocity corresponded to only 91% of the 2A2L velocity. These results are in accordance with those obtained in previous studies (Counsilman 1971; Schleihauf 1979; Maglischo et al. 1986), where the arm stroke was reported to have generated about 90% of the total propulsive force in sprint freestyle. Nevertheless, we have proposed that some attention should be paid to the 10% contribution of the legs in generating force for rapid locomotion in water. Conversely, the effects obtained in situations where arm motion is restricted demonstrated firstly, that it had a smaller influence on swimming velocity and secondly that it provided a particular swimming situation (1A2L) in which the responses underwater trajectory of the wrist showed disproportionate magnitudes when compared to those obtained in previous studies in normal swimming.

An atypical swimming situation (1A2L)

Although 1A2L was interesting in comparison with 1A, i.e. illustrating the effect of leg restriction, we observed in the films of the underwater trajectory of the left wrist that this situation caused some non-typical adaptations. Indeed, it was obvious that an extremely large maximal forward position of the wrist was obtained in 1A2L which would clearly suggest that individuals aimed at maintaining a long-duration gliding position rather than quickly becoming active again with the left arm. Such behaviour, induced by the restriction of the use of the arm clearly does not correspond to the behaviour which has been shown in elite 100-m swimmers who actively slide their hand forward and down for active propulsion (Deschodt et al. 1994). Indeed, in that study which included the best 100-m performers who were filmed in 1994 during the World Championship and Cup, the parameter F had the highest loading in the *velocity* component in the multicomponent statistical analysis. Clearly again, the much higher F obtained in 1A2L when compared to other situations was not associated with the highest velocity. Therefore, the 1A2L situation was classified as a non-typical sprinting situation.

Kinematic analysis of wrist trajectory

The main purpose of the present study was to evaluate by means of video recordings the underwater trajectory of the left wrist during situations in which the subjects were required to swim at maximal velocity but with restricted movements. Such an analysis made it possible to assess quantitatively the magnitude of the changes in wrist trajectory whether the legs contributed or not to propulsion at maximal velocity. All the kinematic parameters of the wrist selected were sensitive to leg action (Table 1) and changed by large amounts. Therefore it is necessary to suggest that the participation of the leg in the 10% increase in velocity could have been in part the consequence of a change in contribution of the arm to propulsion. Other workers have proposed that a swimmer using a skilled leg kick can show a more efficient force generation by the hand (Schleihauf 1979; Maglischo et al. 1986). An additional finding of the present study was that within each situation individual values of F, D and B (see Fig. 2) were correlated to individual values of velocity. Such a result has previously been obtained in our recent study which included the analysis of the 100-m freestyle races performed during the 1994 World Championship (Deschodt et al. 1994) where F and also D and B had high loads on the velocity component in the multicomponent analysis performed. Such results show the importance of maximizing F, D and B to reach a high swimming velocity and we have consequently considered that the changes induced by participation of the legs in F, D and B could in part explain the gain in velocity. Unfortunately, no relationship was obtained between relative individual changes in F, D and B and relative changes in individual velocity. This absence of correlation could have been caused by the methods used. For example, the wrist kinematic parameters obtained could obviously have been atypical; however this hypothesis can be rejected, since the SL we calculated was highly correlated to velocity in each situation ($0.73 < r < 0.92$), similar to correlations that have been obtained between SL and velocity in a large population by Pelayo et al. (1996).

The absence of a relationship between relative changes in F, D and B and relative changes in velocity could therefore be the consequence of some individual responses regarding participation of the legs or, in other words, an individual would change his wrist trajectory by a magnitude depending on the way his arms and legs actually cooperated to generate the propulsive force.

Individual responses to relative changes in kinematic parameters

Figures 4 to 6 indicate clearly that most subjects showed increases in F, D and B parameters when the legs were active, but this did not reach conventional levels of statistical significance ($P < 0.05$). However, some characteristic responses were observed and subjects A, B and C have been selected to illustrate these.

These subjects attained nearly the same 1.75 $m \cdot s^{-1}$ velocity in 2A2L but markedly different effects of the legs on velocity and on F, D and B were observed. Subject A was mainly characterized by a great increase in velocity when the legs were active. Concomitantly, great variations in F, D and B were seen. We propose that subject A gained great benefit from participation of the legs making it possible for him to adjust his wrist trajectory to generate a higher force of propulsion. This is precisely the hypothesis that has been formulated by Schleihauf (1979) and Maglischo et al. (1986).

Subject B also benefitted by involving his legs in reaching a higher velocity but in this situation few changes were seen in his wrist trajectory. We propose that subject B could be classified as a *leg propulsor* in the sense that the participation of the leg kick was the main factor directly contributing to the increase in velocity.

Lastly, subject C showed an interesting small increase in velocity when participation of the legs was involved whereas major changes were observed in wrist trajectory. We suggest that subject C could be classed as an *arm propulsor*, representing an inefficient use of the legs to generate propulsive force. This would suggest that leg kick induced some perturbations in arm movement which followed the same general tendency but surprisingly yielded little increase in efficiency.

This kind of observation seen in subject C could be of great importance in physiological tests. It would make it possible to detect the crucial lack of coordination which is apparent between a *leg-propulsor* and an *arm-propulsor*; it would represent a situation where training armed specifically at legs or arms would probably lead to no gain in performance as the necessary coordination would be lacking.

Subject B provided an example of a clear benefit from the legs which did not accompany a similar benefit from the upper limbs. It is appropriate now to discuss how the leg kick could provide a gain in velocity. Counsilman (1971) and later Maglischo et al. (1986) have suggested that the leg kick could attenuate body oscillations and consequently active drag. In accordance with this idea, we observed in the present study that vertical oscillations of the the hip were of smaller amplitude in 2A2L when compared to 2 A (Fig. 7). Thus, following previous suggestions, the propulsive role of legs could be to provide relative stability to the rest of the body, so the arms could consequently develop a higher amplitude of movement. The role of the legs has been proposed by Schleihauf (1979) to be the development of a high lift force; unfortunately kinematic parameters for underwater displacement of the legs were not obtained in the present study and thus no hypothesis could be formulated concerning the generated lift force that stabilizes the body.

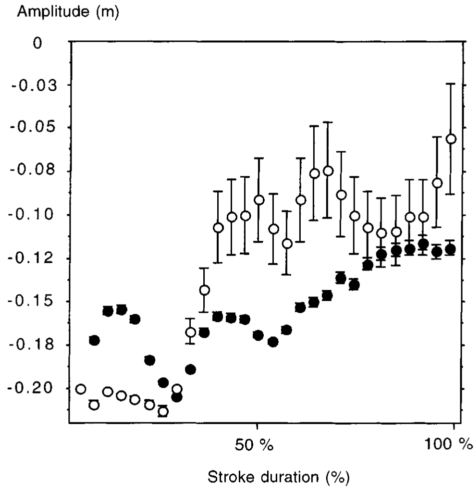

Fig. 7 Vertical trajectory of the hip during the underwater stroke of the wrist in two situations (● *2A* and ○ *2A2L*, for definitions see Table 1)

Conclusion

The magnitude of the contribution of the legs to human locomotion in water at maximal freestyle velocity was assessed to be about 10% in the present study. It was deduced that a significant role for the legs in enhancing speed could be found from the quantitative changes noted in the kinematic parameters of the underwater trajectory of the wrist. Since singular responses were observed as functions of leg involvement it is suggested that tests of individuals are required before giving importance to leg-specific exercises during training. Further studies are necessary in this area.

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