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Short communication

The effect of different inter-pad distances on the determination of active drag using the Measuring Active Drag system

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ABSTRACT

The Measuring Active Drag (MAD) system was developed to determine active drag in swimming by measuring the push-off force exerted at fixed pads placed below the waterline. The imposed inter-pad distance, which to date has been kept constant while using the MAD system, could affect the active drag because it requires the use of different stroke frequencies. The aim of the present study was therefore to determine the effect of inter-pad distance on active drag at a given speed. In particular, drag-velocity curves at three different inter-pad distances (1.25 m, 1.35 m and 1.45 m) were determined using the MAD system for eleven competitive swimmers. Variation of 16% in inter-pad distance (14% change in stroke frequency) revealed no significant difference in calculated active drag between different inter-pad distances and a low ($<5\%$) average coefficient of variation over different inter-pad distances was found. In addition, inter-test reliability, which was determined for the two 1.35 m conditions only, was high (ICC >0.90) for measurements on two consecutive days. The results suggest that it may not be necessary to adapt the inter-pad distance of the MAD system based on anthropometric characteristics of the subject or the velocity-related stroke length in free swimming.

1. Introduction

In swimming, the acceleration (a) which is achieved by a swimmer is the outcome of mainly two forces acting on the body, namely the propulsive force generated by the arms and legs (F_p) to overcome drag (F_d) (Toussaint and Beek, 1992), resulting in the following force balance:

$$F_p - F_d = m \times a \tag{1}$$

The speed that is achieved in steady state depends on the magnitude of the propulsive force and the relationship between speed and drag. It is therefore important to study this relationship.

Since the 1970s, several techniques have been introduced to determine drag during swimming (see Toussaint et al. (2004) for review). With the Measuring Active Drag (MAD)-system, active drag is determined by direct measurement of the propulsive force that the swimmer applies at fixed pads while swimming with his or her arms only (Toussaint et al., 2004; van der Vaart et al., 1987). The average active drag equals the average propulsive force when the speed during a trial is kept constant (van der Vaart et al., 1987).

The most important advantages of measuring active drag using the MAD system are the ability to directly measure push off forces and the possibility to determine drag at submaximal speeds. However, the test apparatus and methodology used in the MAD test also have some drawbacks as highlighted by Havriluk (2007): (1) The push off force from the moment of hand entry until the hand touches the fixed pad is not measured, (2) subjects swim with their arms only, and (3) the hand does not move relative to the water during the push-off. The arm rotates with an instantaneous center of rotation in the free condition approximately at the elbow, whereas it is positioned at the wrist during 'MAD-swimming'. Consequently a larger part of the arm moves forward in the swimming direction and could have a drag increasing effect. In principle, these three disadvantages could lead to a discrepancy between the true drag during swimming and the measured drag on the MAD system. However, they are unavoidable given the design of the MAD system and assumed not to influence the determination of active drag.

One of the aspects in the MAD procedure, which could potentially influence the measured drag value, is the distance between the fixed push-off pads. This so-called inter-pad distance is kept constant during MAD testing for practical reasons. However, an inter-pad distance of for example 1.35 m would be 67.5% of body height for a 2.00 m tall swimmer, while it would be 79.4% for a swimmer who is 1.70 m tall (Toussaint et al., 1990). This difference in ratio could affect the stroke mechanics used to swim over the system and therefore active drag. Furthermore, technique is hypothesized (Colwin, 2002; Toussaint et al., 1988, 1990, 2002;

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Vennell et al., 2006; Wilson and Thorp, 2003) to have an effect on drag. Variation of stroke frequency is therefore expected to influence the active drag. In addition, if the drawbacks described by Havriluk (2007) would influence the drag measured on the MAD system, an effect of stroke frequency on active drag is to be expected. More unmeasured arm entries per time unit (drawback 1) are expected to lower the measured active drag at a higher stroke frequency. On the other hand, when more propulsive phases with a non-moving hand (drawback 3) are made per time unit at a higher stroke frequency, this is expected to have a drag increasing effect. Whether these contrasting effects cancel each other out or lead to an overall increase or decrease in measured active drag at higher stroke frequencies will be determined in the current study.

The influence of stroke frequency on active drag due to changes in technique can be tested by determining the effect of different inter-pad distances on the active drag measured with the MAD system. Toussaint et al. (1990) observed no difference in drag when repeated tests were performed using different inter-pad distances for three swimmers. However, the authors could not determine the reliability of this result due to the small number of subjects. Therefore, in the current study the effect of different pad distances on the measured active drag in swimming, and the potential measurement error specifically on the MAD system, were determined for a substantially larger group of 11 subjects.

2. Methods

2.1. Participants

Eleven competitive swimmers (see Table 1) signed informed consent to participate in the study, which was approved by the local ethical committee.

2.2. Measurements

Active drag was determined using the MAD system (see Toussaint et al., 2004 for a detailed description). The push-off signal was sampled at 200 Hz. After a short warm-up (10 min), three familiarization runs on the MAD system were performed. Next, the speed-active drag curve was determined from the average push-off force of 10 to 12 trials (with approximately 3 min rest between trials) at different speeds ranging from 1.2 m s^{-1} to maximal swimming speed. Subjects swam over the system using only their arms to propel their body forward by pushing off against the pads. In free swimming the leg kick keeps the legs lifted. However, the force generated by the legs could not be measured. This would make the force balance (Eq. (1)) unsolvable, as both drag and propulsive force would be unknown. Therefore, the legs were kept in a non-propulsive, stable position using a pull buoy. This kept the frontal area constant and allowed studying the speed-drag relationship independently of the potential effect of speed on frontal area due to sinking of the legs at lower velocities. The speed-active drag curve was obtained for three different inter-pad distances: short (1.25 m), middle (1.35 m) and long (1.45 m). The middle condition was tested on two consecutive days to determine the test-retest reliability of the MAD test. The active drag in the short and long conditions was determined on either day 1 or day 2.

2.3. Data processing

The speed-active drag curve was determined by least square fitting the A and b coefficient of the function $F_d = A \times v^b$ through the measured data of drag as a function of speed (Toussaint et al., 2004). Next, active drag at 1.25 m s^{-1} and 1.55 m s^{-1} was calculated for each inter-pad condition using the active drag curve, because both speeds fell within the measured range of speeds for all subjects. This resulted in eight calculated active drag values (2 speeds per condition for the distance conditions 1.25 m, 1.35 m day 1, 1.35 m day 2 and 1.45 m), which were used in the statistical analyses. The stroke frequencies given the different inter-pad distances to achieve the speeds 1.25 m s^{-1} and 1.55 m s^{-1} are shown in Table 2.

2.4. Statistical analyses

A 3 × 2 repeated measures ANOVA was used to determine the main effect of different inter-pad distances on active drag using within-subject factors speed (1.25 m s^{-1} and 1.55 m s^{-1}) and inter-pad distance (1.25 m, 1.35 m and 1.45 m). For the inter-pad distance of 1.35 m the average force value of day 1 and day 2 was entered in this ANOVA. Mauchley's test of sphericity was used to correct the degrees of freedom of the ANOVA. The intraclass correlation coefficient (ICC) was calculated using the active drag in the 1.35 m condition measured on day 1 and day 2 to determine the inter-test reliability of the MAD test. Furthermore, the standard error of the measurement (SEM) was calculated for both speeds according to the equation (de Vet et al., 2011):

$$SEM = SD_{pooled} \times \sqrt{(1-ICC)} \quad (2)$$

where SD_{pooled} is the average of the standard deviation at day 1 and day 2. In addition, for each subject the coefficient of variation (CV=(standard deviation/mean) × 100%) was calculated over the three inter-pad distance conditions to determine the mean coefficient of variation.

3. Results

The individual active drag curves for the different inter-pad distances are shown in Fig. 1. In Fig. 2, the active drag forces of the

Table 2
The stroke frequencies required to achieve the speeds 1.25 m s^{-1} and 1.55 m s^{-1} in the different inter-pad distance conditions.

Speed (m/s)	**Inter-pad distance (m)**	**Stroke length (m)**	**Stroke frequency (str min^{-1})**
1.25 m s^{-1}	**1.25**	**2.50**	30.0
	1.35	**2.70**	27.8
	1.45	**2.90**	25.9
1.55 m s^{-1}	**1.25**	**2.50**	37.2
	1.35	**2.70**	34.4
	1.45	**2.90**	32.1

Table 1
Characteristics of the subjects.

Subject	Gender	Height (m)	Mass (kg)	Age (years)	Personal best mean race speed (m/s)	Personal best[a] (% of WR)
1	M	1.76	68	17	1.79	83.8
2	M	1.72	65	18	1.81	84.8
3	M	2.00	87	18	1.79	83.9
4	M	1.78	69	18	1.71	80.2
5	M	1.89	71	37	–	–
6	M	1.92	81	24	1.92	90.0
7	M	1.89	80	21	1.78	83.5
8	M	1.95	75	19	1.69	79.3
9	F	1.68	59	15	1.58	82.1
10	F	1.79	63	15	1.54	80.0
11	F	1.69	58	18	1.68	87.6
Mean ± SD		**1.82 ± 0.11**	**70.5 ± 9.4**	**20.0 ± 6.2**	**1.73 ± 0.11**	**83.5 ± 3.4**

[a] personal best in the 100 m freestyle long course event (data from www.swimrankings.net) as percentage of the World Record (1st of July 2011: male: 46.91 s, female: 52.07 s)

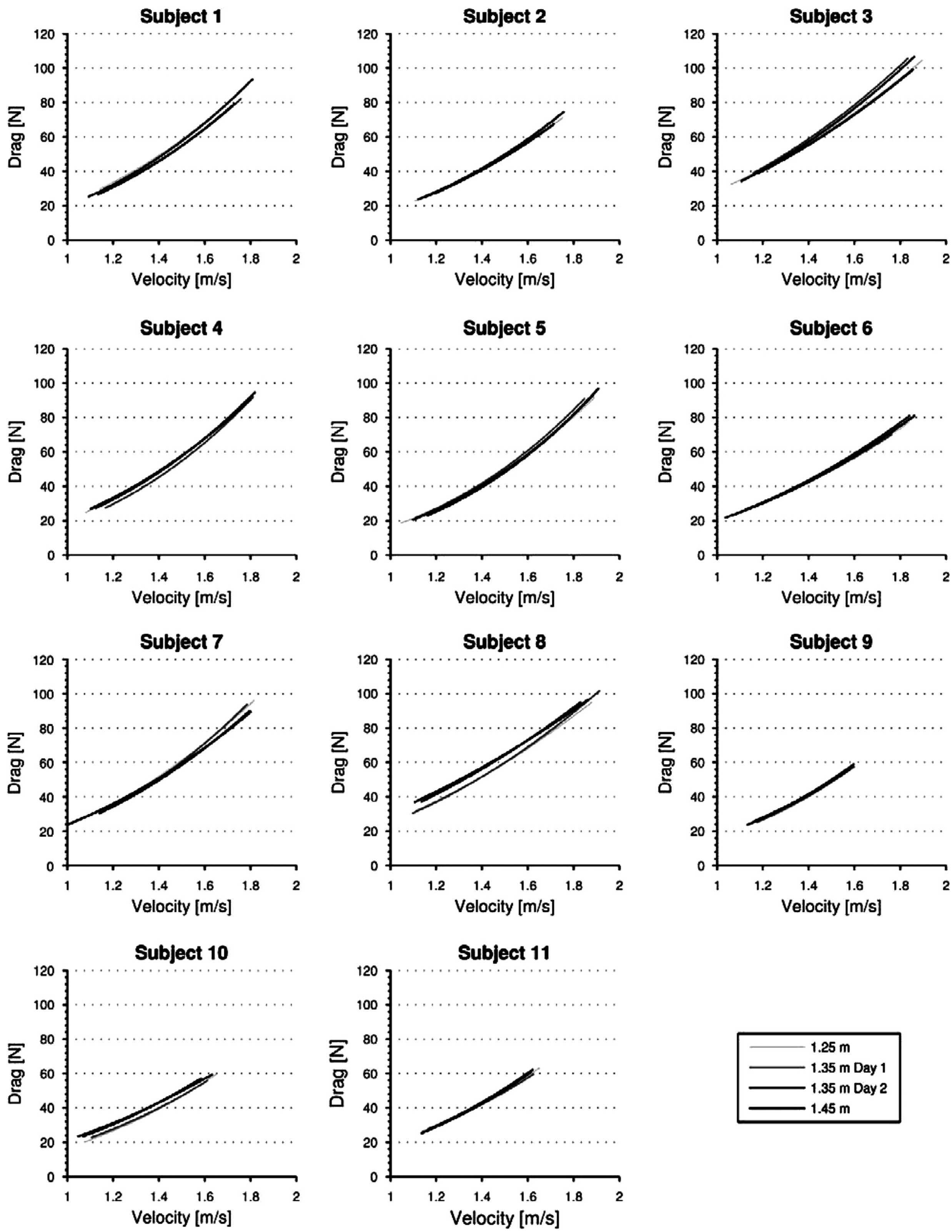

Fig. 1. Fitted active drag curves at the different inter-pad distances for all subjects.

individual subjects in each inter-pad condition are shown. The data seem to be independent of inter-pad distance and reproducible across days. Active drag curve coefficients for the different inter-pad distances are shown for all subjects in Table 3. Although the inter-pad distance was varied by 16%, the average coefficient of variation for the calculated force values over the different inter-pad distances was low at both 1.25 m s^{-1} (2.82 ± 2.08%) and 1.55 m s^{-1} (1.97 ± 1.10%). The coefficient of variation was below 5% in 9 out of 11 subjects at 1.25 m s^{-1} and in all subjects at 1.55 m s^{-1} (see Table 4). Furthermore, there was no significant

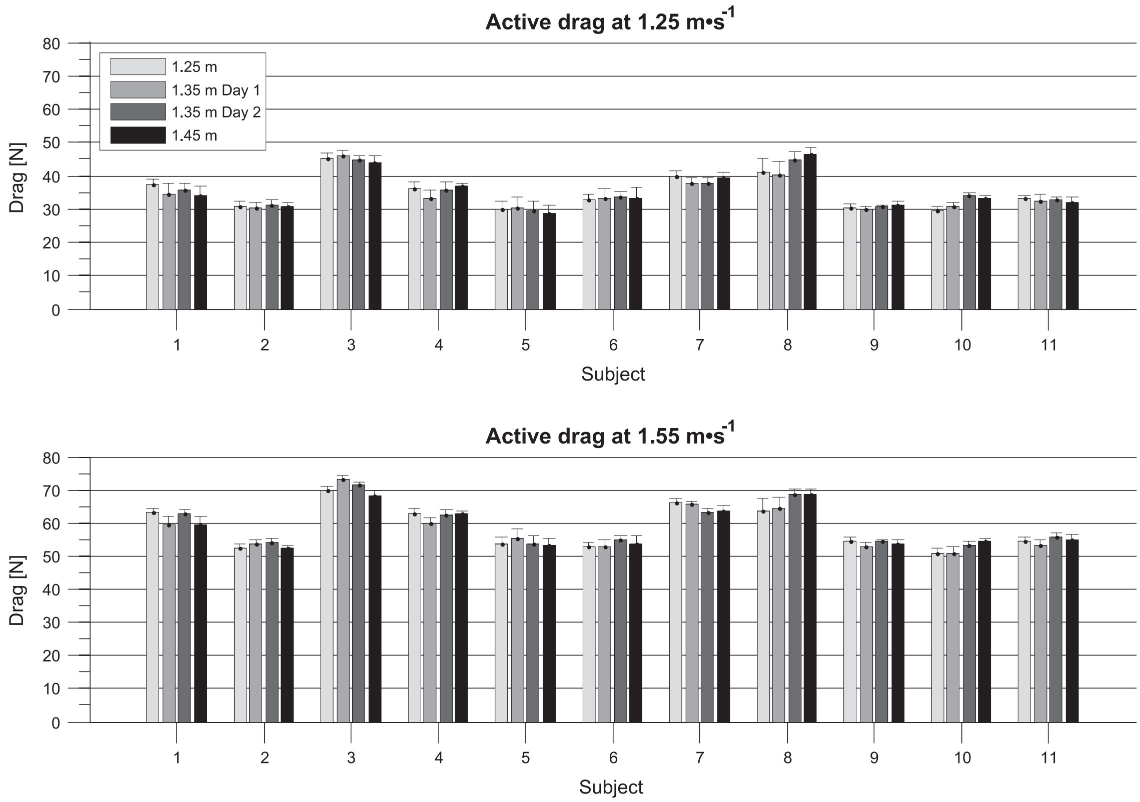

Fig. 2. The calculated active drag and the 95% confidence interval upper bound of the predicted value for the individual subjects at 1.25 m s^{-1} (upper panel) and 1.55 m s^{-1} (lower panel).

Table 3
Active drag curve ($F_d=A^*\upsilon^b$) coefficients ± 95% confidence interval half-widths at different inter-pad distances.

Subject	1.25 m (N m^{-b} s^b)		1.35 m:Day 1 (N m^{-b} s^b)		1.35 m:Day 2 (N m^{-b} s^b)		1.45 m (N m^{-b} s^b)	
	A	**b**	**A**	**b**	**A**	**b**	**A**	**b**
1	21.39 ± 1.72	2.48 ± 0.17	19.65 ± 3.01	2.53 ± 0.32	20.02 ± 1.84	2.60 ± 0.19	19.20 ± 2.99	2.59 ± 0.34
2	17.66 ± 1.71	2.48 ± 0.21	16.92 ± 1.69	2.63 ± 0.21	17.65 ± 1.55	2.56 ± 0.18	17.67 ± 1.24	2.49 ± 0.15
3	28.78 ± 1.55	2.02 ± 0.10	28.31 ± 1.60	2.17 ± 0.11	27.43 ± 1.12	2.19 ± 0.08	27.63 ± 2.21	2.07 ± 0.16
4	20.33 ± 1.95	2.57 ± 0.19	17.98 ± 2.12	2.75 ± 0.22	20.15 ± 1.94	2.58 ± 0.18	21.19 ± 1.09	2.47 ± 0.10
5	16.49 ± 2.22	2.69 ± 0.26	16.24 ± 2.70	2.81 ± 0.31	15.76 ± 2.54	2.80 ± 0.29	14.94 ± 2.17	2.89 ± 0.26
6	20.02 ± 1.53	2.22 ± 0.16	20.33 ± 3.27	2.18 ± 0.32	20.30 ± 1.71	2.27 ± 0.17	20.06 ± 3.29	2.25 ± 0.31
7	23.46 ± 1.57	2.36 ± 0.13	21.49 ± 1.35	2.54 ± 0.13	22.15 ± 1.72	2.39 ± 0.16	23.78 ± 1.64	2.25 ± 0.14
8	25.72 ± 4.38	2.07 ± 0.33	24.87 ± 3.79	2.17 ± 0.28	28.98 ± 2.46	1.97 ± 0.18	30.70 ± 2.53	1.84 ± 0.17
9	16.69 ± 1.25	2.70 ± 0.19	16.34 ± 1.29	2.68 ± 0.20	17.08 ± 0.50	2.64 ± 0.07	17.55 ± 1.61	2.55 ± 0.23
10	16.82 ± 1.47	2.53 ± 0.21	18.01 ± 1.82	2.37 ± 0.27	21.29 ± 1.00	2.10 ± 0.12	20.14 ± 1.01	2.26 ± 0.14
11	19.63 ± 1.25	2.34 ± 0.16	19.18 ± 2.54	2.34 ± 0.32	18.80 ± 1.07	2.48 ± 0.15	18.37 ± 1.63	2.50 ± 0.22
Mean	**20.64**	**2.41**	**19.94**	**2.47**	**20.87**	**2.42**	**21.02**	**2.38**

main effect for inter-pad distance on calculated active drag, $F(1.5, 14.7)=0.06$, $p=0.893$, $\eta_p^2=0.008$. Differences in active drag using the 8% (1.35 m) and 16% (1.45 m) larger inter-pad distance in comparison to the force in the 1.25 m condition were, respectively, −0.10 ± 1.45 N and 0.32 ± 2.41 N at 1.25 m s^{-1} and 0.34 ± 1.72 N and 0.07 ± 2.44 N at 1.55 m s^{-1}. There was a significant main effect for speed, $F(1, 10)=1384.75$, $p=0.006$, $\eta_p^2=0.993$. Overall, active drag was 23.60 N [95% CI 22.19 25.02] higher at 1.55 m s^{-1} compared to 1.25 m s^{-1}. There was no significant interaction between speed and inter-pad distance, $F(2.0, 20.0)=2.32$, $p=0.124$, $\eta_p^2=0.188$.

Test-retest reliability of the active drag using an inter-pad distance of 1.35 m over two consecutive testing days was high (1.25 m s^{-1}: ICC=0.922; 1.55 m s^{-1}: ICC=0.937), which indicates that the MAD system is a reliable measurement device. In addition, SEM at 1.25 m s^{-1} and 1.55 m s^{-1} were 1.43 N and 1.69 N, respectively.

4. Discussion

The main aim of this study was to find out whether the drag measured using the MAD system depends on the inter-pad distance used. The 16% higher imposed inter-pad distance ((1.45/1.25) × 100%)=116% constrained the swimmer to lower stroke frequencies by 14% ((1/1.16) × 100%) to achieve the same speed on the MAD system. However, in the current study we found that the average coefficient of variation for the active drag force within a subject over the different inter-pad distances was low (< 5%).

Table 4
Coefficient of variation (*CV*) for the calculated force values over the different inter-pad distances at 1.25 m s^{-1} and 1.55 m s^{-1}.

Subject	CV at 1.25 m s^{-1} (%)	CV at 1.55 m s^{-1} (%)
1	4.27	3.02
2	0.14	1.49
3	1.83	2.95
4	3.24	1.32
5	2.96	1.47
6	0.82	0.97
7	2.54	1.86
8	6.41	3.77
9	1.16	1.04
10	6.18	3.30
11	1.44	0.49
Mean ± SD	**2.82 ± 2.08**	**1.97 ± 1.10**

Furthermore, the calculated drag at a velocity of 1.25 and 1.55 m s^{-1} was not significantly different between the inter-pad distances 1.25 m, 1.35 m and 1.45 m. Inter-pad distance, and thus stroke frequency, did not seem to influence the measured active drag within the range of frequencies investigated. This finding is in line with the results obtained by Toussaint et al. (1990) in a small group of three swimmers. Therefore, it seems unnecessary to adapt the inter-pad distance to the anthropometric characteristics of the subjects or the velocity-related stroke length in free swimming. In addition, the lack of propulsive force measurement in the phase from hand entry to first pad contact as described by Havriluk (2007) does not seem to have an effect on active drag determination using the MAD system as a higher number of entries per time unit at short inter-pad distance compared to the large inter-pad did not lead to a significant difference in active drag at the same speed and the average coefficient of variation over different inter-pad distances was low ($<5\%$).

The variation in inter-pad distance influenced the stroke frequency at the same speed. A change in stroke frequency will directly affect the amount of intense movement and hand entries per time unit. Also, the duration of the stretched arm position and the duration of the glide phase could be altered at different stroke rates. These aspects of the stroke cycles mechanics have been hypothesized (Colwin, 2002; Toussaint et al., 1988, 1990, 2002; Vennell et al., 2006; Wilson and Thorp, 2003) to influence active drag. However, given the negligible effects measured for the present group of swimmers, we conclude that within the constraints (range of frequencies, range of velocities, ability of the swimmers and MAD methodology) of the current study design, the previously hypothesized drag increasing and drag reducing effects of changes in stroke frequency, brought about by changes in inter-pad distance, are small or their positive and negative effects cancel out. Nevertheless, it still remains possible that adjustments in stroke mechanics could reduce active drag (Clarys, 1979; Kolmogorov et al., 1997; Wilson and Thorp, 2003), but this might require a relatively long training period.

In conclusion, it was found that the magnitude of drag measured with the MAD system at sub maximal speeds was independent of inter-pad distance. Therefore, it appears appropriate to use a fixed inter-pad distance in MAD testing.

Conflict of interest

All authors do not have any financial and personal relationships with other people or organisations that could inappropriately influence (bias) their work.

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