Drafting Distance in Swimming

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ABSTRACT

CHATARD, J.-C., and B. WILSON. Drafting Distance in Swimming. *Med. Sci. Sports Exerc.*, Vol. 35, No. 7, pp. 1176–1181, 2003. **Purpose:** This study investigates the effect of the distance separating the lead and draft swimmers on the metabolic and hydrodynamic responses of the draft swimmer. **Methods:** A nondrafting swim of 4 min at 95% of the best 1500-m pace for 11 swimmers was compared with swimming in a drafting position at four different distances directly behind another swimmer (0, 50, 100, and 150 cm). Swimming performance was assessed by stroke rate and stroke length; the metabolic response by oxygen uptake, heart rate, and blood lactate; and the rating of perceived exertion by the Borg scale. Passive drag was assessed at these drafting distances by passive towing. Then, passive drag was measured in six swimmers towed in six lateral drafting positions, with swimmers separated by ~40 cm, and then measured in two positions at the rear of the lead swimmer with a reduced lateral distance between swimmers of 50 and 0 cm. **Results:** Oxygen uptake, heart rate, blood lactate, rating of perceived exertion, and stroke rate were significantly reduced and stroke length was significantly increased in all drafting positions compared with the nondrafting position. For drag, the most advantageous drafting distances were 0 and 50 cm back from the toes of the lead swimmer. Drag was reduced by 21% and 20%, respectively. In lateral drafting, drag was significantly reduced by 6% and 7%, respectively, at 50 and 100 cm back from the hands of the lead swimmer. **Conclusions:** Swimming behind another swimmer at a distance between 0 and 50 cm back from the toes was the most advantageous, whereas in lateral drafting the optimal distance was 50–100 cm back from the hands of the lead swimmer. **Key Words:** METABOLIC COST, PASSIVE DRAG, TRIATHLON, HYDRODYNAMIC

Drafting while swimming front crawl, i.e., swimming directly behind or at the side of another swimmer, is mainly used in triathlon races or open-water swims. Drafting allows the swimmer to reduce the energy cost of swimming propulsion and hence gain time for swimming at maximum speed (5). Alternatively, energy may be conserved for the cycling and running phases of the event.

In submaximal conditions, at 95% of a maximum speed over a 549-m swim, Bassett et al. (1) showed that drafting affects the metabolic response to swimming. Oxygen consumption was reduced by 8 ± 12%, blood lactate concentration by 33 ± 17%, and the rate of perceived exertion by 21 ± 10%. The lower resistive body drag (passive drag) forces encountered by the swimmers at maximum speed are responsible for the observed metabolic change (5). These forces are 13–26% lower than those for the lead swimmer, depending on the velocity of the triathletes.

Little is known about the distance chosen by the drafter for following the lead swimmer. In other sports such as cycling (9,13), speed skating (18), running (14), and cross-country skiing (15), this distance has been shown to be a determinant factor in drafting. Little is known also about swimming in position beside another swimmer although it is a frequent position in open-water swimming.

The primary purpose of this project was to investigate the effect of the distance (from 0 to 150 cm) separating the lead and the draft swimmer on the metabolic responses of the drafting swimmer performing a 4-min swim in a flume at 95% of their best 1500-m velocity. A secondary purpose was to evaluate the passive drag of the swimmers in the different drafting situations cited above and when drafting 100 cm at the side of the lead swimmer (lateral drafting with a separation between swimmers of ~40 cm) at different positions (from 0 to 200 cm) behind the hands of the lead swimmer.

METHODS

The study was conducted in two parts. Part I studied the metabolic and drag responses to drafting behind the lead swimmer. Part II studied the drag response to lateral drafting. Approval for the project was obtained from the University of Otago Committee on Human Research.

Subjects

Sixteen swimmers (11 triathletes and 5 swimmers) signed informed consent and participated in the studies on a voluntary basis. Eleven subjects (mean ± SD age 24 ± 5 yr, height 178 ± 7 cm, weight 74 ± 6 kg), participated in part I of the study and six subjects (age 23 ± 4 yr, height 178 ± 7 cm, weight 77 ± 3 kg) in part II. For each part of the study, the measurements were made over a 2-wk period.

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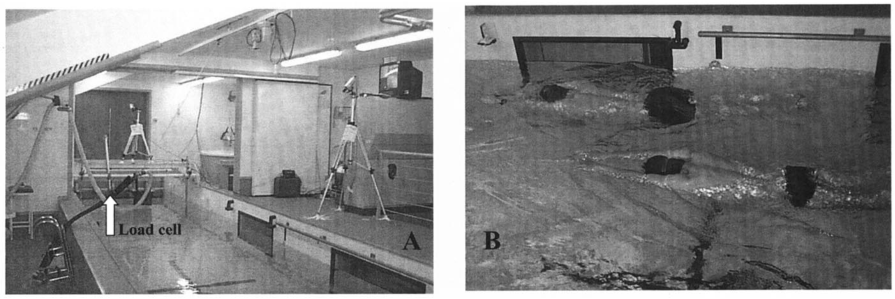

FIGURE 1—Perspective view of the flume environment (A), and swimmer lateral drafting 100-cm distance behind and 100 cm to the side of the lead swimmer (B).

Swimming Tests

The swimmers were tested in the swimming flume of the University of Otago. The flume channel had a test section of length 10 m, width 2.5 m, and depth 1.5 m. The flow in that section could be set at speeds up to 3.0 $m\cdot s^{-1}$ with an accuracy of ± 0.02 $m\cdot s^{-1}$ and steady uniform flow to within 2% (21). Water temperature was 28 $\pm$ 0.2°C. The space over the test section of the flume was a temperature-controlled 15- $\times$ 7-m room with a 2.5-m ceiling height. The load cell used for drag measurements was positioned on a moveable gantry and was adjusted to be directly in front of the drafting swimmer (Fig. 1A).

Before taking part in the study all subjects were familiarized to flume swimming (21). In part I, the subjects swam in the flume first alone for 4-min at a velocity as close as possible to their best 1500-m performance in open water (mean $\pm$ SD = 1.24 $\pm$ 0.10 $m\cdot s^{-1}$). Then, they repeated the 4-min swimming test at the same pace in a drafting position directly behind a lead swimmer at 0-, 50-, 100-, and 150-cm distances, measured from the toes of the lead swimmer to the fingertips of the drafting swimmer. The drafting trials were presented in a randomized order with a 5- to 10-min rest period between trials. Swimmers were tested in pairs, lead and draft swimmer, so that each swimmer always drafted behind the same lead swimmer. During the drafting situation, the lead swimmer was towed passively (no stroking or kicking or assisted flotation) at the same constant speed as for their swimming trials. Whatever the distance, the draftee was instructed to have their fingertips as close as possible to a small floating distance marker attached to the lead swimmer's feet indicating the exact distance to draft. The drafting distance was achieved to within $\pm$5 cm.

Physiological Measurements

Oxygen uptake (O_2, $L\cdot min^{-1}$) was measured from the expired air collected during the 4-min swims. Expired gases were analyzed using a Hans Rudolph (Kansas City, MO) three-way breathing valve (17) and a SensorMedics Metabolic Cart, model 2900Z BxB (SensorMedics Corp., Yorba Linda, CA). Oxygen and carbon dioxide fractions were determined using zirconium and infrared absorption analyzers calibrated with gases of known concentrations. Volumes were measured with a flow meter by thermal conductivity. Oxygen uptake was averaged every 30 s. Within the last 90 s, swimmers were at steady state. Oxygen uptake values changed less than 150 mL during the last 90 s of the trials. Heart rate (HR) was recorded for 5 s immediately at the end of the 4-min swims (HR400) by using a waterproof monitor sending data to a watch receiver (Polar 4000, Sport Tester, Kempele, Finland). The mean value was reported. Postexercise blood lactate concentration was determined in blood sample taken at the finger extremity within the first minute after the 4-min swims. Lactate concentrations were measured with a Lactate Pro meter (Arkay Factor Inc., Shiga, Japan). Immediately after each trial, subjects were asked to provide a rating of their perceived exertion (RPE) using the Borg scale (2).

Stroke Rate and Stroke Length

Simultaneous front and side views of all swims were recorded using two underwater video cameras. The stroke rate, expressed as the number of strokes per minute, was measured with a stopwatch while viewing the trial over the last 2 min of the swim as the number of completed strokes (hand entry to same hand entry) divided by the time to complete the number of strokes. The stroke length was calculated by dividing the mean swim velocity, as determined from the flow rate in the flume, by the stroke rate.

Measurement of Passive Drag

Part I. The subjects were towed in a streamlined prone position (face down), with the legs and feet extended, the head between the extended arms, and the ears pressed between upper arms. In the drafting positions, subjects were directly behind the lead swimmer and attached with a rope via a pulley to a Celtron STC500 load cell (Celtron Technologies, Santa Clara, CA). The load cell was mounted 10 cm above water level and directly ahead of the lead swimmer. In that position, the rope passed just above the leader's body, and drafter's drag could be measured with no perturbation. Before experimentation, the linearity of the load cell was tested between 0 and 98.1 N ($R^2 \approx 1$). The load cell zero was confirmed at the beginning and end of each test session. Adjusting the rope length controlled drafting distance behind the lead swimmer. Subjects were tested in the same pairs as for the physiological testing and were towed at a speed adjusted separately for each subject corresponding to their self-selected 1500-m speed for the drafting and

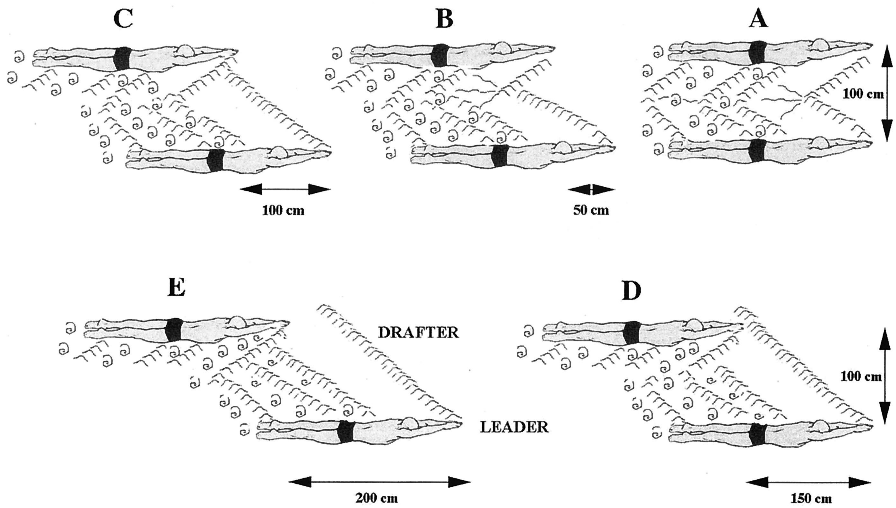

FIGURE 2—Main waves created by two swimmers in lateral drafting. In A, B, C conditions, the first wave created by the leader arrives behind the drafter's hands, whereas in D and E conditions, it arrives ahead. The observed turbulence areas were noted as "@" in the figure.

nondrafting positions. Passive drag was measured using the load cell connected to a MacLab analog to digital converter sampling at 200 Hz (AD Instruments, Dunedin, New Zealand). The digital signal was stored on a personal computer and the average drag over a minimum period of 5 s was subsequently calculated. During the measurements, the subjects held their breath after a maximal inspiration.

Part II. The swimmers were towed at 1.18 $m \cdot s^{-1}$ in six different prone, lateral drafting positions. This speed was set to match as close as possible 1.2 $m \cdot s^{-1}$ and was not set as the mean of the self-selected speeds 1.24 $m \cdot s^{-1}$. However, those speeds were still close, and thus considering the data from each part together is still reasonable. The 100-cm lateral distance was measured between the midlines of each swimmer, which corresponded to a separation distance of ~40 cm between swimmers. This separation was judged to be a close separation distance at which swimmers could swim without risk of contact. Drafting distance was measured differently from part I by defining this as the distance between the level of the hands of the swimmers. At 0 cm, the hands of the draftee where at the same level as the hands of the leader. Additional drafting distances used positioned the hands of the draftee at 50, 100, 150, and 200 cm behind the hands of the lead swimmer (Figs. 1B and 2). At 200 cm, two other positions were studied, with a reduced lateral distance between swimmers of 50 and 0 cm. At 0 cm, swimmers were touching the lead swimmer's toes and were thus in a comparable drafting position as the 0 cm position in part I. In the drafting position, swimmers were again towed with the Celtron load cell mounted 10 cm above water level. Passive drag was measured by the same method as in part I described above. For both part I and part II, the same lead swimmer was used for all drag measurements by a given subject in the various drafting positions.

Statistical Methods

The means, standard deviations and confidence intervals were computed for all variables. A repeated-measures ANOVA (SPSX v. 0.8) was used to compare results in drafting and nondrafting conditions and in all the drag positions. A P value of 0.05 was chosen as the level of statistical significance.

RESULTS

Part I. Results of the selected responses to drafting and nondrafting conditions are reported in Table 1. In all of the four drafting conditions, oxygen uptake, HR, blood lactate, RPE, and stroke rate were significantly reduced while stroke length was significantly higher than in nondrafting ($P <$ 0.05). Oxygen uptake was reduced by 11%, HR by 6%, blood lactate by 38%, RPE by 20%, and stroke rate by 6%, whereas stroke length was increased by 6%, at the optimal drafting distance of 0 or 50 cm. For drag measures, significant drafting effects compared with the nondrafting condition were observed at 0 and 50 cm behind the leader, with a greater than 20% reduction in passive drag.

Part II. Results of passive drag for the lateral drafting positions are reported in Table 2 and Figure 3. Drag was significantly reduced in the lateral position by 6% and 7%, respectively, at 50 and 100 cm back from the hands.

DISCUSSION

The main findings of the present study indicated that the optimum drafting position was in the 0- to 50-cm range behind another swimmer, although a significant reduced metabolic response persisted at the 100- and 150-cm distances. Lateral drafting at 100 cm beside another swimmer and at 50 and 100 cm behind (i.e., when drafter's head is between shoulders and hip level of the leader) significantly reduced drag compared with the free condition. The greatest benefit was when drafter's head was approximately at hip level of the leader.

Drafting behind another swimmer. The optimum position was 0 or 50 cm. In these positions the significant

TABLE 1. Comparison between the nondrafting condition and the various drafting distances for the oxygen cost, heart rate, lactate, perceived exertion (RPE), stroke rate, stroke length, and passive drag.

N = 11	Nondrafting	Drafting Distance	Drafting	Δ	95% CI
Oxygen cost ($L \cdot min^{-1}$)	3.57 (0.44)	0 cm	3.18 (0.30)	0.40*	0.25 to 0.55
		50 cm	3.16 (0.36)	0.41*	0.26 to 0.56
		100 cm	3.26 (0.36)	0.33*	0.12 to 0.54
		150 cm	3.27 (0.33)	0.32*	0.16 to 0.49
Heart rate (bpm)	157 (16)	0 cm	149 (15)	7.8*	4.1 to 11.5
		50 cm	147 (16)	9.0*	3.7 to 14.8
		100 cm	148 (15)	8.5*	4 to 13
		150 cm	152 (15)	5.6*	0.5 to 10.7
Lactate ($mmol \cdot L^{-1}$)	8.7 (4.0)	0 cm	5.4 (2.1)	3.3*	1.14 to 5.4
		50 cm	5.7 (3.3)	3.0*	1.6 to 4.4
		100 cm	5.5 (2.2)	3.2*	1.1 to 5.2
		150 cm	6.0 (2.6)	2.7*	1.3 to 4.1
RPE	14.8 (1.8)	0 cm	11.9 (1.9)	2.9*	1.8 to 4.1
		50 cm	12.7 (1.9)	2.1*	1.0 to 3.3
		100 cm	12.6 (1.6)	2.2*	0.9 to 3.5
		150 cm	12.7 (1.3)	2.1*	0.8 to 3.4
Stroke rate ($c \cdot min^{-1}$)	35.4 (2.5)	0 cm	33.4 (2.5)	2.2*	1.4 to 3.1
		50 cm	33.5 (2.2)	1.8*	0.4 to 3.1
		100 cm	34.2 (2.4)	1.5*	0.3 to 2.6
		150 cm	34.5 (2.6)	1.4*	0.5 to 2.4
Stroke length ($m \cdot c^{-1}$)	2.10 (0.19)	0 cm	2.23 (0.24)	0.13*	0.08 to 0.18
		50 cm	2.24 (0.23)	0.14*	0.03 to 0.19
		100 cm	2.18 (0.23)	0.08*	0.01 to 0.14
		150 cm	2.19 (0.24)	0.09*	0.01 to 0.14
Drag (N)	38.2 (7.2)	0 cm	30.3 (4.6)	7.9*	2.5 to 13.4
		50 cm	30.2 (4.6)	8.0*	2.0 to 14.1
		100 cm	34.9 (4.0)	3.3	−2.1 to 8.7
		150 cm	36.3 (5.0)	1.9	−3.0 to 6.8

Values are mean (SD); * significant at $P < 0.05$.

reductions in oxygen uptake, lactate and RPE were approximately the same magnitude as reported by Bassett et al. (1), who did not report drafting distance. These data are consistent with previous data concerning cycling (9,13), speed skating (18), running (14), and cross-country skiing (15), indicating the drafting distance is a determinant of benefit in drafting. In these sports, the closer the drafter to the leader, the higher the benefit. In swimming, drafting at 0 cm was no more beneficial than drafting at 50 cm. However, swimming at 0 cm is perhaps more difficult than at 50 cm because of the leader's kick rhythm (11). The kick, and in particular the six-beat kick, can create more bubbles or/and turbulence and induce a visual and arm sweep handicap for the draftee (10). Thus, swimming at 50 cm could be easier, confirming the average 60-cm distance spontaneously chosen by draftees (11). The RPE was lower at 0 cm than at the other drafting distances, indicating that swimmers did not suffer from being too close of the leader. However, in the present study, leaders were instructed not to kick during drafting.

A secondary result was that swimming between 100 and 150 cm was almost as beneficial as swimming between 0 and 50 cm. Indeed, the metabolic response was only marginally higher than at 0 and 50 cm (+ 2% for oxygen uptake, + 5% for lactates and + 7% for HR). This observation has a practical application in open-water competition and pool-based training. Even up to 150 cm from the leader, swimmers can still benefit from a 10% reduction in metabolic cost. Thus, energy may be conserved for the end of the swimming part or for the cycling and running phases of the event. In pool-based training, swimmers not leading the lane do not receive the same physiological work out as the lead swimmer. The distance to minimize the effect of drafting remains to be determined. However, by extrapolation of the results presented in Table 1, a distance greater than 2.5 m can be speculated.

When at a distance of 0 cm, oxygen uptake and drag were reduced, indicating that changes in water resistance and metabolic responses were related. Specially, when drag force was reduced due to drafting, a lower metabolic cost was measured presumably because less propulsive effort was required to swim at the same speed. These data are consistent with previous data where reductions in drag were associated with better performances for a given oxygen consumption (4,5). The present study is the first to relate a

TABLE 2. Passive drag (N) measured at 1.18 $m \cdot s^{-1}$ for nondrafting and different positions of drafting for the six subjects.

N = 6	Nondrafting	Lateral Drafting						
Lateral separation (cm)	Alone	100	100	100	100	100	50	0
Distance behind hand's leader (cm)		0	50	100	150	200	200	200
Mean (12 trials)	34.8	34.5	32.6*	32.1*	33.5	34.4	34.2	29.3*
SD	2.6	2.5	2.4	1.9	2.0	2.9	3.3	3.0
Lower limit 95% CI	31.1	30.6	29.1	28.7	30.3	30.4	30.6	26.4
Upper limit 95% CI	38.5	38.4	36.1	35.5	36.6	38.4	37.9	32.2

* Comparison between nondrafting and drafting conditions significant at $P < 0.01$; CI, confidence interval.

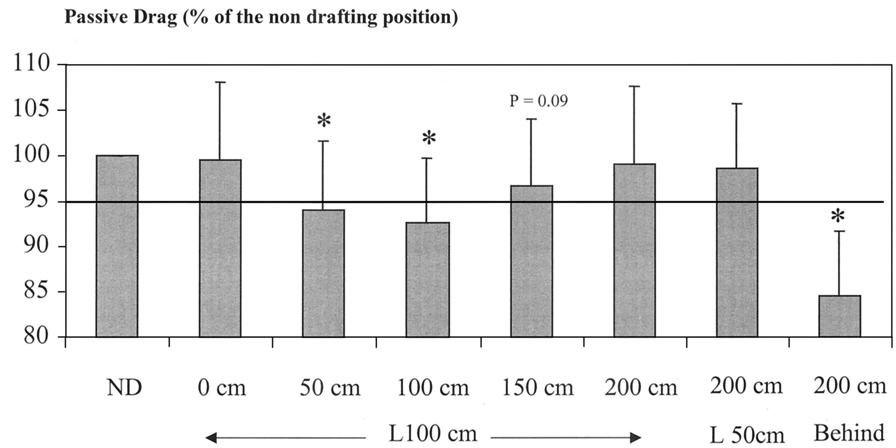

FIGURE 3—Passive drag as a percentage of the nondrafting drag (ND) in different lateral drafting positions. At 0 cm, the hands of the draftee and leader are at the same level. Then, the draftee's hand is at 50, 100, 150, and 200 cm behind the leader's hand. L 100 cm corresponds to a 100-cm lateral distance separating the two swimmers. At 200 cm, the lateral distance between swimmers was reduced to 50 cm (L 50 cm) and 0 cm (behind) directly behind the lead swimmer's toes.

decrease in passive drag and a decrease in oxygen consumption. However, the 10% reduction in oxygen uptake was less than expected, given the 20% reduction in drag. This suggests that swimmers may be swimming less efficiently when drafting compared with nondrafting. Further study on draft swimming is warranted to explain the less than expected reduction in oxygen cost and possible reduced efficiency in draft swimming.

Drafting to the side of another swimmer. The optimum position when 100 cm to the side was 100 cm behind the lead swimmer with the draftee's head located at a level of the hip of the leader. This study is the first to demonstrate that swimming beside another swimmer is beneficial in terms of a reduction in drag. However, the reduction in resistive drag was only one third of the reduction in drag when drafting immediately behind the lead swimmer.

Performance gains. Chatard et al. (3–5) found that in drafting behind another swimmer a 3.2–5% performance gain was associated with a 13–26% reduction of passive drag. Whereas for Toussaint et al. (16), a 5% performance gain corresponded to a 14% reduction of active drag. Thus, in lateral drafting at 50 or 100 cm, the 6–7% drag reduction should theoretically correspond to a 1.5–3% performance gain. At 150 cm, it should correspond to a 1–2% gain. Thus, in a 1500-m open-water race, the gain should be 15–45 m, and over a 1-h race that takes approximately three times as long, the gain should be 45–135 m. However, these gains should not be extrapolated to pool swimming due to the influence of the turns and the floating lane lines that reduce the wave effect of the leader (12).

Explanation of the benefits of drafting. The benefit of drafting for swimmers found in this study can best be described and explained in terms of the fluid flow around the swimmer's body. Waves are created at the water surface, and other regions of disturbed flow appear to the side and rear of the swimmer's body as the swimmer moves through the water. The rate of loss of momentum of the disturbed flow is equal to the drag force acting on a swimmer. The drag force is described as having three components: pressure or form drag, wave drag, and surface or friction drag. Pressure drag is due to the difference in pressure in the fluid acting on the front and rear of the body in the fluid flow and is the largest component of the drag force acting on a swimmer (20). Wave drag is due to the gravitational effects of the disturbance of the water-air interface and is the second largest component of the drag force acting on a swimmer (20). In a swimmer being towed at about 1.2 $m \cdot s^{-1}$ in a streamlined position, waves most often formed at the hands, behind the shoulders, the hips, and the ankle in a three- or four-wave system (6). The waves angle away from the swimmer in a well-defined Kelvin wave pattern (19). The faster the movement of the body relative to the fluid, the higher the wave and the longer the wavelength (12), as shown in Figure 2. The waves travel with the speed of the body, but the fluid flow within the wave, particularly at the upper surface of the wave, may be greater than the speed of the body in the flow. Surface or friction drag is due to the interaction of the fluid with the surface of the body and is the smallest component of the drag force acting on a swimmer (20).

When a swimmer is drafting in a position close behind another swimmer, the reduction in pressure drag is likely to be the most marked effect because pressure drag is by far the greatest drag component. For the drafting swimmer, the flow meeting the front of the swimmer is disturbed flow from the lead swimmer and will result in reduced frontal pressure compared to a nondrafting position. Wave drag may also be reduced in the close-in drafting positions because of the reduced relative velocity in the disturbed flow close to the lead swimmer, and hence lesser height waves will be created by the draftee. Surface drag may also be reduced because the flow direction in the eddying zone is not uniformly directed against the swimmer as would be the case in swimming in a nondrafting position. Additionally, flow patterns behind a lead object have been shown to propel a following swimmer at particular positions behind a lead swimmer (7).

In the present study, the benefit of drafting behind a lead swimmer, a reduction in oxygen uptake and a reduction in drag, reduced as the drafting distance increased although differences in oxygen uptake and drag for 0 and 50 cm compared with 100 and 150 cm were not statistically different. This reduction in benefit is likely to be because the laminar flow tends to reform at some distance behind the swimmer. Because disturbed flow has been described as occurring at distances of 3–5 m behind a swimmer (8), a significant drafting benefit was expected to extend well beyond 2 m. Oxygen cost and passive drag may not have been reduced as much as expected because the drafting swimmer may have been impeded by the waves of 0.5-m wavelength created by the lead swimmer at 1.2 $m \cdot s^{-1}$ (19). Further investigation is required to determine where the wave peaks occurred in relation to the drafting distances chosen.

To help explain the benefit of lateral drafting at the side several subjects, unfortunately not all, were videotaped from above during the experiment. A typical wave system produced by a lead and a drafting swimmer is as follows: between the 0- and 100-cm positions, the first wave created by the hand of the leader was arriving behind the drafter's hands. At the same time, the flow over the drafter's head appeared to be relatively undisturbed laminar flow (Figs. 1B and 2). On the contrary, between 150 and 200 cm, the first wave off the leader was arriving ahead of the drafter's hands, and turbulence from the second wave off the leader appeared to cause turbulent flow over the drafter's head. Thus, because a reduction in pressure drag might be associated with increasingly disturbed flow, the expectation was for a reduction in drag as the lateral swimmer moved to the rear of the lead swimmer. The finding of an optimal position for drag reduction at the 100-cm position is thus postulated to be due to a wave interaction effect perhaps causing a reduction in drag on the draftee moving with the wave created by the lead swimmer.

CONCLUSION

The present study indicated that the optimal drafting swimming distance was at 0 or 50 cm behind a leader reducing by 11–38% the metabolic response of the draftee. At the 100- and 150-cm distances, the gain was still important with reductions in the metabolic responses of between 8% and 31%. In lateral drafting at 100 cm beside another swimmer, the optimal distance was at 50 and 100 cm behind, when drafter's head was approximately at hip level of the leader. The drag benefit was only a third of that when drafting directly behind the lead swimmer. Drafting was always behind or lateral to a passively towed lead swimmer. Further investigation is required to determine whether the benefits of drafting behind or beside a streamlined lead swimmer are likely to be a conservative estimate of the benefit from drafting behind an active stroking and kicking lead swimmer.

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REFERENCES

1. Bassett, D. R., J. Flohr, W. J. Duey, E. T. Howley, and R. L. Pein. Metabolic responses to drafting during front crawl swimming. *Med. Sci. Sports Exerc.* 23:744–747, 1991.
2. Borg, G. Perceived stress as an indicator of somatic stress. *Scand. J. Rehabil. Med.* 2–3:92–98, 1970.
3. Chatard, J.-C., J.-M. Lavoie, B. Bourgoin, and J.-R. Lacour. The contribution of passive drag as a determinant of swimming performance. *Int. J. Sports Med.* 11:367–372, 1990.
4. Chatard, J.-C., X. Senegas, M. Selles, P. Dreanot, and A. Geyssant. Wet suit effect: a comparison between competitive swimmers and triathletes. *Med. Sci. Sports Exerc.* 27:580–586, 1995.
5. Chatard, J.-C., D. Chollet, and G. Millet. Performance and drag during drafting swimming in highly trained triathletes. *Med. Sci. Sports Exerc.* 30:1276–1280, 1998.
6. Firby, H. Wave pattern. In: *Howard Firby on Swimming*, H. Firby (Ed.) London: Pelham Books Ltd, 1975, pp. 110–120.
7. Fish, F. Energy conservation by formation swimming: metabolic evidence from ducklings. In: *Mechanics and Physiology of Animal Swimming*, L. Maddock, Q. Bone, and J. M. Rayner (Eds.). Cambridge: Cambridge University Press, 1991, pp. 193–205.
8. Kolmogorov, S. V., and O. A. Duplishcheva. Active drag, useful mechanical power output and hydrodynamic force coefficient in different swimming strokes at maximal velocity. *J. Biomech.* 25:311–318, 1992.
9. Kyle, C. Reduction in wind resistance and power output of racing cyclists and runners travelling in groups. *Ergonomics* 22:387–397, 1979.
10. Maglischo, E. The front crawl stroke. In: *Swimming Faster*, Palo Alto, CA: Mayfield, 1982, pp. 53–99.
11. Millet G., D. Chollet, and J.-C. Chatard. Effects of drafting behind a two- or six-beat kicker in elite female triathletes. *Eur. J. Appl. Physiol.* 82:465–471, 2000.
12. Ohmichi, H., M. Takamoto, and M. Miyashita. Measurement of the waves caused by swimmers. In: *Biomechanics and Medicine in Swimming V*, A. P. Hollander, P. A. Huijing, G. de Groot (Eds.). Champaign, IL: Human Kinetics, 1983, pp. 103–107.
13. Olds, T. S., I. Norton, E. L. Lowe, S. Olive, F. Reay, and S. Ly. Modelling road cycling performance. *J. Appl. Physiol.* 78:1595–1611, 1995.
14. Pugh, L. C. The influence of wind resistance in running and walking and the mechanical efficiency of work against horizontal and vertical forces. *J. Physiol.* 213:255–276, 1971.
15. Spring, S., E. Savolainen, J. Erkilla, T. Hamilainen, and P. Pihkala. Drag area of a cross country skier. *Int. J. Sport Biomech.* 4:103–113, 1988.
16. Toussaint, H. M., R. Bruinink, R. Coster, et al. Effect of triathlon wet suit on drag during swimming. *Med. Sci. Sports Exerc.* 21: 325–328, 1989.
17. Toussaint, H. M, and A. P. Hollander. Measurement of oxygen cost in swimming. *Med. Sci. Sports Exerc.* 22:402–408, 1990.
18. Van Ingen Schenau, G. J. The influence of air friction in speed skating. *J. Biomech.* 15:449–458, 1982.
19. Vogel, S. *Life in Moving Fluids.* Princeton, NJ: Princeton University Press, 1996, pp. 467.
20. Vorontsov, A. R., and V. A. Rumyantsev. Resistive forces in swimming. In: *Biomechanics in Sports: Performance Enhancement and Injury Prevention, Vol. IX of the Encyclopaedia of Sports Medicine*, V. Zatsiorsky (Ed.). Oxford: Blackwell Science, 2000, pp. 205–231.
21. Wilson, B. D., H. Takagi, and D. P. Pease. Technique comparison of pool and flume swimming. In: *Biomechanics and Medicine in Swimming VIII*, K. L Keskinen, P. V. Komi, and A. P. Hollander (Eds.). Jyväskylä: University of Jyväskylä, Finland, 1999, pp. 181–184.