Effects of Drafting on Hydrodynamic and Metabolic Responses in Front Crawl Swimming

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ABSTRACT

JANSSEN, M., B. D. WILSON, and H. M. TOUSSAINT. Effects of Drafting on Hydrodynamic and Metabolic Responses in Front Crawl Swimming. *Med. Sci. Sports Exerc.*, Vol. 41, No. 4, pp. 837–843, 2009. **Purpose**: Effects of drafting on the hydrodynamic and metabolic responses of the drafter behind and at the side of a passive and an active lead swimmer were related to the influence of a lead swimmer on the flow field of the draftee. **Methods**: Passive drag of the draft swimmer was compared for the nondrafting condition, in the drafting conditions behind a passive and an active lead swimmer, and at the side of a passive and an active lead swimmer. The effect was also evaluated with oxygen uptake measurements. Fluid pressure measurements were made behind and at the side of a passive and an active lead swimmer to examine the flow field. **Results**: Behind a passive lead swimmer, passive drag was significantly reduced by 20%, and behind an active lead swimmer, it was reduced by 9%. At the side of a passive lead swimmer, passive drag was significantly increased by 9%, and at the side of an active lead swimmer, it increased by 8%. Oxygen uptake was significantly reduced by 25% behind a passive lead swimmer, by 11% behind an active lead swimmer, and only marginally changed at the side of a lead swimmer. The pressure measurements indicated a 33% decrease in mean flow velocity behind an active lead swimmer but an increase in peak flow velocities due to the kick of the lead swimmer. These increases could explain the lesser decrease in passive drag behind an active versus a passive lead swimmer. **Conclusion**: The best position for a draft swimmer was found to be directly behind an active lead swimmer at a distance of 0.50 m between the toes of lead swimmer and the hands of drafter, with significant reductions in both passive drag and oxygen uptake when drafting. **Key Words:** TRIATHLON, DRAG, PRESSURE MEASUREMENT, OPTIMAL POSITION

In triathlon swimming, swimmers often swim close behind or at the side of a lead swimmer (see Fig. 1). This drafting allows the swimmer to reduce the energy cost of swimming and hence either to save energy that will enable faster swimming later in the race or to save some energy for other parts of the triathlon (1,5,8).

A recent study of drafting behind another swimmer at triathlon race pace (approximately 1.24 $m \cdot s^{-1}$) reported that the most advantageous drafting position was with the fingertips between 0 and 0.50 m back from the toes, which resulted in 21% and 20% reductions in passive drag (2). In lateral drafting, with a 1.0-m lateral distance between swimmers at a similar speed (1.18 $m \cdot s^{-1}$), the optimal distance was with the fingertips 0.50–1.00 m back from the hands of the lead swimmer resulting in 6% and 7% reductions in passive drag (2).

Contrary to expectations, drafting behind a two-beat kick swimmer was reported to be of no more benefit than drafting behind a six-beat kick swimmer (6). The six-beat kick was also reported to create lots of bubbles and to induce a visual and arm-sweep handicap for the drafter, therefore making draft swimming more difficult than when following a two-beat kick swimmer.

Drafting indeed leads to a reduction in energy cost to overcome drag forces when compared with equal speed swimming alone (free swimming). Previous investigations reported drag reduction for the drafter after a passive lead swimmer. Would an active lead swimmer, as is the case in the actual race condition, lead to similar drafting advantages? To answer this question, it is useful to delve deeper into the different drag components.

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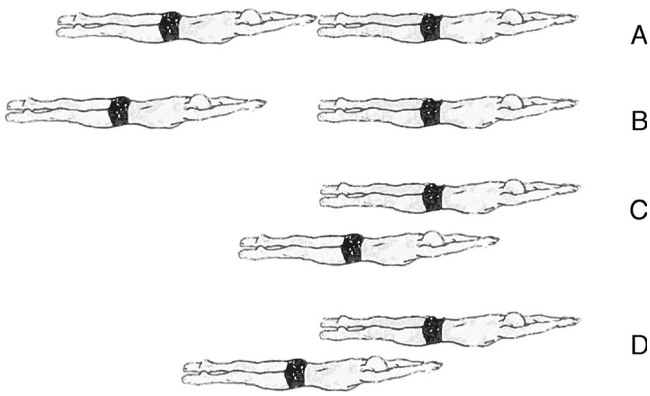

FIGURE 1—Drafting at the side of a lead swimmer (figure from Chatard and Wilson [2]).

Total drag when swimming at the surface comprises pressure drag, wave drag, and friction drag. Pressure drag (or form drag) results when an object has to move a quantity of fluid out of the way to pass through the fluid and, for a fully immersed body, increases with the square of the velocity. When an object moves at the water surface, there is additional resistance due to the gravitational effects of the disturbance of the water–air interface. Wave drag has been stated to increase as the third power of swimming velocity (7,12). However, it will be an important part of total drag when the swimming speed is nearing or in excess of the "hull speed," which for a swimmer is about 1.7 $m{\cdot}s^{-1}$ (10), which is not a regular speed attained in triathlon competition. Recent work by Vennell et al. (11) indicates that wave drag contributes approximately 30% of drag at 1.2 $m{\cdot}s^{-1}$. Frictional drag (or surface drag) is due to the interaction of the fluid with the surface of the object and increases linearly with the velocity (11). The magnitude of the friction drag is influenced by the local flow conditions that will change downstream a swimming body but that may also be influenced by the "wake" behind a lead swimmer.

At the competitive speed for triathlon swimming of about 1.25 $m{\cdot}s^{-1}$, the drag will be dominated by pressure drag. Therefore, this study focused on examining pressure drag. Flow separation from the surface of an object moving through a fluid creates eddies that move downstream as a wake. The faster the flow and the less streamlined the object, the further upstream the flow separates, the larger the wake, the lower the wake pressure and the larger the difference in pressure between the front and the back of the object in the flow. The difference in pressure results in a net force (pressure drag), acting opposite to the direction of the flow (3). A wake behind an object means less frontal pressure for a following object in the wake. That is why drafting gives a benefit for the drafter.

This study examined the reduction in passive drag for drafting behind and at the side of a passive and an active lead swimmer. It was thought that the reduction of passive drag behind an active lead swimmer would be larger than behind a passive swimmer because the less streamlined the swimmer, the further upstream the beginning of the turbulent wake. This would result in a larger wake and hence a lower pressure behind an active lead swimmer and a larger reduction in frontal pressure for the draft swimmer. If drafting behind an active lead swimmer means a reduction in drag for the following swimmer, then there should be a reduction in oxygen cost for a drafting swimmer as well. Hence, the study hypothesis is that the benefits of drafting, that is, a reduction in drag and oxygen cost of swimming, are larger when drafting behind an active lead swimmer than when drafting behind a passive lead swimmer. In this study, the flow field behind and at the side of an active lead swimmer and behind and at the side of a passive lead swimmer was also examined because an active lead swimmer could induce different flow conditions compared with the passive lead swimmer.

METHODS

Measurements were made of passive drag and oxygen uptake on the draft swimmer in a nondrafting condition and in four different drafting conditions both behind a passive lead swimmer and behind an active lead swimmer: at 0 and 0.50 m back from the toes of a lead swimmer and at the side of a lead swimmer with the head of the draft swimmer at hip level and with the head at knee level (see Fig. 2). To examine the flow field, pressure measurements were made with Pitot tubes in a flow volume at the positions

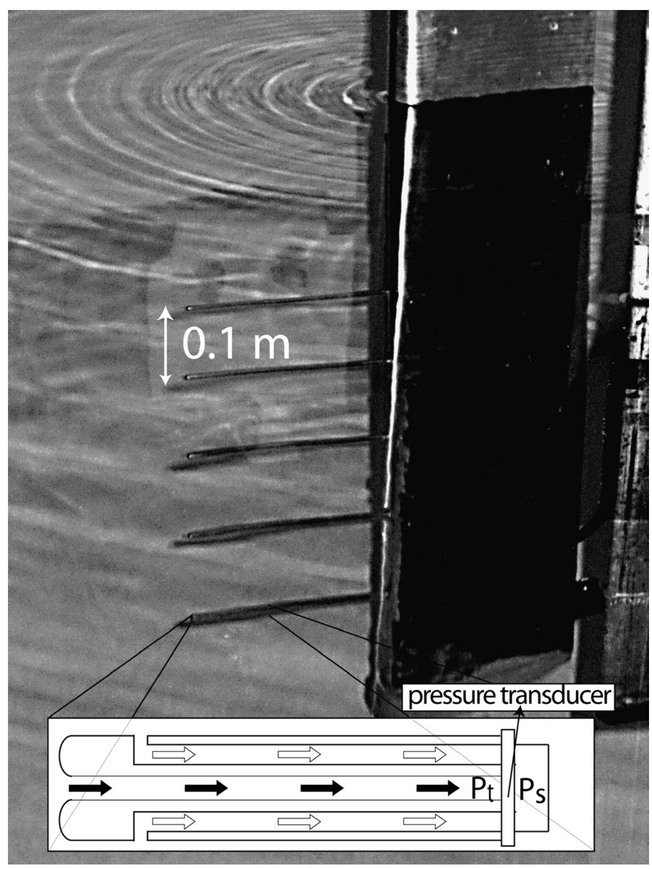

FIGURE 2—Five Pitot tubes on a streamlined beam.

TABLE 1. Personal characteristics of the participants.

Participant (N = 9)	Age (yr)	Height (m)	Mass (kg)	BFM (%)	CSA (m^2)	Draft Swimmer (D), Lead Swimmer (L)
A (m)	49	1.68	80.8	18.5	0.19	D & L
B (m)	22	1.795	79.8	12.8	0.11	D & L
C (f)	21	1.68	58.4	15.9	0.14	D & L
D (f)	22	1.685	63.7	22.0	0.12	D & L
E (m)	38	1.79	85.1	17.8	0.14	D
F (f)	34	1.71	66.8	27.1	0.09	D
G (f)	20	1.75	64.5	24.4	0.16	D
H (m)	51	1.89	100.2	29.1	0.21	L
I (f)	28	1.68	67.4	26.6	0.12	L
Mean	29.4	1.72	71.3	19.8	0.14	—
SD	11.2	5.1	10.4	5.0	0.03	—

f, female; m, male; BFM, body fat mass (%); CSA, cross-sectional area (m^2).

corresponding to a draft swimmer behind a lead swimmer (0–0.50 m) and at the side (head at hip to head at knee level) of a lead swimmer.

Participants

Nine local triathletes voluntarily participated in the study, four as both draft swimmers and lead swimmers, three as draft swimmers only, and two as lead swimmers only. They ranged in age from 21 to 51 yr and all had at least 1 yr of experience in triathlon competition (participants characteristics are presented in Table 1). Cross-sectional area was calculated by using a snapshot from the frontal area while the swimmer was in a passive streamlined position. University of Otago Ethics Committee approval was obtained before the study, and the participants were fully informed of the purpose of the study before giving written consent.

Materials

Swimming flume. The triathletes were tested in the swimming flume of the Otago University, Dunedin, New Zealand. The flume channel has a test section of length 10 m, width 2.5 m, and depth 1.5 m. The flow in that section can be setup to 3.0 $m \cdot s^{-1}$ with an accuracy of 0.02 $m \cdot s^{-1}$ and with a steady uniform flow to within 2% (13). In this study, the velocity was set at 1.2 $m \cdot s^{-1}$ to be able to compare results with the Chatard and Wilson (2) study. The water temperature was 29°C.

Passive drag. The drafting swimmer was attached with a rope to a load cell, approximately 0.10 m above the water level. 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). Calibration of the load cell was checked before and after each test session. The digital signal was stored on a personal computer, and the average drag over a minimum of 10 s was subsequently calculated. The drag force when drafting was taken as the horizontal component of the force on the load cell (force on rope converted for angle of pull).

Oxygen uptake. Oxygen uptake was measured from the expired air collected during a 4-min swim. Expired gases were analyzed using a mask and a three-way breathing valve (9) and a SensorMedics Metabolic Cart (SensorMedics, 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 2 min, swimmers were at steady state for oxygen uptake (2). Steady-state oxygen uptake was taken as the average value of the last 2 min.

Flow field in wake of lead swimmer. Fluid pressure behind and at the side of one of the lead swimmers was measured with a depth corrected Pitot tube system. Pitot tubes measure flow at a single point. Each Pitot tube, of diameter 0.005 m, consisted of a center tube facing the flow and a concentric outer tube with two small holes on the outside of the tube. The outside holes are connected to one pressure transducer, and the center hole in the tube, separate from the outside holes, is connected to another pressure transducer. This arrangement measures the difference in pressure between the two transducers. The center tube is pointed against the direction of the flow, and the outside holes are perpendicular to the flow. The pressure in the tubes of the outside holes is the static pressure, and the pressure in the center tube is the total pressure. Thus, the measurement is the total pressure minus the static pressure (4). The system, including the Pitot tubes, was built at OUSPE, Dunedin, New Zealand. The pressure sensors were Honeywell 26PC pressure sensors. Five Pitot tubes were fixed on a streamlined beam in a vertical row, with a 0.1-m distance between adjacent Pitot tubes (Fig. 2). Flow velocity and pressure measures were collected via a MacLab analog to digital converter sampling at 200 Hz (AD Instruments) and stored on a personal computer. The output of the flow meter was used to validate the output of the Pitot tubes. The average velocity per Pitot tube per point was calculated over 10 s.

Effect of Drafting Position on Passive Drag, Oxygen Uptake, and Flow Field

The passive drag on the swimmer was measured when the swimmer was towed in a streamlined prone position: a posture in which the body and the legs are outstretched, the toes are pointed, the arms are stretched over the head, the hands are topping one another, and the ears are pressed by the upper arms.

In the rear drafting situation, the swimmer was towed behind a lead swimmer at two distances: 0 m (the fingertips from the swimmer almost touched the toes of the lead swimmer) and 0.50 m (0.50 m between toes of the lead swimmer and fingertips of the drafter). At the side, the swimmers were towed with their head at the lead swimmers knee and hip level, with a lateral distance of 0.75 m between the midlines of the bodies. During the measurements, the swimmers held their breath after a maximal inspiration. The duration of each trial was 30 s. The swimmers performed the test three times at each (drafting) position. To standardize the lead swimmer's position, a rope fixed to a belt around the swimmer's waist enabled application of corrective forces.

Oxygen uptake was measured on the draft swimmer in a series of 4-min swims when swimming alone and in the different drafting conditions.

Before each test session, the swimmers were familiarized to swimming in the flume by swimming at 1.1 $m \cdot s^{-1}$, with a minimal swim time of 10 min. A counterbalanced design for test order was used for the different swimmers to avoid an effect of order of testing on the measurements. The swimmers were tested in pairs, lead swimmer and draft swimmer, so that each draft swimmer drafted behind the same lead swimmer for all drafting conditions, with one exception: one draft swimmer drafted behind two different lead swimmers, but in this case the lead swimmers had similar anthropometric characteristics.

To better understand the reduction in drag when drafting behind a passive and an active lead swimmer, measurements of pressure were made in a flow volume of 0.80 m width, 0.50 m depth, and 0.50 m length (steps of 0.10 m in each direction) at the center of the flume in several conditions: (i) with no swimmer in the flume, (ii) behind a passive lead swimmer, and (iii) behind an active lead swimmer (both subject A). This flow volume was at the position corresponding to a draft swimmer (from fingertip to approximate shoulder), behind (0–0.50 m) a lead swimmer. Measurements of pressure were also made for a similar volume at the side of a passive and an active lead swimmer (both subject A). This flow field was at the position corresponding to a draft swimmer at the side (hip and knee level) of a lead swimmer. Pressure measurements are reported as the differences between the mean flow for the five Pitot tube array with no swimmer in the flume and the various experimental conditions behind and to the side of a passive and an active lead swimmer. For practical reasons, pressure measurements were made without the draft swimmer being present in the flow field. The presence of a draft swimmer may have altered the outcome of the measurements.

Statistical Analysis

The means and the SD of the drag and oxygen measurements for each condition were computed for all variables. The significance of any differences between the nondrafting and the drafting conditions was tested using an ANOVA mixed-model repeated-measures design (Stata 8.2). A P value of 0.05 was chosen as the level of statistical significance.

RESULTS

Effect of drafting on drag. There was a large variation of the passive drag values between swimmers drafting in the different drafting conditions (at 1.2 $m \cdot s^{-1}$): values ranged from 20 N for the smallest to 65 N for the largest participant. The mean passive drag for the draft swimmer alone was 43.7 N. When drafting behind a passive lead swimmer, passive drag was significantly reduced by 21% at 0 m and by 20% at 0.50 m (both $P < 0.001$). When drafting behind an active lead swimmer, passive drag on the draft swimmers was reduced by 9% at 0 m and by 10% at 0.50 m (both $P < 0.001$). There was a significant difference in reduction in passive drag between drafting behind a passive and drafting behind an active lead swimmer ($P < 0.001$).

When drafting at the side of a passive lead swimmer, passive drag was significantly increased by 9% when the head was at hip level ($P < 0.05$) and only marginally changed by 1% when the head was at knee level ($P = 0.76$). When drafting at the side of an active lead swimmer, passive drag was significantly increased by 11% when the head was at hip level ($P < 0.05$) and by 8% when the head was at knee level ($P < 0.05$). There was a significant difference in the increase in passive drag between drafting at the side of a passive and drafting at the side of an active lead swimmer ($P < 0.05$). Adjusted means and SE for passive drag on the draft swimmer in the different drafting conditions are presented in Figure 3.

Effect of drafting on oxygen uptake. To achieve the swimming speed set at 1.2 $m \cdot s^{-1}$, swimmers were swimming with a different effort, which gives a large variation in the data. The swimmers, who were swimming at a higher effort, had a larger reduction in oxygen uptake when drafting. The mean oxygen uptake for the draft swimmer alone was 2.95 $L \cdot min^{-1}$. When drafting behind a passive lead swimmer, oxygen uptake was significantly reduced by 25% and 30% at 0 and 0.50 m, respectively (both $P < 0.001$). When drafting behind an active lead swimmer, oxygen uptake was also significantly reduced by 11% ($P < 0.05$) and 12% ($P < 0.05$) at 0 and 0.50 m, respectively. There was a significant difference between the reduction in oxygen uptake for drafting behind a passive lead swimmer and for drafting behind an active lead swimmer ($P < 0.001$).

When drafting at the side of a passive lead swimmer, oxygen uptake for the draft swimmer was only marginally changed by 1% ($P = 0.89$) when the head was at hip level and by 3% when the head was at knee level ($P = 0.69$). When drafting at the side of an active lead swimmer, oxygen uptake for the draft swimmer was also only marginally changed by 0.3% when the head was at hip level ($P = 0.89$) and by 2% when the head was at knee level

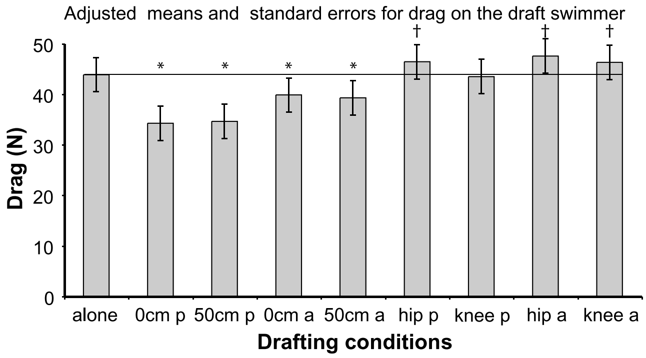

FIGURE 3—Adjusted means and SE for passive drag on the draft swimmer in the different drafting conditions. Data for positions behind the lead swimmer at 0 and 0.50 m, at the side of the drafter positions at hip and knee level. P and A indicate passive and active lead swimmer, respectively. *N* = 9. *Significant *decrease* from "alone" condition; †significant *increase* from "alone" condition.

(*P* = 0.85). There was no significant difference between the oxygen uptake for drafting at the side of a passive lead swimmer and for drafting at the side of an active lead swimmer (*P* = 0.88).

Flow velocity in wake of lead swimmer. Figure 4 shows the reduction in mean flow velocity behind and at the side for one subject (subject A) acting as passive and active lead swimmer (means of the five Pitot tubes depths). The largest reduction (38%) in flow velocity was behind a passive lead swimmer at 0 m that eclipsed the flow reduction at 0.50 m (28%). The center of the flow field corresponds to the midline of the lead swimmer. Behind an active lead swimmer, a similar flow pattern was found as behind a passive lead swimmer, with the exception of the position directly behind the midline of the lead swimmer, where a reduction in flow velocity was 19%, only half the reduction in flow velocity behind a passive lead swimmer at 0 m.

At the side of a lead swimmer, the reductions were larger at the side of an active lead swimmer than at the side of a passive lead swimmer. The highest reduction (30%) in flow velocity was found at 0.20 to 0.10 m left from the center of the flow field, and there was more reduction at hip level (27%) than at knee level (24%). The center of the flow field corresponds with the midline of the position of the drafting swimmer (at a lateral distance of 0.75 m relative the lead swimmers midline).

There were no measurements made behind an active lead swimmer at 0 m or on "40 to the left" at the side of an active lead swimmer because of concern that the leg kick or arm stroke of the lead swimmer would contact the Pitot tubes.

DISCUSSION

The study hypothesis was that the benefits of drafting, that is, a reduction in drag and oxygen cost of swimming, are larger when drafting behind an active lead swimmer

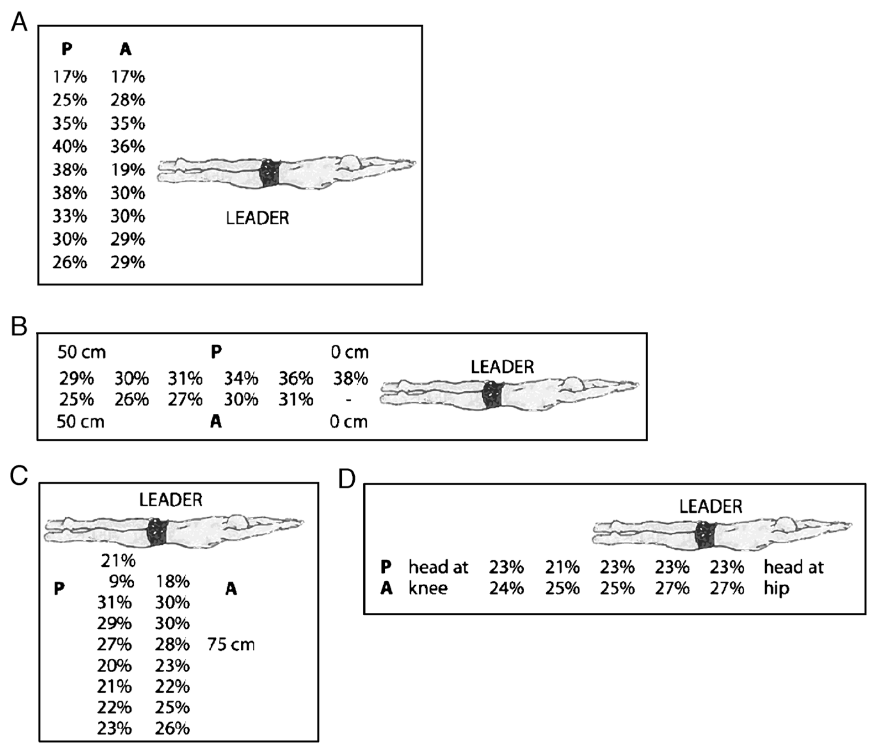

FIGURE 4—Reduction in flow velocity behind and at the side of a passive (P) and an active (A) lead swimmer, reductions are means for total flow field. A. Behind a lead swimmer at 0 m, from 0.40 m to the left to 0.40 m to the right of the midline of the lead swimmer. B. Behind the midline of the lead swimmer, 0 to 0.50 m back from the toes. C. At the side of a lead swimmer, head at hip level, 0.35 m ("40 to the left") to 1.15 m ("40 to the right") distance to the midline of the lead swimmer. D. At the side of a lead swimmer, from hip to knee.

than when drafting behind a passive lead swimmer. The less streamlined the swimmer, the further upstream the beginning of the turbulent wake. This would result in a larger wake and hence a lower pressure behind an active lead swimmer and a larger reduction in frontal pressure for the draft swimmer. There was a large reduction in passive drag for the drafter behind a passive lead swimmer with the most reduction in passive drag obtained at a distance of 0 m (21%). This reduction in passive drag is in agreement with the results of the Chatard and Wilson (2) study, which reported a reduction in passive drag of 21% when drafting at the same position relative the lead swimmer. Drafting at the side of a lead swimmer is generally trained during triathlon swimming and is accepted as an advantage position. The Chatard and Wilson (2) study showed a reduction in passive drag of 7% for drafting at the side of a passive lead swimmer with a 1-m distance between long axes of swimmers. The results of this study, an increase of passive drag by about 10% at the side of a passive and an active lead swimmer, do not support drafting at the side. Further research is required to determine whether the difference between the results of the studies was due to the distance between the long axes (1 m in the Chatard and Wilson [2] study, 0.75 m in this study) of the swimmers.

The reduction of passive drag behind or at the side of an active lead swimmer was hypothesized to be larger than behind or at the side of a passive swimmer. An active lead swimmer is less streamlined than a passive lead swimmer and was expected to create more flow disturbance and a greater wake, resulting in a lower pressure behind an active lead swimmer and a larger reduction in frontal pressure for the draft swimmer (3). But when drafting behind an active lead swimmer, a reduction in passive drag was approximately half that when drafting behind a passive lead swimmer at 0 and 0.50 m. When drafting at the side of an active lead swimmer, there was a larger increase in passive drag on the draft swimmer (11% at hip level and 8% at knee level) than for drafting at the side of a passive lead swimmer (9% at hip level and 1% at knee level). The reduction of oxygen cost behind or at the side of an active lead swimmer was also hypothesized to be larger than behind or at the side of a passive swimmer because if drafting behind an active lead swimmer means a reduction in drag for the following swimmer, then there should be a reduction in oxygen cost for a drafting swimmer as well. But the reduction in oxygen cost was larger behind a passive lead swimmer (25% and 30%) than behind an active lead swimmer (11% and 12%), and no significant difference in oxygen cost reduction was found between drafting at the side of an active or a passive lead swimmer. Hence, the study hypothesis, that the benefits of drafting behind an active lead swimmer are larger than behind a passive lead swimmer, was not supported. The reduction in passive drag and in oxygen cost behind or at the side of an active lead swimmer was smaller than behind or at the side of a passive lead swimmer.

In this study, the flow field behind and at the side of an active lead swimmer and behind and at the side of a passive lead swimmer was also examined because an active lead swimmer could induce different flow conditions compared with the passive lead swimmer. These measurements were performed only on one subject. The pressure measurements showed the greatest reduction in flow velocity behind a passive lead swimmer directly behind the lead swimmer at a distance of 0 m and further to the sides or more back from the toes of the lead swimmer, the reduction in flow velocity was smaller. This corresponds with the pattern of reductions in passive drag found behind a passive lead swimmer. In general, the observed pattern of flow velocity behind an active lead swimmer is similar to that of a passive lead swimmer with the exception that the position directly behind the midline (line from head to toes) of an active lead swimmer shows an exceptional low reduction in flow velocity of only 19% rather than the 38% reduction behind a passive lead swimmer. In addition, the flow was of pulsatory nature whereas in other areas it was more even. Indeed, there were more peak velocities found when examining the raw data at that position, corresponding to the kick frequency of the lead swimmer. Hence, the explanation of the unexpected results of the passive drag not being smaller behind an active lead swimmer could be that with every kick of the lead swimmer, water is accelerated toward the drafting swimmer, which gives an increase in drag for the drafting swimmer. That explanation is also consistent with the observed larger reduction in passive drag at 0.50 m than at 0 m behind an active lead swimmer because at the 0.50-m distance, the flow field from the kicks is likely to be more dispersed and to have lesser velocity peaks than at the 0-m distance. Also, an active lead swimmer disturbs the flow more than a passive lead swimmer, so the oxygen cost needed for swimming behind an active lead swimmer was greater than swimming behind a passive lead swimmer but less than for free swimming.

CONCLUSION

The reduction of passive drag and oxygen cost behind and at the side of an active lead swimmer is smaller than behind or at the side of a passive swimmer. This is in line with the unexpected finding of a smaller reduction in passive drag behind an active lead swimmer than behind a passive lead swimmer, which is likely to be due to a flow acceleration toward the drafter caused by the kick of the lead swimmer. At the side of an active lead swimmer, there was a larger increase in passive drag than for drafting at the side of a passive lead swimmer. Increased passive drag can be attributed to greater waves formed by the active lead swimmer or by the changed nonstationary local flow conditions behind the active lead swimmer affecting frictional drag of the drafter.

The reduction in oxygen cost was larger when swimming behind a passive lead swimmer than behind an active lead swimmer. An active lead swimmer disturbs the flow more than a passive lead swimmer so the oxygen cost needed for swimming behind an active lead was greater than swimming behind a passive lead swimmer. There was no significant difference in metabolic cost found between drafting at the side of an active and a passive lead swimmer.

The reductions of mean flow velocity behind an active lead swimmer are similar to the reductions behind a passive lead swimmer, which is the pattern of the flow field, except for the reductions in mean flow velocity directly behind the lead swimmer, which is relatively lower than behind a passive lead swimmer. An increase in peak flow velocity toward the drafting swimmer due to the kick of the active lead swimmer is the likely cause of the increase in pressure and drag observed for a draft swimmer behind an active lead swimmer.

On the basis of the results from this study, the best position for a draft swimmer would be directly behind an active lead swimmer (as it would be in the competitive situation) at a distance of 0.50 m. An active lead swimmer has a lower wake pressure and thus a larger reduction in frontal pressure for the draft swimmer. Close to the lead swimmer, there are peaks in the frontal pressure for the draft swimmer due to flow acceleration from the kick. At the 0.50-m distance, the flow field from the kicks is likely to have lesser velocity peaks than at the 0-m distance.

This study presents the effect of drafting on hydrodynamic and metabolic responses in front crawl swimming for only one swimming speed (1.2 $m \cdot s^{-1}$). Further research is required to investigate the effect of drafting at different swimming speeds.

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REFERENCES

1. Bassett DR, Flohr J, Duey WJ, Howley ET, Pein RL. Metabolic responses to drafting during front crawl swimming. *Med Sci Sports Exerc*. 1991;23(6):744–47.
2. Chatard JC, Wilson B. Drafting distance in swimming. *Med Sci Sports Exerc*. 2003;35(7):1176–81.
3. Denny MW. *Biology of the Wave-Swept Environment*. Princeton (NJ): Princeton University Press; 1998. p. 72–95.
4. Glenn Research Center. NASA Glenn Learning Technologies [Internet]. 2008 [cited 2008 Jun]. Available from: http://www.grc.nasa.gov/WWW/K-12/airplane/pitot.html.
5. Kreider RB, Boone T, Thompson WR, Burkes S, Cortes SW. Cardiovascular and thermal responses of triathlon performance. *Med Sci Sports Exerc*. 1988;20(4):385–90.
6. Millet G, Chollet D, Chatard JC. Effects of drafting behind a two- or six-beat kick swimmer in elite female triathletes. *Eur J Appl Physiol*. 2000;82:465–71.
7. Rushall BS, Holt LE, Sprigings EJ, Cappaert JM. A re-evaluation of the forces in swimming. *J Swim Res*. 1994;10:6–30.
8. Sleivert GG, Rowland DS. Physical and physiological factors associated with success in the triathlon. *Sports Med*. 1996;22:8–18.
9. Toussaint HM, Meulemans A, de Groot G, Hollander AP, Schreurs AW, Vervoorn K. Respiratory valve for oxygen uptake measurements during swimming. *Eur J Appl Physiol*. 1987; 56:363–66.
10. Toussaint HM, Truijens MJ. Biomechanical aspects of peak performance in human swimming. *Anim Biol*. 2005;55:17–40.
11. Vennel R, Pease DL, Wilson BD. Wave drag on human swimmers. *J Biomech*. 2006;39:664–71.
12. Vorontsov AR, Rumyantsev VA. Resistive forces in swimming. *Biomechanics in Sport: Performance Enhancement and Injury Prevention*. In: Zatsiorsky VM, editor. Oxford: Blackwell Science; 2000. p. 184–204.
13. Wilson BD, Takagi H, Pease DL. Technique comparison of pool and flume swimming. *Biomechanics and Medicine in Swimming VIII*. In: Keskinen KL, Komi PV, Hollander AP, editors. Jyväskylä (Finland): University of Jyväskylä; 1999. p. 181–84.