BRIEF REVIEW

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Consequences of Drafting on Human Locomotion: Benefits on Sports Performance

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In many endurance sports, a large part of an athlete's external power is used to overcome drag. This force has 3 components: friction, pressure, and, in swimming, wave drag. When the athlete's velocity is very low, friction drag dominates. In normal sports activities, pressure drag dominates, but frictional drag is influential in the velocity range in which the airstream changes from laminar to turbulent, which on the other hand depends on the roughness of the athlete's clothing.

The term *drafting* is mainly used in sports physiology and biomechanics to describe the tactic of performing a mode of activity in a sheltered position. The growing success and impact of selected endurance sports in which athletes could take advantage of drafting has generated questions on the physiological characteristics and mechanisms regulating human locomotion in sports such as running,[1] cycling,[2] short-track skating,[3] swimming,[4] and triathlon.[5] An athlete who drafts continuously during a race might achieve a better final placing than would normally be expected with his or her individual physiological capacities. For this reason, many athletes attempt to position themselves behind athletes of the same or slightly better ability.

Benefits of Drafting in Water Activities

Consequences on Physiological Aspects of Performance

Drafting while swimming front crawl, that is, swimming directly behind or at the side of another swimmer, is mainly done in triathlon races or open-water swims. Drafting leads to a reduction in energy spent to overcome drag force and hence gains time for swimming at maximal speed.[6] The effects of drafting during short swimming bouts have been widely studied.[7–9] The main factor of decreased body

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drag with drafting seems to be the reduction in pressure drag induced by the lead swimmer.[4]

In submaximal conditions, at an intensity of 95% of maximal speed over a 549-m swim, Bassett et al[7] showed that drafting affected the metabolic responses to swimming. Oxygen uptake was reduced by 8% ± 12% (mean ± SD), blood lactate concentration by 33% ± 17%, heart rate by 7.3% after 400 m (Figure 1), and the rating 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.[6] For elite front-crawl swimmers, Millet et al[9] suggested that triathletes can use 2 kick rhythms (2- or 6-beat) during the swim part of a triathlon to reduce the propulsive phase of the lower limbs.

A number of studies have examined the effects of swimming on subsequent cycling performance.[10–12] Decreasing the metabolic load during cycling delays the appearance of fatigue and increases performance during running. Despite the lack of experimental studies, recent reviews on triathlon determinants report that the metabolic demand induced by swimming could have detrimental effects on subsequent cycling performance.[13] Experimental studies on the effect of prior swimming on subsequent cycling performance have led to contradictory results. Kreider et al[11] found that an 800-m swimming bout resulted in a significant decrease in power output (17%) during a subsequent 75-min cycling exercise. More recently, Delextrat et al[10] observed a significant decrease in cycling efficiency (ie, ratio of the

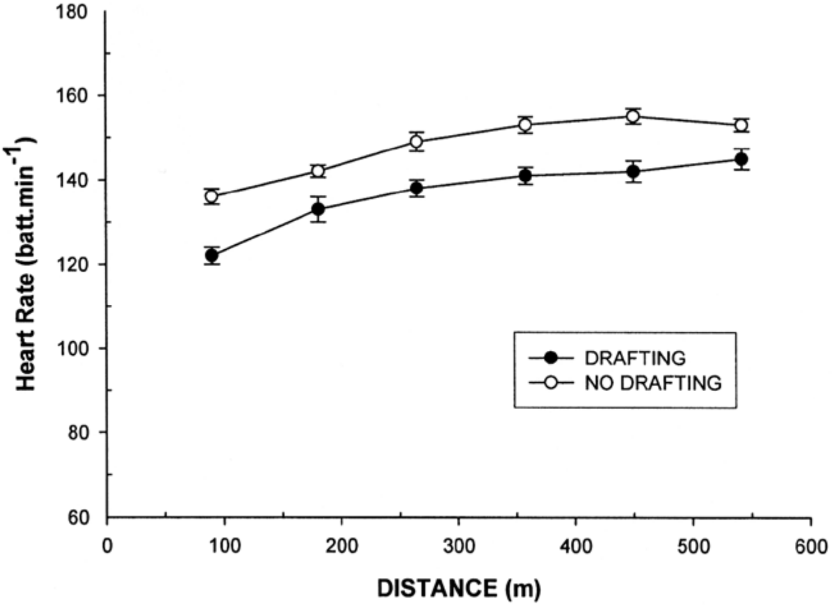

Figure 1 — Heart-rate responses (mean ± SE) to a 549-m swim (95% maximal swim velocity), with and without drafting. There are significant differences between conditions at 100 to 600 m (*P* < .05). Adapted from Bassett et al.[7] Reproduced with permission from Lippincott Williams & Wilkins.

work accomplished to energy expended) after a 750-m swim conducted at a sprint triathlon competition pace when compared with an isolated cycling bout. In an elite Olympic-distance triathlon the strategy of drafting during the cycling part influences the energy demands of this section, as well as swimming and running strategies.[13] Delextrat et al[10] demonstrated that the decrease in metabolic load associated with swimming in a drafting position involved 2 main modifications in physiological parameters during subsequent cycling. First, oxygen-uptake kinetics, at the onset of cycling, were significantly slowed when the prior swimming bout was performed in a drafting position (slower time constant) compared with swimming alone. Second, a significantly higher cycling efficiency (+4.8%), measured at steady-state level, was observed in the drafting condition than with the isolated swim. Because drafting reduces the lower limbs' propulsive phase during swimming, this improvement in cycling efficiency could be mainly accounted for by the lower relative swimming intensity. Presumably, a lower state of fatigue in the muscles of the lower limbs at the beginning of the subsequent cycling session is the explanation for this effect. Consequently, the authors suggested that the increase in cycling efficiency could lead to an improvement in overall performance during a triathlon.

A more recent experiment compared the effects of drafting or reducing exercise intensity during swimming on the power output sustained during a subsequent cycle time trial.[14] These investigators reported that the power output during a 20-minute time trial in cycling was significantly lower after 400 m of all-out freestyle swimming at either 90% of this velocity or in a drafting situation. No significant difference in the power output during cycling performance after swimming at 90% or in a drafting position was observed. This relationship has implications for the training approach in triathlon and the strategies to adopt during World Cup triathlon events.

Other aquatic sports have been studied to optimize physiologic performance and to transfer the scientific basis of performance enhancement into daily practice. For example, a common technique used in flat-water kayak and canoe races is "wash riding," in which a paddler positions his or her boat on the wake of a leading boat and, at a strategic moment, drops off the wake to sprint ahead. It was hypothesized by Gray et al[15] that this maneuver was energy efficient, analogous to drafting in cycling. This study showed that, in highly trained male kayak paddlers examined during steady-state exercise at 10,000-m race pace (3.7 m/s), a significant decrease (–11%) in energy consumption during wash riding was evident, delaying the onset of fatigue. This finding has implications for the design of training programs and competitive strategy plans for kayak racing. Wash riding can reduce energy expenditure under speeds similar to those encountered in competitive events.

Consequences on Biomechanical Aspects of Performance

The distance adopted by drafters in swimming appears to be a consistent parameter linked to overall swimming performance. Chatard and Wilson[4] investigated the effect of the distance (from 0 to 150 cm) separating the lead and draft swimmers on the metabolic responses of the drafting swimmers performing a 4-min swim in a flume at 95% of their best 1500-m velocity. They showed that the optimal 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. Oxygen uptake decreased by 11% and stroke rate by 6%, whereas stroke length increased by 6% at the optimal drafting distance of 50 cm. This result confirmed the average 60-cm distance spontaneously adopted by drafters in high-level triathlon.[9] Another important result of this study was that the drafting distance of 150 cm elicited about a 10% benefit in metabolic cost, whereas drafters had a 20% reduction in drag. This observation could have practical application, especially in pool-based training or open-water competition such as long-distance swimming or triathlon. The context of competition, however, puts some swimmers in a side-drafting situation and not only in a behind-drafting position. The optimal position when 100 cm to the side was 100 cm behind the lead swimmer, with the drafter's head located at a level of the hip of the leader.[4] This study was the first to demonstrate that swimming beside another swimmer is beneficial in terms of reduced drag. Nonetheless, the reduction in resistive drag was only one-third of that when drafting immediately behind the lead swimmer.

Many studies have shown that swimming behind another swimmer in a race is advantageous.[4,7–9] The gain in performance is higher for faster swimmers[6]: This point appears to be inconsistent with the gain reduction in drag observed with velocity. The explanation put forward is that faster triathletes are also better swimmers and thus could gain more benefit from drafting because of their better swimming skills. Another parameter that is taken into consideration by triathletes is wet suits. Delextrat et al[10] demonstrated the influence in swimming alone or in a sheltered position behind a leader on pedal rate during the subsequent cycling for triathletes; a significant pedal rate of 5.6% was observed in cycling when swimming was done before with drafting. The authors reported that this previous situation could have increased blood flow to the muscles of the lower limbs. In the context of swimming, using a wet suit induces significant decreases in active drag at different swimming speeds. The reduction is probably largely the result of an increased buoyancy inducing less frontal resistance.[16,17] Chatard and Millet[17] showed that swimming behind a leader increased swimming velocity by 3.2% (ie, 20-m benefits over 400 m), increased stroke length, and reduced stroke frequency. The gain in performance was related to the swimmers' ability and their skinfold thickness, with faster and leaner swimmers achieving a greater gain. Chollet et al[8] reported that swimming velocity increased from 1.34 to 1.39 m/s when swimmers drafted the leader during a 400-m (Figure 2). They concluded that drafting also contributes to stabilizing the stroke parameters such as stroke frequency and stroke length during swimming (see Figure 2).

Stroke frequency and stroke length decrease throughout a 400-m race. This pattern is probably caused by the acute fatigue developed when swimmers are not sheltered behind another. In the same way, improvements in stroke parameters such as stroke length have also been observed in drafting kayaking.[15] Although the kayak velocity increased significantly during the wash-riding (ie, drafting) trial, the stroke rate of the paddlers was significantly reduced. This scenario indicates that there was likely a change in the stroke mechanics used by the paddlers.

All experimental studies focusing on aquatic sports and their physiological and biomechanical specificities have emphasized the high benefits in the drafting process. Drafting technique and drafting ability need, however, to be integrated into daily practical training programs to help athletes adopt the most efficient position during competitions and therefore reach a better position than would normally be in line with their individual physiological and biomechanical capacities.

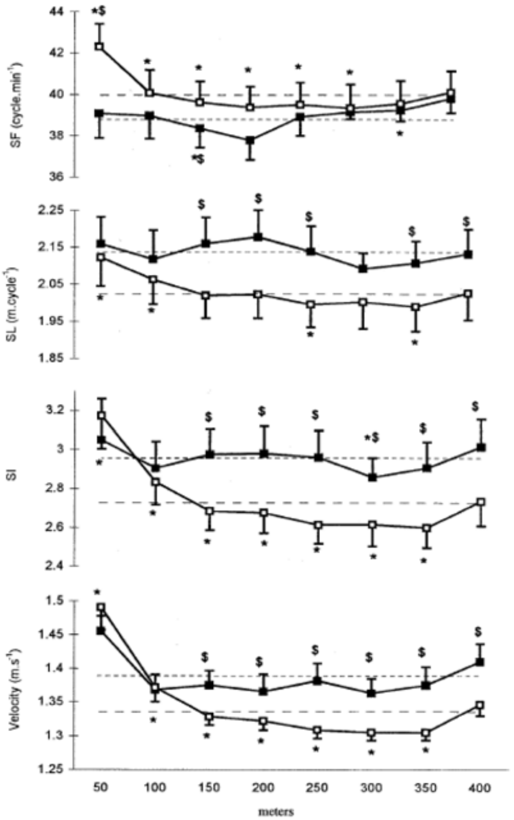

Figure 2 — Differences and variations in swimming velocity, stroke index (SI), stroke length (SL), and stroke frequency (SF) during the drafting (filled squares) and nondrafting (open squares) 400-m swim. $\$P < .05$, differences in drafting versus nondrafting conditions; $*P < .05$, differences between each 50-m value and mean 400-m in drafting (---) and nondrafting conditions (– – –). From Chollet et al.[8] Reproduced with permission from the European Journal of Applied Physiology.

Benefits of Drafting in Land Activities

Consequences on Physiological Aspects of Performance

Cyclists in mass-start events have the opportunity to draft one another. In this context the magnitude of the drafting effect in cycling can be impressive. McCole et al[18] demonstrated that a cyclist can spare about 18% of oxygen uptake at 32 km/h. The benefit of drafting a single cyclist at 37 and 40 km/h was greater (27%) than at 32 km/h. Drafting 1, 2, or 4 cyclists in a line at 40 km/h resulted in the same reduction in oxygen uptake (27%). These authors showed that riding at 40 km/h at the back of a group of 8 cyclists reduced oxygen uptake by significantly more (39%) than drafting 1, 2, or 4 cyclists in a line.

The emergence of new Olympic sports such as triathlon (in Sydney 2000) and open-water swimming (in Beijing 2008) has led sports scientists and national coaches to raise various questions about the physiological processes regulating these new disciplines. Drafting has been studied in each of the 3 disciplines of the triathlon.[1,2,8] Little is known about drafting in cycling and its influences on the following run during a triathlon. The first interesting report was provided by Hausswirth et al,[5] indicating that drafting during the bike course of a triathlon (ie, immediately after the swim leg) lowered energy expenditure, heart rate, and pulmonary ventilation at a drafting distance of 0.2 to 0.5 m behind a lead cyclist. Global reductions in oxygen uptake (–14%), heart rate (–7.5%), and pulmonary ventilation (–30.8%) were observed for an average cycling speed of 39.5 km/h. When we compared these data with those of McCole et al[18] at a cycling speed of 40 km/h, the reduction in oxygen uptake was about 26%. The differences in oxygen uptake are probably related to less efficiency at drafting during the initial phase (ie, first 4 km) of the cycling section of the simulated outdoor triathlon, because of the residual negative effects of the swim stage. Running after cycling in a drafting situation (for similar cycling speeds) significantly improved running speed compared with that of the no-drafting modality (17.8 vs 17.1 km/h). The benefit of drafting in cycling allowed triathletes to push themselves forward in the subsequent run, as demonstrated in Figure 3. Drafting during the bike leg of a triathlon creates the conditions for improved running performance, with higher benefits likely for the stronger runners.

As resistance increases, more energy is needed to generate sufficient tension in the muscles to obtain the pressures required for airflow in the lungs.[19] Some energy is also used to prevent deformation of the chest wall during increased work. Because of the legalization of drafting in cycling during elite triathlon events (ie, Olympic Games) it seems important that triathletes understand the effects of pacing with another cyclist to save energy for the following run leg. Within this framework, Hausswirth et al[20] investigated the physiological responses of riding alternately or continuously behind another cyclist during a simulated indoor sprint-distance triathlon. Each triathlete had to perform 2 triathlons, one with the alternate-drafting process during cycling, in which the triathlete alternately rode in front of or behind another cyclist, rotating every 500 m and keeping the reach speed always constant. In the other modality, the triathlete drafted a professional cyclist whose task was to respect all split times recorded during the alternate bike leg. A 16.5% reduction in oxygen uptake and 11.4% in heart rate were observed during the bike leg done continuously compared with the alternate cycling stage. Hausswirth et al[20] recorded a better 5-km running performance after the continuous-drafting bike leg (+4.2%) than for the run done after the alternate-drafting bike leg. For elite triathletes familiar with drafting technique in training and World Cup triathlon, run performance depends on the previous cycling event, particularly the drafting modalities, pedaling cadence, and stochastic power output.

In speed skating the maximal aerobic speeds are closer to cycling than running (40 km/h for the 10,000-m race). This suggests that a relevant fraction of the total energy expenditure is spent overcoming air resistance. Di Prampero et al[21] quantified the energy spent against wind as being equal for running, skating, and cycling. From this experiment, they concluded that energy spent against forces resulted in the different speeds attained in these exercises for equal power outputs. Rundell[3] demonstrated that the technical difficulties for drafting efficiently, especially while cornering, resulted in less benefit from drafting at high velocity than

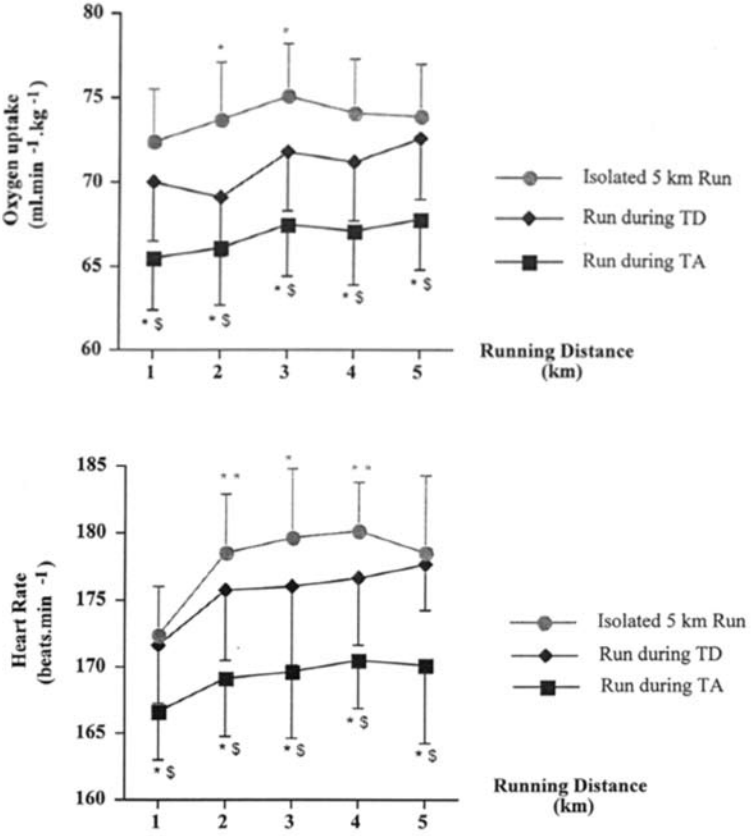

Figure 3 — (A) Changes in oxygen uptake during the run section of drafting (TD) and no-drafting (TA) triathlons. (B) Changes in heart rate during the run section of drafting and no-drafting triathlons. $*P < .01$, $**P < .05$, significantly different from run during TD; $\$P < .01$, $\$\$P < .05$, significantly different from run during TA. From Hausswirth et al.[5] Reproduced with permission from Lippincott Williams & Wilkins.

in other sports. In a short-track race skating at a speed of 32 km/h might in fact compromise the benefits of drafting because of internal power losses to overcome high forces required to skate the tight corners. In this area, an average centripetal force of 866 N was calculated for the American short-track 1000-m record, and the cornering force determined for a male performing the Calgary 1000-m long track event was 482 N. The energy requirement to overcome the high cornering forces of short-track could explain why the drafting benefits observed by Rundell[3] were not as great as those observed in cycling. Most short-track skaters reduced their energy requirements for skating at a constant pace if they drafted another skater. Drafting resulted in a mean of 6 beats/min reduction in heart rate for the 18 skaters of this study. This difference corresponded to an approximate 5% to 5.5% decrease in oxygen uptake,[3] although the coefficient of friction for skating is similar to that for cycling.[21] Drafting at a similar speed resulted in an approximately 31% lower heart rate than when leading.[2] In speed skating, however, maintaining an optimal drafting position in corners appears more difficult because synchronous crossing-over of the legs at higher velocities is technically difficult and can lead to slightly more distance between athletes.[22]

Only a few investigations have dealt with drafting in cross-country skiing. Bilodeau et al[23] found that drafting behind another skier could be a major advantage in a race in which it is possible. A mean reduction of 9 beats/min was observed when drafting a skier (Figure 4) compared with leading the same skier, a significant reduction of 5.6%. The estimated energy cost deducted from the heart-rate–oxygen-uptake relationship during a treadmill-running test was significantly lower when pacing up with a skier. Skiers should work together by sharing the lead to save energy and thus increase speed.

In running, Pugh[24] demonstrated that at a speed of 6 m/s, 80% of the oxygen cost of meeting air resistance was eliminated by running close behind another runner. The oxygen cost of meeting air resistance should be able to exceed the speed corresponding to maximal oxygen uptake by up to 6%, by running behind a pacemaker or a faster competitor. Approximately 7.5% of the total energy consumption is caused by wind resistance at 6 m/s. According to the relation of oxygen uptake and speed in track running found by Pugh,[24] the oxygen uptake corresponding to a speed of 6 m/s is 76 mL · min^{-1} · kg^{-1} and the speed corresponding to a 6%

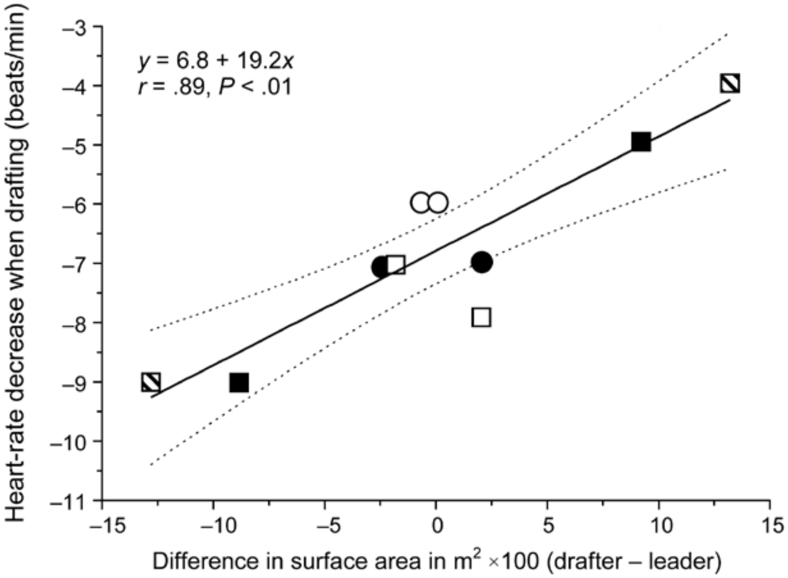

Figure 4 — Relationship between the within-pair difference in average frontal surface area (m^2) and heart-rate decrement while drafting the leading skier. Pairs of similar symbols represent the 2 skiers of the same pair (regression ± 95% confidence intervals). From Bilodeau et al.[23] Reproduced with permission from Georg Thieme Verlag.

greater oxygen uptake (ie, 80.5 mL · min^{-1} · kg^{-1}) is 6.4 m/s. This is equivalent to reducing the time for a 400-m lap from 66.6 to 62.5 seconds. Practical experience, however, suggests that athletes cannot run close enough to one another to gain this much of an advantage. The reduction in oxygen uptake achieved by running behind another runner at 6 m/s was 250 mL · min^{-1} · kg^{-1}; therefore, when running close behind another runner, oxygen uptake is 6.5% less than without shielding. Thus, ~80% of the energy cost of overcoming air resistance can be abolished by sheltering while running.

Consequences on Biomechanical Aspects of Performance

A number of attempts have been made to quantify the biomechanical determinants of drafting in terms of skill. Broker et al,[25] for example, showed that the drafting effect, expressed in terms of mass-normalized power output, varied by as much 1.21 W/kg (20.5% of total power). Kyle[2] used the 4-person team-pursuit models to find that drafting effect is subject to several skill-related factors: pace-line position, interwheel distance between 2 riders, and the drafter's left–right alignment with respect to the leader. Edwards and Byrnes[26] hypothesized that leader drag area is an important determinant of the drafting effect in cycling (see Figure 5). They reported a substantial mean effect of leader drag area, whether that effect is expressed in terms of the drag coefficient or power output. The ratio between the drag area of a leader and the drag area of a drafter is strongly correlated with the drafting effect: 61% of the drafting effect of variance can be accounted for by variation in the leader-drafter-to-drag-area ratio. The drafter's aerodynamic and anthropometric characteristics apparently have little influence on the magnitude of the drafting effects. Mean drafting effects were larger than those reported by either Kyle[2] or Broker et al.[25] Kyle's[2] 38% reduction in aerodynamic drag force is approximately 4% less than Edwards and Byrnes'[26] 42.4% reduction in the drag coefficient. The difference between these estimates was 6.3%. There are several possible explanations for those differences, but the most likely is that the recent study of Edwards and Byrnes[26] involved a greater mean leader drag than either of the other 2.

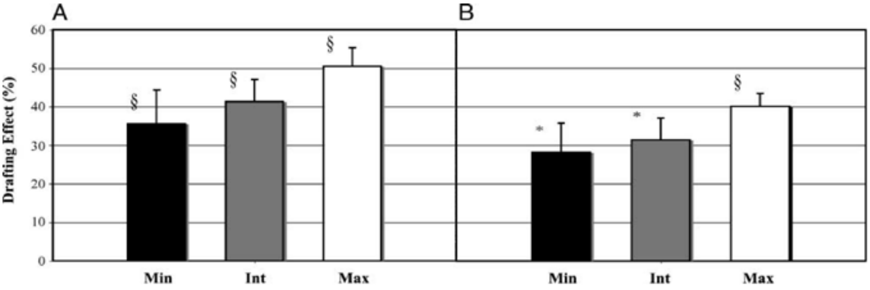

Figure 5 — Depictions of the drafting effect: (A) percent change in drag coefficient or (B) power output from solo condition, observed for the 3 different leaders (minimum, intermediate, and maximum). *Significantly different from maximum drag-area leader. §Significantly different from both remaining leaders. From Edwards and Byrnes.[26] Reproduced with permission from Lippincott Williams & Wilkins.

In most endurance sports a large portion of the external power delivered by the athlete is used to overcome drag. In level cycling and speed skating the speed is entirely determined by equivalence between the mechanical power produced by the athlete that equals the frictional losses.[27] Van Ingen Schenau[28] showed that when a speed skater is shielded by a subject who is standing in the skating posture 2 m in front of him, the drag is decreased by about 16%. At a 1-m distance this shielding effect causes a decrease in drag of 23%. This effect explains the fast lap times in marathon speed skating in which all competitors skate closely behind each other. In contrast, in in-line skating Millet et al[29] demonstrated that the technical difficulties of drafting efficiently, especially while cornering, resulted in a lower benefit of drafting at high velocity than in other sports. Moreover, the need for skaters to adjust their own cycle frequency to that of the lead skater while drafting "close" would explain the lack of significant differences between drafting at about 0.75-m and 1.20-m distances. Moreover, the energy requirement to overcome the high cornering forces could explain why the drafting benefits observed were not as great as those observed in cycling. In this context, Rundell[3] showed for short-track skaters that external power can be estimated from air-friction force and ice-friction force using the calculated cornering force during short-track and long-track skating (~4 N on the straights and ~6 N in corners). At 9.2 m/s the air friction was reduced by 21% from drafting, allowing a decrease of 13% in total power.

Skiing is another form of locomotion in which drafting has been well studied. For example, Spring et al[30] studied the effects of drafting in roller skiing and found that when a skier is in a semisquatting position and pacing up with another skier 2 to 3 m ahead, in the same posture, the drag is decreased by about 25%. Although Street[31] did not study the effect of drafting, he used Kyle's[2] results and estimated that skiing at 5.5 m/s with no headwind would result in approximately a 6% reduction in total mechanical power. Another of his estimations proposed that when skiing with a headwind of 4.5 m/s the total power-output savings for the trailing skier would be about 14%. Street[31] concluded that the advantages of drafting will occur when flow velocity is large and air drag is the major component of the net resistive force.

Given the energy required to overcome wind resistance in triathlon—especially in cycling and running—the biomechanical benefits of drafting behind a leader are important. Hausswirth et al[5] found that the lower energy requirement in the cycling leg of a triathlon in which the triathlete rode behind a leader, compared with alone, is linked to higher freely chosen pedaling rate when cycling in a drafting position (95 rpm) than when alone (89 rpm). This reduction in applied forces might be explained by reduced activation of the vastus lateralis muscle because of decreased wind resistance and connected with reduced energy expenditure. In a simulated indoor sprint triathlon, the triathletes completed 2 triathlons in which they (1) alternately rode in front of or behind another cyclist (ADT condition), rotating every 500 m and keeping speed always constant, and (2) drafted continuously behind a professional road cyclist (CDT condition) whose task was to respect all split times recorded during the ADT condition by the triathlete they were sheltering.[20] Triathletes adopted higher freely chosen cadences during ADT (102 rpm) than during CDT (85 rpm). The authors suggested in the context of triathlon races the necessity to implement drafting techniques in training to save energy for the final run associated with the stride length triathletes adopted immediately after the bike leg (see Figure 6). At the beginning of the run done after biking in the ADT condition, the stride was shorter than in the CDT-condition run (1.63 m vs 1.68 m, respectively). The pedaling cadence in cycling influenced the stride rate in running only during the first part of the run, as evidenced by the lack of change in stride length and stride rate recorded from the second to the fifth kilometer run (Figure 6). Similar stride-length values were obtained from the middle to the end of the final run section of both triathlons (CDT and ADT), suggesting that with exercise duration the triathletes spontaneously adopted the same pattern of locomotion—the one eliciting the lowest energy cost.

Athletes in selected events and sports have the opportunity to draft one another. Drafting is well known to limit the aerodynamic resistive force that athletes experience and affords less physiologically capable individuals the ability to maintain the pace of their more capable counterparts. In doing so, drafting adds complexity to the prediction of racing performance. The respite offered by drafting is the single factor that predisposes mass-start races (ie, triathlon, road cycling, skiing, short-track skating, and kayaking) to a degree of tactical complexity not apparent in individual time-trial competitions. Finally, the practice of drafting should be incorporated into training programs to optimize all physiological and biomechanical adaptations underpinning enhanced performance.

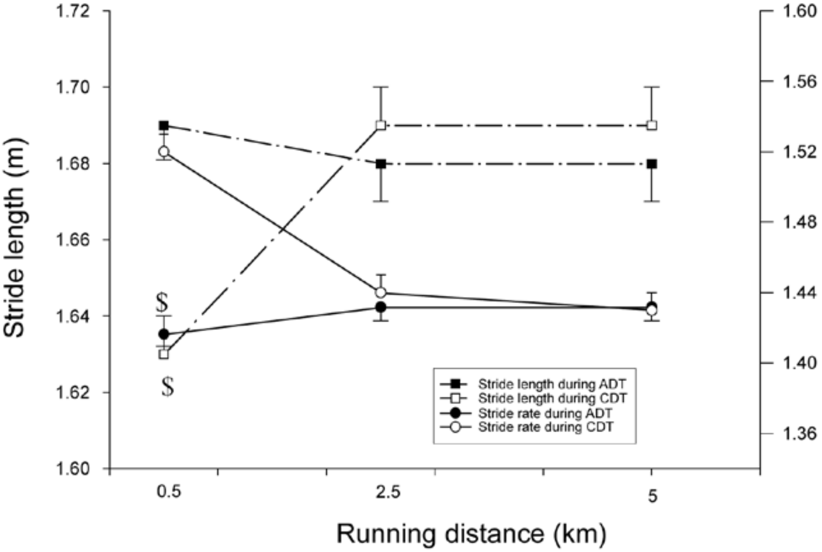

Figure 6 — Changes in stride length and stride rate during the run section of the alternating-draft triathlon (ADT) versus the continuous-drafting triathlon (CDT). Significantly different from the initial value, *$P < .05$. Significantly different from the corresponding ADT value, \$$P < .05$. From Hausswirth et al.[20] Reproduced with permission from Lippincott Williams & Wilkins.

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