Aerodynamic Interaction between Two Speed Skaters Measured in a Closed Wind Tunnel

Ola Elfmark, Lars M. Bardal, Luca Oggiano, Håvard Myklebust

***Abstract*—Team pursuit is a relatively new event in international long track speed skating. For a single speed skater the aerodynamic drag will account for up to 80% of the braking force, thus reducing the drag can greatly improve the performance. In a team pursuit the interactions between athletes in near proximity will also be essential, but is not well studied. In this study, systematic measurements of the aerodynamic drag, body posture and relative positioning of speed skaters have been performed in the low speed wind tunnel at the Norwegian University of Science and Technology, in order to investigate the aerodynamic interaction between two speed skaters. Drag measurements of static speed skaters drafting, leading, side-by-side, and dynamic drag measurements in a synchronized and unsynchronized movement at different distances, were performed. The projected frontal area was measured for all postures and movements and a blockage correction was performed, as the blockage ratio ranged from 5-15% in the different setups. The static drag measurements where performed on two test subjects in two different postures, a low posture and a high posture, and two different distances between the test subjects 1.5T and 3T where T being the length of the torso (T=0.63m). A drag reduction was observed for all distances and configurations, from 39% to 11.4%, for the drafting test subject. The drag of the leading test subject was only influenced at -1.5T, with the biggest drag reduction of 5.6%. An increase in drag was seen for all side-by-side measurements, the biggest increase was observed to be 25.7%, at the closest distance between the test subjects, and the lowest at 2.7% with $\sim$ 0.7 m between the test subjects. A clear aerodynamic interaction between the test subjects and their postures was observed for most measurements during static measurements, with results corresponding well to recent studies. For the dynamic measurements, the leading test subject had a drag reduction of 3% even at -3T. The drafting showed a drag reduction of 15% when being in a synchronized (sync) motion with the leading test subject at 4.5T. The maximal drag reduction for both the leading and the drafting test subject were observed when being as close as possible in sync, with a drag reduction of 8.5% and 25.7% respectively. This study emphasize the importance of keeping a synchronized movement by showing that the maximal gain for the leading and drafting dropped to 3.2% and 3.3% respectively when the skaters are in opposite phase. Individual differences in technique also appear to influence the drag of the other test subject.

***Keywords*—Aerodynamic interaction, drag cycle, drag force, frontal area, speed skating.

I. Introduction

TRADITIONALLY, speed skating has been a sport where competitors individually race each other. The winning margins in speed skating can be in the order of a thousands of a second, so even the smallest improvements in aerodynamics can be crucial for winning. The speed is entirely determined by the balance between power produced by the athlete and the power lost due to the breaking forces (aerodynamic drag and ice friction) [1], [2]. Reducing the aerodynamic drag is of high importance for an athlete, as the drag force can constitute more than 80% of the total breaking force [3]. The drag force acting on a speed skater can be formulated as

$$\vec{F}_D = \frac{1}{2}\rho V_{rel}^2 C_d A_p, \qquad (1)$$

where ρ is the density of air, V_{rel} is the relative air velocity, C_d is the drag coefficient and A_p the projected frontal area of the speed skater [1]. The influence of the drag force, relative to the friction force, will increase with speed as $\vec{F}_D \propto V^2{}_{rel}$. The air density ρ can greatly influence the over all performance in speed skating, but it is not a variable an athlete can influence while racing. The drag coefficient is dependent on the surface roughness, the shape of the object and the Reynolds number and is often combined with A_p in a variable called the drag area (C_dA) [1], [3].

The aerodynamic drag acting on an individual skater has been investigated by van Ingen Schenau [1]. It was showed that the drag force acting on a speed skater is dependent on the body posture. A linear correlation was found between the drag force and the hip and knee angles, shown in Fig. 1.

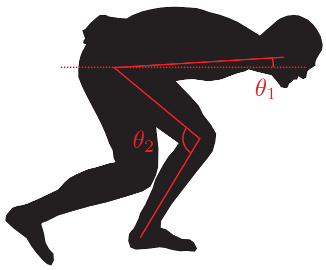

Fig. 1 The hip angle (θ_1) and knee angle (θ_2) determining the skaters posture, defined by van Ingen Schenau [1]

Both an increase in θ_1 and θ_2 yields an increase in the total drag force acting on the athlete [1]. One of the reasons for the colossal improvement in performance in speed skating the decades before 2000 is a big decrease in θ_1 through the years [2]. Van Ingen Schenau also showed that the drag coefficient was Reynolds dependent with a critical speed between 4 and 12 m/s and a big decrease in drag when the athletes changed from a woollen suit to a skin suit. The influence of drafting behind an other athlete was shown by having one athlete

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standing 2 m and 1 m in front of the athlete. The drag force of the athlete drafting decreased with 16% and 23% respectively. The curvature of the back was also investigated, but no significant change was shown. The measurements were only made in one static posture. Van Ingen Schenau mostly looked into what effect different body postures have on drag and only briefly touched the topic of suits [1].

The research around textiles with aerodynamic advantages has grown the last years and is also a hot topic in media in sports like cycling and speed skating. Sætran et al. investigated the effect of different textiles with different roughness for an aerodynamic advantages in speed skating suits [3]. A mannequin in a typical speed skating posture was tested in a wind tunnel, instead of athletes in static postures, to ensure repeatability. By changing the textiles on the legs from a smooth to a rougher textile the results showed an improvement in drag equivalent to around 3 s on a 1500 m. In the Olympic Games in Turin 2006 3 s was the difference between 1st and 23rd place. As the drag coefficient is Reynolds dependent it was also suggested to use different suits for different disciplines, as the average speed is different for different disciplines [3].

An approach with using a mannequin in a static posture will only be valid if the drag coefficient not is affected by the motion of the speed skater. D'Auteuil investigated this topic by using a moving mannequin in scale 1:1 oscillating with different frequencies. It was shown that the drag crisis occurred for the same speeds whether the mannequin was oscillating with various frequencies, lower than 0.67 Hz, or standing in a static posture [4].

Drag measurements of athletes in a dynamic skating posture was conducted by Leirdal et al. [5]. The purpose of the study was to evaluate the effect of different body posture in cross country skiing, but the skating movement of a cross country skier is somewhat similar to the movement of a speed skater. A sliding board was mounted on a force balance in a wind tunnel and measurements were recorded for static tests, 30 s and 3 min dynamic tests, for three different body postures. A reduction in drag of 30% was observed going from a high ($\theta_1 \sim 58°$, $\theta_2 \sim 130°$ in average through the motion) to a deep posture ($\theta_1 \sim 32°$, $\theta_2 \sim 115°$ in average through the motion). A increase in drag was shown from the static to the dynamic measurements for all heights. The frequencies of the only dynamic measurement presented was 0.72 Hz.

Research have been done for many of the different aspects that affect the drag on a speed skater, but little research has been done on the aerodynamic interaction between skaters in a team pursuit. This is a relatively new event in international long track speed skating. It is performed by teams of three athletes, the length is 8 laps and it resembles the team pursuit performed in track cycling. The event was first introduced in the World Cup in 2003 and in the Olympics in 2006. In the Winter Olympics in Pyeong Chang 2018 the average speed for the winning team was 14.7 m/s and the difference between first and second place was only 1.2 s [6]. In the World Cup, and for first time in the World Championship in February 2019, a shorter version with only three laps is also introduced where the speed is even higher. As in all sports, the aerodynamic drag gets more and more important with increasing speed. In a team pursuit, both the aerodynamic factors of an individual athlete and the interactions between athletes in near proximity will be essential.

For less complex bluff bodies, aerodynamic interaction has shown to affect the forces the bodies experience [7]. Interaction between athletes in near proximity is also a essential topic in cycling, where team pursuit also is performed. Blocken et al. analyzed the aerodynamic interaction between two drafting cyclist in three different body postures, using both wind tunnel measurements and Computational Fluid Dynamics (CFD) [8]. Relative to an isolated cyclist, the trailing cyclist was shown to have a drag reduction of 27.1% in the highest posture and 13.8% on the lowest posture from the wind tunnel measurements. The leading cyclist had a drag reduction of 0.8% in the highest and 2.6% in the lowest posture, CFD analysis for the leading cyclist was in the same range as in the wind tunnel (1.6% and 1.3% respectively). These measurements were done with a distance of 0.01 m between the back wheel of the leading cyclist and the front wheel of the trailing cyclist. Aerodynamic interaction between the riders, with respect to their postures, was here seen as the trailing cyclist had a decrease in relative drag reduction going from a high to a low posture, whereas the opposite was seen for the leading cyclist.

Barry et al. investigated the aerodynamic interaction between two cyclists in different lateral and axial arrangement [7]. A decrease in drag of 5% for the leading and 49% for the trailing cyclist was observed by having one cyclist drafting behind the other, both cases with the cyclists laterally inline and minimum spacing axially. The change in drag for the trailing cyclist was strongly dependent on lateral displacement and only minor for changes in the axial displacement. The opposite was seen for the leading cyclist. During an overtaking sequence, when the riders was placed side-by-side, both cyclist had an increase in drag of over 6%. The maximum drag was measured at minimum separation between the cyclists and decreased when the distance increased, both axially and laterally [7]. The same trend seen for two drafting cyclists was also seen by Barry et al. when measuring on four cyclists in a team pursuit simultaneously [9]. The cyclists experienced 5, 45, 55, and 57% change in drag, from the first to the fourth rider respectively, relative to individual measurements of the cyclists. It was also shown a noticeable difference in drag between the cyclist when changing body posture. Aerodynamic interactions between the cyclist were observed, given that it is possible for one athlete to influence the drag of a team mate by changing his own posture [9].

The aerodynamic interaction between athletes in speed skating is not well understood. To some extent, one can look to cycling and assume that the tendency will be the same. But in a team pursuit where 1.2 s can be the difference between first and second place, better knowledge is needed. Some topics regarding aerodynamic interaction will also be specific for speed skating. One example is the difference in aerodynamic interactions that may occur from a synchronized (sync) and an unsynchronized movement (unsync) between two speed skaters. This study aims to develop a better understanding of the aerodynamic interaction between speed skaters in a team pursuit. The investigation will address the change in drag, both for the leading and the drafting speed skater. Both dynamic measurements in sync and unsync, and static measurements in different lateral and axial arrangements will be performed.

II. Methods

A. Subjects

Two well-trained speed skaters (age 26±1 yr, height 1.92±0.02 m, weight 83.5±2.5 kg) at the Norwegian national level participated in the study.The test subjects was selected to be of similar size and were using identical speed skating suits during the tests. Both subjects were instructed to have both arms on the back, to ensure that the possible change in drag did not come from the change in arm position through the tests. As there is big individual differences in skating technique, θ_1 and θ_2 was chosen individually by each of the test subjects both for static and dynamic measurements.

B. General Setup

All experiments were carried out a wind tunnel at Norwegian University of Science and Technology (NTNU), in Trondheim. It uses a 220-kW centrifugal fan to produce wind speeds up to 25 m/s, has a cross section of 4.86 m^2 (height 1.8 m, width 2.7m) and a 12.5 m long test section. A Schenck six-component force balance was used to measure the drag and side force and a pitot-probe was mounted upstream in the wind tunnel for measurement of the wind speed. Cameras were mounted downstream and outside the wind tunnel and a live video feed showing the side and rear view of the test subject was projected on the wind tunnel floor. To help the test subjects keep consistent postures in the static measurements and to control the height of the back for the dynamic measurements, guidelines were overlayed in the video feed.

The Reynolds number is defined as

$$Re = \frac{VW}{\nu}, \quad (2)$$

where W is a characteristic length, V is velocity and ν is the kinematic viscosity. The average speed in a speed skating team pursuit is approximately 14 m/s, thus this is selected as the desired speed for all measurements. Whereas the average temperature in the wind tunnel is approximately 25°C, the temperature in a speed skating competition will usually be around 10°C, and this yields a change in kinematic viscosity of around 9.5%. To ensure that measurements are made in the right Reynolds number regime the speed was set to be approximately 15.3 m/s, by using (2). This correspond to a Reynolds number of 4.9x10^5 using the average width of the hip of the test subjects as the characteristic length.

Throughout all measurements the length scale T was used for the axial distance between leading and trailing test subject. T was set to be the average torso length of the two test subjects, 0.63 m. The length definition and examples for length 1.5T and -1.5T are shown in Fig. 2.

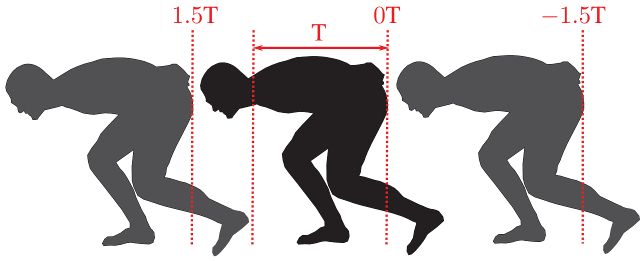


Fig. 2 Average length of torso (T) used as axial length definition for all measurements. The black skater represent the test subject on the force plate and the grey skater the other test subject in two different postures. Starting point for the length was at the lowest point on the torso. T was measured to be 0.63 m

C. Static Measurements

The static measurements were performed with a sampling time of 20 s and a sampling rate of 2 kHz. A relative short sampling time was chosen so the test subject was able to maintain the intended posture throughout the test. Three measurements were made in each posture and the mean value was calculated. At the start and at the end of each measurement a picture of the side and rear view of the test subject was saved. This was done to verify that the intended posture was maintained through the measurement. Two different postures were used for the static measurements, a low posture (P1) and a high posture (P2), both postures was chosen to have a small θ_1, to replicate typical speed skating postures. The postures are shown in Fig. 3.

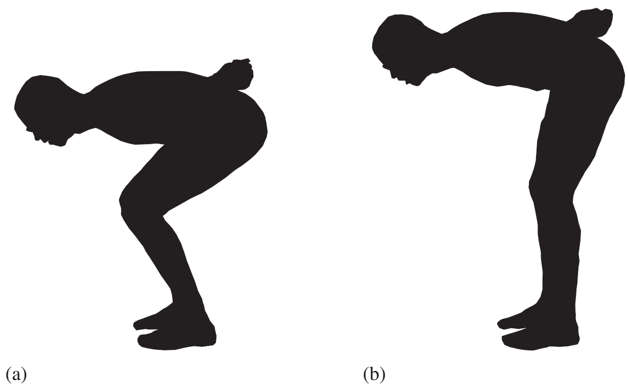


Fig. 3 The two postures tested for static measurements. (a) is showing the low posture P1 with $\theta_1 \sim 10°$ and $\theta_2 \sim 90°$. (b) is showing the high posture P2 with $\theta_1 \sim 10°$ and $\theta_2 \sim 170°$

A small plate (width 0.33 m, length 0.7 m) was mounted on the side of the force balance, 1 m from the nearest wall. This was done to try to ensure that neither of the test subjects would come to close to the walls when measuring side-by-side, which could have had an influence on the results. Each test subject was first measured alone in both postures and all measurements are presented as a value relative to these results for each test subject and posture respectively. Each test subject was tested on the force plate with the other test subject placed in four different axial distances (3T, 1.5T, -1.5T, and -3T) and all combinations of P1 and P2 was tested for each distance. Throughout the paper the notation ”P1P1” will be used, indicating the posture of the athlete in the force plate and the second athlete respectively

The same procedure was used for the test in a side-by-side arrangement. All measurements were done with both test subjects in axial displacement of 0T and measurements were performed for both subjects for three different distances between the test subjects (0W, 1W, and 2W). An example for the configuration P1P2, were test subject 1 (TS1) on the force plate is standing in P1 and test subject 2 (TS2) in P2, with 1W distance between them is shown in Fig. 4.

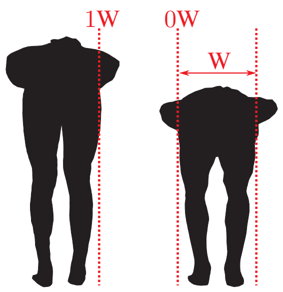


Fig. 4 Example of side-by-side measurements where test subject 1 is standing in P1 and test subjects 2 in P2 with 1W distance between them. W was measured to be 0.35 m

Staggered arrangement of the test subjects was omitted due to time constraints and the uncertainty the blockage effect will have on the results.

D. Dynamic Measurements

The dynamic measurements were performed with a sampling time of 60 s and a sampling rate of 2 kHz. A large plate (width 1.3m length 0.7m) was mounted on the force balance, so the test subject could replicate a dynamic skating motion. A guideline for the maximum height on the test subjects back was overlayed in the video feed. To ensure that the frequency of the motion remained constant throughout the measurements both test subjects used an ear plug with a metronome. The frequency of the metronome was decided by the test subjects to be 0.25Hz, a frequency that was easy to reproduce through the test. Before the dynamic tests each subject got 10 min training on the force plate to find the right pace. First an initial measurement was made for each of the test subjects without wind to identify initial forces produced by the test subject during a measurement, the inertial forces were removed from the time series in the post processing.

As for the static measurement, individual measurement for both test subjects were conducted. After the individual measurement both test subjects were tested in turn on the force plate with the other subject moving in six different distances (4.5T 3T, 1.5T, -1.5T, -3T, and -4.5T). At each distance measurements were made in sync and unsync motion.

A speed skater has a periodical movement, thus it will be fair to assume that the drag also will change periodically through the cycle. The side force and the drag force were measured simultaneously. Each side force cycle will have two wave crests after each other followed by two wave troughs, where the first crest and trough is a landing and the second is a push from one side to the other. A cycle was determined by defining the second wave crest of the side force as the starting point. This crest corresponds to the push-off from right to left. An algorithm was made to extract and normalize each drag and side force cycle in the dynamic time series, and an average of all drag and side force cycles was made. A frequency of 0.25Hz for the test subjects and a measurements of 60 s yields that each presented cycle is an average of 14 complete cycles for all measurements.

E. Frontal Area Measurements

The frontal area of both test subjects was measured for both the dynamic and static postures. A sphere with known diameter was first used as a reference area to calculate pixels per square meter. The test subjects were asked to replicate the movements and postures used in the measurements in front of a green screen, shown in Fig. 5 (a). The resulting binary image is shown in Fig. 5 (b). All white pixels were counted and the frontal area was then calculated using the calibration value from the sphere.

(a) (b)

Fig. 5 Methodology for frontal area measurement. (a) shows the test subjects standing in front of a green screen and (b) the binary picture produced from (a)

A regression model of five different frontal areas from the movement cycle was used to calculate the frontal area of the dynamic measurements. When taking dynamic unsync measurements, the blocked area in the wind tunnel will change from the area of approximately one test subject when they are crossing behind each other to the summed area of two subjects. Therefore separate measurements of the frontal area were made for the unsync movement. Five frontal areas was measured of the two speed skaters trough the unsync motion and a similar regression model was made.

F. Blockage Correction

For the unsync measurements and the static measurements side-by-side, the blockage of the cross section in the wind tunnel will exceed 10%, the rest of the static measurements will have a blockage ratio of 5-10%. Thus, the error occurring from a high blockage ratio in a closed wind tunnel has to be taken into account [10]. The correction model used in the experiment was

$$\frac{C_{du}}{C_{dc}} = 1 + \theta C_{du}\frac{A}{S}, \quad (3)$$

as suggested by Maskell [11]. Here, C_{dc} and C_{du} is the corrected and uncorrected drag coefficient respectively, S is the area of the cross section, A is the area blocking the test section and θ is the blockage constant determined by the aspect ratio of the test object and the base pressure coefficient.

By estimating a constant aspect ratio of a human body of 3, the blockage constant was calculated to be θ = 2.58. Rearranging (3) and inserting for S and θ the correction model becomes

$$C_{dc} = \frac{C_{du}}{1 + 2.58C_{du}(A/4.86m^2)}. \tag{4}$$

For the static measurement of the test subjects in different axial positions, the area of the biggest test subject was used as the frontal area. The frontal area of the two test subjects was summed, when measuring side-by-side. For measurements of the test subjects in sync, the regression model of the biggest frontal area of the two was used. As mentioned, the frontal area for the unsync motion will vary through the cycle and this has to be taken into account. Thus, the separate regression model for the frontal area through the unsync motion was used for a dynamic blockage correction.

III. Results and Discussion

A. Static Measurements

The respective individual measurements of drag area, frontal area and drag coefficient in the postures used for the static measurement for both TS1 and TS2 are presented in Table I. Only small differences were seen in the individual measurements between the test subjects. All results from static measurements are presented as a percentage relative change in drag from the individual test subject in the corresponding posture.

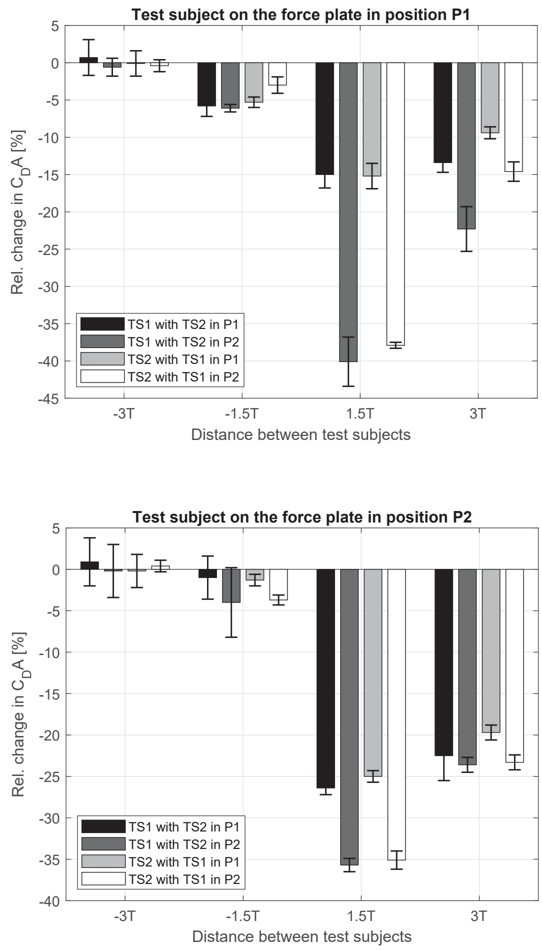
TABLE I
Individual Measurements of Drag Area, Frontal Area and Drag Coefficient for the Two Test Subjects in the Two Different Postures

Test subject	posture	C_dA [m^2]	A [m^2]	C_d []
TS1	P1	0.1643 ± 0.003	0.3145	0.5224
TS1	P2	0.2501 ± 0.001	0.3833	0.6525
TS2	P1	0.1576 ± 0.003	0.3080	0.5117
TS2	P2	0.2506 ± 0.002	0.3934	0.6368

1) Drafting and Leading: The maximum drag reduction for both drafting test subjects was found with the shortest distance between the test subjects in the configuration P1P2 with an average of 39%. Maximum drag reduction for the leading test subject was found at the shortest distance in the configuration P1P1 with an average of 5.6%.

The static measurements for the test subjects drafting and leading directly behind each other are presented in Fig. 6. The drag was measured on both test subjects leading and drafting at two different distances (1.5T and 3T). The negative distances indicates that the drag is measured on the leading test subject. Fig. 6 (a) shows the relative change when the test subject on the force plate is standing in posture P1 and Fig. 6 (b) in P2.

The distance between the test subjects is strongly influencing the drag both for the leading and drafting test subject. For all cases, the leading test subjects does not have a change in drag when the drafting test subject is placed at -3T. Further, the biggest gain for the leading skater is when the drafting skater replicate the posture (P1P1 and P2P2). A drag reduction of 3-6% was observed for all measurements of the leading test subject at this distance except for the configuration P2P1, which had a smaller drag reduction. The upper body will produce a greater wake than the legs. The configuration P2P1 is the only configuration where this wake not is disrupted by the drafting test subject. This may be the reason for the smaller drag reduction for this configuration. This is also the only configuration where the leading test subject has a considerably higher C_dA than the drafting test subject and this can affect the results, as was seen also by Barry et al. when studying the interaction between four drafting cyclists in a team time trail [9].



(a)

(b)

Fig. 6 Change in drag, relative to individual measurements, for the drafting and leading test subjects. (a) shows the test subject on the force plate in P1 and (b) in P2. Positive values on the x-axis indicates that the force is measured on the drafting test subject and negative on the leading test subject. The error bars are indicating the standard deviation with n=3

As expected, a large drag reduction was observed for all arrangement when drafting. The results at the longest separation distance 3T corresponds quite well with the results from van Ingen Schenaus [1] who showed a drag reduction of 16% and 23% for a static posture at 2 m and 1 m separation respectively. The drag reduction, in general, seems to be higher when the test subjects are close. Whereas the leading test subject experiences a smaller drag reduction for P2P1, the opposite tendency is observed for the drafting test subject with a significant difference in drag reduction between P1P1 and P1P2. The change in drag between the different configurations in Fig. 6 (b) is expected as the drafting test subject becomes more exposed to the wind when the leading test subject is in a lower posture. For all distances between the test subjects and different postures of the drafting test subject, the drag reduction is highest when the leading test subjects is in P2. Going from P2P2 to P1P1, the relative change in drag for the drafting test subject decreases while an increase is seen for the leading test subject. The same tendency was shown by Blocken et al. when having two cyclist going from an upright to a dropped posture [8]. For both distances tested, the leading test subject seem to be able to greatly influence the drag of the drafting test subject by changing posture.

2) Side-by-Side: During an overtaking situation in a team pursuit, the athletes will be side-by-side for some time. Whereas the aerodynamic interaction between cylinders have been well studied, among others by D. Sumner [12], the interaction between other bluff bodies is not well studied. An increase in drag is observed for cylinders in a side-by-side arrangement when being in near proximity, and this increase gets higher as the cylinders are moved closer together.

The same tendency can be seen when placing to speed skaters side-by-side. All measurements with the test subjects side-by-side yielded an increase in drag. The biggest average increase for the two test subjects was observed to be 25.7% for the configuration P1P2 at 0W and the lowest at 2.7% at 2W for P1P1. As expected, the greatest increase was seen at 0W where the test subjects were standing as close as possible without touching each other. An interesting results is that the test subjects could influence the drag of the other by changing posture. For a scenario where both test subjects are in P1 and one is moving to P2, the one moving is increasing the drag of the other with 13% (doubling the drag increase from 13-26%). It is important to notice that the drag of the moving test subject also then will be increasing. All results are shown in Fig. 7.

For the side-by-side measurements the blocked area in the wind tunnel will vary between ∼13% and ∼16% and the results are compared with individual measurements where the blocked area is ∼6%. Even with blockage correction there will be an uncertainty in these measurements due to the big change in blockage. However, the tendencies of the results are consistent for all measurements and corresponds well with recent studies. Barry et al. investigated the aerodynamic interaction with different spatial positions for cyclist [7].

For the side-by-side configurations between two cyclist, a drag increase of ∼4% and ∼7% with a distance of 0.75 m and 0.5 m respectively between the cyclists was observed. Distances of 0.5 and 0.75 m corresponds to 1.4W and 2.1W respectively, and the average of all measurements for 2W

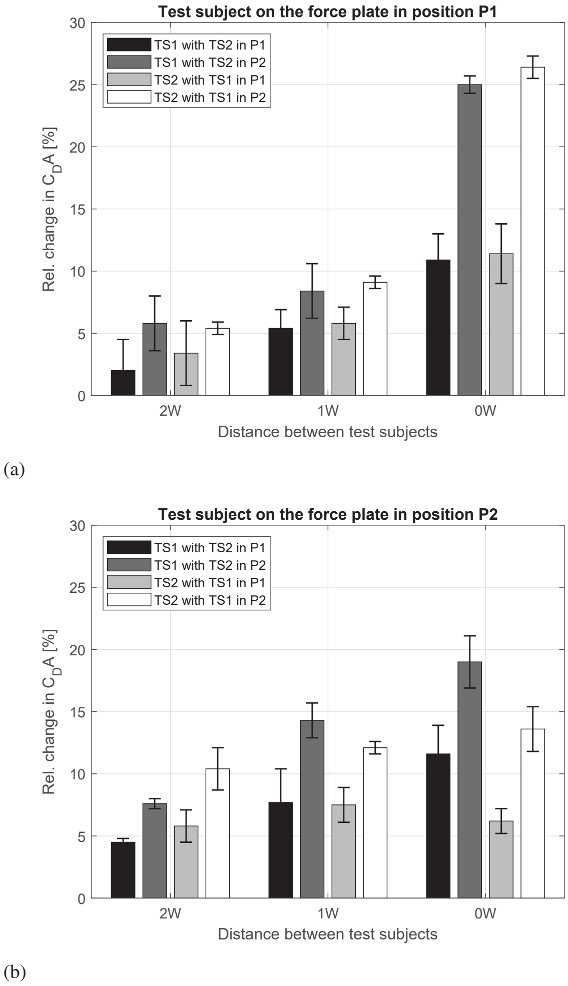


Fig. 7 Change in drag, relative to individual measurements, for two test subjects side-by-side. (a) shows the test subject on force plate in P1 and (b) in P2. The error bars are indicating the standard deviation with n=3

and 1W was 5.6±2.4% and 8.8±2.8% respectively. The big variation is due to the different configurations and postures between the test subjects.

When a bluff body is moving through a free stream, the free stream gets disturbed and has to accelerate around the body. The highest speed will then be near the bluff body and decay both outwards and down stream. This yields that two test subjects standing close to each other will experience a higher wind speed, thus the drag will increase. The fact that the drag is increasing when the test subjects are close and decreasing outwards is also corresponding well with D. Sumner's theory on interaction between cylinders [12].

B. Dynamic Measurements

Unlike an alpine skier or a cyclist, a speed skaters posture is highly dynamic and looking at static measurements may only gives an approximate view of how the drag is changing. As for the static measurements all results for aerodynamic interaction were compared to individual measurements for each of the athletes. The respective individual mean values of drag area, frontal area and drag coefficient of the movement cycles are presented in Table II.

TABLE II
AVERAGE VALUES OF DRAG AREA, FRONTAL AREA AND DRAG COEFFICIENT FOR THE INDIVIDUAL DYNAMIC MEASUREMENTS OF THE TWO TEST SUBJECTS

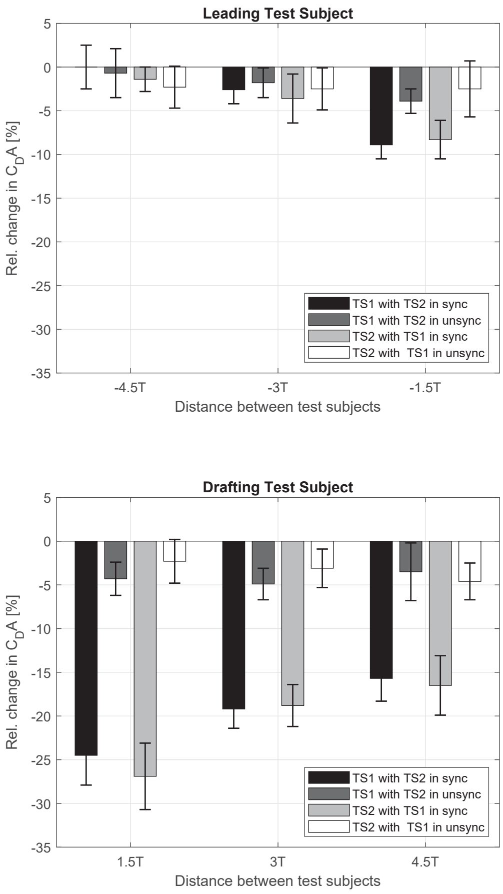
Test subject	mean C_dA [m^2]	mean A [m^2]	mean C_d []
TS1	0.1712 ± 0.004	0.3340 ± 0.002	0.5126
TS2	0.1675 ± 0.005	0.3420 ± 0.002	0.4898

The average values for all dynamic measurements are presented in Fig. 8 as a relative change from the mean values from Table II. The synchronized movement is illustrated in Fig. 9 and the unsynchronized movement is illustrated in Fig. 10, where the black and grey speed skater symbolize the two different test subjects and how they are moving with respect to one another.

The leading test subject seems to have a small aerodynamic advantage even when having the drafting test subject at -3T. Here, the aerodynamic advantage is in the same range for the sync and unsync motion. The leading test subjects seems to be independent of the drafting test subject first at -4.5T. The decrease in drag for the leading test subject becomes greater as the drafting test subject is moving closer. At -1.5T a difference can also be seen between a sync and unsync motion. The leading test subject will gain almost three times as much (3.2% vs. 8.6%) by having the drafting test subject in sync, thus a drafting speed skater can manipulate the drag of the leading speed skater both by choosing the distance between them and by synchronizing the motion with the leading speed skater. Compared to the static measurements, the trends for the leading test subjects are similar. However, with respect to the distance between them, the effect seems to be greater for the dynamic measurements than for the static measurements.

Interestingly when the two speed skaters are in an unsync motion, the distance between the drafting and leading test subject does not affect the aerodynamic drag of the drafting skater much. There is still a small aerodynamic advantage for the drafting test subject, well under 5%, the aerodynamic advantage seems to be in the same range for the drafting and leading speed skater. Hence, if two speed skaters are unsync in near proximity, the leading and drafting speed skater will experience the same small aerodynamic advantage. As seen for the individual drag cycles, the sliding part from one side to the other will only take approximately 0.5 s and this will be the part where the drafting test subject is passing behind the leading one. The time the drafting test subjects actually is drafting is less then 1/4 of the drag cycle. The test subjects will also never be perfectly overlapping as the position of their legs will differ. Through the rest of the cycle the drafting athlete is both exposed to the free stream wind and the accelerated wind the leading test subject induce, thus the test subject will experience an as high or higher wind speed than for an individual measurement for 3/4 of the drag cycle.

For drafting in sync one can see a clear aerodynamic advantage for all distances. The advantage is decaying almost linearly with distance when moving the leading test subject upstream, but a clear advantage of over 15% is still observed



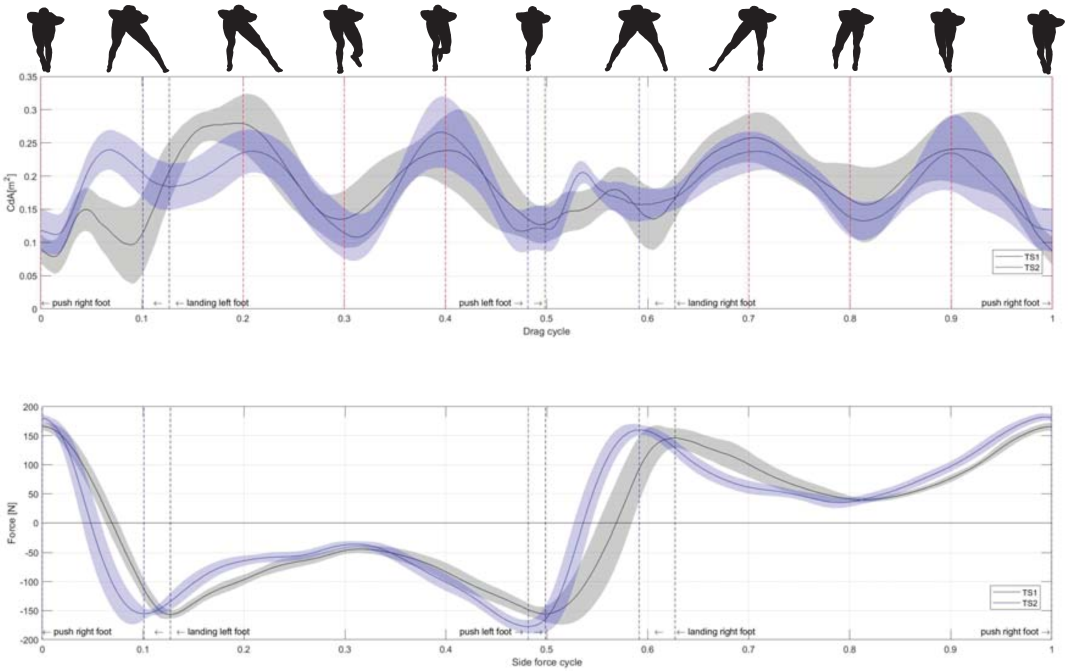
(a)

(b)

Fig. 8 Change in drag, relative to individual measurements, for dynamic measurements of two test subjects in sync and unsync. (a) shows the change for the leading test subjects and (b) for the drafting test subjects for three different separation distances. The error bars are indicating the standard deviation with n=14

at 4.5T. The drafting results can be compared with the static measurements where both test subjects are standing in the same posture (P1P1 and P2P2) and the results are in the same range and shows similar trends. The fact that there is an advantage drafting in sync may not come as a surprise for any speed skater, but the big difference between a sync and unsync motion may. The fact that a speed skater can gain over 15% even at 4.5T (∼2.8 m) if perfectly synchronized with the leading speed skater is knowledge that also can be utilized in an individual competition when the speed skaters are changing lanes. There will be an aerodynamic advantage for the drafting speed skater to synchronize the movement to the leading.

Whereas the mean value of a dynamic measurement gives an overview over the magnitude of the drag, a time series provides more information of the drag throughout the cycle, and may be a good tool to explain why the drag is changing. The drag cycle, side force cycle and an illustration of the movement for individual measurements of TS1 and TS2 are presented in Fig. 9.



(a)

(b)

Fig. 9 Time series of the averaged drag cycle (a) and side force cycle (b) for an individual dynamic measurements of the two different test subjects. The shaded error bands indicates the standard deviation with n=14. The blue and the black dashed lines indicates when the test subject is pushing from one side to the other and the landing defined from the side force cycle. The movement of a skater through a cycle is illustrated in (a) with red dashed lines indicating the corresponding point in the drag cycle

The individual frontal area was used for a dynamic blockage correction. Looking at the standard deviation of the frontal area, the test subject kept a fairly constant frontal area through the motion. As for the static measurements, TS2 has a bigger frontal area yet a smaller C_dA, but only small differences can be seen between the test subjects when only looking at the mean values of the dynamic movement. But the side force cycle together with the drag cycle in Fig. 9 shows individual differences in technique. The landing was defined at the first wave trough and crest as this is easily identified, this wave maximum will come when the test subject has moved the center of mass to the landing foot. Each cycles was defined to start at the second wave crest, which will be the largest force in the push off from right to left. By comparing the side force and drag cycle of the two test subjects, technical differences and similarities can be detected.

With a frequency of 0.25Hz, one cycle will approximately take 4 s. TS1 has an average sliding phase (from a push to a landing) of 0.511 ± 0.003 s and TS2 0.422 ± 0.018 s. Whereas there are only minor differences between a left and right push for an individual, there are differences between the test subjects, which also can be seen in Fig. 9. A shorter sliding phase should also yield a more distinct push from one side to the other, which can be observed by looking at the difference of magnitude of the side forces at the push-off.

At first sight, the movement of a speed skater from left to right will seem symmetrical with the movement from right to left. An interesting observation is that both test subjects seem to have a more or less asymmetrical movement. While the side force cycle shows a fairly symmetrical push from side to side, the drag force in Fig. 9 (a) shows that both test subjects are somewhat asymmetrical in their movement. A symmetric similarity can be observed for TS1 but the magnitude of the forces is greater, pushing from right to left for the first part of the cycle (0-0.3 compared to 0.5-0.8). An asymmetric movement can also be seen for TS2, where both magnitude and the shape of the drag cycle are different for the first part of the movement, the second part (0.3-0.5 compared to 0.8-1) shows only slightly higher in the magnitude. This difference in the movement for TS2 was also seen in a video recording as TS2 moved the legs differently from one side to the other, it is expected that the asymmetry may be explained by this technical difference.

To detect whether or not a speed skater has a symmetrical motion was never the intention of this study, but came up as an interesting topic when looking at the individual measurements of the test subjects. However, in this study the test subjects are just imitating a speed skating motion on a force plate, thus a great uncertainty will be related to whether the same will be the case on ice. However, to assume that a speed skater has a symmetrical movement in the first place, may also be wrong. A speed skater will only train and compete on straights and left turns which could make a difference in both strength and flexibility of the legs, this may cause an asymmetrical movement over time.

That being said, general similarities can be found in the drag cycle for the two test subjects. Both test subjects has a drop in drag right before each push. This is the point where the frontal area will be the smallest. The test subject is preparing for pushing, hence reducing the knee angle and putting one leg behind the other. The drag will have an small increase through the sliding phase, followed by a compression when landing (hence a small decrease). The test subject is then adjusting and stretching out (around 0.2 and 0.7), where the frontal area and drag will be at a maximum. At 0.3 and 0.8 the test subjects is balancing on one leg, and a small reduction of the knee angle of the supporting leg and a big reduction of the knee angle of the other leg induce a decrease in frontal area, hence the decrease in drag area. The increase in drag from 0.3-0.4 and 0.8-0.9 will then most likely come from moving the legs together. The frontal area will remain constant and the increase in drag will be related to a change in the drag coefficient. This increase can be looked at in the same way as for the side-by-side configuration, where bluff bodies are moving closer together. The last decrease will then again come from the lower posture right before the push.

Time series for TS1 drafting behind TS2, both in sync and unsync, are shown in Fig. 10 (a) and TS1 leading in front of TS2 in Fig. 10 (b). The drag cycle starts when TS1 is pushing from right to left (black speed skater in Fig. 10) thus, TS2 is then pushing from left to right (grey speed skater in Fig. 10) The time series corresponds to the black and dark grey bar at -1.5T and 1.5T in Fig. 8.

Whereas the drag cycle of TS1 drafting in sync corresponds well with the individual measurement for TS1, only with a lower magnitude of the forces acting on TS1, the unsync measurement needs more explanation. Looking at Fig. 10 (a), through the first sliding part (0-0.1) the drag in the unsync motion is in the same range as the sync. Only a small increase is observed, which could be explained by the fact that TS1 never are perfectly in sync with TS2. From 0.1 to 0.4, and 0.75 to 1, TS1 is experiencing higher drag being in unsync, this may be because TS1 both are exposed to the free stream wind and the wind accelerated around TS2. Right before and right after the push with the left foot (0.4-0.5 and 0.65-0.75) two regions occur with a slightly lower drag for the unsync motion. By looking at the individual drag cycle (0.9-1 and 0.1-0.2 in Fig. 9 (a)), these are the regions where the individual differences are the biggest and this may affect the results. The two test subjects also uses different time on the sliding phase and a phase shift could then occur if TS1 tries to compensate for the individual differences between the two. The difference in the push from 0.5-0.6 can then be explained by a combination of the same phase shift together with the big drag TS2 has when pushing from right to left (0-0.1 for TS2 in Fig. 9 (a)).

All together this supports the earlier hypothesis that the drafting speed skater is exposed to the free stream wind and accelerated wind around the leading speed skater in an unsync motion. Individual differences in technique from the leading speed skater can also affect the drafting one. The synchronized motion for TS1 leading 1.5T in front of TS2 corresponds well with both the individual measurements and the synchronized motion of TS1 drafting, with an average magnitude between the two measurements.

The tendencies of the unsync in Fig. 10 (b) motion can be compared with Fig. 10 (a). For the first part of the cycle (0-0.25) and the last part (0.65-1) the drag is slightly higher or in the same range as for the sync. This will be expected as leading test subject not is influenced in the same way by drafting as it is the other way around. The part between 0.25 - 0.65 is where the biggest individual differences is in the movement of the two test subjects. The differences for the leading test subject is smaller than in Fig. 10 (a), but the tendencies are the same. The slightly higher drag for the push from left to right at 0.5-0.6 compared to the other push phase is the same tendency as observed when TS1 was drafting and may be explained in the same way. The effect of the movement of TS2 will be of a smaller magnitude as TS1 is leading.

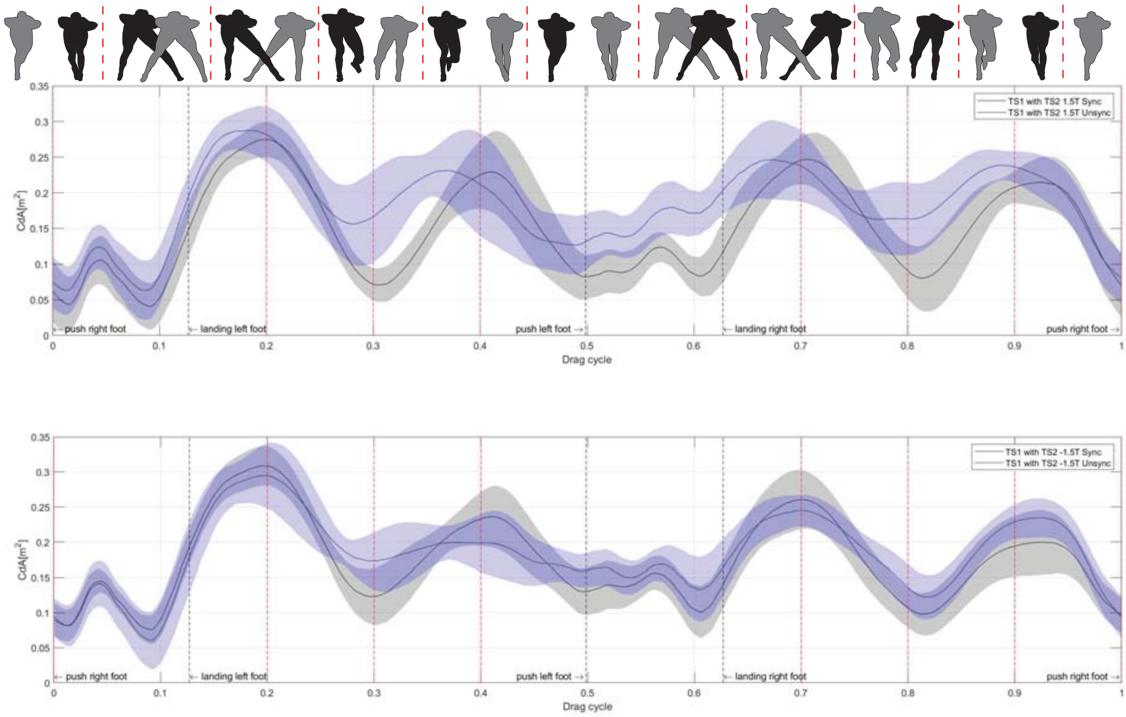
As shown by the static measurements, the biggest gain for both speed skaters in a team pursuit is found when they are closely spaced in a synchronized motion. The leading and drafting speed skater can have a drag reduction of about 8.5% and 25.7% respectively whereas the gain drops to 3.2% and 3.3% respectively for an unsync motion. Thus, strong aerodynamic interaction between the two speed skaters has been observed. Another interesting observation is that individual differences between TS1 and TS2 can be seen in the drag measurement of TS1 when being in near proximity of each other. The drafting effect also appears to be effective at longer separation distances for the dynamic than the static measurements. The leading test subject has a positive effect of the drafting even at 3T and the drafting had a clear positive effect of over 15% even for the longest distance, 4.5T. Measuring a dynamic time series and defining how the drag change through the motion has also helped detecting small differences in technique. These differences has also been shown to influence the drag of the other speed skater.

IV. Conclusion

In this study, investigations of the aerodynamic interaction between two speed skaters in a team pursuit has been performed. Both the drag of the leading and drafting speed skater was investigated in different static postures and dynamic motions and for various separation distances. A strong interaction between the test subjects was shown when being in near proximity. The aerodynamic interaction was shown to be stronger for the drafting speed skater and variables like posture, size, technique and distance influence the interaction between the two speed skaters.

In static postures, a drag reduction was observed for all distances and configurations of postures for the drafting test subject. A maximum drag reduction of 39% and 5.6% for the drafting and leading speed skater respectively was measured at the shortest distance was shown. An increase in drag was seen for all side-by-side measurements. The biggest increase was observed to be 25.7% at the shortest distance. A clear aerodynamic interaction between the test subjects and their postures was seen for all arrangements.

The dynamic measurements showed an even stronger aerodynamic interaction between the test subjects. The leading



(a)

(b)

Fig. 10 Time series of the drag cycle of a dynamic motion for TS1 drafting (a) and leading (b). (a) shows TS1 drafting 1.5T behind TS2 and (b) TS1 leading 1.5T in front of TS2 (TS2 located at -1.5T) in a sync and unsync motion. The shaded error bands indicates the standard deviation with n=14. The movement of the unsync motion through the drag cycle is illustrated in (a) where the black speed skater represents TS1 starting with the push with the right foot and the grey speed skater represents TS2. The black dashed lines indicates the push and landing for TS1 and the red dashed lines the corresponding points with the illustration of the unsync motion. The sync motion will be the same as illustrated in Fig. 9. The drag cycles in (a) and (b) corresponds to the black and dark grey bar at 1.5T and -1.5T in Fig. 8 (a) and (b) respectively

test subject experienced a drag reduction even with the drafting test subject 3T ($\sim$ 1.9 m) behind, and the drafting test subject had a drag reduction of 15% even at 4.5T ($\sim$ 2.8 m) when being in sync with the leading test subject. The biggest drag reduction was observed at the shortest distance with a reduction of about 8.5% for the leading test subject and 25.7% for the drafting test subject. The results from this study emphasize the importance of being in sync by showing that the gain for the shortest distance between the speed skaters dropped to 3.2% and 3.3% for the leading and drafting test subject respectively by being in an unsync motion. Indications are found that individual differences in technique also influence the drag of the other test subjects. The behaviour of drafting at different distances is consistent with literature on other bluff bodies.

The big variation in aerodynamic interaction between two speed skaters for various posture, size and technique emphasize the importance for optimization of speed skating teams. The best strategy for speed skaters in a team pursuit will be to stay as close as possible to each other, as long as they are in a synchronized motion. It will also be important to have a sufficient lateral separation when overtaking each other. The aerodynamic interaction between the speed skaters is biggest when being in near proximity. Different body postures, distances, size of the other speed skater and technique affect the drag of the other speed skater for almost all measurements, hence a clear aerodynamic interaction between speed skaters in an team pursuit has been shown.

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