Low Aerodynamic Drag Suit for Cycling
Design and Testing

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Abstract: The focus on garment aerodynamics is increasing in high velocity sports where aerodynamics is crucial such as cycling, speed skating and alpine skiing. Recently published research show that a low drag suit manipulating the flow around the body can considerably enhance an athlete's performance. This project seeks to improve the Norwegian sportswear manufacturer Trimtex Sport AS' pro cycling kit using the best currently available textiles. Changes from the original design are made with the intention of optimizing fabric zones and seam placement. Drag measurements on cylinder models, cyclists and full-scale mannequins of the upper and lower body were conducted in the wind tunnel. The reduction in aerodynamic drag was significant on cylinders, and final power savings of 8 watts due to drag reductions was obtained on the jersey and 5 watts on the bib shorts for a cyclist racing at 50 km/h.

1 INTRODUCTION

Road cycling is one of the sports with high velocities and infinitesimal time gaps where marginal gains are crucial. Aerodynamic drag accounts for as much as 90% of the total resistance to be overcome when cycling at a normal race pace, 70% of which is created by the rider (Underwood and Jermy, 2011). Aerodynamic drag can be expressed as

$$F_D = 0.5 c_D \rho U^2 A \tag{1}$$

where C_D denotes the drag coefficient, ρ the air density, U the air flow velocity and A the projected frontal area (White, 2006). Besides optimizing the rider's position and suit fit to reduce the frontal area, it is possible to reduce the total drag by improving the surface texture of the rider's clothing and thus achieve a lower drag coefficient (Underwood, 2012; Chowdhury et al., 2010).

Research on sport garment aerodynamics has been progressing since the Nike Swift Spin project based on the work by Brownlie in the early 2000. Over 200 fabrics were tested and their final suit offered a 3,9% reduction in F_D compared with the typical 2001 suits worn by competitors (Brownlie, 2009). Some of the most renowned brands of bike clothing have recently been improving their time trial suits by full-scale testing of suits with different textiles in wind tunnels (Baker, 2010; Bioracer, 2014). Even though the results have been good, the typical textiles used in regular road race cycling suits on all levels are still smooth and seemingly made only with focus on fitting and breathability. However, a low drag cycling kit can give the necessary advantage in a road race by reducing the effort needed at a given velocity. The 1989 Tour de France was won by Greg LeMond by a winning margin of 8 seconds and by Alberto Contador in 2007 by 23 seconds illustrating the minuscule margins and the need for perfectionism in the cycling sport.

It is known that the drag coefficient of bluff bodies suddenly drops at a certain critical velocity during transition from laminar to turbulence flow in the boundary layers (Zdravkovich, 1990) commonly called the drag crisis. The Reynolds number at which the drop occurs, the magnitude of the drop and the subsequent rate of increase in C_D is highly dependent on the surface roughness (Achenbach, 1971). A rough surface induces an early transition but at the same time decreases the drop and increases the post-critical drag coefficient (Auteuil et al., 2010). Hence, the flow around a bluff body can be manipulated by mixing various patches of textile with different surface morphology to prevent or delay flow separation at strategic places.

The aim of this work is to find the material and

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design that could improve the overall aerodynamic performance of the pro cycling suit produced by Trimtex Sport AS using facilities in the wind tunnel laboratory at the Department of Energy and Process engineering at the Norwegian University of Science and Technology (NTNU). In the preliminary tests, cylinders are covered with 27 different fabrics and tested in a wind tunnel to separately assess the flow around each body part. This method has been used in several previous studies with good results (Bardal and Reid, 2012: Chowdhury et al., 2010, Underwood and Jermy, 2011; Oggiano et al., 2013). The most promising fabrics were also tested on tandem cylinders and with a steel grid creating intense turbulent flow in the tunnel. Two different cycling kits with the original design but patched with the new materials and one jersey with an alternative design have been tested on both cyclists and full-size upper and lower body mannequins.

1.1 Rules and Regulations

According to the UCI (Union Cycliste Internationale) regulations for clothing material, only “plain textile material” with no other purpose than that of clothing can be used. Textile is here defined as “a material made up of yarns and fibres which has an open mesh “fabric” structure”. No seams should be present on a suit that does not hold two pieces of fabric together and coating other than logos and labels are not allowed .The apparel should serve the unique purpose of clothing and has to “conform to the curve of the body in any case” without any “non-essential parts” to improve aerodynamic resistance (UCI, 2012). All materials tested in this project comply with the UCI regulations.

2 METHODS

2.1 Fabric Testing

2.1.1 Experimental Setup

The measurements were conducted in a small scale wind tunnel at NTNU with a cross section of 0,55x1,0 meters and a maximum wind speed of 28 m/s. To measure the wind speed, a pitot tube was placed 2,70 m in front of the cylinder. The temperature was monitored by a thermocouple type K (chromel-alumel) and its value used to calculate density and dynamic viscosity of the airflow. The forces on the cylinder were measured by an AMTI BP400600HF force plate that consists of strain gauges in three directions. In this experiment, only the drag- or y-direction force was used.

When riding aggressively, the shoulder and upper arm are positioned perpendicular to the flow. Riding slightly more upright, the angle increases to 10 or 15 degrees. The critical Reynolds number remains constant with various angles of attack while a rough surface reduces cylinder drag for angles up to 25 degrees (Oggiano et al., 2013; Chowdhury, 2012). Testing was therefore conducted on cylinders positioned with the long axis perpendicular to the flow. The fabrics for the torso was also tested on a vertical cylinder as the differences in friction drag can be foreseen from a vertical cylinder measurement (Bardal and Reid, 2012).

Two circular cylinders with diameters of 11 and 16 cm were used. The smallest cylinder was 40 cm long with a gap of 9,7 cm above and 5,0 cm below while the largest cylinder was 47 cm long with 4,3 cm above and 3,4 cm below. The smooth fabrics for the torso were tested on the 16 cm diameter cylinder because of the lower velocity drag crisis on this cylinder, while the rougher fabrics were tested on the 11 cm diameter cylinder.

The steel grid used to create turbulence had circular bars 10 mm in diameter and cells of size 40x40 mm that covered the whole cross section of the tunnel. It was placed 0,35 m behind the pitot tube and 2,35 m in front of the cylinder. The flow produced by the grid was probably of too high turbulence intensity compared with normal outdoor conditions although it was not measured. Nevertheless, the results indicate how disturbances in the flow affect the drag of various surface structures.

For the measurements with tandem cylinders, the 11 cm diameter cylinder was placed with a separation distance of 17 and 23 cm in front of the larger cylinder of 16 cm diameter. Drag was measured on the second cylinder only. This configuration is a simplification of one limb in front of another such as an arm in front of a thigh.

2.1.2 Textiles

The fabrics were fitted with 25% stretch. According to Oggiano (Oggiano et al., 2013), there is a weak linear relation between the critical velocity and the stretching of the fabric, but he concludes none the less that it does not seem to affect the flow transition. Bardal found that stretch is of no practical significance in the design of alpine skiing suits (Bardal and Reid, 2012). The textiles tested in this project are significantly thinner than textiles used in an alpine suit, so it may all the same be a minor factor. All textiles were tested with the seam centred on the leeward side to minimize its influence. Sublimation printing was done prior to testing since the print makes the surface smoother and thereby changes the aerodynamic properties (Oggiano et al., 2013).

Figure 1: Upper and lower body mannequins.

2.2 Full Scale Testing

2.2.1 Experimental Setup

Testing of the cycling kits on the mannequin models and cyclist were conducted in the large wind tunnel at NTNU. It is equipped with a 220KW fan engine, has a maximum speed of 30 m/s and the test section measures 2,7x1,8x12,5 meters. A pitot tube and a thermocouple type K was used to monitor the wind speed and temperature respectively. The drag was measured with a Schenck six component force balance where only the axis of the drag direction was used. The drag forces presented are normalized to 20 degrees celsius.

2.2.2 Mannequin Models

Testing on both mannequin models was conducted at five velocities ranging from 35 to 72,5 km/h or 9,7 to 20,1 m/s. The mannequin used for testing the jersey was a full-scale upper body including head and upper arms belonging to a model of height 170 cm and weight 70 kg. Its position was adjusted to imitate that of a cyclist in the drop bars and the forearms removed to reduce the amount of uncertainty. The lower body mannequin had an inner leg length of 90 cm with a mid-thigh circumference of 58 cm. Only one leg was used with the other cut at 16 cm. A 1,0 cm thick plate fixed the loose part of the shorts. Photographs of the mannequins are presented in Figure 1.

Figure 2: Cyclist in an upright dropped position.

In addition to drag measurements of the jerseys, measurements were conducted on all combinations of jerseys and sleeves to investigate the contributions from sleeves separately. To examine the importance of sleeve length, drag measurements were conducted with the mannequin wearing nothing but the different sleeves in both the original length (17 cm) and elbow length (30.5 cm). Note that when the original length is used on the loose sleeves, they do not have the smooth 4 cm bi-elastic band at the ends. The loose sleeves therefore have the sleeve material 4 cm longer than the jersey sleeves.

2.2.3 Cyclist

A regular road bike was placed on a roller so that the tires were not touching the wind tunnel floor. The front wheel was kept stationary and supported by a custom-made wheel stand. The back wheel was only spinning in the dynamic tests. The cyclist was positioned comfortably in the drop bars and live video acquired from a side-mounted camera was projected on the floor in front of the rider. The video was showing the position superimposed with an outline of the initial position in order to keep it as consistent as possible.

Mean values of the drag force were calculated from three times 30 seconds dynamic pedalling on a cadence of 90 RPM and three times 30 seconds static with left leg at 0 degrees (Figure 2). This was done alternately a total of three times at each of the velocities, 35, 50 and 65 km/h (9,7, 13,9 and 18,1 m/s).

Table 1: Mean velocity distribution from an assortment of men's elite road races.

	26-35kmh (7-10ms)	36-45kmh (10-13ms)	46+kmh (13+ms)
National	0.267	0.378	0.356
International	0.241	0.408	0.351
Total average	*0.254*	*0.393*	*0.354*

2.3 Speed and Force Calculations

Based on a total of eleven men's elite road races, the mean velocity distribution for three domains was found. Not counting velocities less than 25 km/h, the percentage of total time in each domain is listed in Table 1. The velocity profile was used to calculate the weighted mean drag of the materials.

Assuming similar conditions for an individual time trial (ITT) as in a solo breakaway or in front of the peloton, ITT races are used to illustrate time savings of the various apparel. Theoretical time savings were calculated using Bassett's empirical model (Bassett, 1999) from his study of hour records from 1967 to 1996. The dropped position on the road is identical to that of Eddy Merckx in 1972, but modern bicycles and cycling suits have lower drag than those used in Bassett's study. The power P needed to overcome air and rolling resistance on a cycling track is:

$$P = 0.00953MV + 0.00775V^2 + 0.007551AV^3 \quad (2)$$

M is the total weight of the cyclist and the bike in kilos, A is the frontal area and V is the velocity.

The time savings are illustrated on two constructed persons. Person 1 has a weight of 70kg, person 2 60 kg and the bikes 7 kg. With respective heights of 1.83 and 1.70m correspondingly, the frontal areas of person 1 and 2 are 0.337 and 0.308m^2 using Bassett's formula for frontal area (Bassett, 1999).

3 RESULTS

3.1 Jersey

3.1.1 Fabric Testing

The results from the cylinder tests of the original and chosen jersey materials are shown in figure 3 plotted against the velocity normalized to common racing conditions of 20 degrees and 1 atm. Table 2 shows the material used on the various jersey patches.

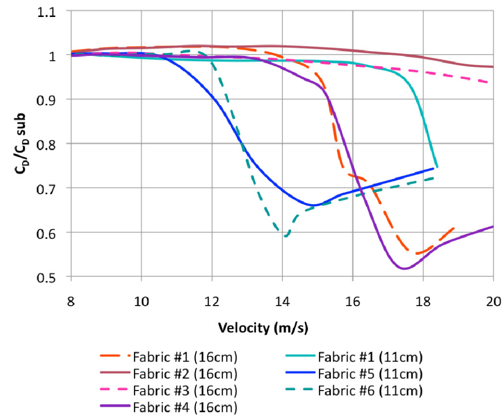

Figure 3: Jersey material on 11 and 16 cm cylinders. The C_D values are normalised with the sub-critical C_D.

Table 2: Material used in the different fabric zones.

	Jersey A	Jersey B	Jersey C
Front	#2	#3	#3
Back	#1	#3	#3
Upper Back	#2	#5	#3
Sides	#1	#5	#4
Sleeves	#3	#5	#6

Whereas the original jersey (A) has relatively smooth materials on all panels, the differences in surface roughness on the new jerseys are more pronounced. Since the flow pattern around a cyclist throughout a stroke is asymmetrical with an "S" forming on his back (Crouch et al., 2012), the fabric on the back should be homogenous and as smooth as possible such as fabric #3. This thin and breathable fabric is used on the front and back on jerseys B and C. Fabric #5 has an asymmetrical mesh-like macrostructure similar to prism formed dimples with microstructure in the dimples and no fuzziness while fabric #6 has a traditionally dimpled structure with a smooth surface. With a minimum drag coefficient of 0.47 at Reynolds number 107 000, fabric #5 seems equally or better suited to enhance transition on the prioritized velocities than most textiles tested by others (Chowdhury et al., 2010; Brownlie et al., 2009; Bardal and Reid, 2012). The weighted mean of the drag coefficients of fabric #5 was 0.686 while the mean for #6 was as low as 0.652 due to its lower post-critical drag. The latter could be owing to its smooth and dimpled surface structure since this can reduce post-critical drag with respect to other kinds of structure (Zdravkovich, 1990; Bearman and Harvey, 1993; Oggiano et al., 2013). Fabric #5 is used on the sleeves, sides and top of the back of jersey B aiming to enhance transition to turbulence in the boundary layer at the patches most exposed to the free stream. Jersey C is a compromise between jersey A and B with fabric #6 on the sleeves and the sheer and semi-smooth fabric #4 on the sides.

The resulting drag profiles using the steel grid show, as expected, that a less rough surface structure is needed to enhance transition at the same velocities when the flow is turbulent. The fact that smoother materials were more influenced by the turbulence emphasizes the importance of a smooth surface where friction drag is dominant such as on the back of a cyclist. These effects are also observed for the tested bib fabrics. The intense turbulence amplified the post-critical differences in drag for fabric #5 and #6 from 3,5 to 5%, possibly indicating an accentuated effect of dimpled surfaces in turbulent flow. The smoother surface of fabric #6 is most likely an important factor as well although it did not alter the critical velocity with respect to fabric #5.

3.1.2 Full Scale Testing

The jerseys were tested on the mannequin against the original Trimtex Pro cycling jersey. Whereas the drag coefficients of jersey B and C are constant and nearly identical, the original jersey A clearly has a higher drag at low speeds as seen in figure 4. The difference decreases with increasing velocity and stabilizes at 15 m/s. The improvement in drag force is 25-35 grams at all velocities with a standard deviation of 8 grams or 0.37%. Table 3 shows how the performance is improved by the reduced drag. The fact that the drag on jersey B and C were nearly identical can indicate that the sleeves are the largest contributor, and that the rougher panels on jersey B do not have a significant impact on the flow.

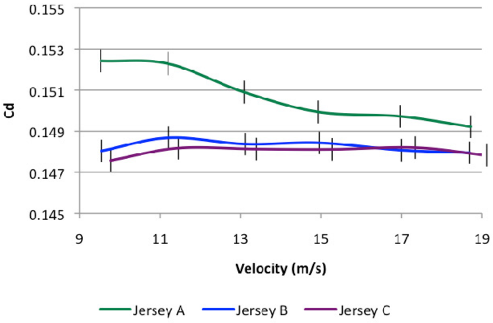

Figure 4: Jerseys tested on mannequin with error bars.

To study how the drag is affected by sleeve roughness alone, loose sleeves of the respective qualities where placed on top of the original jersey. Figure 5 shows that the drag is nearly equal for all sleeves up to 14 m/s where the rougher sleeves have similar and increasingly lower drag at higher velocities. At 19 m/s the difference is 26 grams for #5 and 43 grams for #6 compared with sleeve #3. Lengthening the loose sleeves to the elbows, the overall drag is lowered with the ratios kept constant so that the difference between the sleeves doubles to 54 grams for #5 and 87 grams for #6. These differences are expected based on the cylinder measurements and are assumed to be a result of the dimpled surface structure of fabric #6. Note that the drag obtained with loose sleeves cannot be compared directly to the drag of the full jerseys since the loose sleeves are tucking in some extra fabric in the armpits.

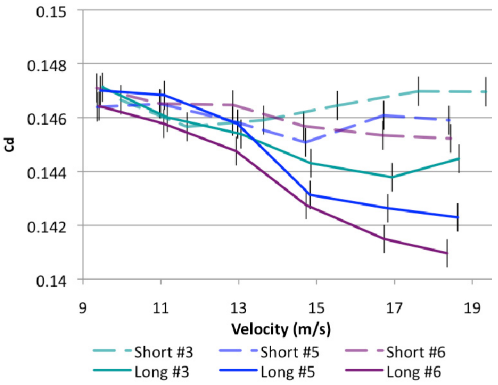

Figure 5: Effects of sleeve length and roughness from the mannequin tests with error bars showing the standard deviation.

Both figure 4 and 5 indicate a critical velocity at 13-15 m/s on jersey A that corresponds to Reynolds number 85 000 for the arms of the mannequin. The arm had a circumference of 28 cm, so these results are in good correspondence with the critical velocity of fabric #5 and #6 at Reynolds number 85 000 on the 11 cm cylinder. The transitions seem to have taken place at even lower velocities for jersey B and C due to the rougher patches. However, the effect of a rough sleeve fabric will in all probability be less on a cyclist than on the mannequin due to increased disturbance in the flow.

A fourth jersey (D) was designed based on the mannequin tests. Its materials are similar to those of jersey C but the sleeves are extended by 2 cm and the elastic grip has a slightly structured surface. The elastics on both sleeves and pockets are tightened to minimise flapping. The side panel is wing shaped so that the seam runs in the stream-wise direction to the back extending the front patch along the lower sides of the jersey.

Figure 6 shows the drag difference of jersey B, C and D with respect to the original jersey (A) when tested on the cyclist. All jerseys have similar properties at 9,7 m/s, but the rougher jerseys have a clear advantage at higher velocities. Surprisingly, jersey D had higher drag than the other jerseys despite the assumed profitable changes in design. By tightening the pocket band, wrinkling perpendicular to the flow increased somewhat on the sides of the torso. This could be the main reason for the increase in drag compared with jersey C since the material in the side panels do not seem to play a critical role. As listed in table 3, the improvement of jersey C with respect to the original jersey is of 60 grams or 8.2 watts at 13,9 m/s (50 km/h).

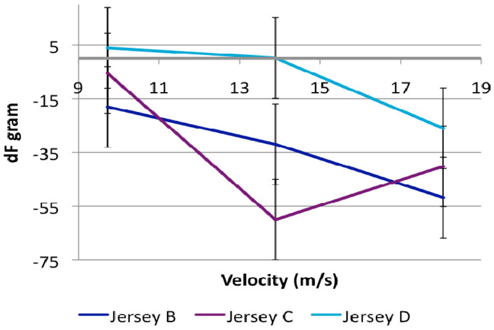

Figure 6: Dynamic testing on cyclist. Difference in drag (grams) of jersey B, C and D compared with jersey A, with error bars.

The dynamic tests show approximately 5% lower drag than the static tests, and the differences between the jerseys were smaller, probably due to the fact that leg motion will trigger flow transition (Brownlie et al., 2009). The standard deviations were 15 grams or 0.33% for the dynamic tests and 19 grams or 0.43% for the static tests.

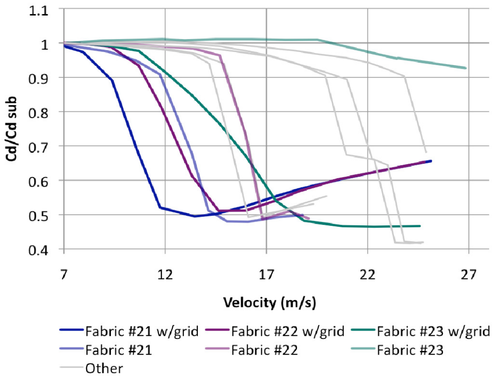

Figure 7: Bib fabric with and without grid on a 16 cm diameter cylinder. The C_D-values are normalised with sub-critical C_D.

Wearing a correctly fitted jersey is of outmost importance. The jersey in size small fitted the cyclist comfortably yet tightly with few wrinkles and would be the natural choice for a racing jersey. The medium-sized jersey was still relatively tight and well fitted, but the wrinkles on the side panels were more pronounced. This seemingly small difference in size increased the drag by 104 grams or 14 watts at 50 km/h, as shown in the last line of Table 3.

3.2 Bib Shorts

3.2.1 Fabric Testing

The flow around the thighs is the most difficult to

Table 3: Theoretical drag, power and time savings of the various jerseys and bibs at 50km/h compared with the original kit.

Mannequin			Drag difference (g)	Power difference (W)	Drag increase* (%)		Time difference 1h, 50km/h (s)	
					Person 1	Person 2	Person 1	Person 2
	Jersey	B	-30	-4.1	-1.1	-1.2	-00:14	-00:16
		C	-33	-4.5	-1.2	-1.3	-00:15	-00:17
	Bib	B	-9	-1.2	-0.3	-0.4	-00:04	-00:05
		C	-22	-3.0	-0.8	-0.9	-00:10	-00:11
Cyclist								
	Jersey	B	-32	-4.4	-1.2	-1.3	-00:15	-00:17
		C	-60	-8.2	-2.2	-2.4	-00:28	-00:31
		D	0	0	0	0	00:00	00:00
	Bib	B	-4	-0.5	-0.2	-0.2	-00:02	-00:02
		C	-35	-4.8	-1.2	-1.4	-00:16	-00:18
Sizing								
	Jersey size	M	+104	+14.2	-3.8	-4.2	+0:48	+00:53

*From 374W for person 1 and 340W for person 2 predict as the free stream flow is disturbed upstream by the front wheel, cockpit and forearms in addition to the thigh movements. As the flow regime characterizing the aerodynamics of a cyclist changes throughout the stroke cycle, materials with an asymmetrical pattern having varying properties depending on the leg position could present an interesting compromise. When in the upper part of the stroke, the air remains attached alongside the thigh and follows a downward trajectory into the wake. With the leg perpendicular to the flow, the flow separates over the hip following an upward path into the wake (Crouch et al., 2012). A striped pattern aligned with the thigh would therefore be alternately in line with the flow having the properties of a smooth fabric and perpendicular to the flow enhancing transition. Various striped patterns were tested against traditional smooth materials and fabrics with a homogenous structure.

On the 16 cm cylinder, a broadly striped material with a smooth surface (#21) had the lowest critical velocity while the original smooth fabric #23 did not undergo transition even at 25 m/s. A narrowly striped fabric (#22) with properties in between of the two extremes was chosen alongside fabric #21 for further testing against the original bib. The results are shown in Figure 7 both with and without grid in the tunnel and favour the broadly striped fabric.

With the cylinders in tandem configuration, a rough surface texture is desired at the rear cylinder regardless of the distance to and surface roughness of the cylinder in front. Nevertheless, the importance of the material on the second cylinder decreased significantly with decreasing distance between the two cylinders. The effect is similar to that of the grid produced turbulence confirming that disturbances in the flow reduce the effect of surface roughness.

3.2.2 Full Scale Testing

Bib A is the original bib with fabric #23 while fabric #21 and #22 is used on bib B and C respectively. Testing on the one-legged lower body mannequin was conducted to study the effect of three-dimensional effects due to the shape of the thigh muscles. A clear drop in the drag coefficient is seen in Figure 8 for all bibs at 15 m/s, but eventual variations in critical velocity are not pronounced. The original smooth bib had highest sub-critical drag while bib C had the lowest. The super-critical values were similar for all bibs. A fourth bib with a slightly rougher bi-elastic band was also tested, but the influence was too small to be observed. The standard deviations were 10 grams or 0,53%.

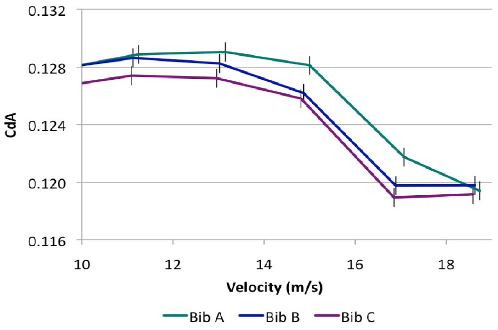

Figure 8: Bib shorts tested on mannequin with error bars.

When tested on the cyclist, the difference between bib A and B was less than the standard error on both the dynamic and static tests while bib C had the lowest drag in both cases with 35 grams or 5 watts less drag than bib A at 50 km/h. The results presented in Figure 9 indicate that bib B enhanced transition at velocities slightly lower than bib A and that the rough surface of bib C led to the highest super-critical drag. These changes in properties compared with the cylinder measurements may be explained by increased stretching of the fabrics on the mannequin and the cyclist. The surface structure of bib B became less pronounced than on the cylinder and bib C got a rougher, more homogenous surface.

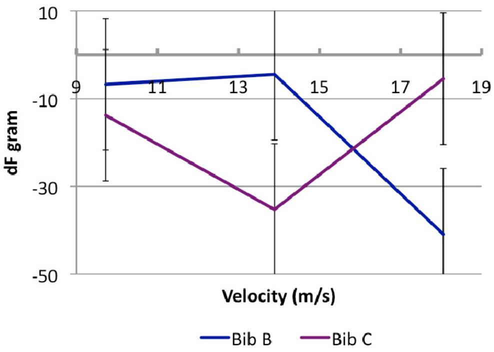

Figure 9: Dynamic testing on cyclist. Difference in drag (grams) of bib B and C compared with bib A, with error bars.

4 CONCLUSION

The cycling kit developed in this project has considerably lower drag than a traditional kit with smooth fabrics only. Rough material on the sleeves clearly improves the aerodynamic qualities of a jersey, and the results indicate that dimpled fabric having a smooth surface is favourable to other types of surface morphology. Since the gain increases with sleeve length, the sleeves should be as long as comfort and regulations allow. A structured surface is preferred on bib shorts as well. The rough materials tested in this project were the roughest currently available fabrics both complying with the UCI regulations and suitable for use in a cycling kit. It is likely that a sleeve and bib material with a more pronounced surface structure could further reduce the drag. Jersey designs with the seams to a greater extent in the stream-wise direction and distinctly striped bib material are of particular interest for future work.

The results from this project can be applied to other cycling garments. Loose sleeves normally have a smooth fabric all over but should rather have a rough surface on the part covering the upper arms. The same applies to time trial suits. Loose legs should probably be of the same material as the bib shorts above the knee, and transition could be induced on the lower leg by a rougher material (Brownlie et al., 2009) as in speed skating (Sætran and Oggiano, 2008). Aerodynamic shoe covers should likewise be roughly structured above the calf.

REFERENCES

Achenbach 1971. Influence Of Surface Roughness On The Cross-Flow Around A Circular Cylinder. *Journal Of Fluid Mechanics,* 46**,** 321-335.

Auteuil, Larose & Zan 2010. Relevance Of Similitude Parameters For Drag Reduction In Sport Aerodynamics. *8th Conference Of The International Sports Engineering Association (Isea).* Elsevier L.Td.

Baker. Dec 10. 2010 2010. Testing Velocity Speedsuit At The A2 Wind Tunnel. Available From: Http://Blog.Hincapie.Com/Post/Testing-Velocity-Speedsuit-At-The-A2-Wind-Tunnel.Aspx 2014].

Bardal & Reid 2012. Testing Of Fabric For Use In Alpine Ski Competition Suits. *Engineering Of Sport Conference 2012.* Elsevier Ltd.

Bassett 1999. Comparing Cycling World Hour Records, 1967-1996: Modelling With Empirical Data. *Medicine & Science In Sports & Exercise,* 31.

Bearman & Harvey 1993. Control Of Circular Cylinder Flow By The Use Of Dimples. *American Institute Of Aeronautics And Astronautics Journal,* 31.

Bioracer. 2014. *Bioracer Speedmaster, Medal Winning Technology* [Online]. Bioracer. Available: Http://Www.Bioracer.Com/En/News/318/Bioracer-Speedmaster-Medal-Winning-Technology [Accessed Nov 8 2014].

Brownlie, Kyle, Carbo, Demarest, Harber, Macdonald & Nordstrom 2009. Streamlining The Time Trial Apparel Of Cyclists: The Nike Swift Spin Project. *Sports Technology Journal,* 2**,** 53-60.

Chowdhury 2012. Aerodynamic Design Of Sports Garments. *In:* Colman, D. J. (Ed.) *Applied Aerodynamics.* Intech.

Chowdhury, Alam & Subic 2010. Aerodynamic Performance Evaluation Of Sports Textile. *8th Conference Of The Internationsl Sports Engineering Association (Isea).* Elsevier Ltd.

Crouch, Sheridan, Burton, Thompson & Brown 2012. A Quasi-Static Investigation Of The Effect Of Leg Position On Cyclist Aerodynamic Drag. *Procedia Engineering***,** 3-8.

Oggiano, Brownlie, Troynikov, Bardal, Sæter & Sætran 2013. A Review On Skin Suits And Sport Garment Aerodynamics: Guidelines And State Of The Art. *6th Asia-Pasific Congress On Sports Technology (Apcst).* Elsevier L.Td.

Sætran & Oggiano 2008. Skin Suit Aerodynamics In Speed Skating. *In:* H., N. (Ed.) *Sport Aerodynamics.* Cism International Centre For Mechanical Sciences.

Uci 2012. Clarification Guide Of The Uci Technical Regulation *In:* (Uci), U. C. I. (Ed.) 23.04.2014 Ed.

Underwood. 2012. *Aerodynamics Of Track Cycling.* Doctor Of Philosophy, The University Of Canterbury.

Underwood & Jermy 2011. Fabric Testing For Cycling Skinsuits. Elsevier L.Td.

White 2006. *Viscous Fluid Flow*, Mcgraw Hill.

Zdravkovich 1990. Conceptual Overview Of Laminar And Turbulent Flows Past Smooth And Rough Circular Cylinders. *Journal Of Wind Engineering And Industrial Aerodynamics,* 33**,** 53-62.