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Drag reduction and aerodynamic performances in Olympic sports

Thesis for the degree of Philosophiae Doctor

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Norwegian University of Science and Technology
Faculty of Engineering Science and Technology
Department of Energy and Process Engineering

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To the little star that silently shows me the road

Abstract

In sports where high speed is involved, races are often won by milliseconds.
Any advantage can then be important in order to reach the success. The drag acting on the athletes is often the highest force that the athletes have to fight against and, even a small reduction of drag, can create an advantage in terms of performances. However, in sports like ski jumping, the aerodynamic involved gets to be more complex, involving drag and lift force.
Wind tunnel measurements have been carried out in the last century in order to understand the physics behind phenomena linked to sport activities (for example ball aerodynamics) or in order to optimize postures and materials.
With the performances enhancement as final goal the aerodynamics behind a number of sports have been previously studied.
Posture optimization, low drag bycicles, skin suits or even the recent and famous Speedo swimming suits are only some of the achievements of the research carried out.
In the present thesis, a wide approach to the topic with particular focus on textile aerodynamics has been used.
The thesis has then be divided into two main areas:

A research Area 1 named *Textiles and their effect on the aerodynamics of athletes* and referred RA1 where the influence of textiles and clothing equipement on the drag acting against the athletes have been studied and a Research Area 2 named *Performances and Prototyping* where more practical examples of how aerodynamics can directy affect athletes performances are given and exposed.

In RA1 the topography of textiles have been studied and the surface structure properties has been linked to the aerodynamic properties with particular regards to drag reduction and turbulence tripping.
In order to simplify the case the athlete's body has been simplified as a serie of cylindrical shapes and tests have been carried out mostly on cylinders.
Effect of yaw angle, different speed, different diameter, different roughness, different material and distance between body parts have been analyzed. At the same time, test on existing suits have been carried out and a mathematical model in order to estimate performances in speed skating has been made.
In RA2 different side projects have been carried out and the results can be summarized as follow:
Effects of body weight in ski jumping has been analyzed in order to figure out if the new rules imposed by the FIS (International Ski Federation) were effective in order to reduce the increasing problem of anorexia amongst ski jumpers.
Wind tunnel measurements were carried out in order to find the aerodynamic forces acting on a ski jumper in his flight path.
The experimental data were then implemented into a mathematical model which is able

to simulate the in-run and the flight path.
In cycling, the attention was focused on the posture assumed by the cyclists with the goal of reducing the drag while keeping a good biomechanical efficiency. The rules imposed by UCI (International Cycling Union) set the boundaries. However, a impressively good result has been obtained focusing the attention on each athlete and finding a subjective optimum posture for each of the athletes tested.
A low drag ski boot have been designed with a airfoiled shape which permitted to obtain an impressive drag reduction on the total drag acting on a downhill skier.
Speed skating suits have been tested in order to quantify the influence of different model suits on skating performances.
The suit used by torwegian Olympic team of ski-cross has been designed using the knowledge acquired and presented in RA1. An impressive drag reduction has been obtained and it helped two norwegian athletes to win a silver and a bronze medal at the Winter Olympic Games in Vancouver 2010.

As previously mentioned, the research areas are:

- Research Area 1 - Textiles and their effect on the aerodynamics of athletes
- Research Area 2 - Performances and prototyping

The main contributions are:

P1: Reducing the Athlete's aerodynamics

P2: Experimental analysis on parameters affecting drag force on athletes

P3: Aerodynamic and comfort properties of single jersey textiles for high speed sports

P4: Aerodynamic behavior of single sport jersey fabrics with different roughness and cover factors

P5: Effect of different skin suits on speed skating performances

P6: Aerodynamic optimization and energy saving of cycling postures for international elite level cyclists

P7: Effects of body weight on Ski Jumping performances under the new FIS rules

P8: Airfolied design for alpine skiers boots

P9: Aerodynamic and Comfort Characteristics of A Double Layer Knitted Fabric Assembly for High Speed Winter Sports

P10: A Low Drag Suit For Ski-Cross Competitions

Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) for partial fulfilment of the requirements for the degree of philosophiae doctor.

This doctoral work has been performed at the Department of energy and processing, Trondheim, with Lars Sætran as main supervisor and with co-supervisors Sveinung Løset.

The thesis was financed by the Norwegian Olympic committee with the purpose of helping the National teams

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I would like to thank everybody who helped me through these four years. First of all my girlfriend Mette who is my muse, my shoulder and the one who helps me always in good and bad moments.

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I would like to thank Lars who guided me in the experiments, always believing in me.

A special thank to "THE OFFICE". Yes, "THE OFFICE". There are no other definitions for it. Gursu, Fabio, Eze and Leo made my stay at NTNU pleasant and happy. Thanks guys, i will never forget you!

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Thanks also to the Norwegian Olympic committee which founded the project and especially to Arne Lier, always helpful and with interesting suggestions.

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Thanks also to the RMIT staff (Firoz, Alex, Francesco, Angelo, Inna, Olga) which helped me during my stay in Australia.

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Contents

Abstract i

Preface v

Acknowledgements vii

Contents xiii

List of Figures 1

1 Introduction 3
- 1.1 Progress and devlopent in sport technology: a continuum. 7
- 1.2 Research Context 8
- 1.3 Aerodynamics and drag:when are they relevant? 9
  - 1.3.1 High speed sports 11
  - 1.3.2 Textiles 12
- 1.4 Thesis structure 14
  - 1.4.1 List of papers 14

2 State of the Art 23
- 2.1 General theory about flow around cyliders 23
  - 2.1.1 General theory about drag resistance on bluff bodies with particular attention to cylinders 23
  - 2.1.2 Concept of drag resistance 23
  - 2.1.3 Transition from laminar to turbulent flow 24
  - 2.1.4 Effects of transition on a cylinder 24
- 2.2 Correlation between drag and roughness on cylinders 25
- 2.3 Drag and textiles 26
- 2.4 Aerodynamics and sports 27
  - 2.4.1 Speed skating 27
  - 2.4.2 General 27
  - 2.4.3 Cycling 30
  - 2.4.4 Ski jumping 31

3 Context and Research Design 33
- 3.1 Textiles area 33
  - 3.1.1 c_D-Re curves for cylinders 33
  - 3.1.2 Drag reduction by using textiles 33
- 3.2 Surface analysis and roughness models used 34
- 3.3 Research Process 34

3.4 Performances and prototyping area 37

4 Results 39
4.1 Study Area 1 - Textiles 39
4.1.1 Commercial Textiles (P1 and P2) 39
4.1.2 Knitted textiles (P3, P4 and P9) 42
4.2 Study Area 2 - Performances and Prototyping 46
4.2.1 Suits prototyping and testing 46
4.2.2 Ski jumping and BMI 47
4.2.3 Cycling and drag reduction 47

5 Conclusions 49

Glossary 49

6 P1 51
6.1 Introduction 51
6.2 Effect of transition and separation 53
6.3 Experimental setup 54
6.3.1 Wind tunnel 54
6.3.2 Cylinder position in the wind tunnel 54
6.3.3 Six components balance 54
6.3.4 Textiles 56
6.4 Results 57
6.4.1 c_D-Re curves 57
6.4.2 Roughness coefficient correlation 58
6.5 Conclusions 60
6.6 References 60

7 P2 61
7.1 Introduction 61
7.2 Experimental apparatus and method 62
7.2.1 Wind tunnel 62
7.2.2 Textiles 63
7.3 Results and discussion 63
7.3.1 Flow parameter 63
7.3.2 Geometrical parameters 66
7.4 Conclusions 69
7.5 References 69

8 P3 71
8.1 Introduction 72
8.2 Experimental 73

8.2.1 Fabric preparation 73
8.2.2 Instruments used 73
8.2.3 Roughness model 74
8.3 Principle of test methods 75
8.3.1 Roughness method 75
8.3.2 Aerodynamic performances of fabric 75
8.3.3 Liquid moisture management properties of fabrics 77
8.4 Conclusions 78
8.5 References 79

9 P4 **81**
9.1 Introduction 81
9.2 Experimental Methods 84
9.2.1 Knitting and finishing of samples 84
9.3 Results and discussion 90
9.3.1 Fabric characterisation 90
9.3.2 Aerodynamic performance 93
9.4 Conclusions 99
9.5 References 100

10 P5 **103**
10.1 Introduction 103
10.1.1 Forces acting on a skater 104
10.1.2 Speed 106
10.2 The power balance model 106
10.3 Methods 107
10.3.1 Suit Test 107
10.4 Discussion and conclusions 110
10.5 References 110

11 P6 **113**
11.1 Introduction 114
11.2 Methods 116
11.2.1 Subjects 116
11.2.2 Wind Tunnel 116
11.2.3 Aerodynamic test 116
11.2.4 Physiological methods 116
11.3 Results and discussion 117
11.4 conclusions 118
11.5 References 119

12 P7 **121**
12.1 Introduction 122

12.1.1 Forces acting on a ski jumper 123
12.2 Experimental Setup 124
12.3 Numerical simulation of the in-run 124
12.4 Experimental investigation on the aerodynamic forces 125
12.4.1 Ski and mannequin position in the wind tunnel 125
12.4.2 The flight path 126
12.5 Results 126
12.6 Conclusions 129
12.7 References 129

13 P8 131
13.1 Introduction 131
13.1.1 Introduction 131
13.1.2 Forces acting on a downhill skier 132
13.2 Experimental Setup 133
13.2.1 Wind tunnel 133
13.2.2 Balance 133
13.2.3 Different design tested 133
13.3 Results 134
13.3.1 Normal boots 134
13.3.2 Short spoiler (2-a and 2-b) 134
13.3.3 Long Spoiler (3) 135
13.3.4 Airfoiled shape (4) 135
13.4 Conclusions 136
13.5 Acknowledgments 137
13.6 References 137

14 P9 139
14.1 Introduction 140
14.2 Experimental 142
14.2.1 Structure of instruments used and principle of the test methods . . 142
14.3 Methods 144
14.3.1 Surface analysis of double layer knitted fabric assemblies by using optical image technique 144
14.3.2 Aerodynamic performances of double layer knitted fabric assemblies 144
14.3.3 Moisture management properties and Cover Factor relationship of double layer knitted fabric assemblies 146
14.4 Conclusion 147
14.5 References 147

15 P10 149

15.1 Introduction 150
15.2 Methods 151
    15.2.1 Wind Tunnel 151
    15.2.2 Textiles 152
    15.2.3 Preliminary test: cylinder tests 152
    15.2.4 Suit design 154
15.3 Results 155
15.4 Acknowledgements 156
15.5 References 156

Bibliography **159**

List of Figures

1.1 Evolution of ski jumping style. (a) Wilbert Rasmussen 1952 (b) Parallel sky style 1978 (c) The V-Style (Jan Boklöv) 1986 6
1.2 Evolution of skating suits (a) Jaap Eden 1920 (b) Richard Terrance (1940) (c) Knut Johanssen (1960) (d) Shani Davis (2006) 7
1.3 Influence of drag in cycling 11
1.4 Average speeds in different sports 11
1.5 Average speed during world records in speed skating (a), running (b) and track cycling (c) 12
1.6 Experiments on textiles 13
1.7 Thesis structure 14

3.1 NTNU Wind tunnel 35
3.2 RMIT wind tunnel 36

4.1 Correlation between r and Re_{TRANS} 40
4.2 $c_D - Speed$ curve for a 0° yaw angle cylinder 40
4.3 $c_D - Speed$ curve for a 45° yaw angle cylinder 41
4.4 The corresponding segmented image, where the black areas correspond to the openings. The white lines within the black areas correspond to the feret diameters 43
4.5 Correlation between feret diameter and CF 44
4.6 Form factor and CF 45
4.7 Correlation between area and CF 45
4.8 Correlation between area and CF 46

6.1 Variation of c_D with Reynolds number for smooth and rough sphere and golf ball 52
6.2 Flow around cylinder 53
6.3 Wind tunnel 54
6.4 Cylinder in the wind tunnel 55
6.5 The five different textiles used 55
6.6 Roughness parameters of the different textiles used 56
6.7 11cm cylinder 57
6.8 20cm cylinder 58
6.9 31cm cylinder 59
6.10 Correlation between r and Re_{trans}. 59

7.1 The three textiles used and relative k factor values. S is the smooth cylinder. Three different coolurs have been associated to each textile: Red, Black and Grey while the smooth cylinder is orange. 63

7.2 Typical c_D-speed curve for a cylinder 64
7.3 Yaw Angle model 64
7.4 In this figure the textile with the lowest drag is marked by a color. 64
7.5 Correlation between V_{TRANS} and Yaw angle α 65
7.6 Correlation between c_{DMIN} and Yaw angle α 65
7.7 Influence of cylinder diameter on V_{TRANS} 66
7.8 Influence of cylinder diameter on c_{DMIN} 66
7.9 In this figure the textile with the lowest drag is marked by a color. 67
7.10 Side by side test model. Top view 67
7.11 In this figure the textile with the lowest drag is marked by a color. 67
7.12 Influence of D/Diam on c_{DMIN} 68
7.13 Influence of D/Diam on V_{TRANS} 68

8.1 Table 1 74
8.2 (a) - Roughness parameters considered in the roughness model (b) - Leg model 75
8.3 Correlation between CF and roughness coefficient k_{TEX} 75
8.4 Influence of textiles on c_d-Speed curve:Position 1 76
8.5 Influence of textiles on c_d-Speed curve:Position 2 76
8.6 Effect of different CF on V_{TRANS} 77
8.7 Effect of different CF on c_{DMIN} 77
8.8 Correlation between CF and WTt (top surface) and WTb (bottom surface) 78
8.9 Correlation between CF and ARt (top surface) and ARb (bottom surface) 78

9.1 Target stitch length (mm) and cover factor values for fabrics prepared in this study 85
9.2 Summary of finishing procedures for fabrics prepared in this study 86
9.3 Physical properties of finished fabric samples 86
9.4 Technical face (left) and technical back (right) of a single jersey knitted fabric 87
9.5 Technical face of a single jersey knitted fabric 87
9.6 2D simplification of excrescence characterisation. (a) Technical front geometry, (b) technical back geometry, (c) 2D simplification measurement point 89
9.7 Leg (a) and cylinder (b) models 91
9.8 Variation in fabric dimensions with tension and statistical analysis 92
9.9 CF and (interpolated) roughness coefficients of finished fabric samples . . 92
9.10 Correlation between k_{TEX} and CF 93
9.11 c_D-speed curves for technical front side of the textiles relatives to the cylinder model. 94
9.12 c_D-speed curves for technical back side of the textiles relatives to the cylinder model. 94

9.13 c_{DMIN} - k_{TEX} curves for technical front and technical back of the textiles relatives to the cylinder model. 96
9.14 V_{TRANS} - k_{TEX} curves for technical front and technical back of the textiles relatives to the cylinder model. 96
9.15 c_D - speed curves for techincal back side of the textiles using the leg model 98
9.16 c_D - speed curves for techincal front side of the textiles using the leg model 98
9.17 Variation of c_{DMIN} for the front side and the back side fabrics 99
9.18 Variation of V_{TRANS} with k_{TEX} on leg model and cylinder model for the front side and the back side fabrics 100

10.1 Angles which characterize a speed skater posture 105
10.2 A picture of the 6 suits tested. All the suits have different patterns in the different parts of the body. Suits 1,3,5,6 have a moderate rough textile on their legs while suit 2 has an extreme rough pattern and suit 4 is totally smooth. 107
10.3 Smoothness parameters for each suit 107
10.4 Relation between smoothness factor s and roughness coefficient r 108
10.5 c_DA-Speed curves for the 6 different suits tested. 109
10.6 Results from the 1500m race simulation 109

11.1 Forces acting on a cyclist 114
11.2 (a) Drag percentage on total force. (b) Maximum speed reachable with different power values. 115
11.3 The six positions tested in the wind tunnel. All positions are adjusted form each cyclists normal position 117
11.4 117
11.5 (a) Change in power output per velocity per position. (b) Estimated change in oxygen consumption per position per velocity. (c) Estimated change in % of maximal aerobic capacity per position per velocity. (d) Estimated change in heart rate per position per velocity. (e) Estimated energy saving per position pr velocity. (f) Estimated change in velocity pr position at 400 W power output. 119

12.1 BMI compared to weight status 123
12.2 BMI trend in ski jumping competitions during the last 40 years 123
12.3 In-run path. 124
12.4 Effect of increase of BMI in the speed at take off calculated for the Granåsen jumping hill in Trondheim (Norway). 125
12.5 Different angles between ski jumper and wind direction. α is the angle between wind direction and skis, β is the angle between wind direction and ski jumper's body and ϕ is the angle between wind direction and horizon line. 126
12.6 Experimental data for drag and lift 127

12.7 Experimental data and FIS table 127
12.8 Comparison between the FIS rules and the data obtained with the wind tunnel experiments 128
12.9 Simulated flight path 128

13.1 The 5 different versions tested. 134
13.2 Short spoilers 135
13.3 Long Spoilers 136
13.4 (a)Airfoiled shape. (b) Mannequin test 136
13.5 Drag coefficient reduction for the different boot versions at 25m/s 137

14.1 Fabric assemblies' details and matrix of test conducted 143
14.2 (a) area and (b) feret diameter, measured with the optical scanner technique 144
14.3 (a) V_{TRANS}-CFt plot; (b) V_{TRANS}-CFb plot; (c) ΔTr-CFb plot 145
14.4 a) accumulative one way transport index vs CF; (b) overall moisture management capacity vs CF; (c) average moisture absorption rate at the bottom surface vs CF 146
14.5 Correlation between Area, Vtrans and AOWT 147

15.1 (a) The three different types of textiles used (smooth, rough and dimpled) (b) List of the 13 textiles tested. (c) Schematical results from the preliminary tests carried out on cylinder models 153
15.2 ((a) Jacket prototype with different patching areas b) Pants prototype with different patching areas (c) Tables showing the type of textiles used on the different patching areas 154
15.3 (a) - CDA-speed curve for the pants tested on the mannequin model . (b) CDA-speed curve for the different jackets teted on the mannequin model . 155

CHAPTER 1

Introduction

*Revolution:*a far-reaching and drastic change, esp in ideas, methods, etc.
Evolution: A gradual process in which something changes into a different and usually more complex or better form.
What are we talking about? Revolution or evolution?
There are two different ways to approach problems and carry out research. The safest way is based on improving previous theories with a personal touch, pushing the boundaries a little bit further and developing a constant enhancement of methods. The risky way is based on a non defined mixture of: knowledge, geniality, bravery in different doses and it can lead to enormous success but in most of the cases it will not be recognized or will lead to a silent failure. However, a right balance between these two philosophies is crucial in order to achieve important results.
The history of sport is full of examples of pioneers and athletes that revolutionized their own discipline.
Their stories are often interesting and curious and their genius mixed with their athletical capacities was able to create a powerful mix which gave them a sensational advantage in competitions.
Richard Douglas Fosbury (born March 6, 1947 in Portland, Oregon) is one of the most famous sport revolutionary. He was a former track and field athlete specialized in high jumping. He had always been interested in high jump even since he was young, however, when competing at high school level he found hard to jump using the "straddle jump" which was the dominant jumping technique at that time.
The straddle jump consists in a complex motion where an athlete went over the high jump bar facing down, and lifted his legs individually over the bar and Forsbury never managed to have full control of the technique. Instead of giving up due to the poor results obtained in the high school competitions, he developed a new technique which involved going over the bar headfirst and backward, with one's body horizontal to the ground. The great advantage in using this technique immediately catapulted Dick Forsbury amongst the best athletes in the world in high jump.
The highest peak of his career has been reached during the Olympic games of Mexico 1968 when he won the gold medal in high jump collecting with his gracious moves the eyes of millions of people.1968 was the year where the Racial tensions on the U.S. Olympic team where high, it was the year that saw the assassinations of Martin Luther King Jr. and Robert F. Kennedy it was the year that saw the sprinters Tommie Smith and John Carlos became famous for their raised-fist gestures of protest. The shy and apoliti-

cal Forsbury managed anyway to retail a small piece of history all for himself and set a milestone in the track and field competitions.

And in that period, in 1968 an American teenager was probably watching the TV and living the politically heaviest Olympic games of the history (together with Los Angeles 1994). This teenager was named Bill Koch and at that time he wasn't probably aware that in a few years he would revolutionized the Cross country skiing competitions inventing the skating style.

In fact, the skating technique has ancient origins. The Lapps were used to use skis of uneven length: a short ski for propulsion and a long ski for gliding. Standing on the long ski and pushing on the shorter ski, they were then sliding on the snow with a sort of single side skating step. The myth says that the first athlete who introduced (or reintroduced) the skating style in cross country skiing was a Finnish athlete: Pauli Siitonen. Siitonen was a police officer from Helsinki who developed his skiing skills in southern Finland where there is little snow during the winter. Siitonen was an orienteering competitor and, in order to be able to read a map while skiing, he was used to ski with a sort of skating style.

This ability developed with orienteering became very useful when he randomly discovered the new style at the middle of a race he already thought was lost. After switching to skating Siitonen managed to win the race, to his surprise and even bigger surprise of the audience and other participants. However, it was Bill Koch that thanks to the skating won (in 1982) the Cross-country skiing World Cup for cross-country.

With the old technique (now called classical) the athletes ski on prepared trails that have pairs of parallel tracks cut into the snow. Skate skiing on the other hand looks similar to ice skating and, involves a weight transfer onto one ski angled and then the other. This technique resulted to be especially advantageous when going uphill and in the winter Olympic Games in Sarajevo 1984, most of the athletes begun to use the skating technique instead of the traditional one. This forced the FIS (international ski federation) to organize separate events for classical style (where athlete are obliged to use the traditional style) and free-style (where athletes are free to use any kind of skiing technique).

More recent and equally interesting is the story of Greame Obree, the so called "Flying Scotsman". Born in 1965 Obree spent most of his life working in a bike repair shop but he always wanted to be "on the other side of wall". He wanted to be a professional cyclist. His career as a professional cyclist was pretty short: after joining a professional team in France was fired before his first race with the team. A funny anecdote about his very first race says that he turned up wearing shorts, anorak and hiking boots. He thought the start and finish were at the same place and stopped where he had started, 100m short of the end. He had started to change his clothes when officials told him to continue. He still finished in about 30 minutes. Obree genius is all in this anecdote: a man that was unable to live his life on a trail.

He tried to commit suicide several times in his life, once by sniffing the gas he used to weld bicycles, and another time with an overdose of aspirin. Luckily his life has been saved both times.

His decision to attempt the world hour velodrome record came when the shop he was running failed. Before that he already figured out that he was able to bike in a different position than the one used by most cyclists. His very first approach to the postion that will be remembered as "the Obree's position" was in 1987. He used a standard bike, just flipped the handlebar upside down and biked crunched on the handlebar. With this posture he was able to minimize the frontal Area thus the drag acting on his body, getting a large advantage in terms of maximum reachable speed. He won national championships in the following years and broke the British hour record.

When he decided to attempt the world hour record he built a special bike which was able to improve the posture used on the bike with flipped handlebars. The bike was built with low cost materials, from bearings from a washing machine to a handlebar used in a BMX bike. However, the bike was perfectly designed for the purpose and he was able to ride completely crunched on the handlebar with his head leaning forward. Following tests carried out in the wind tunnel [Grappe 1997] showed that this posture was able to reduce the drag of 15% which leads to an increase in speed of 2km/h.

With this posture, Obree managed to get the record, the 16th of July 1993 in Hamar (Norway) at his second attempt. His record was beaten by Chris Boardman a few months later. However Obree did not give up and decided to participate to the the world championship pursuit the same year. One hour prior his race, he was told that his riding position was banned by the Union Cycliste Internationale (UCI) and he got disqualified by the judges. Obree didn't give up and came up with a new position, the so called "Superman position". He used a normal bike, a very long stem and an extended aerobar. His arms were stretched out and the hands before the front hub. Using the superman position he won the world pursuit championship and, using similar positions, the Italian team won two gold medals during the Olympic Games in Atlanta 1996.

Another modern sport revolutionary need to be cited here Jan Boklöv: the man who "invented" the V-style in ski jumping and put a milestone in the ski jumping competitions. He dominated the national swedish competitions for a few years and won the world cup in 1998/1999.

The V-style that he invented became the standard among ski jumpers since the 1990s. It's curious to know how he developed the V-Style because he actually developed it totally inadvertently. Since his legs were shaped in a particular way, he was unable to jump with the parallel style which was the standard at that time. Helped by his coach he then developed the style that became known as V-Style.

Of course the FIS (international ski federation) tried to stop the trend punishing Boklöv with point reductions when he was jumping with the V-Style. However, further experiments showed that the V-style allows the athletes to have higher lift and thus fly longer!

But sport has not only been dominated by revolutionaries. The evolution of the equipments during the years shows a constant work and constant research on material which helped the athletes to improve their performances. Adolf (Adi) Dassler for instance dedicated his whole life to the improvement of sport equipement. Born in 1900 in Herzogenaurach Germany he was the founder of the German sportswear company Adidas together

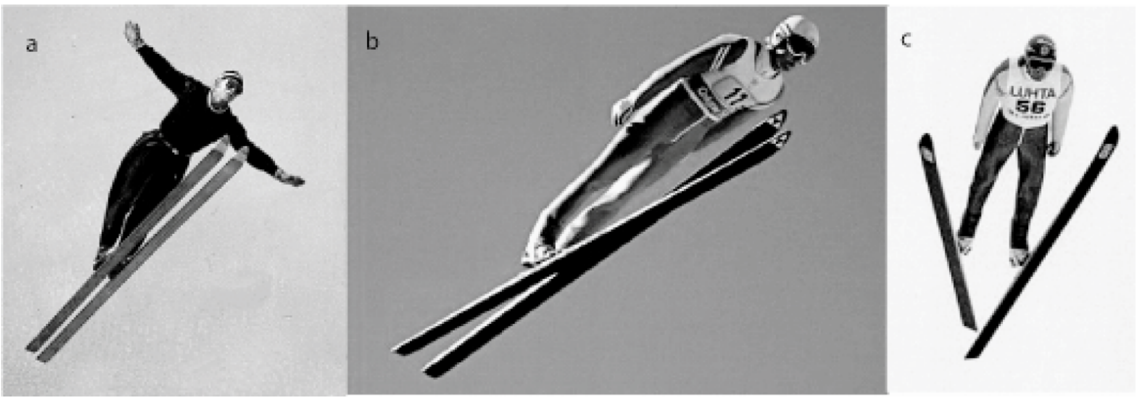


Figure 1.1: Evolution of ski jumping style. (a) Wilbert Rasmussen 1952 (b) Parallel sky style 1978 (c) The V-Style (Jan Boklöv) 1986

with his brother Rudolf Dassler in 1924. The company was at that time called Dassler Brothers Shoe Factory. Already in the Olympic Games of 1928, the Dassler brothers equipped a big number of athletes with their shoes.

However, the big step suddenly happened during the 1936 Summer Olympics in Berlin when Jesse Owens was equipped with Dassler shoes. Jesse Owens won four gold medals in the year and Adi became a sort or myth. In 1948, after the second world war, some divergence in opinions leaded to a division between the two Borthers. Adi founded Adidas and rudolf founded Puma.

Adi Dassler dedicated his whole life to improve sport equipements, with particular attention to shoes.

He invented the first running shoes with spikes, the first shock absorbing shoes, pushing the boundaries during his whole life and often spending days and and nights to test the prototypes by himself.

There are many examples of equipment evolution and a complete list of them would take an enormous effort in order to be accurate. However, some examples are interesting and noticeable.

Speed skating suits for instace tremendously evolved from the beginning of the century when skater were used to compete using normal pants and jacket to the modern times where speed skating suit which can reduce the drag on the athletes of about 20% if compared with a normal clothing. This allow the athletes to reach higher speed with less effort.

Also the skates and blades used in speed skating competition evolved and improved during the years allowing the skaters to get a better grip on the ice especially in the curves thus optimize the use of the power generated.

A milestone in the skates development has been set by Van Ingen Schenau in the early 80's. He is the inventor of the clap skates. Before the clap skates, the blade was mounted under the boot so that boot and blade were one rigid piece. Van Ingen Schenau had the intuition that, fixing the blade only in the front part of the boot with a movable joint would

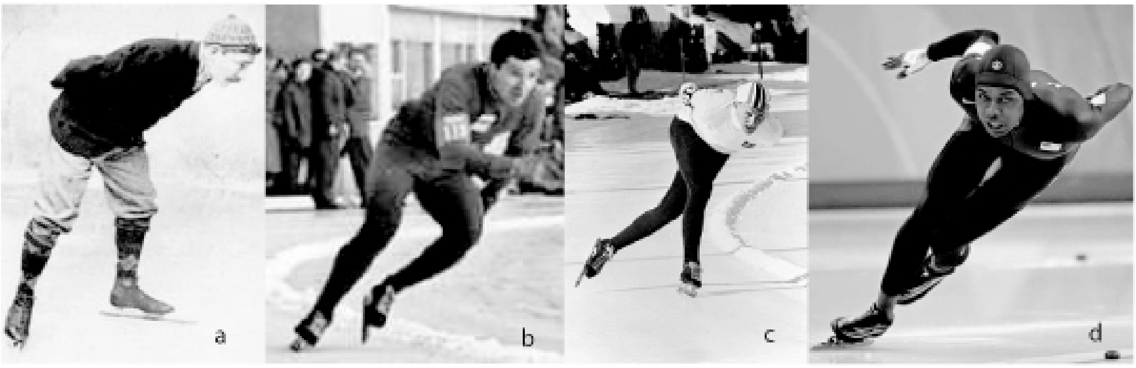


Figure 1.2: Evolution of skating suits (a) Jaap Eden 1920 (b) Richard Terrance (1940) (c) Knut Johanssen (1960) (d) Shani Davis (2006)

have allowed the skaters to keep the blade in contact with the ice surface for a longer time. The clap skates have been first used in 1985 but the idea was never taken seriously until the 1996/1997 when the female Dutch team first used them with great success. After that, almost all the skaters switched from the rigid skate to the clap skate. The evolution in materials improved performances in any sport! The carbon fiber poles helped Sergey Bubka (which has been the first one to use them and train with them) to be 6 times world champion and break the pole Vault world record for 35 times!

Carbon fiber rackets added more precision in tennis matches.

New materials and an accurate research on aerodynamics of spheres improved the golf balls and soccer balls. The dimpled surface on golf balls was a sort of revolution for the sport and it allowed the ball to travel two times further than a smooth ball hit with the same intensity. New surface textures on footballs reduced the drag of the balls and allowed more unpredictable trajectories. Progress is still going on and the research carried out and presented in this thesis is part of this progress. A brick in the infinite wall of development and improvement.

A step forward in understanding how textiles and aerodynamics of human bodies are linked and a resume of how aerodynamics can sensibly affect athletes' performances.

1.1 Progress and devlopent in sport technology: a continuum.

Progress and technological development is a continuous process.

In sports, where performances are the dominant factor, equipment are constantly improved in order to give a favorable advantage to the athletes.

Narrowing the attention on the aerodynamics: suits, athlete postures and external factors which can influence the performances of the athletes need to be taken into consideration when trying to help the athletes to fight against against the drag.

A clear understanding of the influence of the textiles on the aerodynamic properties of the human body is then crucial in order to reach a sensible improvement in performances.

Parallel research which is able to quantify the effect of postures, mass, speed and external factors is also important.

A modern speed skating suit is able to reduce the drag acting on a speed skater up to 10%, a correct and optimized posture while cycling is able to reduce the drag of about 20%, a correct V-Style position in ski jumping is able to increase the efficiency of the ski jumper of about 10%.

However, even if the work carried out in the past years boosted the ahtletes' peformances, improvements are still possible in large extents.

Some examples can be cited.

The correlation between surface structure and aerodynamic properties is still not clear and both the results published and the products available on the market are mostly the results of extensive tests on different textiles.

A combination of wind tunnel testing and biomechanics and physiological analysis is crucial in order to optimize cyclists postures and results demonstrate that a specific test for each athlete is needed in order to reach an optimum.

The complexity of the ski jumping flight path makes the complete understanding of the phaenomenon still hazy.

The field of research is then wide and unexplored and the interest of the community for sport events, gives to the sport engineering field not only a pure research context but also great media attention.

1.2 Research Context

The thesis have been financially supported by the Norwegian Olympic committee. The main goal of the research work was to understand how drag and aerodynamics influence the performances of the athletes. A second step was to help the athletes, through experimental work in the wind tunnel, to improve their performances by reducing the aerodynamic drag acting on their body.

A deeper look at the textiles and the effect that textiles have on athletes aerodynamics have been done. A number of commercial textiles, in collaboration with Spinno, have been tested and their aerodynamics performances have been analyzed. Some textiles, in collaboration with the Textiles and Fashion department from RMIT in Melbourne have been produced and analyzed and their aerodynamic properties have been described.

Some side projects financed by the Norwegian Olympic committee have been carried out.

A number of speed skating suits have been tested and their aerodynamic performance have been analyzed and estimated using a mathematical model.

The experiments concerning the aerodynamics have been carried out in the wind tunnel at NTNU in Trondheim and partially in the wind tunnel at RMIT in Melbourne.
All the comfort tests have been carried out at the Textiles and Fashion department at RMIT in Melbourne.
As a conclusion of the research process, a low drag suit for the Norwegian Olympic team of Ski-cross has been designed, developed, tested and produced in collaboration with Spinno.

1.3 Aerodynamics and drag:when are they relevant?

Considering sports where the main goal is to cover a certain distance in the shortest possible time (cycling, speed skating, skiing, running, etc.) a certain number of forces is acting against the athletes during their motion.
The power generated by the athlete is then spend to overcome these negative forces and at the same time reach the highest possible speed.
Amongst these forces, the three most important forces that act against the athletes are drag, friction and inertia. Drag (D) is a funtion of the speed and it increases with the speed.
Focusing the attention on speed skating, the friction between blade and ice is both is a negative force which oppose to the skater's motion but it is also used in order to tranfer the power to the ground and thus increase the speed of the athlete during the pushing phase.
In cycling the friction forces acting agaist the cyclist are a sum of the rolling friction due to the contact wheel/ground and the friction forces due to the transmission of the motion from the pedals to the wheels.
Inertia becomes important acts only when accelerations are presesent. This leads to the fact that the inertia force has a higher importance in short distance competitions where the speed of the athletes is increasing.
In order to be able to understand when the drag becomes large and thus a drag reduction can be relevant to improve the athletes' performances, a physical definition of the drag (D) itself should be given.
The drag can be written as:

$$D = \frac{1}{2} A_p c_D \rho V^2 \tag{1.1}$$

where A_p is the frontal area ρ is the air density, V is the wind speed and c_d is the non dimensional drag coefficient. The power that an athlete has to spend in order to overcome the drag is proportional to the cube of the speed and can be written as:

$$P_D = D \cdot V = \frac{1}{2} A_P C_D(V, suit) \rho V^2 V \tag{1.2}$$

Frictional forces are harder to analyze and they are different in different sports. In speed skating for instance, the only fricitonal force acting against the skater is the friction force between ice and the skate's blade.
A representation of the frictional forces in speed skating has been suggested by Bowden [Bowden 1953] and it has been widely used successively [DeKoning 2005a].

$$f = \mu N \tag{1.3}$$

where μ is the coefficient of friction and N is the normal force.

The power that an athlete has to spend in order to overcome the drag can be then written as:

$$P_f = \mu N V \tag{1.4}$$

The coefficient the coefficient of friction μ has been widely analyzed but the results are controversial. Bowden [Bowden 1953] found out that μ decreases with the velocity and he explained this decrease with a higher surface melting under the blades and thus a better lubrication. DeKoning [DeKoning 2005a] found the exact contrary.

The frictional forces actinng in cycling and have been analyzed by a number of authors [Hennekam 1990]and also here results are controversial.
A balance of the forces acting against the athletes during their motion have been proposed by DeKoning [DeKoning 2000],[DeKoning 2005b]:

$$P_u = P_f + P_D + \frac{dE_{mcb}}{dt} \tag{1.5}$$

where P_u is the power gerated by the skater, P_f are the frictional losses averaged due to the ice/blade friction, P_D are the frictional losses averaged due to the drag $(D]$ and $dE_{mcb/dt}$ the rate of change of the kinetic and potential energy. Having a deeper look at this power balance equation, for an athlete moving at a constant speed can suggest a few conclusions:

- the rate of change of the kinetic and potential energy will be zero
- considering the frictional forces in speed skating or cycling independent on the speed [Hennekam 1990],[DeKoning 1992b],[DeKoning 2005b] leads to the fact that $P - f$ is going to be proprtional to the speed
- being the drag proportional to the square of the speed as shown above, the power spent in order to overcome the drag is proportional to the cube of the speed.

It is then easy to postulate that speed is the most important factor when evaluating the contribution of the drag on the total forces acting against the athletes.
The higher the speed is, the more a reduction in drag is crucial in order to use the power generated to reach a higher speed.
Considering the examples of cycling, where the forces acting on a cyclist can be divided in: rolling friction, drag and inertia, at 10m/s, the drag is ca. 80% of the total forces acting on the cyclist.

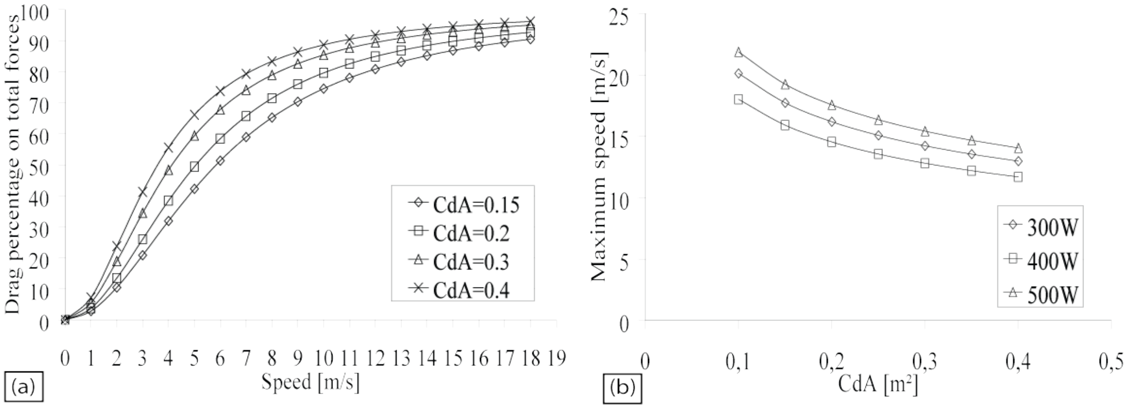


Figure 1.3: Influence of drag in cycling

1.3.1 High speed sports

As previously mentioned, research has been carried out in parallel in the two main Areas of Study. A deeper look has been done to textiles and their aerodynamic properties while side projects have been made.
However, the two areas are linked by the fact that the textiles analyzed can be used in high speed sports such as speed skating, cycling or downhill skiing.
The average speeds reached by the athletes in different disciplines are shown in fig. 1.4.
A deeper look on cycling and speed skating is required in order to better estimate what

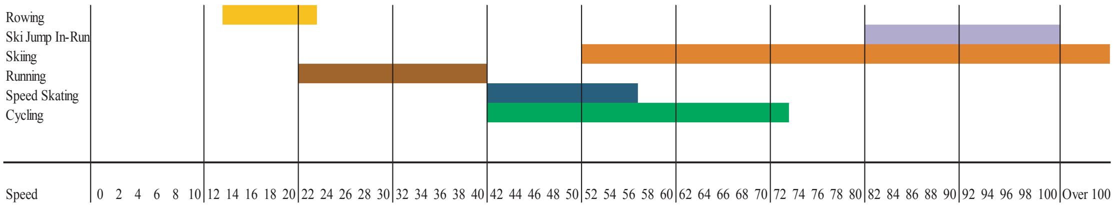
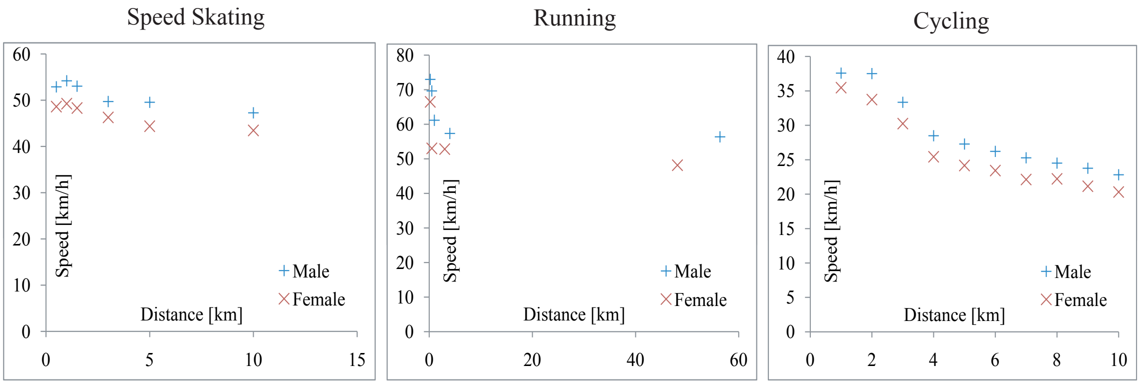


Figure 1.4: Average speeds in different sports

are the speeds during the different distances competition. In order to do that, the average

speed in each event during the world record attempt have been calculated for both speed skating and cycling. From fig. 1.5a, 1.5b and 1.5c it can be seen that two factors strongly affects the average speed of a sport event.
- The first factor is the sex gender. Women always have a lower average speed than men in all the events taken into consideration.
- The second factor is the distance. Long distance events have usually a lower average speed than short distance events.
Cycling events have a higher speed than Speed skating and running events with a maximum speed of ca. 80km/h which is reached in short distance track competitions.
As expected, speed in running are lower than in the other sports.



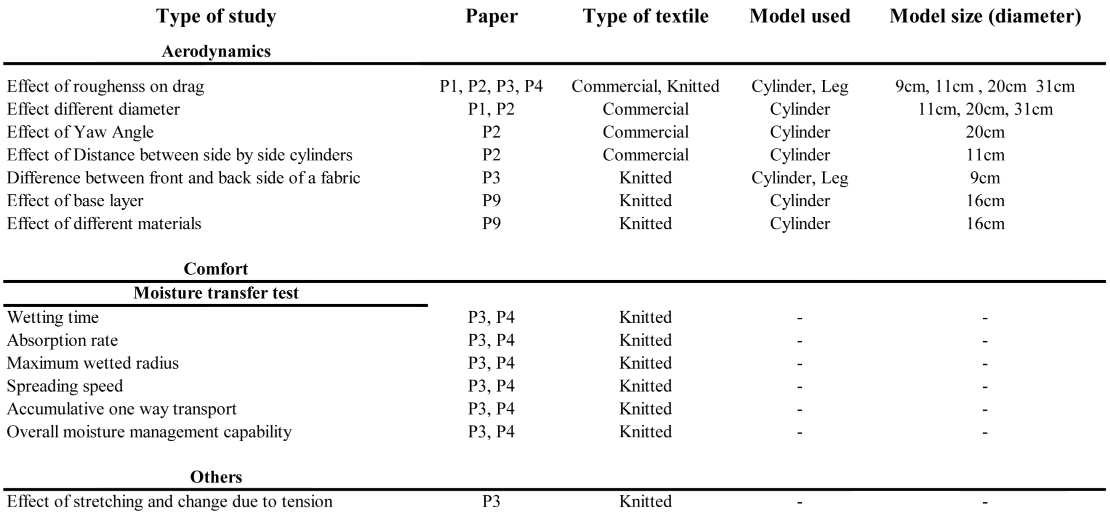
(a) (b) (c)

Figure 1.5: Average speed during world records in speed skating (a), running (b) and track cycling (c)

1.3.2 Textiles

The main studies on textiles were focused on textiles used in speed skating skin suits in order to understand how different fabrics affect the aerodynamic of the athletes.
All the studies on textiles have been carried out on cylindrical models except for P3, P4 and P9 which has data relative to a Leg model.
In P1 and P2 three different commercial textiles with different roughness have been analyzed and studied while in P3 and P4 the attention was focused on knitted textiles. Ten knitted textiles with different knitted parameters (loop length and thus cover factor were produced). Knitted textiles have been chosen because they are the simplest fabric and their structure is not as complex as normal warp knitted commercial textiles.
In order to correlate the aerodynamic properties with the physical properties of the textile, a roughness model has been developed from P1 and P2 and a second model has been modeled to P3 and P4.

Comfort analysis has been carried out in P3 and P4 on knitted textiles in order to evaluate not only the aerodynamic properties but also moist transfer and transpiration of the textile. The same textiles tested in P1 and P2 have also been tested in P5 where six commercial speed skating suits used from different national teams have been tested. These suits have been modified by patching the legs with different roughness textiles.



Type of study	Paper	Type of textile	Model used	Model size (diameter)
Aerodynamics				
Effect of roughenss on drag	P1, P2, P3, P4	Commercial, Knitted	Cylinder, Leg	9cm, 11cm , 20cm 31cm
Effect different diameter	P1, P2	Commercial	Cylinder	11cm, 20cm, 31cm
Effect of Yaw Angle	P2	Commercial	Cylinder	20cm
Effect of Distance between side by side cylinders	P2	Commercial	Cylinder	11cm
Difference between front and back side of a fabric	P3	Knitted	Cylinder, Leg	9cm
Effect of base layer	P9	Knitted	Cylinder	16cm
Effect of different materials	P9	Knitted	Cylinder	16cm
Comfort				
Moisture transfer test				
Wetting time	P3, P4	Knitted	-	-
Absorption rate	P3, P4	Knitted	-	-
Maximum wetted radius	P3, P4	Knitted	-	-
Spreading speed	P3, P4	Knitted	-	-
Accumulative one way transport	P3, P4	Knitted	-	-
Overall moisture management capability	P3, P4	Knitted	-	-
Others				
Effect of stretching and change due to tension	P3	Knitted	-	-

Figure 1.6: Experiments on textiles

Textiles were analyzed with the electronic microscope in order to correlate the micro structure and be able to create a parameter that connects the most important characteristics of the textile itself.

Some other projects have been carried out and the attention have been focused on improving the athletes performances and analyze different aspects of the performances.

In P6 the attention have been concentrated on cycling and how postures affect the drag acting against a cyclist.

In P7 it has been evaluated how the BMI influences ski jumping performances under the new FIS rules.

In P8 a novel downhill ski boot model has been produced in order to reduce the drag acting on the athletes legs

All the articles are based on experimental work. In P5,P6 and P8 some mathematical models have been made in order to reproduce the performance.

In P5 the Power balance model made by Dekoning [DeKoning 2005b] have been used to estimate the performance of a speed skater with different suits.

In P7 a mathematical model has been made to simulate the effect of BMI on the in-run and on the flight path of a ski jump.

In P8 a simple mathematical model has been made to estimate the advantage of using airfoiled boots instead of normal boots in a downhill competition.

In P9 the effect of the base layer on a double layer knitted assembly has been investigated.

In P10 the study carried out in order to produce a prototype of a ski-cross suit for the Winter Olympic Games in Vancouver 2010 has been described.

1.4 Thesis structure

The thesis has been divided in two separate research areas. One area (Area1) with focus on textiles and aerodynamic and comfort properties of them and a second area (Area2) with focus on performances and on how aerodynamic improvements can improve athlete's performances.

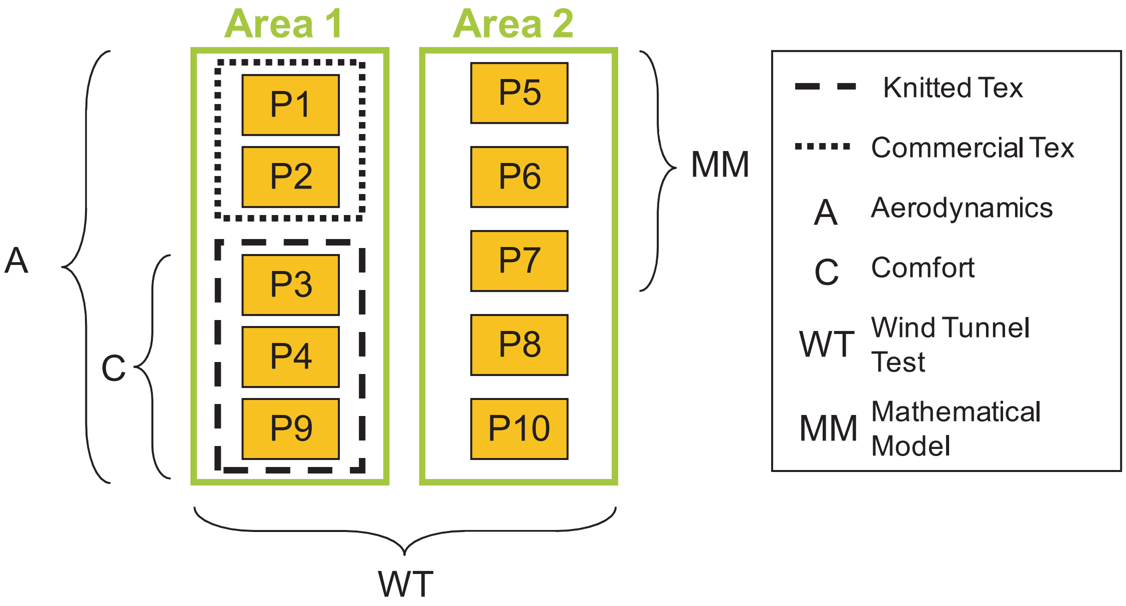


Figure 1.7: Thesis structure

1.4.1 List of papers

P1

Reducing the athletes aerodynamical resistance
Oggiano, Luca; Sætran, Lars Roar; Løset, Sveinung; Winther,Ronny
Published on: *Journal of Computational and Applied Mechanics, 2007, Vol. 8(2), pp. 163-173*

Relevance to this thesis: This paper presents the initial findings successively developed in P2 and deeply in P3 and P4 with use of different roughness parameters. It is based on drag reduction on cylinders covered with different textiles and show a logaritmic correlation between the roughness parameter defined and the Reynolds number when transition occurse Re_{TRANS}

Abstract: This paper presents an experimental investigation on the effect of surface roughness on athletes legs and arms. Because of their cylindrical shape, arms and legs of an athlete can be approximately studied as flow over circular bodies. The variation of roughness has been obtained using three different textiles and changing the diameter of the cylinder. To evaluate the results, three more textiles have been tested on the 20cm diameter cylinder. Two of them are utilized in two alpine suits used by the Norwegian alpine ski team and one is from a ski suit produced by Eschler. All the results have been compared with a cylinder with a smooth surface. The critical Reynolds number for a significant drop in the drag coefficient decreases by increasing surface roughness.

My contribution: This paper was written in collaboration with the Norwegian Olympic committee. I ran all the experiments and analyzed the data. I was the leading author of this paper.

P2

Experimental analysis on parameters affecting the drag force on Athletes
Oggiano, Luca; Sætran, Lars Roar
Published on: *The impact of technology on sport, 2009, Vol. 3, pp. 383-389*
ISBN 13978-1-921426-38-4

Relevance to this thesis: This paper follows the pervious paper P1 and analyze some other parameters not mentioned in the previous article. These parameters are: Yaw angle, Distance between two side by side cylinders and Diameter of the cylinder. The results show the correlations between c_{DMIN}, V_{TRANS} and the above mentioned parameters

Abstract: In sports where high speed is reached and drag is the main force acting on the athlete's body, the posture highly influences the total drag. Due to the fact that the total drag is proportional to the frontal area, the athletes minimize their frontal area keeping the trunk parallel to the air flow (cycling, speed skating, downhill skiing).
In these disciplines, the aerodynamic resistance acting on the legs counts up to 1/3 of the total drag. In order to reduce the drag, rough textiles with different patterns have been used in sport suits. However, a certain number of parameters need to be considered in order to optimize the aerodynamic performance of a textile. These parameters are: speed, diameter of the leg, yaw angle, distance between the legs and roughness of the textile.

My contribution: This paper was written in collaboration with the Norwegian Olympic committee. I ran all the experiments and analyzed the data. I was the leading author of this paper.

P3

Aerodynamic behaviour of single sport jersey fabrics with different roughness and cover factors
Oggiano, Luca; Konopov, Inna: Troynikov, Olga; Alam, Firoz; Subic, Aleksandar
Published in: *Journal of sport engineering, 2009, Vol. 12(1), pp. 1-16* ISSN 1360-7072

Relevance to this thesis: In this paper the aerodynamic properties of single jerseys textiles made with polyester yarns have been studied. A Roughness model which was able to link the roughness properties of the material with the cover factor have been made.
Results showed a clear correlation beteeen the roughness parameter ktex and the aerodynamic properties of the textiles. A strong correlation between K_{TEX} and V_{TRANS} was found

Abstract: The paper addresses the effects of geometry and physical parameters of knitted fabric structures on their aerodynamic and comfort properties. In order to evaluate whether significant aerodynamic and comfort advantages may be achieved by changing the geometrical parameters of knitted structures, 9 different knitted fabrics in plain structure (Single Jersey) were produced. Their geometry and physical parameters were measured and analyzed. A fabric surface roughness model was developed and correlations between fabric geometry, manufacturing and aerodynamic parameters were established. To evaluate an aerodynamic behavior of the fabrics produced, a series of aerodynamic tests were carried out in the industrial wind tunnel.
Fabric samples were placed on a leg model and 2 different positions of the leg were tested in order to avoid uncertainties in the drag due to the asymmetrical shape of the leg. cd-Speed curves were obtained. The aerodynamic resistance was acquired at different incremental speeds from 20km/h to 80km/. Correlation between aerodynamic parameters (V_{TRANS} and c_{DMIN}) and fabric manufacturing parameters was established and analyzed. Evaluation of the comfort properties of the fabrics was carried out. Measurements of dynamic comfort properties of the fabrics were obtained. As part of this evaluation fabrics' liquid moisture transport properties in multi-dimensions (moisture management properties) were acquired. The moisture management capacity of all knitted fabrics was assessed and classified by simulation of the liquid sweat on the skin absorbed and transferred to the outside of the fabric. Correlations between the fabric geometrical parameters and comfort properties were established.

My contribution: This paper was written in collaboration with the school of fashion and textiles in Melbourne of Aerospace, Mechanical and Manufacture engineering at RMIT in Melbourne. I ran all the experiments and analyzed the dataconcerning the aerodynamics. I was the leading author of this paper.

P4

Aerodynamic and comfort properties of single jersey textiles for high speed sports
Oggiano, Luca; Konopov, Inna: Troynikov, Olga; Alam, Firoz; Subic, Aleksandar; Sætran, Lars Roar
Published in: *The impact of technology on sport, 2009, Vol. 3. pp. 163-173* ISBN 139781921426384

Relevance to this thesis: This paper extend the studies presented on A3 on single jersey textiles and analyze the comfort of the textiles as well. Test have been carried out on a leg model and not anymore on a cylinder model.

Abstract: Wind tunnel testing has been carried out on nine knitted single jersey fabrics (100% polyester) using cylinder and leg models to determine their aerodynamic behaviour (c_{DMIN} and

V_{TRANS}) over a range of speeds (20 - 80 km/h) representative of sports activities. Strong correlation between fabric manufacturing (cover factor) and fabric roughness parameters and aerodynamic parameters has been established. Similar aerodynamic behaviour of fabrics was observed when tested on the cylinder model and on the leg model.

My contribution: This paper was written in collaboration with the school of fashion and textiles in Melbourne of Aerospace, Mechanical and Manufacture engineering at RMIT in Melbourne. I ran all the experiments and analyzed the dataconcerning the aerodynamics. I was the leading author of this paper.

P5

Effect of different skin suits on speed skating performances
Oggiano, Luca; Sætran, Lars Roar
Published in: *Computer science in sports, 2008, Vol. 3, pp. 163-173, World academic union*
ISBN 9781846260315

Relevance to this thesis: This paper is in the research area 2 and it focus on the effect of skin suits on speed skating performances. Wind tunnel tests have been carried out and a mathematical model have been made in order to simulate a 1500m race for men and women and ideally quantificate the advantage of using different suits.

Abstract: Drag in speed skating is the most important frictional loss. This paper presents a numerical and experimental investigation on how rough textiles are able to affect the drag in competition speed skating suits. The attention has been mostly focused on the legs of the athletes. Methods: Experiments with a doll in scale 1:1 have been carried out. Drag at different speeds (from 4m/s to 17m/s) has been acquired and C_D-Speed curves for each suit have been plotted. A mathematical model based on the balance between the power generated and the power spent by the athletes has been used in order to estimate the final time in a 1500m long track competition for women and men. Results: Speed skating suits do affect speed skaters performances. A maximum difference in drag of about 10% has been acquired and a maximum difference in final time of about 3s has been estimated. Rough textiles on the suits legs are able to reduce the drag at low speeds (V<11m/s) but negatively affects performances at high speed (V>13m/s).

My contribution: This paper was written in collaboration with the Norwegian Olympic committee. I ran all the experiments and analyzed the data. I was the leading author of this paper.

P6

Effects of body weight on ski jumping performances under the new FIS rules
Oggiano, Luca; Sætran, Lars Roar
Published on: *The Engineeeing of Sport 7,2008, Vol. 1, pp. 597-604 Springer Publishing Company*
ISBN 9782287094101

Relevance to this thesis: This paper focus on the effect of BMI on ski jumping performance. Wind tunnel tests on skis with different lenghts and mannequins have been carried out and a mathematical model able to calculate the Speed at take off and the flight path has been made

Abstract: Based on the results of several different experiments, it has been concluded that the weight of a ski jumper is crucial in performing a long ski jump. In response to this conclusion, many of the best ski jumpers in the world began dieting to reduce their weight, resulting in many underweight athletes and some incidents of anorexia. In order to deal with this problem the International Ski Federation (FIS) introduced a new rule where the ski length is determined by both the jumper's height and weight. An athlete with a Body Mass Index (BMI) of less than 20 must reduce the length of his or her skis.
To evaluate the effect of the new rules a numerical and experimental investigation on the effects of the BMI on ski jumper's performances has been done. A numerical model has been built in order to evaluate the effects of BMI on the final speed in the in-run path. The numerical results obtained from the model match experimental data present in the literature. Experiments in the wind tunnel have been made in order to evaluate the aerodynamic forces acting on the ski jumper and on the skis during the flight path according to the new FIS rules. Experiments have been carried out on a doll mounted on a 6 components balance and different positions and ski length have been tested. The data acquired have been introduced into a numerical model and the final jump length has been then estimated.
In conclusions it has been found out that the current FIS rules do reduce the problem addressed but experiments shows that it is still more advantageous to lose weight and consequently cut the skis, compared to gaining weight in order to keep the full ski length.

My contribution: I ran the experiments in this article and analyzed the data relative to the aerodynamics. I was the leading author of this paper.

P7

Aerodynamic optimization and energy saving of cycling postures for international elite level cyclists
Oggiano, Luca; Leirdal, Stig: Sætran, Lars Roar; Ettema, Gerardus Johannes C.
Published in: *The Engineering of Sport 7 , 2008, Vol. 1 pp. 597-604 Springer Publishing Company*
ISBN 9782287094101

Relevance to this thesis: This paper focus on the important of a correct posture in cycling. Tests to quantify the drag in different positions have been made and physiological values and energy savings for the different postures have been calculated.

Abstract: Introduction: Drag in cycling counts for as much as 90percent of total resistance opposing motion in a normal time-trial course. A small gain in term of drag reduction can, over a longer time-span (30 - 60 minutes) give a large advantage to the cyclists in terms of power output saved or velocity gained. The aim of present study was to aerodynamically optimize the cycling posture for each cyclist and thereby improve the athletes' performances. We also wanted to quantify the power output saving, velocity gains and energy savings of this optimization.
Methods: 11 elite cyclists with a maximal aerobic power output of 481 W were tested at 6 different positions on their time-trial bicycle in a wind tunnel with an air flow at 14.5 m/s. All positions

were adjusted from their regular position and included both adjustment of seat and handlebar. All cyclists also went through an extensive physiological test, including lactate threshold and VO2max tests, allowing for individual efficiency calculations at several power outputs.
Results: From the wind tunnel test individual power-output - velocity curves were plotted, showing the effect of the different positions in terms of saved power generation. Showing an average 21.9 W saving in power output and an average of 0.75 km/h gain in velocity at 500 W for the most aerodynamically position. Using each cyclist's efficiency we calculated the theoretical effect of oxygen consumption, Kcal/h and heart rate. Average results show a 0.34 l/min, 101.5 Kcal/h and 14 BPM for the heart, in saving, for the most aerodynamically position.
Conclusions: The effect of small adjustments on elite cyclists can have large effect on performance and energy saving. However, care should be taken as the new position can negatively affect power generation and pedaling technique, which might become more energy consuming. Data on this is also collected in present study but needs further analysis.

My contribution: i carried out the experiments in this article and analyzed the data relative to the aerodynamics. I was the leading author of this paper.

P8

Airfoiled design for alpine ski boots
Oggiano, Luca; Sætran, Lars Roar: Agnese, Luca
Published in: *The impact of technology on sport, 2007, Vol 2. s.163-173*
ISBN 0415456959

Relevance to this thesis: This paper is in the research area 2 and it focus on the effect of ski boots on the total drag of a downhill skier. The boots design has been improved and a significant drag reduction has been found.

Abstract: The aerodynamic effects in sport competitions increase with the speed. In some sports like skating, skiing or cycling the athletes have an average speed from 70km/h up to 150km/h. The aerodynamic drag coefficient increases with the square of the speed.
This means that, by reducing the aerodynamic drag coefficient, it is possible to increase the athleteŠs speed and improve their performances.
The drag of a human body when assuming the position of an alpine skier is divided approximately in 1/3 given by the legs, 1/3 given by shoulders an arms, 1/3 given by the chest. On bluff bodies like cylinders or spheres (we can consider the human body as a bluff body) the larger part of drag is given by the difference of pressure between the front and the rear part of the body. That's due to the boundary layer separation.
In this paper we focus on the reduction of drag on skiers legs by modifying the shape of the boots from a cylindrical shape to an airfoiled one. Four different solutions with different designs have been studied, each solution has been experimentally analyzed and a CdA-Speed curve has been obtained.
By reattaching the boundary layer with a different design of the boot it has been possible to de-

crease from 10% up to 70% the drag coefficient. This means that a drag coefficient reduction of approximately 10% of the total drag of an alpine skier has been obtained.

My contribution: The experiments for this article have been carried out by Luca Agnese and i analyzed the data. I was the leading author of this paper.

P9

Aerodynamic and Comfort Characteristics of A Double Layer Knitted Fabric Assembly for High Speed Winter Sports
Konopov, Inna; Oggiano, Luca; Chinga-Carrasco, Gary; Alam, Firoz; Troynikov, Olga
Published in: under publication

Abstract: In this paper, the double layer concept of knitted fabrics suitable for performance sportswear, where each layer is unique in that it is completely separate from the other layerĎ was studied. Aerodynamic properties of this double layer fabric assembly, where the base layer is made of 100% wool and an external layer made of 100% continuous filament polyester were determined. Each fabric layer was produced with varying geometrical parameters and tested for their aerodynamic properties separately as well as a double layer assembly.
All fabric samples were placed over a single diameter cylinder that was used to imitate the leg, using the approximation that arms and legs are cylindrically shaped. All aerodynamic tests were performed in the wind tunnel, equipped with a 220KW fan that can produce a variation of speeds between 0.5 - 30 m/s. The aerodynamic resistance was acquired at different incremental speeds relevant to sports such as cycling or speed skating.
In addition, evaluation of the comfort properties of each layer as well as a double layer assembly was carried out. Measurements of dynamic comfort properties of the each layer and a double layer knitted fabric assembly were obtained. As part of this evaluation fabricsŠ liquid moisture transport properties in multi-dimensions (moisture management properties) were acquired. The moisture management capacity of double layer fabric assembly was assessed and classified by simulation of the liquid sweat on the skin absorbed and transferred to the outside of the fabric.
Results from the series of aerodynamic tests demonstrated that the base layer influences the aerodynamic characteristics of the entire double layer knitted fabric assembly.

My contribution: i carried out the experiments in this article and analyzed the data relative to the aerodynamics. I was the second author for this paper

P10

A low drag suit for ski-cross competitions
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Abstract: Ski cross is a modern discipline which will be included in the Winter Olympics events from Vancouver 2010. In a ski cross competition, a group of four skiers take simultaneously part

of the race and attempt to reach the end of the course. The first two to cross the finish line will advance to the next round.
It is then not a timed racing event like the other ski competitions.
Since it has been proved that low drag apparels have a major role in sports where high speeds are involved and speeds in ski cross can vary from 50km/h to 100km/h (depending on the track), a low drag suit could give an advantage to the athletes. Knowing that it is possible to design suits which are capable to shift the transition from laminar to turbulent regime (giving a great advantage in terms of drag reduction) it has been chosen to use different textiles with different roughness in different parts of the body to minimize the aerodynamic drag.
This had to be matched with the rules about how the suits should be made. The rules present in the FIS regulation states that skin suits like the one used in Skiing and Speed Skating can not be used and that *The gap in the material must be a minimum of 80mm, measured everywhere around the circumference of the thigh of each leg from the mid thigh to the top of the ski boot and 60mm everywhere around the elbow and the bicep*. The flappin" effect should then be taken into consideration. The suit design has been carried out in following steps:
1-A preliminary wind tunnel test on a athlete from the Olympic team has been carried out and different suits have been tried. The major parameters which influence the drag have been addressed
2-12 textiles have been chosen basing the choice on the different patterns present on the textile and on the experience. All the textiles had different roughness and thickness.
3-A preliminary wind tunnel test on cylinder models has been carried out on the textiles and 8 textiles have been discarded. 4 different pants and 3 different jackets design have been suggested.

My contribution: i organized the project, carried out the experiments and analyzed the data relative to the aerodynamics. I was the leading author of this paper.

CHAPTER 2

State of the Art

2.1 General theory about flow around cyliders

2.1.1 General theory about drag resistance on bluff bodies with particular attention to cylinders

Approximating the human body shaped as a series of cylinders [Shanebrook 1974], the attention can be focused on cylindrical model. In a smooth cylinder in a low-turbulence level stream, the critical Reynolds number (when transition is happening and the drag coefficient fall) it is around $3 \cdot x10^5$. The introduction of a surface roughness in the cylinder can shift the transition at lower Reynolds number. Usually we can say that higher the roughness parameter is, lower the value of the critical Reynolds is but smaller the fall in c_D is. [Achenbach 1977],[Achenbach 1964], [Bearman 1993],[Bearman 1976]. From Achenbach experiments [Achenbach 1977], for post-critical regime, an increase in roughness on a sphere leads to an increase in drag coefficient if we compare it with a smooth surface sphere.

2.1.2 Concept of drag resistance

The total drag acting on a bluff body can be split in two different parts. A part of drag is due by the skin friction and it is called friction drag and another part is due to the difference between the high pressure in the front part of the body (close to the stagnation point) and the rear region (separated region) and it is called pressure drag.

$$c_{DTOT} = c_{Dpressure} + c_{Dfriction} \tag{2.1}$$

The relative contribution of friction and pressure drag depends on the body shape and especially on its thickness. In bluff bodies such cylinders, the pressure drag is dominant and it reaches up to 90% of the total drag [White 1991]. In streamlined bodies, where the wake is smaller, the friction drag is dominant.

2.1.3 Transition from laminar to turbulent flow

There is not a complete theory about the transition from laminar to turbulent, especially for bluff bodies. As the boundary layer develops in the streamwise direction, it is subjected to numerous disturbances. The disturbances may be due to surface roughness, temperature irregularities, background noise, etc. Usually these disturbances amplify and the boundary layer becomes turbulent.
The transition from a laminar boundary layer depends on different parameters

1. Pressure gradient
2. Surface roughness
3. Compressibility effects (usually related with Mach number)
4. Surface temperature
5. Suction or blowing at the surface
6. Free stream turbulence

In general, transition is supported by: adverse pressure gradient, surface roughness, blowing at the surface and free-stream turbulence. On the contrary, favorable pressure gradient increased Mach numbers, suction at the surface and surface cooling delay the transition. The transition starts for a specific Reynolds number called "critical Reynolds number" Re_{crit}. Another Reynolds number which represents the transition can be defined: Re_{TRANS}. This can be defined as the Reynolds number where the c_D reached half its drop. Once the critical Reynolds number is exceeded, the boundary layer will contain regions with the following characteristics:
LAMINAR:
Laminar flow
TRANSITION:
Unstable flow containing 2D Tollmien- Schlichting (T-S) waves
A region where 3D unstable waves develop
A region where vortex breakdown produces locally high shear
Fluctuating, 3D flow due to the cascading of vortex breakdown
A region with turbulent spots
TURBULENT:
Fully turbulent flow

Stability theory predicts and experiments verify that the initial instability is in the form of two dimensional T-S waves that travel in the mean flow direction. The experimental transition illustrate that the process starts with T-S waves. Surface roughness or suction can reduce or eliminate one or more of the five transitional regions described above. [White 1991] For a smooth cylinder the transition occurs at $Re = 3.5 \cdot 10^5$ but from $Re = 2 \cdot 10^5$ the formation of the first T-S waves can be seen.

2.1.4 Effects of transition on a cylinder

For cylinders (and in general for bluff bodies) the transition from laminar to turbulent increases the skin friction because we have to add the Reynolds stresses to the friction drag but, on the other hand, the pressure drag decreases by a large margin by moving the separation point to the back of the cylinder and diminishing the width of the wake.

2.2 Correlation between drag and roughness on cylinders

Hoerner [Hoerner 1965] first and Shanebrook and Jaszczak [Shanebrook 1974],[Shanebrook 1976] after approximated the drag force on the human body with the help of a model consisting of series of circular cylinders which were used to simulate arms, legs and trunk and a sphere to simulate the head.

The concept behind this model was to link the the shape of the human body with shapes with known aerodynamic characteristics.

Following this hypothesis, most of the text have been carried out on cylinders.

Aerodynamic of cylinder have been extensively studied in the past years and a large number of references is present in literature.

The flow around circular cylinders is characterized by the occurrence of transitions marked by abrupt changes in mean flow parameters. It is known that the occurrence of laminar separation-turbulent reattachment bubbles is responsible for the low values of the drag coefficient (c_D) which-mark the end of the lower or critical transition.

Two main flow states can be then described:

- **Subcritical:** The first ($1.5 \cdot 10^5 < Re < 3 \cdot 10^5$) is characterized by symmetric pressure distributions, a gradual but substantial decrease in c_D.

- **Post-critical:** The second subregime begins at about $Re \approx 3 \cdot 10^5$ and it can be divided in 2 phases:
  - a first phase marked by intense flow oscillations due to formation and bursting of a single bubble on one or the other side of the cylinder, first intermittently on either side then oscillating from side to side. During this phase the c_D suddenly drops and it reaches its minumum value
  - a second phase where, as Re increases, the wake is formed by two-bubble flow pattern. In this phase the c_D slowly increases

Already in 1929 Fage and Warsap [Fage 1929] found out that the size of the roughness present on a cylinder could affect its aerodynamic properies stating that a cylinder could be considered smooth if teh excrecences do not affect the flow around the cylinder.

The concept has been further elaborated by Prantl [Prandtl 1961] who said that the roughness does not affect the flow if they are completley embedded in the laminar boundary layer. However, when the Re increases and the boundary layer gets thinner, the excrecenses might affect the flow causing an increase in drag.

However, not only the size of the excrecenses is important but the texture too. The two parameter caracterizing the roughness on a cylinder are then:

- The relative size of the excrecences k/Diam
- The texture
  - Shape of the excrecences
  - Distribution of the excrecences

Different kind of roughness texture and shape have been studied and applied to cylinders:

- Tripping wires and separation wires [James 1972],[Alam 2003b],[Naumann 1968]
- Tripping spheres [Mizuno 1970]
- Eddy generators [Joubert 1962]
- Sand rougheness [Achenbach 1977]
- Dimples [Bearman 1993]

James and Truong [James 1972] found out that the drag coefficient (c_D) could vary by 40% depending on the type of protrusion used on the cylinder. The data showed that the protuberance shapes, a trip-wire and an overlap, are nearly identical in their effect on the aerodynamic characteristics, and that their effect depends much more on location than on size.
An even higher drag reduction in terms of c_D has been obtained by Alam [Alam 2003b] positioning tripping rods of 5mm in diameter at 30°. At this angular position of the tripping rods, c_D was reduced by 67%. Farrell and Fedyiuk in [Farell 988] used wire-gauze shaped roughness for their experiments. The tests were carried out ona cylinder with a diameter of 5.08cm and steel wire cloths were used as roughness, in two sizes, with wire diameters 0.165mm and 0.254mm leading to a $k/Diam$=0.65% and $k/Diam$=1% respectively. A considerable decrease of the Re_{TRANS} has been found.
Buresti [Buresti 1980] used emery cloth to simulate the roughness and noticed that the critical regime could be reduced (and even eliminated) depending on the roughness size. His results also showed that it is not possible to characterize the flow by means of a Reynolds number based on the size of the roughness.
However, being the meaning of this project to lower the drag of the athletes during their race, leading to better performances. previous results show that dimpled surfaces (considered as negative rougheness) are able to lower the c_D at high Re, in the post-critical flow fase.
Bearman and Harvey [Bearman 1976] showed how dimples can affect the aerodynamic properties of golf balls and discussed why a golf dimpled ball is able to fly farther than a a smooth ball.
Their esperiments in 1993 [Bearman 1993] were carried out applying the golf ball dimples to a cylindrical surface.

2.3 Drag and textiles

Kyle [Kyle 1986], Brownlie [Brownlie 1992] noticed that loose clothing increase the frontal area of the athlete leading to an increase of drag of about 40%. Thight skin suits are then highrly recomended in order to lower the drag. Kyle in particularly noticed that a a suit two size larger could increase the drag of 3% on a nordic skier. Van Ingen schenau, already in 1982 [VanIngenSchenau 1982], found out that different materials are able to reduce the drag on the athletes. He noted that a wool suit has less drag than a lycra suit for speed below 7m/s while, for higher speed, the lycra suit has lower drag. Kyle [Kyle 1988] found out that a a lycra suit was able to reduce the drag of a cyclist of ca. 7%. Further experiments carried out by Browlie [Brownlie 1987] showed that textiles are able to textiles are able to affect the flow transition on bluff bodies. However, if fabrics are coated and thus their surface is smooth, then the roughness will not be enough to induce to flow transition. The importance of a tight fit has also been addressed by Browlie which found out that coated Lycra suits are able to keep a tight fit to the body even when the body is in movement. Porosity has also been taken into considerations by a number of authors. Watanabe [Watanabe 1989] found out that textiles with high permeability had higher drag than textiles with low permeability. The same findings were found by Holden [Holden 1988] which explained the increase of drag pointing that porous materials create surface flapping and move the separation point in the front side of the model leading to higher drag. A third reason for increase of drag is that the ventilation through porous fabrics traps the air inside the fabric and it leads to an increase of the skiers mass. This assumption have also been confirmed by Browlie [Brownlie 1987]which suggested the use of coated fabrics in order to redcuce the problem.

2.4 Aerodynamics and sports

2.4.1 Speed skating

2.4.2 General

Speeed skating as sport has been widely analyzed. Wind tunnel tests have been made in the past years in order to have a clear understanding of the effect of the athletes posture on the total drag. Already in 1976 Di Prampero studied the correlation between the power generated by a speed skater and the power needed in order to overcome the force caused by the air resitance (Drag). Van Ingen Schenau in 1982 [VanIngenSchenau 1982], following Di Prampero hypothesis [DiPrampero 1976] tried to measure the air friction in speed skating considering c_D being independent from the speed

$$D = \frac{1}{2} A_P c_D \rho v^2 = K_1 v^2 \tag{2.2}$$

This hypothesis has been also used by Watanabe and Ohtsuki which considered the c_D constant with the speed in alpine skiing. However Pugh [Pugh 1974], already in 1971, supposed that c_D would be dependent on the speed and can not be considered as a constant. His supposition was based on previous tests carried out on cylinders. He used the supposition the aerodynamic characteristics of the human body can de resembled to the ones for a cylinder [Hoerner 1965]. Hoerner, in his experiments showed that c_D is fairly constant over a range of Re values extending from 10^3 to 10^5 with a progressive fall in c_D for $Re > 10^5$ reaching a new low level at about $Re = 5 \cdot 10^5$, which is known as the critical Reynold's number (Re_{crit}). However, Pugh's experiments were

within a subrticritical range of Re and he was not able to reach the transition and consequently the fall in c_D. Van Ingen Schenau in 1982 [VanIngenSchenau 1982] concentrated his attention on the effect of speed, skater posture, velocity and clothing on the total drag.
A linear correlation between a normalized trunk angle position and drag was found and the same results have been obtained for the knee angle.
A more complete evaluation of the the forces acting agaisnt a speed skater during its motion has been developed by DeKoning [DeKoning 2000] Some previous models about external power in speed skating dealed with constant speed [VanIngenSchenau 1982]. However, during a speed skating race and especially during short races the speed is not constant. During the start of 500m race, the speed increase up to 14m/s within a span of 10s leading to a high power expense in order to increase the kinetic energy. The power balance equation presented by DeKoning [DeKoning 2000],[DeKoning 2005b] is:

$$P_u = P_f + \frac{dE_{mcb}}{dt} \tag{2.3}$$

where P_u is the power gerated by the skater, P_f are the frictional losses averaged and $dE_{mcb/dt}$ the rate of change of the kinetic and potential energy which can be rewritten as:

$$\frac{dE_{mcb}}{dt} = \frac{d\frac{1}{2}mv^2}{dt} = mv\frac{dv}{dt} \tag{2.4}$$

if we consider the energy of the mass center moslty determined by the rate of change in kinetic energy. The frictional losses P_f has been considered as a sum of the air frictional losses P_{air} and the ice frictional losses P_{ice} The variations during a stroke were considered negeligibles usind the Delnoy assumption [Delnoy 1986]. This model has been tested and improved by the same authors and validated

2.4.2.1 Speed skating suits

Speed skating suits fastly evolved during the last deacades, after researchers and scientist noticed that drag reduction on the athletes was possible by using different suits. A list of the milestone changes in terms of speed skating apparel has been diven by Kuper and Sterken [Kuper 2008]:

1976 - Skin suits are introduced by a Swiss skating veteran Krienbühl.
1998 - Ducth team used ziz zag stripes on their suits to shif t the transition to turbulent at lower regime thus reduce the drag.
2000 - Nike introduced the skin swift suit with rough patches on legs and arms.

Already in 1982, experiments carried out by van Ingen Schenau [VanIngenSchenau 1982] showed that modern skin suits indeed appeared to be faster than the woollen suit. He concluded that at speeds higher than 6-7 m/set the woollen suit causes more drag than the skin suit. At lOm/sec the difference is about 7% and at 14m/sec about 10%. A general conclusion was then that for speed higher than 6-7 m/s the new suits were able to reduce the drag compared to the old woolen suits

which, on the other hand, performed better at lower speeds.
This was due to the rough textile present in the new suits which is able to trip the transition to turbulent regime of the flow around the athletes. Some other minor parameters like the curvature of the back and the shielding were analyzed.
Len Browlie [Brownlie 1992] in his PhD thesis work analyzed the effect of different textiles. Tests have been carried out on different dimensions cylinder models and on mannequins.
In his work, Browlie addressed the problem of understanding how the textiles roughness can be expressed. His final finding was that skin suits can give high advantage in terms of performances due to the lower drag.
A deeper look at how different speed skating suits can influence performances in speed skating was given by Kuper and Sterken in 2002 [Kuper 2008]. They analyzed the effect of speed skating suits on speed skating performances basing their work on the data collected during the Olympic games in Salt Lake city 2002, focusing the attention on the new Nike suit with rough patches on arms and legs.
Their main findings were that for men there was a significant positive contribution to skating speed of the Nike suit for most distances. For women there, a significant positive contribution of the Nike suit was found especially for the longer distances (1500 meters and more). While for the other suits they did not do not find any positive contribution.
These results are somehow matching with what Browlie found in 2002 where he compared the average change in times between the skaters' Salt Lake performances and their previous Pre Salt Lake personal bests [Brownlie 1992]:

- Nike Swift Skin - US team athletes 0.91% faster
- Nike Swift Skin - Netherlands team athletes 0.93% faster
- Generic (non-branded) speedskating suits 0.05% faster
- The three other suits from major manufacturers all were slower, with negative percentages

In a successive study, Kuper and Sterken [Kuper 2008] stated that the suits, even if they give an advantage to the skaters in terms of drag reduction, do not affect the final performance. In order to analyze the effectiveness of speed skating suits they used the full set of speed skating results of the 2002 Olympic Winter Games of Salt Lake City and modeled the average skating speed of both male and female speed skaters at distances from 500 to 10 000 m.
Speed correlates with the physical characteristics of the skaters, past performance, and technical equipment, like speed skating suits that reduce drag.
Kuper and Sterken evaluated the parameters which affects athletes performances and included them in a weight model The parameters considered were:

- Home factor
- Lane
- Suit

  - Nike suit
  - Hunter
  - Descente
  - Mizuno

The average skating speed has been modeled using the individual skaters characteristics like age, length, weight and pre-event performance. As final conclusions they found out that pre-event results matter while the home advantage is unimportant. Nike's Swift Skin suit outperform other suits in terms of results, but once corrected for selection bias, non of the suits seem to overperform the others.

2.4.3 Cycling

Aerodynamics in cycling have been extensively studied. A number of publications with results based on wind tunnel testing is present [Kyle 2004],[Kyle 1984],[Kyle 1986],[Nonweiler 1956], [Davies 1980],[Pugh 1974],[DiPrampero 1979],[Capelli 1993]. However, some other authors, attempted to measure the drag on the field measuring the average external mechanical power of the cyclist, Pext(W) at constant V on each lap and thus finding the drag as follows: [Grappe 1997]:

$$Drag = P_{ext}/V \tag{2.5}$$

where the external power P_{ext} was measured by a simple device in with an indirect method.
In his article Grappe addresses the problem of different positions in cycling and tries to establish if there is any advantage in terms of aerodynamic reduction between four different positions:

- Upright position
- Dropped Position
- Aero position
- Obree position

He found out that considering the upright position as the reference position, a sensible drag reduction is possible. The drag reduction between the Obree position and the upright position was in fact 27.8%
However, as mentioned earlier, a number of other authors analyzed the influence of different positions on the total drag acting against a cyclist. Comparison of data from different authors ([Grappe 1997],[Whitt 1982],[Gross 1997]) show that the Obree position is by far the postion with the lowest drag. The effect ot textiles on cyclists performances has been analyzed by Kyle [Kyle 2004]

2.4.4 Ski jumping

Ski jumping is, together with skiing, the sport who has been most extensively studied.
The flight trajectory and the consequent flight length has been first analyzed by Tani [Tani 1971] and Komi [Komi 1974] 1974. In their studies they concentrate the attention on how the flight path is influenced by the different angles of attack of the body. A deeper analysis of the flight path has been done by Remizov [Remizov 1984] who analyzed the flight path and estimated the optimal angles during the flight path itself.
While Komi [Komi 1974] was considering a static position of the jumper during the flight, Remizov [Remizov 1984] and Tani [Tani 1971]] took into consideration that during the flight path, the ski jumpers body is subject to variable Drag and Lift forces. In order to complete the mathematical model, Remizov used the data from Grozin [Grozin 1971] obtained from wind tunnel testing.

$$m\frac{dV'}{dt'} = -F_D - mgsin\theta \tag{2.6}$$

$$mV'\frac{d\theta}{dt'} = -F_L - mgcos\theta \tag{2.7}$$

$$\frac{dx}{dt'} = V'cos\theta \tag{2.8}$$

$$\frac{dy}{dt'} = V'sin\theta \tag{2.9}$$

where t' is the time instant after the take off, x and y are the coordinated of the center of gravity, m is the mass of the system, g is the gravitational acceleration, F_D and F_L are respectively Drag and Lift which can be written as:

$$F_D = \frac{1}{2}\rho v^2 Ac_D(\alpha) \tag{2.10}$$

$$F_D = \frac{1}{2}\rho v^2 Ac_L(\alpha) \tag{2.11}$$

where ρ is the density of the air, A is the frontal area and c_D and c_L are the drag and lift coefficients which are dependent on the angle of attack α.
By solving a a Cauchy problem generated from the equation of the flight, Remizov was then able to determine the optimal flight path which is able to maximize the flight length.
At the same time he calculate the dependency of flight path from different parameters such as velocity at take off and Frontal Area A.
In the same period Ward Smith and Clemens [Ward-Smith 1982] reached the same results with a different mathematical simulation. While the Remizov approached was more focused on optimizing the flight path, Ward Smith tended more to analyze the factors that influence the flight path. In this article the effect of friction between ski and snow, jump technique at take off angle of

incidence of the jumper and effect of air density have been investigated.
The article was based on a mathematical model built on the equations for the in run:

$$\frac{dV}{dt} = gsin\beta - \mu gcos\beta - \frac{\rho v^2 A}{2m} - \frac{\mu v^2}{r} \tag{2.12}$$

where mV^2/r is the centrifugal force due to the change of curvature of the sruface slope, r is the slope radius, V is the speed, m is the mass of the skijumper, and β is the relative angle between the skier and the horizon

And flight path:

$$m\frac{d^2x}{dt^2} = -\frac{\rho V^2}{2}(c_D cos\theta + c_L sin\theta) \tag{2.13}$$

$$m\frac{d^2y}{dt^2} = mg - \frac{\rho V^2}{2}(c_L cos\theta - c_D sin\theta) \tag{2.14}$$

The main findings of Ward Smith were that the velocity at take off considerably affects the jump length matching the results from Remizov [1984] and an optimal angle during the flight of 35degrees has been found.
The air density has been found to influence the jump length, the lower the density is, the shorter the jump will be.
A complete review of the research carried out in ski jumping has been done by Schwameder [Schwameder 2001] and he found out that most of the studies can be divided into three main areas (a) field studies of hill jumps, (b) laboratory studies of simulation jumps, and (c) computer simulation of the flight phase.
A resume of the results shows dicrepancy in the correlations between release velocity and jump distance and correlations between vertical release velocity and jump distance. Correlation between body weight and jump lentgth has been first studied by Schmolzer [Schmolzer 2002],
[Schmolzer 2004] which addressed to the problem that ski jumpers were losing too much weight in order to improve their performances.
The solutions suggested by Schmolzer was that the ski length sould be adjusted to the Body mass index of the athlete. This lead to the fact that a ligher athlete should use shorter skis than an heavier one.

CHAPTER 3

Context and Research Design

3.1 Textiles area

3.1.1 c_D-Re curves for cylinders

One of the target of the present study was to link the aerodynamic properties of textiles to their surface structure. A c_D-Re curve, as described before can be split into three main regions. A first part of the curve, when the flow around the cylinder is still laminar and the c_D has a value close to 1.1. This region goes from Re=0 to $Re = Re_{crit}$ A second part, where the flow start becoming turbulent and the c_D drops until reaches its minimum value c_{Dmin}. This region goes from $Re = Recrit$ to $Re = Re(c_{Dmin})$ A third part where the flow is fully tubulent and the c_D value increases. $Re > Re(c_{Dmin})$ In the second area of the c_D-Re curve, a particular Reynolds number can be defined Re_{TRANS} which is the Reynolds number when the c_D has gone through half its drop.
In order to evaluate the performances of the textiles, Re_{TRANS} and c_{Dmin} has been chosen as reference parameters. Re_{TRANS} (or V_{TRANS}) for a certain textile gives a precise idea of the Re or the speed when the transtion (thus the drop in drag) is going to happen.
c_{Dmin} is the lowest value of c_D reached in a c_D-Re (o c_D-$speed$) curve or a and it also indicates the end of the transition phase. When a cylinder model reaches the c_{Dmin}, the flow around the model is fully turbulent. The main goal of this research area has been to link Re_{TRANS} and c_{Dmin} to the surface structure of the textiles.

3.1.2 Drag reduction by using textiles

A number of authors studied the correlation between roughness and drag reduction on cylinders. Particularly important and relevant is the contribute of Browlie that in the experiments carried out for his PhD thesis tested a large number of textiles and found out that different textiles can influence the aerodynamic performances of a cylinder and thus of the athletes by reducing the drag. The concept behind using textiles in order to reduce the drag of the athletes is well known in fluid mechanics. Textiles can be seen as distributed roughness on the athletes' body.
In general, drag on cylinders can be reduced in two different ways either by controlling the flow passively or by using some form of active control. Active control of the flow around the cylinder can be done using suction or blowing of the boundary layer. Among the passive control devices there is the introduction of roughness, vortex generators, interaction of wakes, etc. The main goal of this study is to find out how surface roughness influences the aerodynamic resistance.

The surface roughness, as previously mentioned in Ch.2 can be obtained using sand, stripes, dimples, etc However, from a practical point of view, textiles are the only solution in order to add a roughness to the human body. A number of authors carried out studies on cylinders, however a link between the aerodynamic characteristcs of the textiles and the surface structure has not yet been found.
Drag measurements has been carried out in order to find correlations between the surface structure of the textiles and the aerodynamic characteristcs.

3.2 Surface analysis and roughness models used

Two different models have been used for the commercial textiles analyzed in P1 and P2 and for the knitted textile analyzed in P3, P4 and P9. In commercial textiles in P1 and P2 were dimpled textiles with relative smooth surface and dimples of different size distributed on the surface. A parameter which was able to link the dimple depth and distribution has been used

$$k = \sqrt{width \cdot depth} \tag{3.1}$$

where width is the distance between two dimples and depth is the average depth of the dimples.
In the knitted textiles, the surface structure has been simplified in a two dimensional structure and the wales which are the main structure in a knitted textile have been considered as excrecences on the textile surface.Three parameters have been taken into consideration and linked into a new roughness coeffiecient k : the height of the wales present on the textile, the distance beteween two wales and the depth of the wales.

$$k = \sqrt{A \cdot width \cdot depth} \tag{3.2}$$

where in this case width is the width of a wale, A is the distance between two wales and depth is the average height of the wales. Optical porosity has also been measured with a electronic microscope. In the late part of the study, a new technique has been used in order to determine the surface structure of the knitted textiles in order to quantify the dimension of the holes present in the textiles analyzed. Digital images of areas of approximately 40 x 40 mm2 were acquired with a scanner, in transmission and reflection modes and the dimensions and shapes of the openings were quantified automatically.

3.3 Research Process

Drag measurements were carried out in order to correlate aerodynamic characterstics of the textiles with the surface structure. The surface structure was analyzed with microscope and two different models based on the excreces shape were made.
For the experiments, the wind tunnel at NTNU and the wind tunnel at RMIT were used:

NTNU wind tunnel
The test section of the wind tunnel is 12.5 meters long, 1.8 m high, and 2.7 m wide.
The wind tunnel is equipped with a 220KW fan that can produce a variation of speeds between 0.5 - 30 m/s.

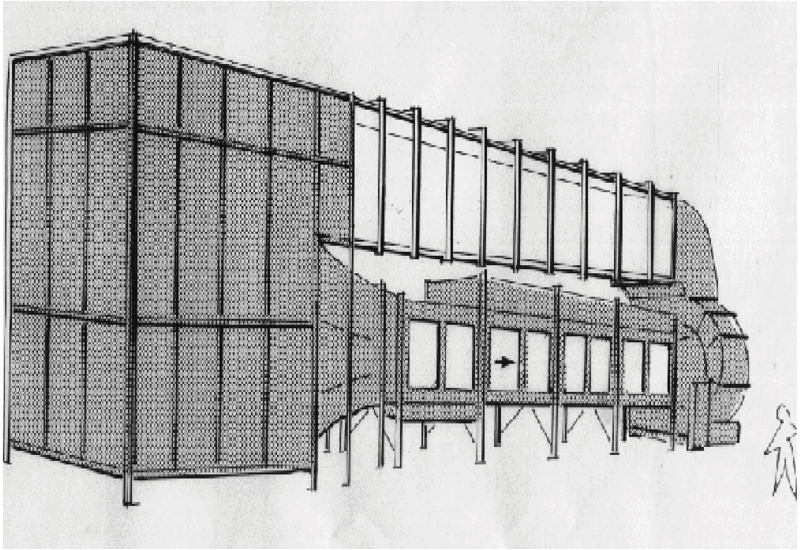

Figure 3.1: NTNU Wind tunnel

The balance (Carl Schenck AG) used is a six component balance capable to measure the three forces and the three momentums around the three axes. The voltage outputs are measured by a LABVIEW based PC program.

RMIT wind tunnel
It is a closed return circuit wind tunnel with a turntable to simulate the cross wind effects. The maximum speed of the tunnel is approximately 150 km/h. The dimension of the tunnelŠs test section is 3m wide, 2m high and 9m long and the tunnel's cross sectional area is $6m^2$.
The free-stream turbulence intensity is approximately 1.6%. Flow angularity is guaranteed to 3% in both pitch and yaw. There is no flow straightening or turbidity reduction hardware in the chamber. The diffuser operates within an angle of 5%, which is comparatively small. The nacelle wake does not close before the downstream turning blades.
The wind tunnel is equipped with a 6-component force sensor (type JR-3) which was used for the drag force measurements. The sensor provides 2 b/s serial data stream with 3 forces and 3 moments data at 8 kHz.
The sensor was mounted under the wind tunnel floor and was connected to the model with a support. Frequency filtering has been used in order to remove the background noise frequencies and a sampling frequency of 200 Hz was used during the experiments.

Models used at NTNU:

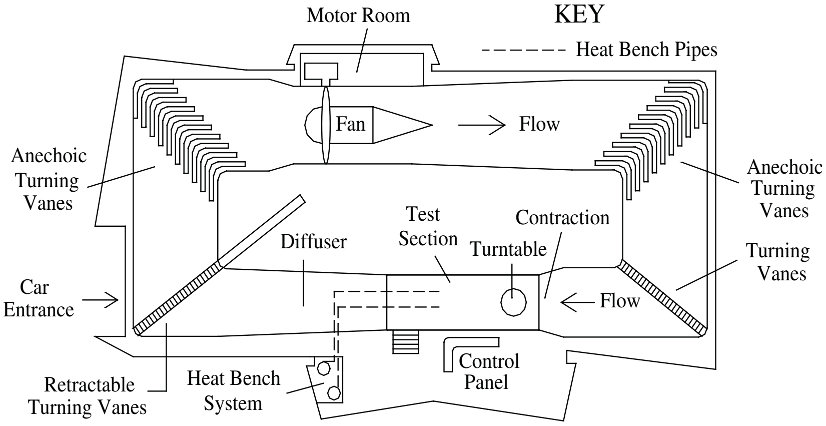

Figure 3.2: RMIT wind tunnel

Horizontal cylinder model: Three horizontal cylinder model made in PVC were used for experiments. Each cylinder has a different diameter (11cm, 20cm and 31cm) The cylinder moden is connected to a 6-component rotating balance positioned under the wind tunnel floor through a cylindical support with known drag. Two "dummy" cylinders are placed at the extremities of the cylinder model in order to simulate an infinite cylinder. A small gap of 5 mm was left between the two dummy cylinders and the test cylinder in order to avoid contact. The model is able to rotate on the vertical axis leading to the possibility to measure the effect of yaw angle. The length of the cylinder models is length is 120cm.

Vertical cylinder model: A vertical cylinder model was used in order to simulate the legs of an athlete. It consists in a support with a rail and 2 sliding cylinder models placed inside the rail. The distance between the cylinders can be varied and the model can be rotated along the vertical axis. Two dummy cylinders are placed above the cylinder model in order to simulate an infite cylinder. A small gap of 5 mm was left between the two dummy cylinders and the test cylinder in order to avoid contact. The diameter of the cylinder used is 11cm and the length is 40cm.

Mannequin: A full adustable mannequin has been used for the experiments carried out and presented in P5, P7 and P10. The mannequin has adjustable joints and represents a human body in scale 1:1. The height is 165 cm and the weight 70kg The mannequin can be connected to the 6 components balance with a cylindrical support.

Bycicle support: A bike supoort has been used when carrying out the experiments presented in P6. The bike support allows to connect a bycicle to the 6-components balance and thus to measure the force acting on the cyclist. It could be used either in a static or non static mode allowing the cyclists to bike while the forces are acquired.

Models used at RMIT:

Cylinder model A plastic cylinder model was used in order to test the aerodynamic properties of the knitted samples. Two dummy cylinders were added to reduce the 3D flow effects and to have a model, which suit d the infinite length hypothesis. The test cylinder has a diameter of 10cm, a length of 40cm and consequently a frontal area of 400cm^2. The two dummy cylinders are 15cm long and they also have a diameter of 100 mm. The test cylinder is connected to a 6-component balance with a stick which passes through the first dummy cylinder placed on the floor of the wind tunnel. The second dummy cylinder is placed above the test cylinder and it is connected to the wind tunnel floor with a steel support, placed 500 mm in the back stream direction in order not to influence the wake behind the cylinder and thus the drag. A small gap of 5 mm was left between the two dummy cylinders and the test cylinder in order to avoid contact between them that could affect the results.

Leg model A mannequin leg was cut to leave just the foot up to the knee. The foot and the knee were used as dummies in order to reduce the 3D flow effect. The model is made of fibreglass and was connected to a 6-component balance with a metal support. The test section of the model was 400-mm long and it had a maximum width of 100mm and a minimum width of 50mm. The frontal area was estimated to be approximately 30.000mm^2. A small gap of 5mm was left between the two dummy sections and the test section of the leg model in order to avoid contact between them which could affect the results.

3.4 Performances and prototyping area

Mannequin: A full adustable mannequin has been used for the experiments carried out and presented in P5, P7 and P10. The mannequin has adjustable joints and represents a human body in scale 1:1. The height is 165 cm and the weight 70kg The mannequin can be connected to the 6 components balance with a cylindrical support.

Bycicle support: A bike support has been used when carrying out the experiments presented in P6. The bike support allows to connect a bycicle to the 6-components balance and thus to measure the force acting on the cyclist. It could be used either in a static or non static mode allowing the cyclists to bike while the forces are acquired.

Bindings plate: A plate connected to the 6-components balance with bindings mounted on it has been used when human models have been used for the tests (P10). The plate is screwed to the 6-components balance and 2 adustable alpline ski bindings are welded to the plate. The bindings are adjustable both in width and length.

CHAPTER 4

Results

4.1 Study Area 1 - Textiles

4.1.1 Commercial Textiles (P1 and P2)

4.1.1.1 Transition shifting and $Re_{TRANS} - r$ correlation

It is possible to shift the transition to turbulent regime and consequently lower the drag by covering cylindrical models with textiles. The three textiles tested had different roughness parameters which were calculated using an optical microscope.
The roughest textile (Red textile in P1 and T1 in P2) was able to shift the transition at lower speed than the other textiles due to the higher r parameter. This lead to a lower drag at lower speeds. However, at higher Re, this effect fades and higher roughness leads to higher speed due to the increase of friction drag.
A logarithmic corralation between the Re_{TRANS} parameter and the relative roughness coeffcient r has been found.
This correlation is crucial in order to be able to link the right textile to the right Reynolds number and it allows to chose the textile which causes the transition on the cylinder model at the wanted speed when knowing the diameter of the cylinder.

4.1.1.2 Effect of the yaw angle on the $c_D - Re$ curves

Yaw angle has been proved to highly effect the aerodynamic characteristics of the flow around the cylinder and consequently on the $c_D - Speed$ curves.
Results showed that higher yaw angles reduce the positive effects caused by the roughness distributed around the cylinder.
When the yaw angle is >30° an increase in roughness on the cylinder surface corresponds to an increase of drag at any speed leading to the fact that using rough textile in order to reduce the drag is not suggested if the wind direction is not perpendicular.
From fig 4.2 and fig 4.3 can be seen how yan angle influences the c_D-Speed curves.
Some main conclusions can be drawn: -The absoloute value of the c_D is lower at higher yaw angle
-The drop due to the transition to turbulent regime is smaller at higher yaw angles
-The drag reduction caused by the roughness at low yaw angle is not present at higher yaw angles
-A clear decrease in the value of c_{DMIN} can be noticed for all the textiles tested -The yaw angle

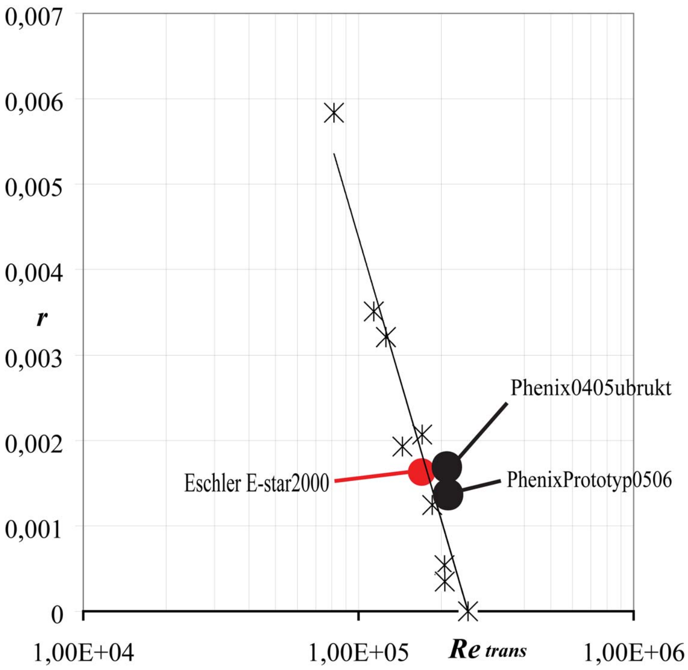

Figure 4.1: Correlation between r and Re_{TRANS}

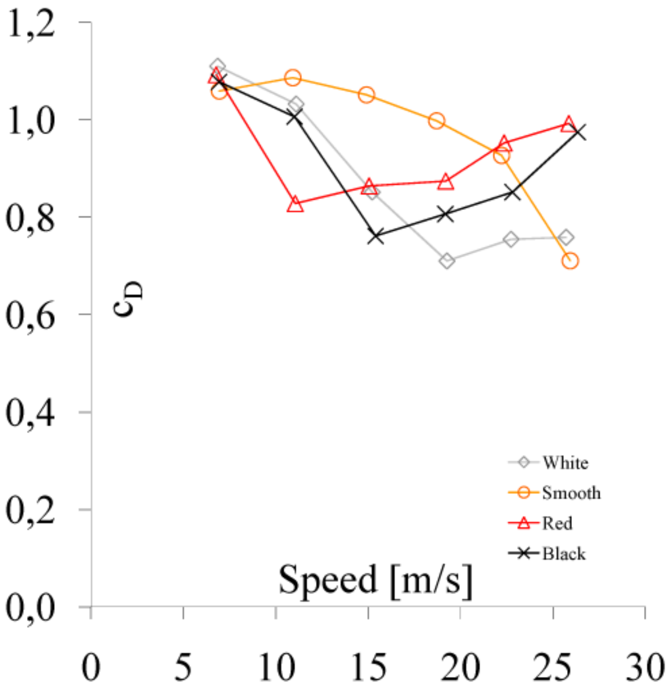

Figure 4.2: $c_D - Speed$ curve for a 0° yaw angle cylinder

influences V_{TRANS} which slowly decreases while α increases for all the different textiles tested (fig 4.4)

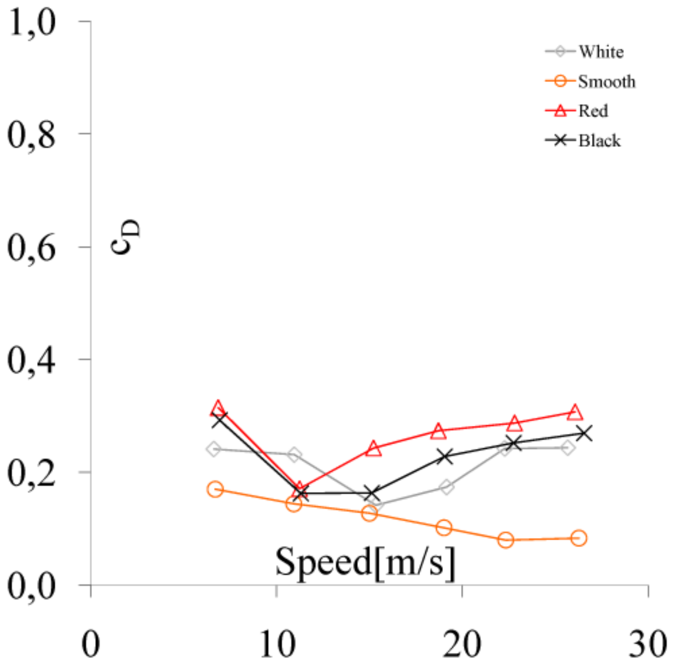

Figure 4.3: $c_D - Speed$ curve for a 45° yaw angle cylinder

4.1.1.3 Effect of the model dimensions on the $c_D - Re$ curves

Three cylinders with different diameters have been used for this test (11cm, 20cm and 31cm). The dimensions of the model affects the aerodynamic properties of the model.

Results show that a combined effect of roughness and change in diameter affects the aerodynamic properties of the cylinder.

As noticed by Fage and Warsap [Fage 1929], the correlation between roughness k (where k was for Fage and Warsap the average height of the excrescences) and the diameter of the cylinder Diam are strictly correlated and they should be linked into a parameter called relative roughness:

$$r = \frac{k}{Diam} \tag{4.1}$$

The diameter influences V_{TRANS} and c_{DMIN}.

An increase in diameter shifts the V_{TRANS} to a higher value and the same happens for c_{DMIN}. This lead to the fact that, for the large diameter cylinder tested (31cm), if low drag is needed, it is convenient to use smoother surfaces than the one used for the smaller diameter (11cm). For the 11cm diameter the lowest c_D is reached with the cylinder covered with T3 for 6 m/s<V<15 m/s and covered with T2 for 15m/s<V<26m/s. For the 31cm diameter cylinder

4.1.1.4 Effect of distance between two models

The distance between the models has been proved to affect the flow around the models and thus the aerodynamic properties of the model itself.
In particular, if the distance D between two vertical cylinders is smaller than than the Diameter of the cylinder, the drag reduction induced by the rough textiles does not occurs.
Some main conclusions can be then drawn:
-When D increases, both parameters (V_{TRANS} and c_{DMIN}) decrease.
-If for $D/Diam$=1 the advantage of using rougher patterns to shift the transition at lower speed is almost negligible.

4.1.1.5 Interpretation of the results and practical use of them

Applying the results show above to a practical level like for instance the design of a skin suit for cycling or speed skating, a few aspects needs to be taken into consideration:
the first aspect is that the human body is far more complex than a cylinder and that the wake produced by a human body, and thus its drag are is generated from the interaction of a number of shapes and parameters.
However, the results can help in order to minimize the drag. A clear attention needs to be given to the posture that the athlete assume during its motion. For instance in speed skating, back, head and thighs are often hit by the wind with an angle which is larger than 45° leading to the fact that smoother textile will guarantee a lower drag for these body parts.
On the other hand, lower legs, shoulder and often arms are almost perpendicular to the flow and the use of rough textiles could help reducing the drag acting on these body parts.
Speed has been proved to be another crucial factor. At lower speed, a higher roughness leads to lower drag than a smoother one.
Another important factor which needs to be considered is the size and the shape of the body parts. Arms and legs for instance have different sizes and, from the results shown, a rougher textile is suggested on smaller body parts.

4.1.2 Knitted textiles (P3, P4 and P9)

4.1.2.1 Structure and surface analysis of knitted textiles

The surface structure has been analyzed with two different methods. In P3 and P4, the surface analysis has been carried out with an electronic microscope and a surface texture model has been made in order to simplify the texture.
In P9, where the effect of the base layer on a double layer (wool+polyester) textile has been studied, the surface structure analysis has been carried out using the scanner method suggeted by Chinga-Carrasco [Chinga-Carrasco 2009].

Roughness model

in order to be able to quantify the roughness of the textiles a roughness model has been created and a roughness parameter has been defined using the main geometrical characteristics of the textiles. A 2D model was chosen so that the complex 3D morphology of the textile could be simplified.
A linear correlation between the cover factor parameter and the roughenss parameter defined has been found for both front and back side of the polyester textile. An extensive analysis of the results can be read in P3.

Scanner analysis

Digital images of areas of approximately 40 x 40 mm2 were acquired with an Epson Perfection 4990 desktop scanner, in transmission and reflection modes. The resolution was 2400 dpi, giving a pixel size of approximately 10.6μm.
The images were processed with the ImageJ program ([Rasband 1997]. The images were thresholded automatically. Particles less than 50 pixels were removed. The dimensions and shapes of the openings were quantified automatically with the Shape descriptor
The following shape descriptor were considered; i) area, ii) form factor and iii) feret diameter. The area is given by the total number of balck pixels within each opening. The Feret diameter corresponds to the longest axis within a given object, as exemplified in Fig. 4.4b. The form factor is represented by the area/perimeter ratio as given by:

$$FormFactor = \frac{4\pi Area}{Perimeter^2}$$

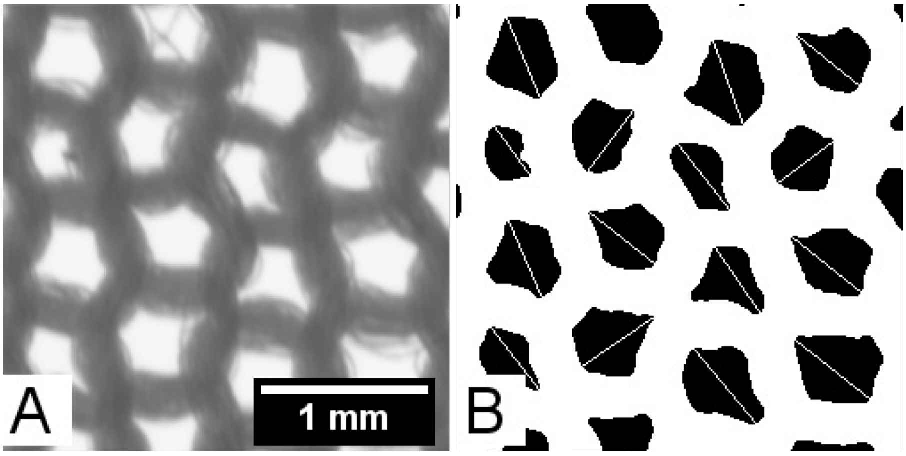

Figure 4.4: The corresponding segmented image, where the black areas correspond to the openings. The white lines within the black areas correspond to the feret diameters

From the surface analysis some main conclusions can be drawn:
-Increasing the CF increases the number of openings. The openings become smaller, i.e. the

opening areas decreases.
-The openings become more elongated when (i.e. the form factor decreases) when increasing the CF.
-The feret diameter gets smaller when the CF gets higher.

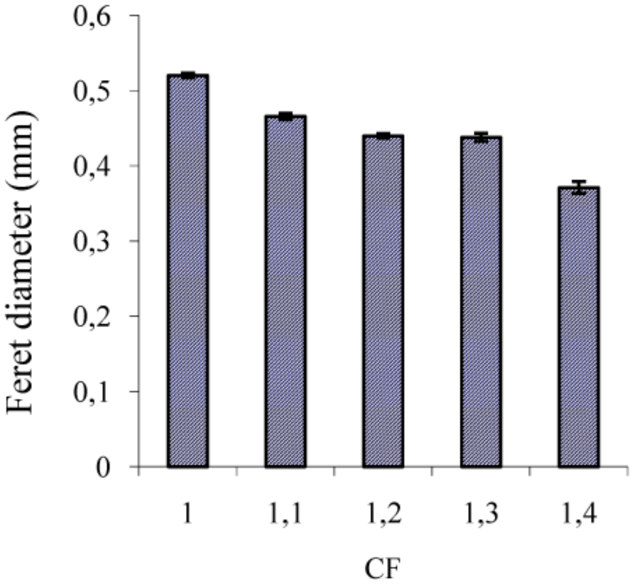

Figure 4.5: Correlation between feret diameter and CF

4.1.2.2 Aerodynamic of polyester knitted textiles

General remarks
The cover factor has been proved to influence the surface structure of the textiles and thus the aerodynamic performances of the textiles.
A higher cover factor corresponds to a smoother surface structure. This leads to the fact that a cylinder model covered with a textile with higher CF will reach the transition at higher speed than a textile covered with a textile with lower cover factor (and then rougher).
The same results have been obtained for a cylidrical model and for a leg model leading to the fact that a cylidrical model can approximate a leg model.
The polyester textiles has been tested in both sides (technical front and technical back) and the results show that the shape of the excrecences influences the aerodynamic properties.

Influence of base layer on double layer textiles (P9)
The base layer has been proven to influence the aerodynamic properties and the surface structure of the textiles.
Each layer in the fabric assembly has its own significant impact on the aerodynamic and moisture management properties of the entire assembly; however the results from the series of aerodynamic

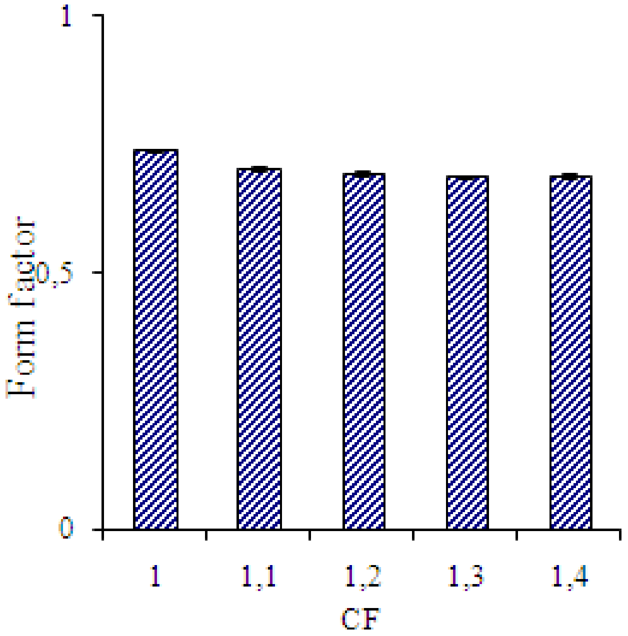

Figure 4.6: Form factor and CF

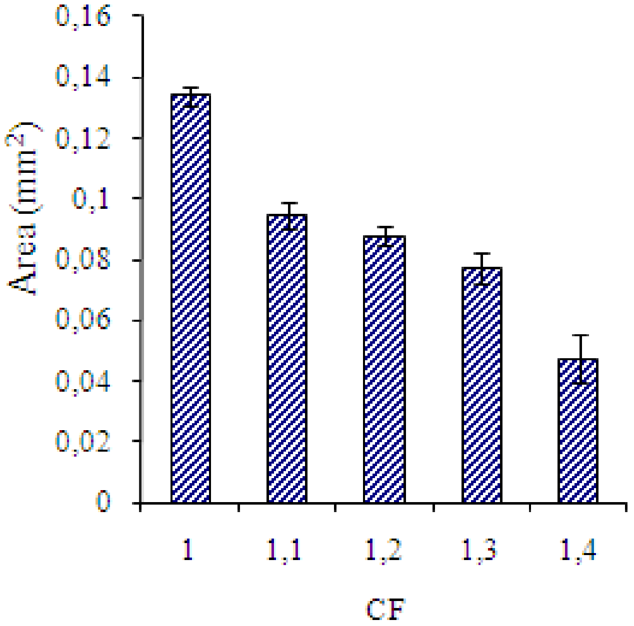

Figure 4.7: Correlation between area and CF

tests demonstrate that the base layer gains more importance in terms of aerodynamic performance when CF of the top layer increases.

The top layer influences the aerodynamic performaces more than the base layer since it directly modifies the external surface structure of the model.

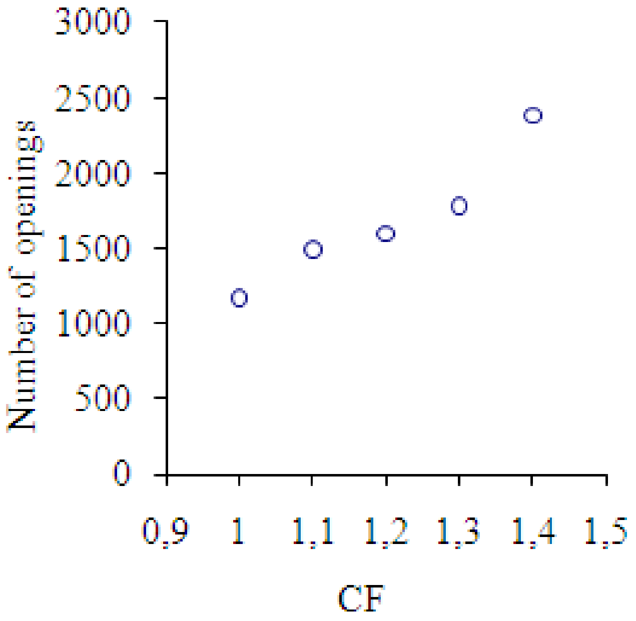

Figure 4.8: Correlation between area and CF

4.2 Study Area 2 - Performances and Prototyping

4.2.1 Suits prototyping and testing

In P5 the effect of rough textiles on speed sating suits has been studied and some interesting results have been found.

A mathematical method based on a balance between the power output generated by the athlete and the power spent in order to overcome inertia, friction (ice-blade) and drag has been used to simulate the performances of the different suits tested.

Due to the different power output generated by a female and male athletes, which leads to a different speed reached during the skating motion, some suits work best for women than for men and viceversa.

The results show that it is desirable to have a rougher pattern on the female suits legs, than on the male suits legs.

The same results have been obtained when comparing long distances races to short distances races: a rougher textiles are advantageous on longer races where the average speed is lower.

However, if the textile on the legs is too rough, the performances can be negatively affected by an increase of drag especially at high speeds.

Rough textiles has been proven to work in order to reduce the drag also on loose fit suits. In P10 a suit for ski cross competition has been designed using the database of data acquired and presented

in P1, P2 , P3 and P4.
Basic tests have been carried out on cylinders in order to evaluate the effect of the texture and of the thickness of the textiles.
In a loose fit suit, the thickness covers an important role. A thicker textile leads to a higher surface area and thus to higher drag.
A right combination between thickness and roughness has been found.
A final suit with a drag reduction of 15% has been made and used by the Norwegian ski-cross team during the Winter Olympic Games in Vancouver 2010 helping two Norwegian athletes to win a silver and a bronze medal.

4.2.2 Ski jumping and BMI

The experiments carried out showed that the actual rules used in ski jumping in order to reduce the dangerous trend of underweight atlhetes do not efficiently work.
Even if heavier jumper have an advantage in terms of speed at take off due to the higher mass, the higher lift induced by longer skis is not enough to compensate the negative effect induced by the higher mass.
However, the idea of cutting the skis if the BMI value of the athlete is too low, partially worked since the lift acting on the jumper is reduced when the skis are shorter.

4.2.3 Cycling and drag reduction

Results presented in P6 showed that small adjustments in the cyclist posture can give a gain in terms of drag reduction without compromising the biomechanics.
The results clearly show that it is not possible to define a general optimum posture but it is crucial to act on each athlete separately optimizing the biomechanics with the aerodynamics.

CHAPTER 5

Conclusions

The studies presented in this thesis shows that wind tunnel testing are still crucial in order to optimize the athletes's aerodynamics either by improving thier equipement or their posture.
Textiles can affect the aerodynamic properties of the human body if placed on the right body parts.
Results clearly shows that a correlation between the roughness present on the textiles and the aerodynamic properies is possible.
However some points still need to be clearified and future work is needed in order to link the high number of parameters which defines the surface structure of textiles to the aerodynamic properties.
The multidisciplinary approach of evaluating comfort and aerodynamic properties of the textiles with different approaches is innovative for the field and it has a high potential.
All the question directly posed by the olympic committee has been answered and solutions and motivations were found.
A resume of the questions and answer is listed below:
Q: Can rough textiles influence the aerodynamic of speed skaters?
A: Yes, if the textiles are used in the right way. Considering important parameters such as speed, size of the body parts, angle of attack of the body parts and distance between the body parts.
Q: Can a speed skating suit with a too rough surface on the legs have a higher drag than a skin suits with the legs covered with a smoother textile?
A: Yes, the use of rough textiles is effective only if optimizied on the wind speed and size of the athletes' body.
Q: In order to jump longer in a ski competiton: is it better be light and use shorter skis or be heavier and get the advantage of using longer skis which generates more lift?
A: With the current rules, it is still advantageous to be light and use short skis instead of be heavy and use longer skis.
Q: Is it possible to use rough textiles to reduce the drag also in loose fit suits like the one used in ski-cross?
A: Yes, but in this case, thickness plays an important role as well. An accurate balance between roughness and thicnkess is then needed in order reach the optmimum.

CHAPTER 6

P1

Reducing the athletes's aerodynamical resistance

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Abstract: This paper presents an experimental investigation on the effect of surface roughness on athletes legs and arms. Because of their cylindrical shape, arms and legs of an athlete can be approximately studied as flow over circular bodies. The variation of roughness has been obtained using three different textiles and changing the diameter of the cylinder. To evaluate the results, three more textiles have been tested on the 20cm diameter cylinder. Two of them are utilized in two alpine suits used by the Norwegian alpine ski team and one is from a ski suit produced by Eschler. All the results have been compared with a cylinder with a smooth surface. The critical Reynolds number for a significant drop in the drag coefficient decreases by increasing surface roughness.

6.1 Introduction

In many sports the aerodynamical resistance (drag - *D*) is of primary importance for the athlete's performance - e.g. in speed-skating where *D* is about 80% of the physical forces acting against the athlete's speed; and in a ski-jumper's in-run where the velocity at take-off is determined by 60% for the ski/snow friction and 40% by *D*.
Estimates using these figures show that a speed-skater will reduce his lap-time by one tenth of a second per % reduced *D*, and that a ski-jumper can increase significantly the velocity at take-off by a modest reduction in *D*.
D can be defined as:

$$D = \frac{1}{2} c_d A V^2 \tag{6.1}$$

The drag D is proportional to the square of the velocity V, where c_DA is the product of the Drag coefficient and a characteristic cross sectional area - and is an important parameter to evaluate and work on to minimize.

One can work on this parameter by either 1)reducing and 'streamlining' the body, and/or 2) by manipulating the flow close to the body such that flow separation from the body is delayed - producing a smaller wake zone and thereby less drag force.

The athletes themselves normally have no quantitative feedback on how effective their body posture and equipment is minimizing D. The wind tunnel equipped with instrumentation for measurement of physical forces represents an efficient way of quantitatively optimizing body posture and develop aerodynamically clothing and equipment for the athletes.

For a speed-skater the leg, from the skate and up to the knee, represent about 1/3 of the skater's total air resistance. By tripping the airflow boundary layer on the leg, using certain material textures, separation can be delayed and the leg's D significantly reduced.

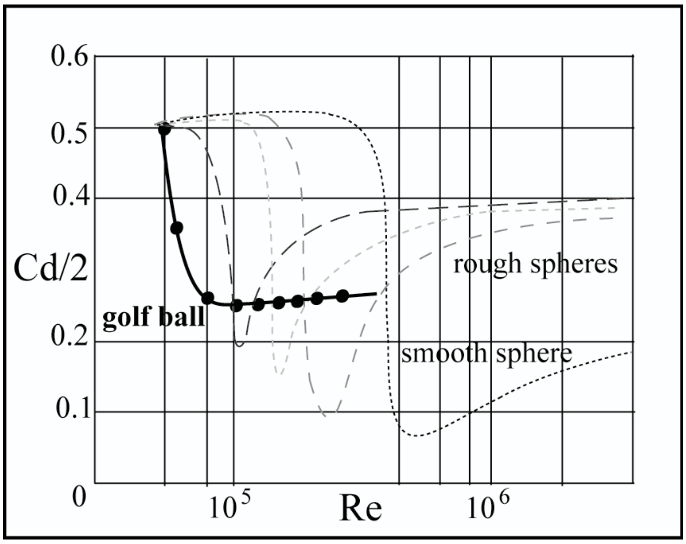

Figure 6.1: Variation of c_D with Reynolds number for smooth and rough sphere and golf ball

Working on body postures for ski-jumpers (in-run) resulted in an increased speed of 1 km/h at take-off for the Norwegian national team (in average) In the experiments carried out it has been chosen to focus the attention on the reduction of drag in legs and arms using different textiles with different surface roughness (or dimples).

Using the approximation that legs and arms are cylindrically shaped the textiles has been tested on cylinders with different diameters. For smooth cylinders in a cross flow the critical Reynolds number (when transition occurs and the drag coefficient fall) is around $3 \cdot 10^5$. The introduction of surface roughness on the cylinder surface can shift the transition to lower Reynolds number.

Increasing the roughness parameter induce a reduction in the value of the critical Reynolds number but also a lower the fall in c_D. That has been shown by Achenbach [Achenbach 1977] for spheres and by Bearman and Harvey [Bearman 1976] for cylinders. From Achenbach's experiments [Achenbach 1977], for the post-critical regime, to increase the roughness on a sphere means increasing the drag coefficient if it is compared with a smooth surface sphere (Fig. 6.1). Flows

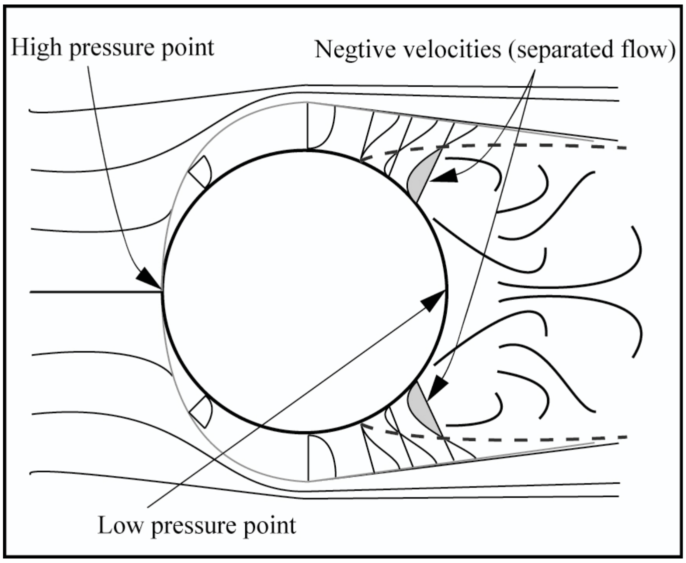

Figure 6.2: Flow around cylinder

around spheres and cylinders are very similar so it can be expected that the results carried on from the experiments done will be close to the results of what Achenbach [Achenbach 1977] and Bearman-Harvey found [Bearman 1993], [Bearman 1976]. The target is to obtain the same drag reduction for a cylinder as obtained for a golf ball (Fig. 6.1) by covering the cylinder surface with clothing of different textures thereby varying the roughness coefficient.

This will permit the estimation of the drag reduction in the cylindrical parts of the athlete's body.

6.2 Effect of transition and separation

The total drag can be split in two different parts. A part of drag is due to skin friction and is called friction drag and another part is due to the difference between the high pressure in the front part of the body (close to the stagnation point) and the low pressure on the rear region (separated region) and is called pressure drag.

$$c_{dTOT} = c_{dFRICTION} + c_{dPRESSURE} \tag{6.2}$$

The relative contribution of friction and pressure drag depends on the body shape, especially its thickness. The cylinder is a bluff body and most of the drag, even with a rough surface, will be contributed by the pressure drag.

For cylinders (and in general for bluff bodies) the transition from laminar to turbulent increases the skin friction because of the Reynolds stress but, on the other hand, the pressure drag decreases by a large margin by moving the separation point to the back of the cylinder and diminishing the width of the wake.

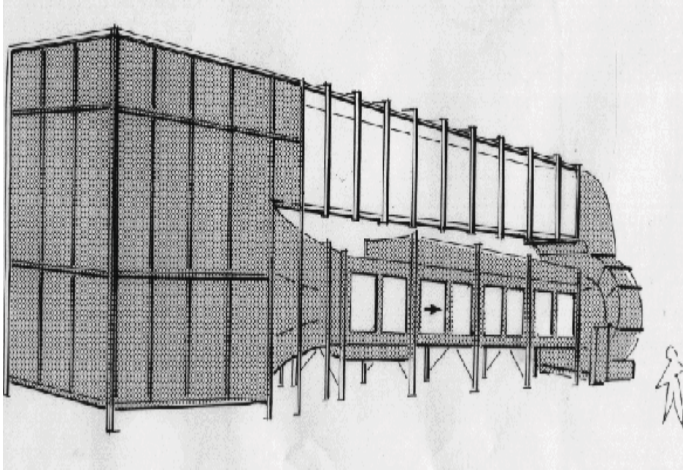

Figure 6.3: Wind tunnel

6.3 Experimental setup

6.3.1 Wind tunnel

For the experiments, the wind tunnel of NTNU (Norwegian University of Science and Technology) in Trondheim has been used. (Fig. 6.3). The contraction ratio is 1:4.23, and the test section of the wind tunnel is 12.5 meters long, 1.8 m high, and 2.7 m wide. The wind tunnel is equipped with a 220KW fan that can produce a variation of speed between 0 - 30 m/s.

6.3.2 Cylinder position in the wind tunnel

The cylinder is mounted as shown in and it is connected to a balance positioned under the wind tunnel floor. The cylinder is mounted in the wind tunnel on a support and two dummy cylinders are connected to the wall but not to the balance to reduce the finite cylinder length effect. This solution permits a comparison of the results with an infinitely long cylinder. The cylinder length is 120cm (for all the 3 cases: 11cm, 20 cm, 31cm diameter.)

6.3.3 Six components balance

The balance (Carl Schenck AG) used is a six components balance capable of measuring the three forces and the three momentums around the three axes. Variations of forces and momentum are measured using strain gauges glued to the balance body.
The voltage outputs are measured by a LabVIEW based PC program.

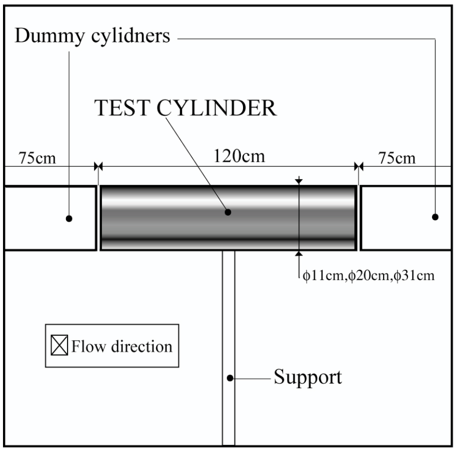

Figure 6.4: Cylinder in the wind tunnel

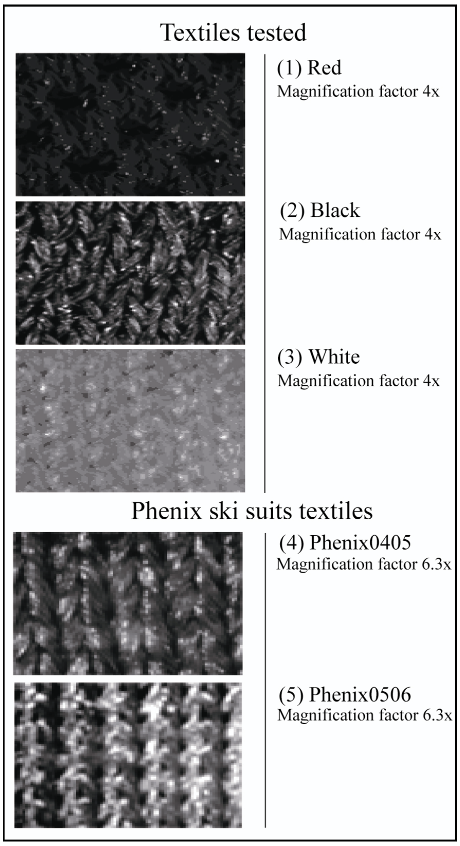

Figure 6.5: The five different textiles used

6.3.4 Textiles

The following chapter shows the different textiles used to change the surface roughness on the cylinders. The five textiles have all different surface roughness Fig. 6.3.4.
Different roughness has been obtained manufacturing each textile in a different way and with a different pattern. Fig. 6.5.
The roughness factor for each textile was found using an electronic microscope with a magnification factor of 20X. Based on structure width and depth a surface parameter can be defined as:

$$k_{surface} = \sqrt{w \cdot d} \tag{6.3}$$

Only for the black textile it has been chosen to use a different surface because of the different structure of this textile. The black textile presents in fact an inner-seam and an outer-seam. The roughness calculated is the average between inner and outer roughness.

$$k_{surfaceTOT} = \frac{k_{inner} + k_{outer}}{2} \tag{6.4}$$

Fig. 6.5 represents five pictures of the textiles. The first three (1),(2),(3), are obtained using a magnification factor of 4X.

	k	***r***
11cm Red (1)	642	5.84E-03
11cm Black (2)	386	3.51E-03
20cm Red (1)	642	3.21E-03
20cm Black (2)	386	1.93E-03
31cm Red (1)	642	2.07E-03
31cm Black (2)	386	1.25E-03
11cm White (3)	108	9.82E-04
20cm White (3)	108	5.40E-04
31cm White (3)	108	3.48E-04
20cm 0405 (4)	273	1.37E-03
20cm 0506 (5)	335	1.68E-03

Figure 6.6: Roughness parameters of the different textiles used

The red textile is the roughest and some dimples are present on the structure. The black structure presents a roughness parameter *k* between the red and the white textile. Some dimples are presents also in the black textile structure but it is not possible to localize them in the picture shown.
Figures Fig. 6.5(4) and Fig. 6.5(5) shows the pictures obtained with a magnification factor of 6.3 of the two textiles used in the alpine suits.
The roughness parameter *k* is a surface length scale that will influence on the flow close to the cylinder surface.

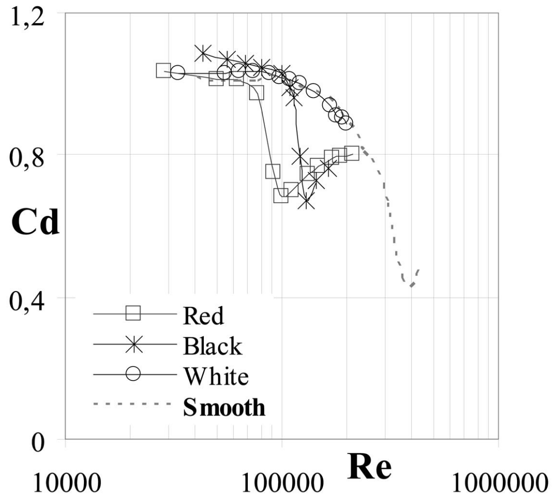

Figure 6.7: 11cm cylinder

The surface curvature (given by the cylinder diameter) determines the pressure gradient that influences on the flow separation conditions. Then combining these two parameters in a dimensionless roughness coefficient *r*:

$$r = \frac{k}{Diam} \tag{6.5}$$

6.4 Results

6.4.1 c_D-Re curves

The four curves in figure Fig. 6.7 represent the c_D-Re curves for the 11cm diameter cylinder. The transition for the black ($r = 3.51 \cdot 10^{-3}$) and the red ($r = 5.84 \cdot 10^{-3}$) textile occurs at lower Reynolds number than for the smooth cylinder and for the white ($r = 9.82 \cdot 10^{-4}$) material The results are conform to the literature: increasing the roughness, the transition to turbulent starts at a lower Reynolds numbers which means that it is possible to reduce the drag of about 40%. Over a certain Reynolds number range the white textile has a c_D-*Re* curve similar to the c_D-*Re* curve for the smooth cylinder.

Choosing the correct material for the correct speed enables a drag coefficient reduction of about 40%-45%. Comparing the 20 cm diameter cylinder results Fig. 6.8 with the same graph for the 11cm diameter Fig. 6.7 it is easy to recognize the same trend (increase roughness means shift the transition to lower Reynolds number).

Until a certain Reynolds number ($Re = 1.75 \cdot 10^5$) the red textile ($r = 3.21 \cdot 10^{-3}$) minimizes the drag coefficient most. Between $Re = 1.85 \cdot 10^5$ and $Re = 2.7 \cdot 10^5$ the black ($r = 1.93 \cdot 10^{-3}$)

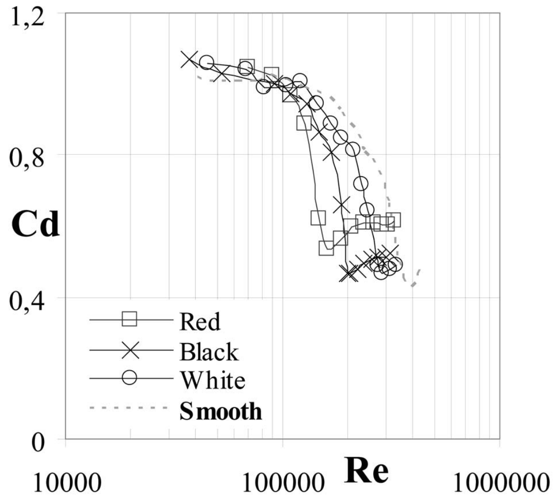

Figure 6.8: 20cm cylinder

and for a $Re > 2.7 \cdot 10^5$ the white textile ($r = 5.4 \cdot 10^{-4}$) produce the lowest drag coefficient. Increasing the Reynolds number ($Re > 3.2 \cdot 10^5$), the cylinder with the red textile has a c_D higher than the c_D measured for the smooth cylinder. The c_D-*Re* curves trend for the 31cm diameter cylinder is comparable to the tendency shown in Fig. 6.8 and Fig. 6.7 for the 11cm and 20cm diameter cylinders.

For the lower Reynolds number region the cylinder dressed with the red textile ($r = 2.07 \cdot 10^{-3}$) is the one with the lowest c_D, for the middle region the black textile ($r = 1.25 \cdot 10^{-3}$) minimizes the drag coefficient and for high Reynolds number the material that minimizes the drag coefficient more than the others is the white textile. ($r = 3.48 \cdot 10^{-4}$).

It is also easy to see, that now the drag coefficient reduction is about 20-30% which is less than the 40-45% found for the other cylinders (11cm and 20 cm diameter).

6.4.2 Roughness coefficient correlation

The correlation between the roughness parameter *r* and the trend of the c_D-*Re* curves has been analyzed defining a specific Reynolds number Re_{TRANS}.

This specific Reynolds number has been chosen to give an approximate description of where transition occurs.

Defining Re_{TRANS} as the Reynolds number where the c_d curve has gone through half its drop, Re_{TRANS} can be correlated with the roughness coefficient *r* (Fig. 6.10), and the results can be expressed by the correlation

$$r = A + B\ln(Re_{trans}) \tag{6.6}$$

where the best fit for our limited data base is for A=0.0594, B=-0.0048

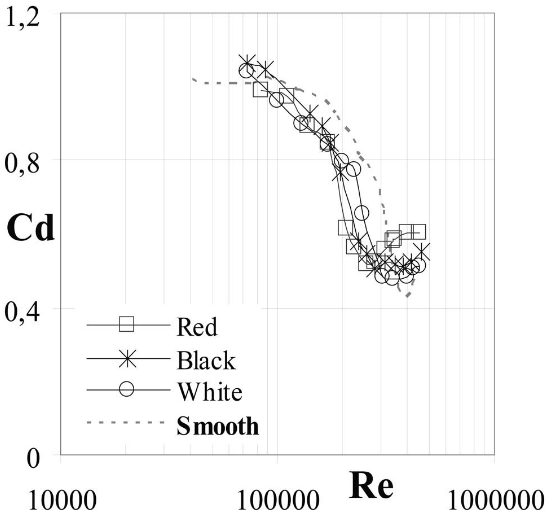

Figure 6.9: 31cm cylinder

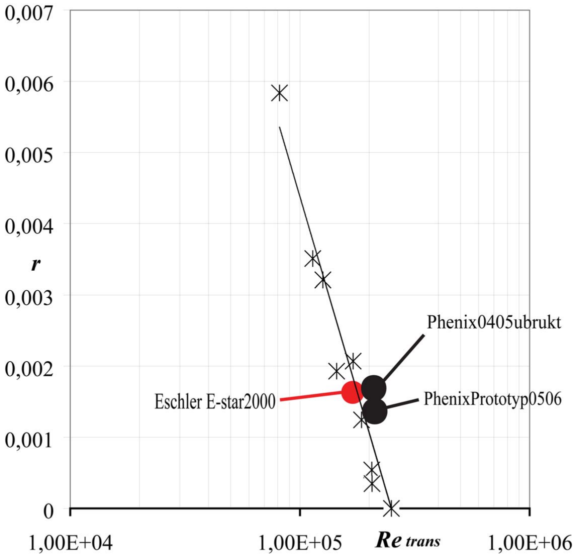

Figure 6.10: Correlation between r and Re_{trans}.

The 3 round marks present in the (Fig. 6.10)are relatives to the data acquired for 3 textiles from 2 different ski suits used by the Norwegian national team and one from a new suit produced by Eschler

6.5 Conclusions

Experiments carried out on cylinders dressed with different textiles show that the introduction of surface roughness (dimples), cause the critical regime to occur at lower Reynolds numbers than for smooth cylinders. For increasing roughness, the experiments show that transition occurs at lower Reynolds numbers.

An explicit correlation between the roughness factor *r* and the typical Reynolds number Re_{TRANS} has been suggested The results for drag reduction presented here can be used for choosing the right textiles when designing suits for athletes, thereby reducing the athlete's aerodynamical resistance.

6.6 References

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CHAPTER 7

P2

Experimental analysis on parameters affecting drag force on athletes

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Abstract:
In sports where high speed is reached and drag is the main force acting on the athlete's body, the posture highly influences the total drag. Due to the fact that the total drag is proportional to the frontal area, the athletes minimize their frontal area keeping the trunk parallel to the air flow (cycling, speed skating, downhill skiing). In these disciplines, the aerodynamic resistance acting on the legs counts up to 1/3 of the total drag. In order to reduce the drag, rough textiles with different patterns have been used in sport suits. However, a certain number of parameters need to be considered in order to optimize the aerodynamic performance of a textile. These parameters are: speed, diameter of the leg, yaw angle, distance between the legs and roughness of the textile.

7.1 Introduction

The human body can be approximated as a series of cylinders with different shape and inclination. This assumption has been made for the first time by Hoerner [Hoerner 1965] first and Shanebrook and Jaszczak [Shanebrook 1974],[Shanebrook 1976], and it is adopted by a number of scientist ([Brownlie 1992], [Oggiano 2007]) in order to estimate the influence of textiles on the total drag of the athletes. When covering a cylinder with a textile, the same effect as adding an artificial roughness to a cylinder can be obtained.
Previous results ([Fage 1929],[Bearman 1993],[Achenbach 1977]) shows that roughness is able to generate turbulence and affect the flow around the cylinder.
Three factors have been highlighted by Fage and Warsap [Fage 1929]

- Relative roughness k/Diam

- Shape of excrescences
- Distribution of the excrescences

The relative roughness is then correlated to the diameter of the cylinder itself and the shape and distribution of the excrescences is a characteristic of the textile used.
In order to decide which textile should be placed on each body part, an accurate analysis of the main parameters which determines the drag should be done. These parameters can be divided in:

- Flow parameters
- Geometrical parameters

Flow parameters: The athlete's body, during its motion, assume different positions and the air flow almost never hits any body parts perpendicularly. At the same time, distance between the legs varies from discipline to discipline. De Koning [DeKoning 2000], addressed that the posture of a skater during a race can be defined using two angles (ϑ_1,and ϑ_2) where ϑ_1 is the angle between the trunk and the horizon (trunk angle) and ϑ_2 is the angle between upper and lower leg (knee angle).
The average values found for these angles are ϑ_1= 13.7° and ϑ_2=106°.
These effects need then to be studied separately and the effect of textiles in each of the above mentioned configurations need to be taken into account in order to have a clear picture of how textiles influences the aerodynamic properties of athletes bodies.
Geometrical parameters: Each body part has a different size and can be represented with a cylinder with different diameters *Diam.* In a number of sports involving high speed (downhill skiing, speed skating, ski-jump in run) the legs can be considered as side by side cylinders and the aerodynamic properties of side by side cylinders are different than the properties of single cylinders and can be linked to the distance D between the cylinders.

7.2 Experimental apparatus and method

7.2.1 Wind tunnel

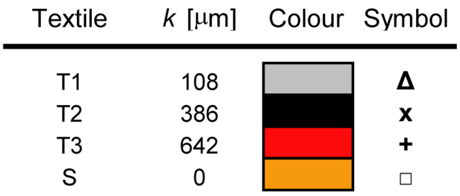
All tests have been carried out in the NTNU wind tunnel The test section of the wind tunnel is 12.5 meters long, 1.8 m high, and 2.7 m wide. The wind tunnel is equipped with a 220KW fan that can produce a variation of speeds between 0.5 - 30 m/s. The balance (Carl Schenck AG) used is a six component balance capable to measure the three forces and the three momentums around the three axes.

7.2.2 Textiles

Three different textiles with different roughness have been used. To determine the roughness coefficient *k*, a model based on length between the dimples present in the textiles and dimples depth have been used.
k can be defined as:

$$k = \sqrt{w \cdot d} \tag{7.1}$$

where *w* is the distance between two dimples and *d* is the depth of the dimples



Textile	*k* [µm]	Colour	Symbol
T1	108	⬜	Δ
T2	386	⬛	x
T3	642	🟥	+
S	0	🟧	□

Figure 7.1: The three textiles used and relative k factor values. S is the smooth cylinder. Three different coolurs have been associated to each textile: Red, Black and Grey while the smooth cylinder is orange.

7.3 Results and discussion

7.3.1 Flow parameter

7.3.1.1 c_D-Speed curves for cylinders

An accurate analysis of a typical c_D-Speed curve for cylinders is relevant in order to be able to evaluate the performances of each textile. In literature these curves are often represented as c_D -Re where Re is a non dimensional parameter called Reynolds number and it is defined as:

$$Re = \frac{V \cdot Diam}{\nu} \tag{7.2}$$

Where V is the speed, *Diam* is the diameter of the cylinder and ν is the kinematic viscosity of the fluid. However, a correlation between textile properties, drag and speed is more useful for practical purposes. The c_D-Speed curve can be divided into 3 main regions : Pre critical zone [V<V_1]: the boundary layer around the cylinder is laminar, the c_D is constant and its value is around 1,1. Critical zone [V_1<V<V_2]: the flow is in transition from laminar to turbulent regime and c_D drops from $c_D PRE$ to c_{DMIN} . The size of the drop (Δc_D) from c_{DPRE} to c_{DMIN} depends on a number of parameters including roughness type, roughness shape, and diameter of the cylinder. A specific velocity (V_{TRANS}) has been defined in order to give an approximate description of where transition occurs and it is defined as the velocity where the c_D curve has gone through half its drop (Δ c_D /2). A simplified model of the critical zone permits to define the transition with V_{TRANS} and c_{DMIN}. Post critical zone: [V>V_2]: the flow is fully turbulent and c_D slowly increases

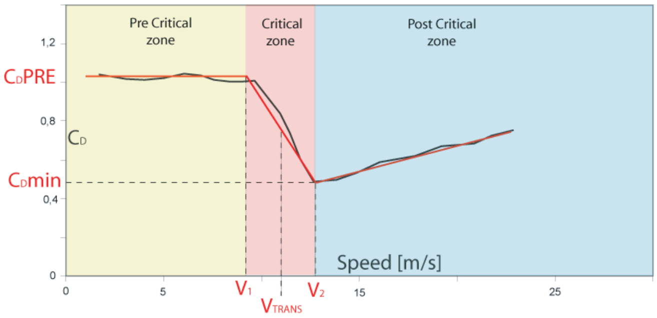


Figure 7.2: Typical c_D-speed curve for a cylinder

7.3.1.2 Effect of yaw angle

Due to the fact that the wind is almost never coming from a normal direction on athlete's arms and legs, it is important to evaluate the effect of the side wind combined with the use of rough textiles. This has been done testing a cylinder covered with different textiles 4 different angles (from α = 0° to α= 45° have been tested and c_D *-Speed* curves have been acquired. Results show that yaw angle α affects c_D -Speed curves (Fig 7.4). When the yaw angle α increases, the drag crisis and the consequent drag reduction gets smaller for all the textiles tested.

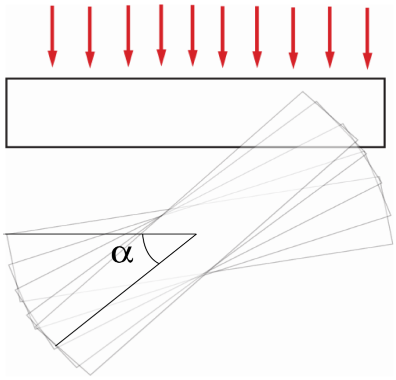
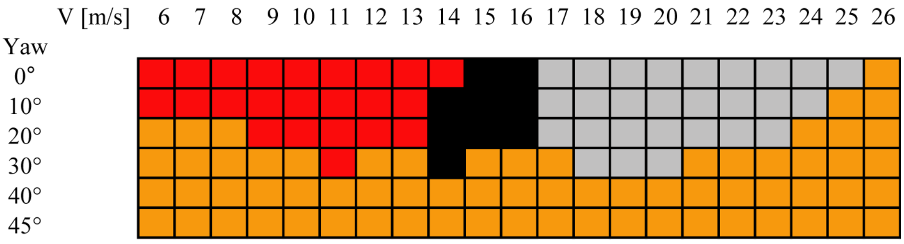


Figure 7.3: Yaw Angle model



Yaw \ V [m/s]	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
0°	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟧
10°	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟧	🟧
20°	🟧	🟧	🟧	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟧	🟧	🟧
30°	🟧	🟧	🟧	🟧	🟧	🟥	🟧	🟧	⬛	🟧	🟧	🟧	⬜	⬜	⬜	🟧	🟧	🟧	🟧	🟧	🟧
40°	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
45°	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧

Figure 7.4: In this figure the textile with the lowest drag is marked by a color.

While for α= 0° a noticeable difference between the textile is shown and the rough textiles re-

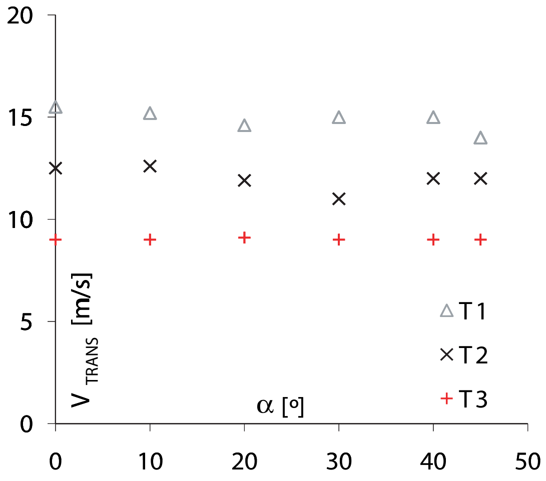


Figure 7.5: Correlation between V_{TRANS} and Yaw angle α

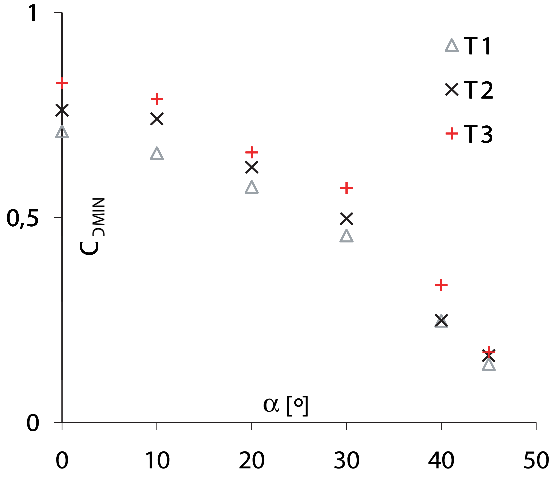


Figure 7.6: Correlation between c_{DMIN} and Yaw angle α

duces the drag in the cylinder model, for α= 45° (Fig 7.6) the textiles have the opposite effect (they increase the drag). This is a direct consequence from the fact that V_N has a major effect on the flow compared to V_T [Zdravkovich 1997].
Since only the dependence on the free stream velocity V has been considered, a decrease in drag due to the decrease of V_N should be expected. The plot in fig 2-a shows the dependence of c_{DMIN} from the yaw angle α. A clear decrease in the value of c_{DMIN} can be noticed for all the textiles tested. The yaw angle influences V_{TRANS} which slowly decreases while α increases for all the different textiles tested (Fig 7.5).
Considering the roughness k, results show that, while for low values of α (α<20°) there is an advantage in using rougher textiles so that transition can be shifted at lower speed, this advantage disappears when for α= 40°.
Fornα= 40° a smooth texture on the cylinder permits to obtain a lower drag (fig 7.4).

7.3.2 Geometrical parameters

7.3.2.1 Effect of diameter

Three different cylinder models with different diameters (11cm, 20cm and 31cm) have been tested in order to simulate the effect of rough textiles on legs with different size. c_D-Re curves have been acquired also in this case.

Results show that a combined effect of roughness and change in diameter affects the aerodynamic properties of the cylinder The effect of roughness has been extensively covered in the past [Fage 1929] and there is a clear agreement on the fact that almost any kind of surface roughness is able to shift the transition to turbulent regime at lower speed with a consequent drop in terms of c_D.

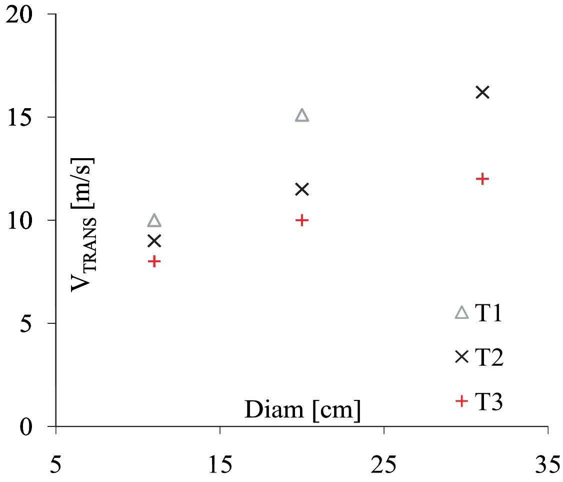


Figure 7.7: Influence of cylinder diameter on V_{TRANS}

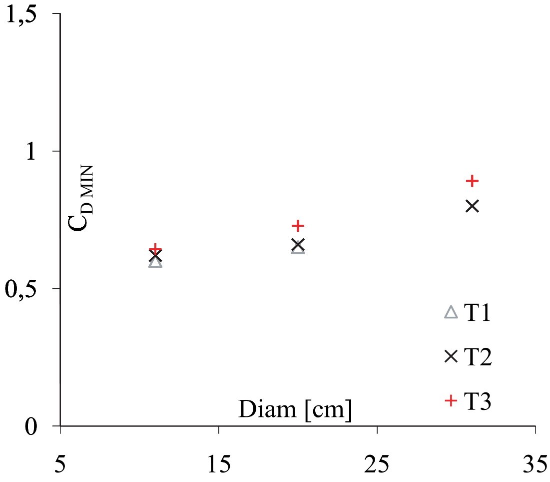
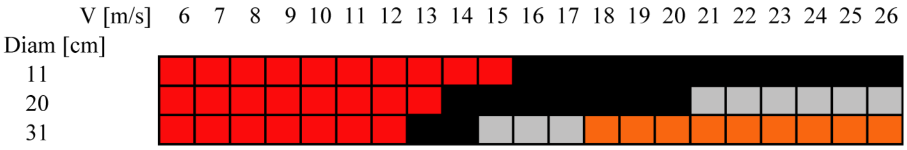


Figure 7.8: Influence of cylinder diameter on c_{DMIN}



V [m/s]	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Diam [cm]																					
11	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛
20	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬜	⬜	⬜	⬜	⬜	⬜
31	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬜	⬜	⬜	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧

Figure 7.9: In this figure the textile with the lowest drag is marked by a color.

These findings are also shown in the results from the experiments carried out.
The diameter influences V_{TRANS} and c_{DMIN} . An increase in diameter shifts the V_{TRANS} to a higher value and the same happens for c_{DMIN} (Fig 7.7 and Fig. 7.8). This lead to the fact that, for the largest diameter cylinder tested (31cm), if low drag is needed, it is convenient to use smoother surfaces than the one used for the smaller diameter (11cm).

7.3.2.2 Effect of distance between 2 side by side cylinders covered with textiles with different roughness

The legs of the athletes constantly vary their distance during a competition and depending on the discipline. This effect has been simulated acquiring the drag acting on a model consisting of two vertical cylinders (placed side by side) with variable distance between them (Fig 7.10). From the experiments carried out results show that there is a correlation between D and the aerodynamic properties of the textiles. When D increases, both parameters (V_{TRANS} and c_{DMIN}) decrease (Fig 7.12 and Fig 7.13). However, while c_{DMIN} decrease slowly while D increases, V_{TRANS} drops from passing from D/Diam=1 to D/Diam=2 for both T2 and T3.

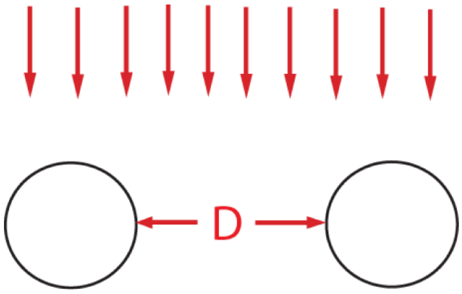
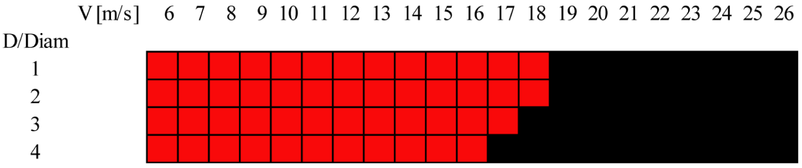


Figure 7.10: Side by side test model. Top view



V [m/s]	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
D/Diam																					
1	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛
2	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛
3	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛
4	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛

Figure 7.11: In this figure the textile with the lowest drag is marked by a color.

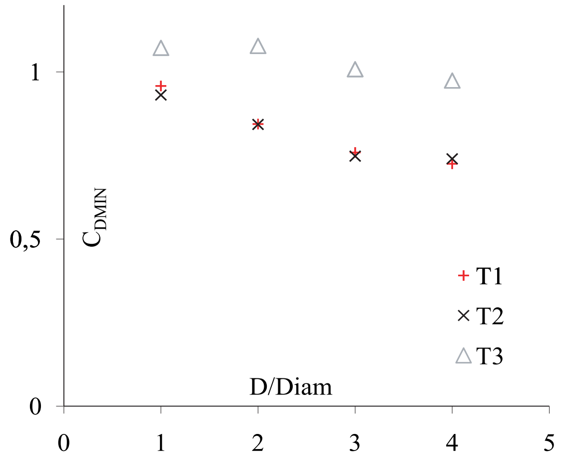


Figure 7.12: Influence of D/Diam on c_{DMIN}

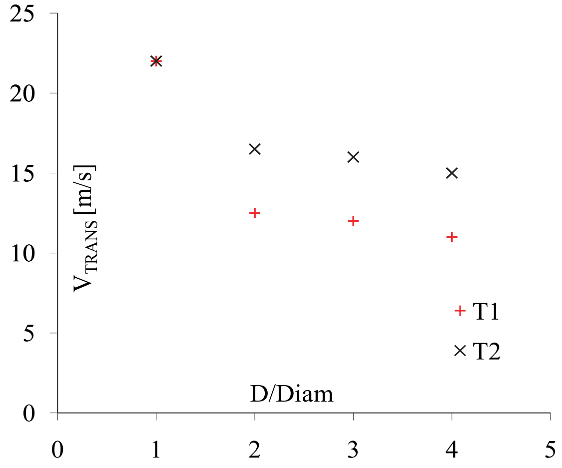


Figure 7.13: Influence of D/Diam on V_{TRANS}

For low speed (from 6m/s to 18m/s) T3 is the model with the lowest drag while for V>18m/s the model T2 is the one with the lowest aerodynamic resistance. This trend is confirmed when D/Diam increases, however, for D/Diam=4 T3 has lower drag than T2 only until the speed is 16m/s.
If for D/Diam =1 the advantage of using rougher patterns [T2, T3] to shift the transition at lower speed is almost negligible, already for D/Diam=2 the trend changes and a considerable gain in terms of drag reduction can be noticed.

7.4 Conclusions

Results show that rough textiles influence the drag on cylinders. However the effect that the fabrics have on the aerodynamic parameters is correlated to some geometrical aspects. The main outcomes of this study are: Rough textiles are able to shift the transition at lower speed only for low yaw angles Rough textiles are able to shift the transition on a side by side cylinder model at lower speed only if the distance between the cylinders is 2 times larger than the cylinders diameter The effect of rough textiles on cylinders is higher if the cylinder diameter is smaller.

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CHAPTER 8

P3

Aerodynamic and comfort properties of single jersey textiles for high speed sports

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Abstract:
The paper addresses the effects of geometry and physical parameters of knitted fabric structures on their aerodynamic and comfort properties. In order to evaluate whether significant aerodynamic and comfort advantages may be achieved by changing the geometrical parameters of knitted structures, 9 different knitted fabrics in plain structure (Single Jersey) were produced. Their geometry and physical parameters were measured and analyzed. A fabric surface roughness model was developed and correlations between fabric geometry, manufacturing and aerodynamic parameters were established. To evaluate an aerodynamic behavior of the fabrics produced, a series of aerodynamic tests were carried out in the industrial wind tunnel. Fabric samples were placed on a leg model and 2 different positions of the leg were tested in order to avoid uncertainties in the drag due to the asymmetrical shape of the leg. c_D-Speed curves were obtained. The aerodynamic resistance was acquired at different incremental speeds from 20km/h to 80km/. Correlation between aerodynamic parameters (V_{TRANS} and c_{DMIN}) and fabric manufacturing parameters was established and analyzed. Evaluation of the comfort properties of the fabrics was carried out. Measurements of dynamic comfort properties of the fabrics were obtained. As part of this evaluation fabrics' liquid moisture transport properties in multi-dimensions (moisture management properties) were acquired. The moisture management capacity of all knitted fabrics was assessed and classified by simulation of the liquid sweat on the skin absorbed and transferred to the outside of the fabric. Correlations between the fabric geometrical parameters and comfort properties were established.

8.1 Introduction

Today sport races are won by fractions of second. Every advantage in speed becomes critical. According to Kyle [Kyle 2004] improving the athlete's aerodynamic performance is crucial in high speed sports such as speed skating, cycling and downhill skating. In the past years a number of factors that contribute to the improvement of the aerodynamic performance of an athlete were identified by Barelle [Barelle], Grappe [Grappe 1997], Lukes [Lukes 2005]) and Laing [Laing 2002]: a) Posture of the athlete's body during the activity, b) Equipment's aerodynamic properties, c) Aerodynamic attributes of the garment surface , d) Fit of the garment/s worn, e) Design and styling of the garment/s worn. The importance of the aerodynamic attributes of the garment surface and textile materials used in the garment itself were highlighted by numerous studies ([Kyle 2004]), [Brownlie 1992], [Oggiano 2007]). Kyle [Kyle 2004] studied the use of zoned cycling garments to reduce the aerodynamic drag of bicycle racing apparel. In this study wind tunnel measurements of drag force and air velocity were made on cylinders, limb models and live cyclists clad in samples or suits sewn with up to 200 stretch fabrics, with finding that that some textiles were able to improve the aerodynamic of the athletes. From the classical aerodynamic theory, the drag acting against the athlete can be represented as:

$$D = \frac{1}{2} A_p c_D \rho V^2 \tag{8.1}$$

Where A_p is frontal area of the cylinder, c_d is a drag coefficient, ρ is the air density and V is the air velocity. Di Prampero [DiPrampero 1979] considered these parameters as constant and included them into a constant coefficient K.Achenbach [Achenbach 1977] established that the introduction of a surface roughness on cylinders or spheres can shift the transition of the flow at low speeds.

If V_{TRANS} is the speed, at which the transition from laminar to turbulent flow occurs, then it was established by the above research that the rougher the surface, the lower V_{TRANS}. As the skin of the athlete is normally covered by the garments worn, a deeper look at the parameters affecting the aerodynamic properties of the fabrics and consequently the garment surface is needed. These parameters are construction, porosity, tightness or openness, thickness, fiber composition and the construction of the yarn used.

In addition to the importance of aerodynamic attributes of the fabrics, fabric assemblies, garment and garment assemblies, the performance of the athlete is influenced by the comfort of the garment worn. The wearer comfort can enhance or suppress their performance and efficiency. Comfort is a complex concept influenced by a multitude of various factors, such as physiological and psychological [Elshner 2003].

Comfort is directly related to the physiological interaction between body, environment and clothing. Environmental parameters such as cold, heat, humidity, atmospheric pressure play an important role in determining the success of the athlete's performance.

Although these environmental variables can not be controlled, an understanding of how the environment affects human physiology and how we might best compensate for these variables help to reduce their impact on the performance. During all the activities, due to metabolism, the human body produces heat. As the human body regulates its core temperature around 37 degrees, it is essential that the heat is removed from the body at the same rate as it is produced. The heat transport from the body is affected by "dry" heat caused by conduction, convention and radiation and by "latent" heat created by sweat evaporation. The 'dry" heat depends on the textile thermal insulation and the "latent" heat on its moisture transport properties.

The thermal, vapor and moisture transfer properties of a fabric and thus its comfort will significantly depend on the properties of that fabric that either promotes or restricts the passage of heat, moisture vapor and sweat through the fabric. The main parameters important in maintaining fabric comfort properties are fiber physical structure and composition, yarn structure, fabric construction, fabric thickness and "openness", and fabric finishes. Fabric porosity, tightness ("openness") and thickness are resultant characteristics dependent on the fabric construction, yarn count, stitch length and knitting machine gauge. As defined by Spencer (2001) knitted fabric tightness could be expressed as a Cover Factor (CF):

$$CF^2 = \frac{TEX}{L^2} \tag{8.2}$$

Where TEX is the Yarn Count measured in g/1000m and L is a stitch length measured in mm. Thus CF is a ratio of the area of knitted fabric covered by yarn to the area covered by the gaps in between the loops. Therefore, the fabric CF could be considered one of the most important numbers linking manufacturing parameters and geometrical and physical attributes of a knitted fabric. In this study, the CF of the knitted fabric samples was used to identify and link manufacturing parameters of the knitted fabric to its aerodynamic and comfort performance.

8.2 Experimental

8.2.1 Fabric preparation

Knitted fabric samples were produced on a Lawson Hemphill FAK - S, Fabric Analysis Knitter, circular 24 gauge laboratory size, 8.9 cm diameter, total number of needles 260 knitting machine. Single jersey fabric construction was selected to produce all the knitted fabric samples with 100percent Polyester (PET), 1/150D/48f, flat, optically bright yarn. The amount of yarn fed in one machine revolution was changed in order to produce fabrics with different stitch length and hence to achieve incremental fabric Cover Factor (CF). After knitting, the samples were conditioned for 24 hours at relative humidity of 45percent then a laboratory washing machine (Werner Mathis AG) was used to wash all the samples under controlled conditions (all the parameters such as speed, time, and temperature were controlled). Once the washing process was completed, the fabrics were tumble dried at 60°C for about 25 minutes. A hand held iron (Sunbeam, Model: Ultura 5600) was used after the completion of finishing for a final steam pressing.

8.2.2 Instruments used

For aerodynamic testing, the RMIT Industrial Wind Tunnel was used. The details about the tunnel can be found in [Alam 2003a]. A leg model was made out of a mannequin leg (Fig. 8.2b). The leg was cut and only the part from the foot up to the knee was used as a test model. The foot and the knee were used as dummies in order to reduce the 3D flow effect. The model was made of fiberglass and was connected to a 6-component balance with a metal support. For all nine fabric samples produced with different cover factors, roughness parameters were measured (Fig. 8.1). Fabrics were cut and shaped in order to fit the leg model without distortion and each fabric was tested in the wind tunnel acquiring the drag of the model fitted with and without the textile. c_d-Speed curves were made and correlations between the V_{TRANS}, c_{DMIN} and roughness were found. The leg was tested in 2 different positions in order to simulate the influence of the side wind. Position 1 refers to the leg being parallel to the flow and position 2 refers to the leg being rotated at 10 degrees with respect to the position 1, see (Fig. 8.2b). A moisture management tester (MMT) instrument was used to test the liquid water transfer and distribution of knitted fabric samples. During testing, each fabric specimen was placed flat between the top and bottom sensors and a predetermined quantity (0.15g) of the testing solution was pumped onto the upper surface of the fabric to simulate a drop of liquid sweat. All fabrics were tested under the same laboratory conditions. The upper surface of the fabric is the surface close to the skin of the human body and the bottom surface of the fabric is the closest to the neighboring environment. The parameters measured were: Wetting time, Absorption rate, Maximum wetted radius, Spreading speed, Accumulative one way transport, and Overall moisture management capability.

Knitted	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Stich length (mm)	3.52	3.36	3.21	3.07	2.94	2.82	2.71	2.61	2.50
Cover Factor	**1**	**1.05**	**1.05**	**1.15**	**1.15**	**1.25**	**1.25**	**1.35**	**1.35**
K_{TEX}	3.646	3.116	3.200	2.931	2.967	2.882	2.516	2.443	2.463

Figure 8.1: Table 1

8.2.3 Roughness model

In order to link aerodynamic and comfort fabric performance with its physical properties a roughness model was created. The fabrics were analyzed microscopically and the 3 parameters (length: the width of a wale, depth: the distance between the top and the bottom of the excrescences present on the fabric surface (lowest and highest points of the stitch, and A: the distance between two fabric wales) were chosen.
These 3 parameters were then combined in a single roughness coefficient k_{TEX}

$$k_{TEX} + \sqrt{Length \cdot Depth \cdot A} \tag{8.3}$$

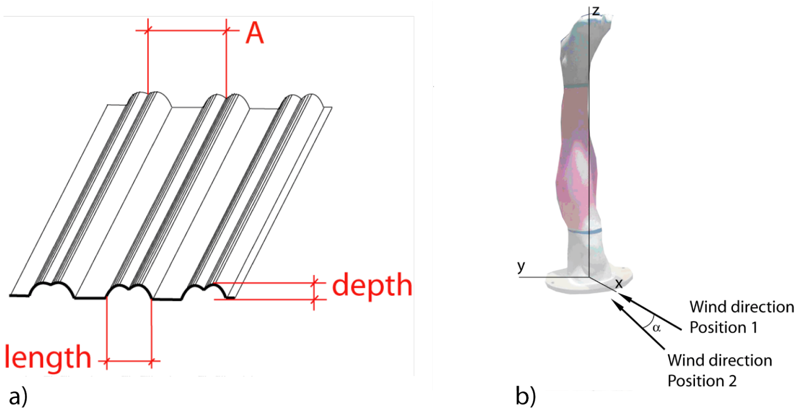

Figure 8.2: (a) - Roughness parameters considered in the roughness model (b) - Leg model

8.3 Principle of test methods

8.3.1 Roughness method

It was established and is evident from the scatter plots (Fig. 8.3) that as the CF increases, the k_{TEX} linearly decreases. These results provide strong evidence that Cover Factor is directly and negatively related to roughness.

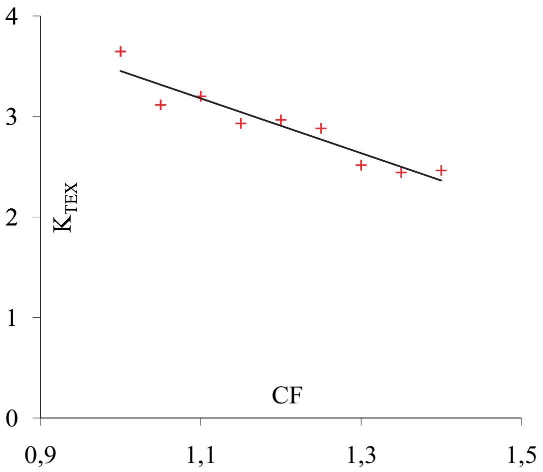

Figure 8.3: Correlation between CF and roughness coefficient k_{TEX}

8.3.2 Aerodynamic performances of fabric

The aerodynamic measurement results as shown in Figure 3 indicate that the rougher the fabric is, the lower the value of V_{TRANS}. This finding corresponds to the results previously obtained by

Achenbach and Bearman for spheres and cylinders covered with sand roughness. Additionally, it also shows that the rougher the fabric is, the lower the c_{DMIN}. V_{TRANS} tend then to an asymptotic value of 53km/h for position 1 and 51km/h for position 2 (Fig. 8.6).

The curves (Fig. 8.4 and Fig 8.5) represent the leg with no fabric (considered as smooth) and the leg tested with the 2 extreme fabrics (CF =1 and CF =1.4). A considerable drag reduction was noticed after the transition speed (V_{TRANS}) for both samples tested. A connection between the V_{TRANS} value and CF and between c_{DMIN} in value and CF was established (Fig.8.6 and Fig. 8.7). From the scatter plots in Figure 4 (a) and Figure 4 (b) it is clear that the higher the CF is, the higher V_{TRANS} is and as CF increases the c_{DMIN} decreases.

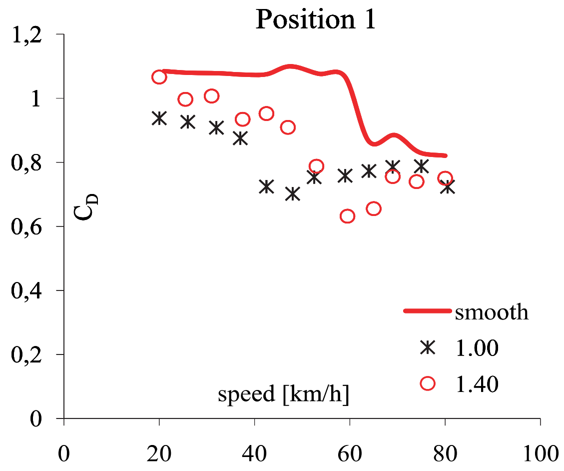

Figure 8.4: Influence of textiles on c_d-Speed curve:Position 1

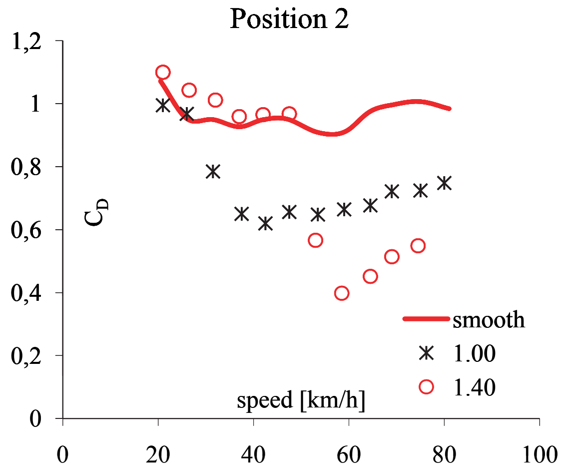

Figure 8.5: Influence of textiles on c_d-Speed curve:Position 2

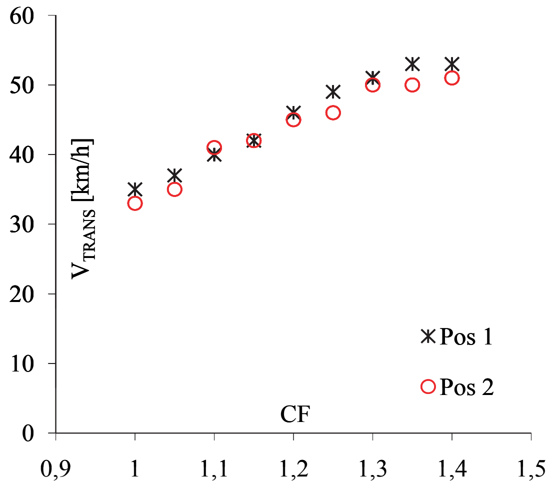

Figure 8.6: Effect of different CF on V_{TRANS}

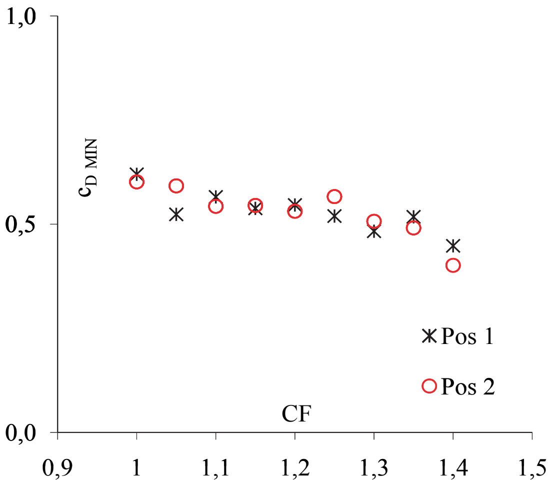

Figure 8.7: Effect of different CF on c_{DMIN}

8.3.3 Liquid moisture management properties of fabrics

It was established and is evident from the scatter plots in (Fig.8.8) that the Top Wetting time decreases with the increase in CF, while Bottom Wetting time has an inversely proportional relationship with the CF. The scatter plot CF versus AR (Fig. 8.9) shows that the relationship between the Cover Factor and the Top Surface Absorption Rate and Bottom Absorption Rate is identical. As the CF increases the Top and Bottom Absorption Rate decreases. It can be observed from the CF versus WT (Fig. 8.8) diagram that as the Cover Factor increased the Wetted Radius (Top and Bottom) become larger.

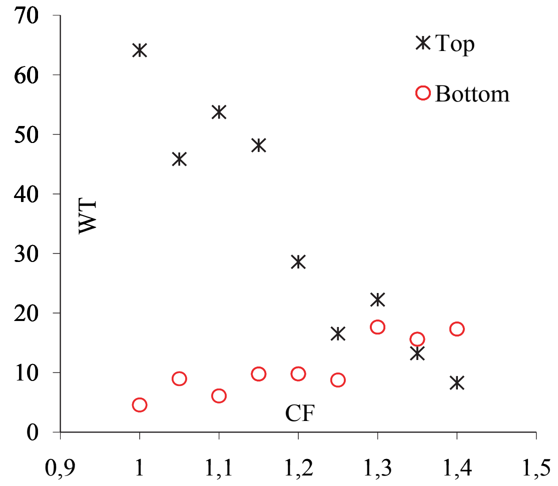

Figure 8.8: Correlation between CF and WTt (top surface) and WTb (bottom surface)

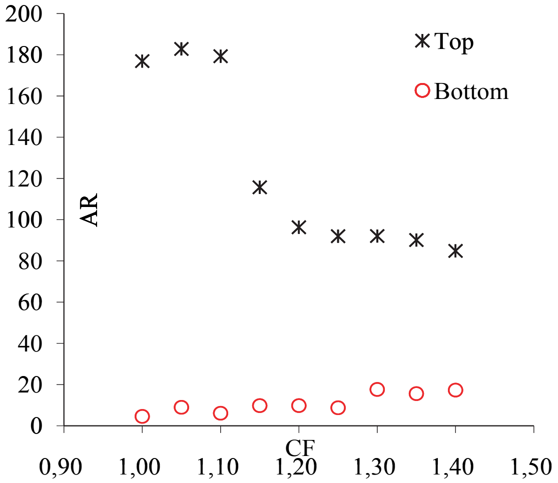

Figure 8.9: Correlation between CF and ARt (top surface) and ARb (bottom surface)

8.4 Conclusions

The aerodynamic tests demonstrate that fabric samples with lower Cover Factor and higher roughness were proven to perform better and reduce an aerodynamic drag for low speeds. Fabric with a higher roughness permits shift of the transition point at low speeds resulting in drag reduction. The comfort tests indicate that all fabric samples performed relatively well in terms of moisture management. The results obtained confirmed that the tighter construction polyester fabrics do not support the liquid moisture concentration near the skin. Liquid moisture diffuses through the fabric easily and quickly keeping the skin feeling dry. It was also established that the Cover Factor influences the comfort performance of the fabric.

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CHAPTER 9

P4

Aerodynamic behaviour of single jersey sport fabrics with different roughness and cover factors

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Abstract:
Wind tunnel testing has been carried out on nine knitted single jersey fabrics (100% polyester) using cylinder and leg models to determine their aerodynamic behaviour (c_{DMIN} and V_{TRANS}) over a range of speeds (20 - 80 km/h) representative of sports activities. Strong correlation between fabric manufacturing (cover factor) and fabric roughness parameters and aerodynamic parameters has been established. Similar aerodynamic behaviour of fabrics was observed when tested on the cylinder model and on the leg model.

9.1 Introduction

Improvement of aerodynamic performance is critical in high-speed sports, such as speed skating, cycling and downhill skating. Hence, the interest increased in the garments that have effects on aerodynamics performance in sports [Bird 1995], [Kuper 2008]]. Research to date has identified a number of factors that contribute to the improved aerodynamic performance of athletes [[Barelle], [Grappe 1997], [Kyle 1986], [Laing 2002]]:

- Aerodynamic properties of sport equipment used
- Position of the athlete's body during the activity

- Design and styling of the garment/s worn
- Fit of the garment/s worn
- Aerodynamic attributes of the garment surface.

Garments' design and styling as well as fit, can give a major improvement in the aerodynamics of a moving athlete. This has been demonstrated in a number of sports, including running, cycling, downhill and cross-country skiing, bobsled and speed skating. It has been previously shown that drag can be reduced by up to 10% through the appropriate use of clothing as suggested by Laing [Laing 2002]. Several approaches in determining the effect of the garment design and styling on its aerodynamic performance have been adopted. For example, a study by Kyle and Caiozzo [Kyle 1986] used wind tunnel tests on materials and wigged-head models, from which mathematical modelling predicted that wind resistance could be lowered by about 0.5% to over 6% by covering the hair and by using elastomeric clothing materials with a close body fit. Similar results were obtained by Brownlie [Brownlie 1987] from other laboratory trials in which five garment styles/materials (singlet and shorts, elastomeric body suit, nylon rain suit and two manufactured prototypes) for running were compared. Brownlie [Brownlie 1987] also conducted a human performance running trial using the most promising of prototypes manufactured into a closefitting garment and demonstrated a significant reduction (1.17%) in running time over 100 m.

However, further comparison of loose-fitting and close-fitting garments for orienteering analysis of the physiological responses of wearers failed to detect any differences likely to affect field performance [DeKoning 2005b].

Spring [Spring 1980] studied the drag area of three male cross-country skiers as a function of their speed, which was determined from their retardation when they were gliding on roller-skis over a horizontal smooth asphalt surface in a subway. In that study the difference in the drag area between a normal outdoor suit and a tight-fitting ski suit was found to be as much as 30%. In a study by Brownlie [Brownlie 1987] stretch fabric suits were designed and custom close fitted to athletes without wrinkles or loose fabric areas. In these suits seams in attached flow were aligned parallel to the air stream, where practical; the majority of seams were located in the rear, in separated flow zones where they would not raise aerodynamic drag. These garment styling and design features along with use of zoned surface areas of the suit resulted in aerodynamic drag reductions of 7.5with single cylinders and up to 6% with cyclists.

Focus on the legs of the body is of prime importance as, in cycling and speed skating, legs and arms are the only parts of the body that are perpendicular to the flow and where the transition from laminar to turbulent regime could be beneficial in terms of drag reduction. As mentioned by Kyle [Kyle 1986], the other parts of the body (head, torso and shoulders) require smooth textiles in order to minimise the friction drag, and the use of rough textiles in these areas would then negatively affect the aerodynamic characteristics. The importance of the aerodynamic attributes of the garment surface and textile materials used in the garment itself has been highlighted in numerous studies [Brownlie 1992], [Kyle 1986], [Oggiano 2007]. Kyle [Kyle 1986] studied the use of zoned cycling garments to reduce the aerodynamic drag of bicycle racing apparel. In this study, wind tunnel measurements of drag force (D) and air speed (V) were made on cylinders, limb models and live cyclists clad in samples or suits sewn with one or more of 200 stretch fabrics. Non-dimensional drag coefficient (c_D) and Reynolds numbers (Re) were used to characterise the ability of the various assemblies and fabrics to generate premature flow transition or a drag crisis.

It is not clear how the experimental fabrics were selected and it seems that the selection was not systematic in terms of fabrics physical parameters and performance attributes, while each body segment of the cyclist was assigned a Reynolds number based on the speed and size of the segment. This approach led to the aerodynamic properties of bluff bodies and, in particular, to the effect of the transition from laminar to turbulent regime. The drag acting on the athletes is often represented as:

$$D = \frac{1}{2} A_p c_D \rho V^2 \tag{9.1}$$

where, AP is the projected frontal area. Transition of the flow around the athlete from laminar to turbulent and the consequent drop in drag was predicted by Pugh [Pugh 1974]. Pugh's prediction is closely connected to the studies carried out in the past on bluff bodies and in particular on spheres and cylinders. The introduction of a surface roughness on cylinders can shift the transition at lower speed. Usually the higher the roughness of the surface, the lower the value of the critical speed (V_{TRANS}). This behaviour was exhibited in Achenbach's [Achenbach 1977] experiments for spheres and in Bearman and Harvey's [Bearman 1993] experiments for cylinders. Rough patterns have been already used in golf balls in order to reduce the value of the critical speed (V_{TRANS}) and thus reduce the drag. This effect, commonly called the golf ball effect is an optimised transition from laminar to turbulent regime. Above the critical speed (V_{TRANS}) the flow becomes fully turbulent and a consistent drag drop occurs. The same method can be used in order to reduce the drag on the cylindrical parts of the human body. For instance, manufacturers of speed skating suits have obtained good results by using dimpled or rough textiles on the legs of the suits to trip the transition to turbulent at low Reynolds number. Kuper and Sterken [Kuper 2008] analysed the effect of skating suits on skater's performances and they demonstrated that some suits, especially in long-distance events, significantly increase the average skating speed.

The same study established that the Nike swift skin suit can reduce lap times by up to 0.2-0.3 s on a 400 m oval. The effects of garments on aerodynamic performance noted above have not been related to the garment textile parameters, which affect the surface characteristics of the garment and include:

- Construction
- Porosity
- Tightness or openness
- Thickness
- Fibre composition and the construction of the yarn used.

The relationships between these parameters and aerodynamic performance need to be established. For tighter-fitting garments, knitted fabrics are preferred over woven fabrics. Knitted fabrics can be weft or warpknitted, depending on the stretch and recovery attributes required for the level of fit of the garment. Porosity, tightness and thickness are resultant characteristics of the fabric which depend on fabric construction, yarn count, stitch length and knitting machine gauge. As defined by Spencer [Spencer 2001] knitted fabric tightness (compactness) could be expressed as a cover factor (CF):

$$CF^2 = \frac{TEX}{L^2} \tag{9.2}$$

where TEX is the yarn count measured in grams per km and L is a stitch length measured in mm. Yarn count indicates the yarn diameter or fineness and is based on the mass of the yarn per unit length (direct system) or the length per unit mass (indirect system) of the yarn. Stitch length is the length of yarn in a knitted loop (stitch), where the loop can vary in size altering its length. This parameter is independent of the diameter of the constituent yarn, although usually, within a knitted construction, the yarn size is commensurate with the stitch length [Spencer 2001].

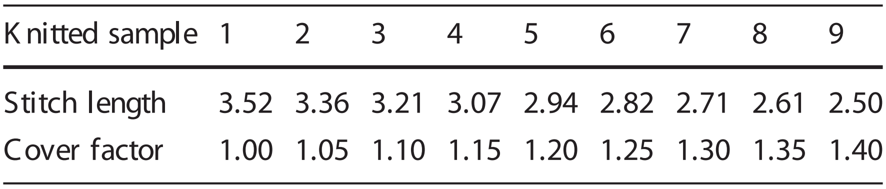
Machine gauge is a notional indication of the number of needles per unit length of a needle bed. In current practice a common unit of length of one English inch (25.4 mm) is used for most types of knitting machines. Cover Factor (CF) indicates the extent to which the area of a fabric is covered by the yarn. It is also an indication of the relative looseness or tightness of the knitted structure, where CF is a ratio between the yarn diameter and its stitch length in the knitted structure. The CF value does not refer to the area occupied by the stitch, and so is unaffected if the knitted structure is subjected to tension, when the stitch tends to change its shape rather than the stitch length. Therefore, the state of the fabric structure does not affect the ratio. This ratio is the most important factor for the definition of knitted fabric physical properties and is directly related to the appearance, mass per unit area, thickness, porosity and other geometrical factors of the knitted fabric. If this relationship is maintained through a range of fabrics for a given knitted structure, then those fabrics are related in their tightness and other physical characteristics [Brackenbury 1992]. Dias and Delkumburewatte [Dias 2008] studied the effect of fabric tightness or cover factor on porosity of knitted structures. This study demonstrated that there is a relationship between the stitch length, course spacing, wale (vertical stitch) spacing, fabric thickness, yarn count and fabric tightness. In addition this study observed how appearance, mass, fabric thickness and porosity changed with cover factor and concluded that the fabric cover factor is an important element which can cause the fabric parameters, such as porosity and weight to have an inversely proportional relationship. Thus, the fabric cover factor is an important parameter linking manufacturing parameters and geometrical and physical attributes of a knitted fabric. In this study, the CF of knitted fabric samples was used to identify and link manufacturing parameters of knitted fabric to its aerodynamic performance.

9.2 Experimental Methods

9.2.1 Knitting and finishing of samples

Nine experimental knitted samples were produced with varying stitch lengths (between 2.50 and 3.52 mm) to achieve incremental fabric Cover Factor values between 1.00 and 1.40 (Fig. 9.1) using a Lawson Hemphill FAK - S, Fabric Analysis Knitter, circular 24 gauge laboratory size, 8.9 cm diameter, total number of needles 260 knitting machine. This machine is equipped with an automatic, positive and accurate stitch control system. This is an essential feature to maintain the identical production of fabrics and accurate reproduction of any fabric. In any knitting application, the yarn tension and the yarn feed control are very important; any changes in these knitting parameters will result in variation of stitch length. The system used in this study maintains yarn consumption to 0.5% tolerance to obtain a predetermined course length in the fabric and corrects for run-out. The system also detects any variance between the machine yarn consumption and feed rate and maintains these two in balance. This precision knitting produces appropriate and consistent fabrics for standard and specialised fabric.

Due to practical considerations and to limit the number of variables, fabric construction, fibre composition, yarn count and construction were kept constant. Single jersey fabric construction was used to produce all the knitted fabric samples due to its simplicity. It is relatively easy to determine fabric geometrical parameters for single jersey construction in order to establish correlation with its aerodynamic properties.



Knitted sample	1	2	3	4	5	6	7	8	9
Stitch length	3.52	3.36	3.21	3.07	2.94	2.82	2.71	2.61	2.50
Cover factor	1.00	1.05	1.10	1.15	1.20	1.25	1.30	1.35	1.40

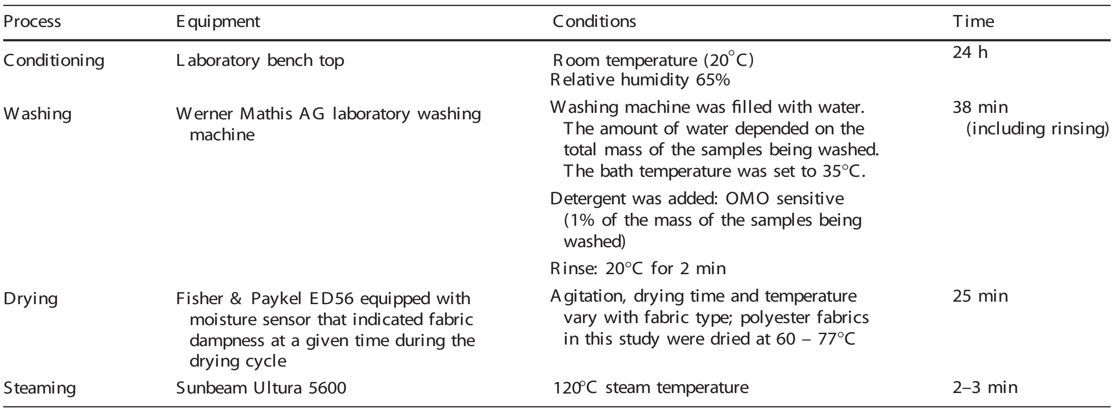
Figure 9.1: Target stitch length (mm) and cover factor values for fabrics prepared in this study

As much as 100% polyester 1/150/48 denier, flat, optically bright yarn was selected due to its uniformity and smooth surface nature, so that the variations in yarn unevenness could be eliminated; the flat surface section was selected to give a greater covering power resulting in more compact fabrics. After knitting the samples were conditioned for 24 h at relative humidity of 65%, in accordance with an Australian Standard method (AS 2001.1-1995) and then finished in laboratory conditions, Fig 9.2.

The Werner Mathis AG laboratory washing machine used is based on a rotary drum and is equipped with an inbuilt computer, which controlled parameters, such as speed, time and temperature. The Fisher and Paykel, Model: ED56 fabric dryer allowed control of cycle time and temperature of the tumble drying stage. A Sunbeam, Model: Ultura 5600 hand-held iron was used after the completion of finishing for a final steam pressing.

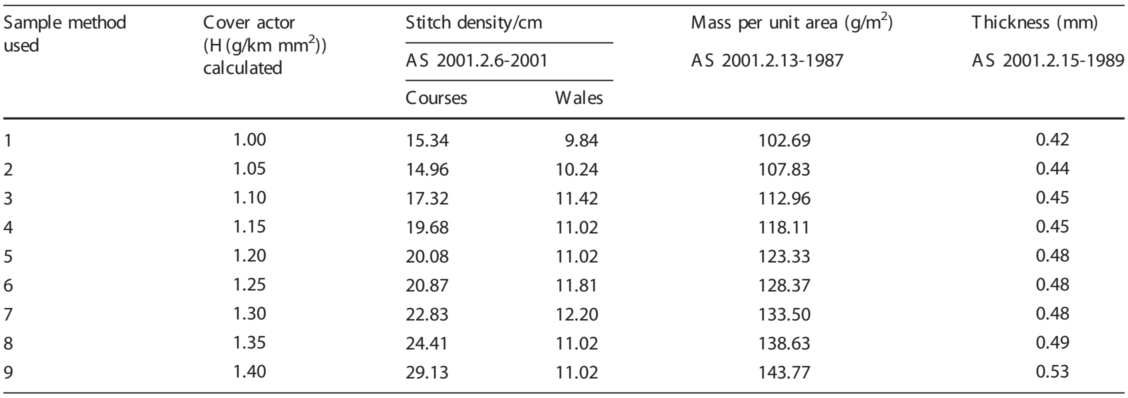
9.2.1.1 Fabric characterisation

Stitch density, mass per unit area and thickness of the knitted samples were determined based on Australian Standard Test Methods, cover factor values were calculated in accordance with Eq. 9.1; the values are summarised in Table 3. A Motic Chine Group digital microscope with Motic Images Plus 2.0 ML image capture and analysis software was used for this and for determining parameters



Process	Equipment	Conditions	Time
Conditioning	Laboratory bench top	Room temperature (20°C) Relative humidity 65%	24 h
Washing	Werner Mathis AG laboratory washing machine	Washing machine was filled with water. The amount of water depended on the total mass of the samples being washed. The bath temperature was set to 35°C. Detergent was added: OMO sensitive (1% of the mass of the samples being washed) Rinse: 20°C for 2 min	38 min (including rinsing)
Drying	Fisher & Paykel ED56 equipped with moisture sensor that indicated fabric dampness at a given time during the drying cycle	Agitation, drying time and temperature vary with fabric type; polyester fabrics in this study were dried at 60 – 77°C	25 min
Steaming	Sunbeam Ultura 5600	120°C steam temperature	2–3 min

Figure 9.2: Summary of finishing procedures for fabrics prepared in this study



Sample method used	Cover actor (H (g/km mm^2)) calculated	Stitch density/cm		Mass per unit area (g/m^2)	Thickness (mm)
		AS 2001.2.6-2001		AS 2001.2.13-1987	AS 2001.2.15-1989
		Courses	Wales		
1	1.00	15.34	9.84	102.69	0.42
2	1.05	14.96	10.24	107.83	0.44
3	1.10	17.32	11.42	112.96	0.45
4	1.15	19.68	11.02	118.11	0.45
5	1.20	20.08	11.02	123.33	0.48
6	1.25	20.87	11.81	128.37	0.48
7	1.30	22.83	12.20	133.50	0.48
8	1.35	24.41	11.02	138.63	0.49
9	1.40	29.13	11.02	143.77	0.53

Figure 9.3: Physical properties of finished fabric samples

used to calculate surface roughness (see below). In order to determine changes of dimensions of fabric samples, each fabric sample was placed flat on a laboratory bench and six 100 mm 9 100 mm^2 (SQ1-SQ6) were measured by means of template and marked by four points in the height and width directions by a black stitch. The measurement was recorded and used as a reference point. The fabric samples were then placed over a fixed diameter

The cylinder and the leg model (see below) and stitched into the cylindrical shape by hand under a constant tension and the distance between black marked stitches was measured in the length and width directions. The changes of dimensions of fabric samples were calculated from the differences in distance between the marked stitches in relaxed (on a bench) and tensioned (on a model) states and expressed as the average percentage change in width (top and bottom) measurements (W-average) and the average percentage change in height (left and right) measurements (H-average). One way ANOVA was carried out at the 5% level of significance to determine whether variation in dimension was significant.

Finished fabric samples were converted into cylinder and leg shapes for testing and evaluation of its aerodynamic properties. All samples were used in two series of aerodynamic experiments: one set where the technical face (front side) of the fabrics was in contact with the surface of the

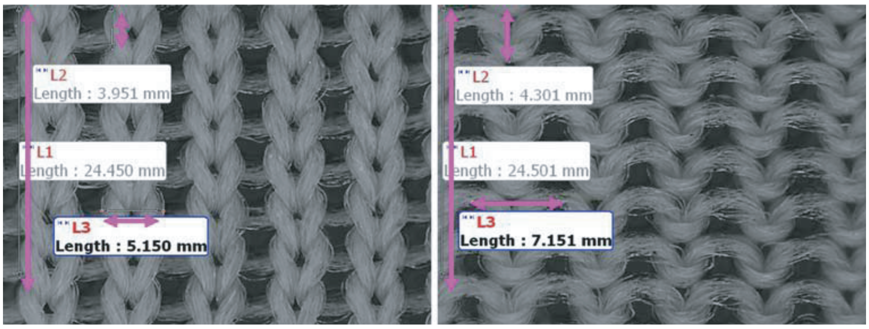


Figure 9.4: Technical face (left) and technical back (right) of a single jersey knitted fabric

cylinder and the leg, and the second set where the technical back (back side) of the fabric was in contact with surface of the cylinder and the leg. This is due to the different surface structure of the technical face and the technical back of single jersey fabrics, Fig. 9.4. Fabric samples were placed on the cylinder and the leg shape so that the vertical raw of stitches (wales) were oriented vertically and horizontal row of stitches (courses) horizontally. This positioning would be standard for the majority of knitted garments, where the wales are oriented along the torso and the limbs, unless some special effects are deliberately desired. Considerable care was exercised to ensure invariant tension when placing the fabric samples over the cylinder and the leg. A roughness coefficient was defined both for front and back sides of the knitted fabrics. Surface roughness affects the drag of a cylinder as the roughness generates turbulence that affects the flow around the cylinder. This phenomenon was noticed as early as 1929 by Fage and Warsap [Fage 1929]. The roughness on cylinders (r) is usually expressed as the ratio between the mean value of the excrescences (k) and the diameter of the cylinder ($Diam$) as follows:

$$r = \frac{k}{Diam}$$

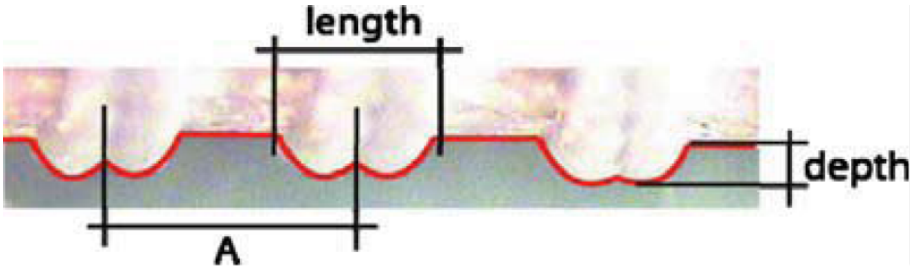


Figure 9.5: Technical face of a single jersey knitted fabric

The flow around the cylinder and consequently the drag is influenced not only by the parameter k but also by:

- The shape of the excrescences

- The distribution of the excrescences

For this study, front and back sides of the fabrics were analysed. As the distribution and the shape of the excrescences are different from the back side to the front side of the fabrics, a comparison between them was not possible, thus the front and the back of the fabrics were treated as separate cases. A number of different types of roughness have been previously tested by Achenbach [Achenbach 1977], and Fage and Warsap [Fage 1929] on cylinders and results almost always showed a strong dependence between the drag parameters and the roughness itself. However the roughness added by textiles has not been investigated. In most cases, tests on a rough cylinder were carried out using randomly distributed roughness, obtained by covering the cylinder model with different sand paper (from coarse to fine). The roughness parameter k represented in these cases is the mean height of the excrescences. A more accurate analysis of the effect of roughness on cylinders was carried out by Achenbach using a pyramidal surface roughness [Achenbach 1977]. k in this case was considered to be the height of the pyramidal excrescences. In general, k can be considered as a parameter that is, in an undetermined way, related to the excrescences present on the cylinder surface, but at present there is no general way to define it.

Three digital images of all samples (front and back) (Fig. 9.4), were taken with the Motic Chine Group digital microscope. From these images the length (average of 8 measurements from 8 random locations on the sample), depth and A were determined. A is the parameter which defines the distance between two wales (Fig. 9.5). The microscope analysis also showed that the shapes of the excrescences present on the front side and the back side of the fabric were different with those on the front side having shorter length, greater depth and a sharper shape (Fig. 9.6a) than those on the back side (Fig. 9.6b).

9.2.1.2 2D simplification

Up to the transition point in the aerodynamic tests the air flow should be 2D around the fabric-covered cylinder/leg Fig 9.4 Technical face (left) and technical back (right) of a single jersey knitted fabric Fig. 9.5 Example section through front of a fabric with CF = 1.4 Aerodynamic behaviour of single sport jersey fabrics 5 form. Hence, any variation in the wale direction was ignored with the surface being characterised by the three parameters noted above and shown in Fig. 9.6.

In addition, the double hump shown by the excrescences was simplified by a single hump characterised by length, depth and spacing (A). Interpolated values of these parameters (to reduce scatter) were then used to define the roughness coefficient, k_{TEX}, as:

$$k = length \cdot depth \cdot A \tag{9.3}$$

9.2.1.3 Aerodynamic test

Wind Tunnel:

The RMIT University Industrial Wind Tunnel was used to experimentally measure the aerody-

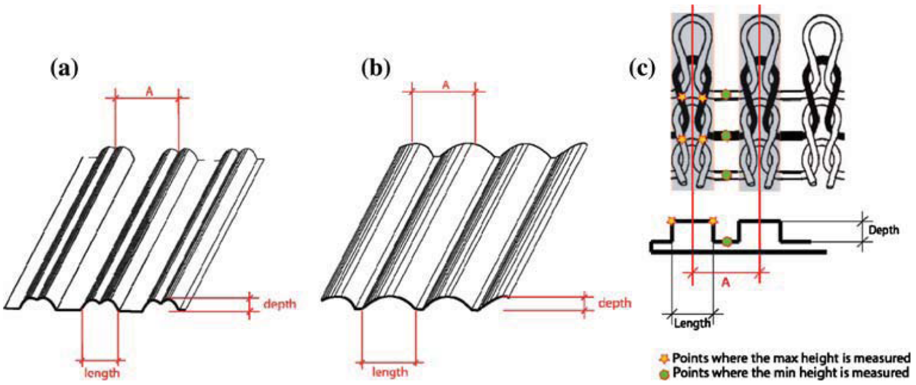


Figure 9.6: 2D simplification of excrescence characterisation. (a) Technical front geometry, (b) technical back geometry, (c) 2D simplification measurement point

namic properties on cylinder and leg models. The tunnel is a closed return circuit wind tunnel. The maximum speed of the tunnel is approximately 145 km/h. The rectangular test section dimension is 3 m (wide) x 2 m (high) x 9 m (long) with a turntable to yaw suitably sized objects. More details about the tunnel can be found in Alam et al.[Alam 2003a]. A zero measurement was taken before each series of measurements in order to eliminate possible errors due to the offset. The aerodynamic resistance was acquired at different incremental speeds from 20 km/h to 80 km/h in order to cover the range of speeds relevant to sports such as cycling or speed skating. The tunnel was calibrated before conducting the experiments and the tunnel's air speeds were measured via a modified NPL ellipsoidal head pitot-static tube (located at the entry of the test section) connected to a MKS Baratron pressure sensor through flexible tubing. Purpose made computer software was used to compute all 3 forces and 3 moments (drag, side, lift forces, and yaw, pitch and roll moments) and their non-dimensional coefficients. The free-stream turbulence intensity is approximately 1.6%. Flow angularity is guaranteed to 3% in both pitch and yaw. There is no flow straightening or turbidity reduction hardware in the chamber. The diffuser operates within an angle of 5%, which is comparatively small. The nacelle wake does not close before the downstream turning blades. The accuracy in speed acquirement was 0.5km/h

Force Balance:
A 6-component force sensor (type JR-3) was used for the force measurements. The sensor provides 2 megabit per second serial data stream with 3 forces and 3 moments data at 8 kHz. The sensor was mounted under the wind tunnel floor and was connected to the model with a support. Frequency filtering has been used in order to remove the background noise frequencies and a sampling frequency of 200 Hz was used during the experiments. Samples taken were 20 s long, 3 samples have been taken and averaged. Data varied by a maximum of 5% between two different tests. Based on these initial results, force values were taken as the average of a 1 minute run for a single sample.

Cylinder model:
A plastic cylinder model (Fig. 9.7a) was used in order to test the aerodynamic properties of the

knitted samples. Two dummy cylinders were added to reduce the 3D flow effects and to have a model, which suited the infinite length hypothesis. The test cylinder has a diameter of 100mm, a length of 400mm and consequently a frontal area of 40000mm^2. The 2 dummy cylinders are 150mm long and they also have a diameter of 100mm. The test cylinder is connected to a 6-component balance with a stick which passes through the first dummy cylinder placed on the floor of the wind tunnel. The second dummy cylinder is placed above the test cylinder and is connected to the wind tunnel floor with a steel support, placed 500mm in the back stream direction in order not to influence the wake behind the cylinder and thus the drag. A small gap of 5 mm was left between the two dummy cylinders and the test cylinder in order to avoid contact between them that could affect the results.

Leg model:
A mannequin leg was cut to leave just the foot up to the knee (Fig. 9.7b). The foot and the knee were used as dummies in order to reduce the 3D flow effect. The model is made of fibreglass and was connected to a 6-component balance with a metal support. The test section of the model was 400mm long and it had a maximum width of 100 mm and a minimum width of 50mm. The frontal area was estimated to be approximately 30,000mm^2. A small gap of 5 mm was left between the two dummy sections and the test section of the leg model in order to avoid contact between them which could affect the results.
The c_D variation with speed plots for both models and all fabrics were analysed to determine c_{DMIN} i.e. the minimum value of drag coefficient that was reached and V_{TRANS}, the speed where the c_D curve has gone through half its drop (δc_D/2). These parameters were correlated with fabric characterisation parameters. $c_{DMIN}$was typically located after the transition area of the c_D - speed plot with the Reynolds transition being defined as:

$$Re = \frac{V_{TRANS} \cdot Diam}{\nu} \tag{9.4}$$

where ν is the kinematic viscosity of the fluid (air in this study) and *Diam* is the diameter of the cylinder (100 mm).

9.3 Results and discussion

9.3.1 Fabric characterisation

CF:
Using equation 9.1 CF values were determined for all nine sample fabrics produced; these are summarised in Fig. 9.3. These data show that, as CF increases, the stitch density, mass per unit area and the thickness of the fabric samples increase as well. Since all the fabrics used the same construction and yarn, this indicates that relationships exist between CF and the other physical parameters of the fabric samples, although these have not been quantified in this study.

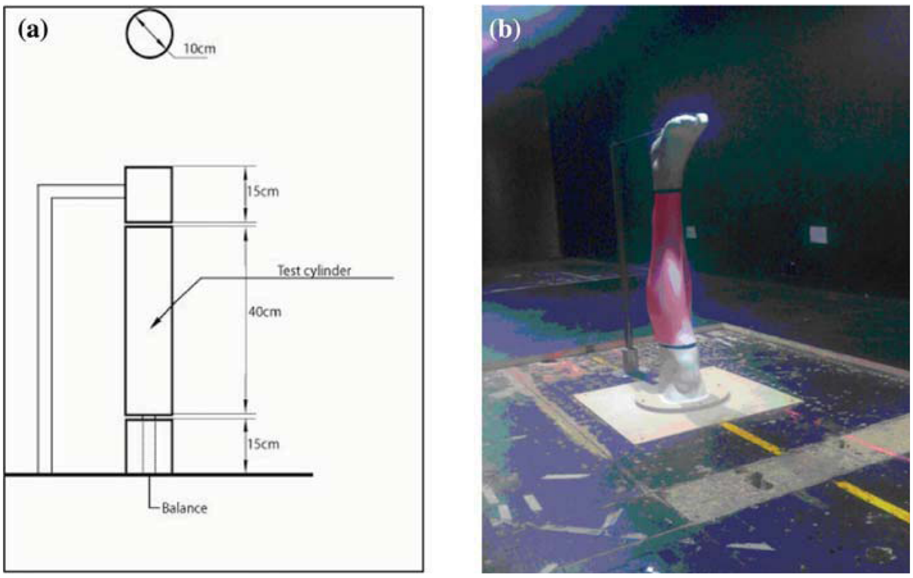


Figure 9.7: Leg (a) and cylinder (b) models

Depth:
The depth values measured for the front and back sides of the fabrics in this sample decrease as CF increases with an approximately linear relationship. Microscopic analysis shows that this is due to the stretching of the yarn in the fabric structure. In a fabric with a higher CF, the yarn is stretched more, and, due to this, it has narrower width, which influences the depth parameter. It was also noted that the yarn stretching is higher on the front side of the textile than on the back. The standard regression values show that data are not perfectly aligned but are scattered, especially in the back side measurements. However, the trend shows a linear correlation for both front and back fabric sides.

Length:
The lengths measured for front and back faces differed due to the difference in shape between the front and the back of the fabric. However, the same trend was established for the front side and the back side: the higher the value of CF, the smaller thelength is. This trend influences the roughness itself in such a way that, the smaller the length is, the smoother the fabric is (so roughness is smaller). On the back side of the fabrics, the length measured does not drastically change with change in CF and there was only a weak linear relationship established: lengthback = -1.9871*CF + 10.1 and the square correlation coefficient is R^2 = 0.5738. On the front side the changes are much larger. With an increase in CF the tightness of the wales increases, which causes length to decrease. A strong linear correlation was found: lengthfront = -6.688*CF + 14.284 and the square correlation coefficient is R^2 = 0.9484.

Parameter A:
From the manufacturing point of view, this parameter should be fixed for each of the fabrics tested due to the use of a constant gauge of the knitting machine. However, some changes were observed

CF (H (g/km mm^2))	Change due to tension (%)							
	Sample	SQ1	SQ2	SQ3	SQ4	SQ5	SQ6	p value
1.0	W-average	0.00	0.00	0.50	0.88	0.00	0.00	0.0670
	H-average	0.00	0.44	0.00	0.75	0.00	0.00	0.0660
1.1	W-average	0.00	0.00	0.01	0.29	0.50	0.00	0.0629
	H-average	0.35	0.00	0.75	0.00	0.01	0.03	0.0644
1.2	W-average	0.76	0.00	0.03	0.00	0.00	0.88	0.0529
	H-average	0.00	0.96	0.00	0.75	0.00	0.00	0.0590
1.3	W-average	0.01	0.00	0.78	0.82	0.01	0.01	0.0517
	H-average	0.02	0.00	1.01	0.05	0.43	0.03	0.0595
1.4	W-average	0.34	0.15	0.01	0.98	0.00	0.03	0.0521
	H-average	0.08	0.49	0.00	0.03	0.01	1.01	0.0523

Figure 9.8: Variation in fabric dimensions with tension and statistical analysis

when the fabrics were analysed with the digital microscope. Results were also scattered and a consistent trend was hard to define. It seems that the higher the cover factor CF is, the smaller the parameter A is, while A is the same for the front and the back side of each fabric sample.

The results for fabric dimensions measured flat on a laboratory bench and after fitting (under tension) to a cylindrical model, Table 4, showed a maximum variation of around 1 %. The p-values determined from statistical analysis of these data revealed that there were no significant changes in fabric dimensions with tension at the stresses applied during this study.

Sample	1	2	3	4	5	6	7	8	9
CF ((g/km mm^2)$^{-1/2}$)	1.00	1.05	1.10	1.15	1.20	1.25	1.30	1.35	1.40
Stitch length (mm)	3.52	3.36	3.21	3.07	2.94	2.82	2.71	2.61	2.50
k_{TEX} front (mm$^{3/2}$)	3.598	3.443	3.290	3.138	2.988	2.839	2.692	2.547	2.403
k_{TEX} back (mm$^{3/2}$)	3.631	3.549	3.467	3.386	3.305	3.225	3.145	3.066	2.988

Figure 9.9: CF and (interpolated) roughness coefficients of finished fabric samples

Roughness, k_{TEX}:

The roughness coefficient k_{TEX} was obtained by combining depth, length and A. As noted above, depth and length both decrease with increasing CF, whilst A remains approximately constant. Thus k_{TEX} is expected to show a modified linear dependence on CF. Some non-linearity is expected from equation 9.4 as the general relationship would be:

The variation of k_{TEX} and CF for the fabrics produced in this study is shown in Fig 9.9 and Fig 9.10 and does show a largely linear relationship of k_{TEX} decreasing with increasing CF, i.e. the fabrics becoming smoother with the increase of cover factor. This could also be explained by the definition of cover factor as a numerical representation of the percentage of empty area over the area filled with the yarn in a fabric. The looser the fabric is, the more holes it has, and thus the higher its roughness coefficient k_{TEX} is. The correlation between the roughness coefficients calculated for front and back side of the textiles needs to be further analysed. These relationships differ due to differences in excrescence shape (as noted above) and this study has not established a clear link between the two sides nor between the shapes of the excrescences.

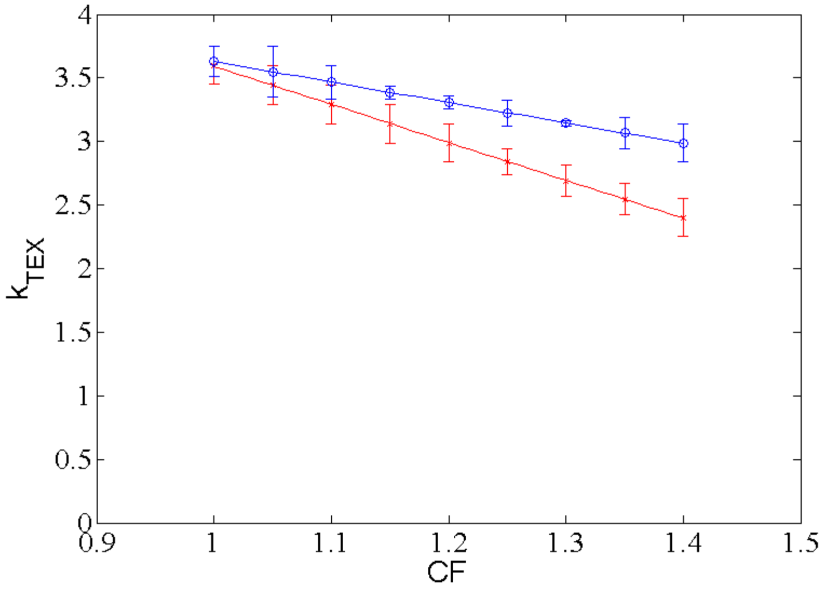


Figure 9.10: Correlation between k_{TEX} and CF

9.3.2 Aerodynamic performance

9.3.2.1 Cylinder tests:

In order to characterise the aerodynamic behaviour of the different fabrics produced, c_D versus Speed curves were generated (Fig. 6a, Fig. 6b). The fabrics' behaviour confirms the results presented in literature for rough cylinders (Fage and Warsap 1929), with the rougher fabrics (higher k_{TEX} values) reaching the drag crisis first and then shifting to turbulent regime at a lower speed compared to the smoother fabrics. However, as noted in a number of studies on roughness of cylinders, the rougher the fabric is, the lower the transition speed is; but, at the same time, at higher flow speeds, drag increases more rapidly (Fage and Warsap 1929,Zdravkovich 1997, Fu 2002, Achenbach 1977, Oggiano et al. 2008).

This makes the choice of the right fabrics complicated due to the fact that each fabric performs best at a certain speed or, in the best case scenario, over a certain range of speeds. Another important parameter, beside the roughness, which needs to be considered in order to be able to choose

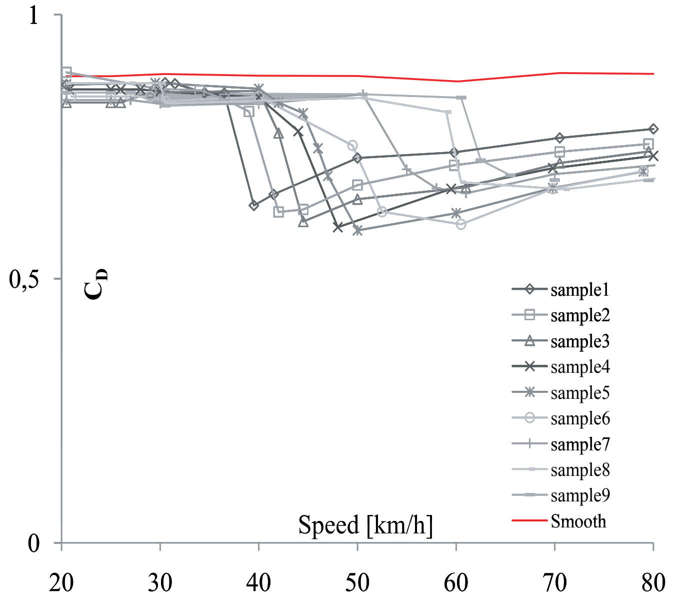


Figure 9.11: c_D-speed curves for technical front side of the textiles relatives to the cylinder model.

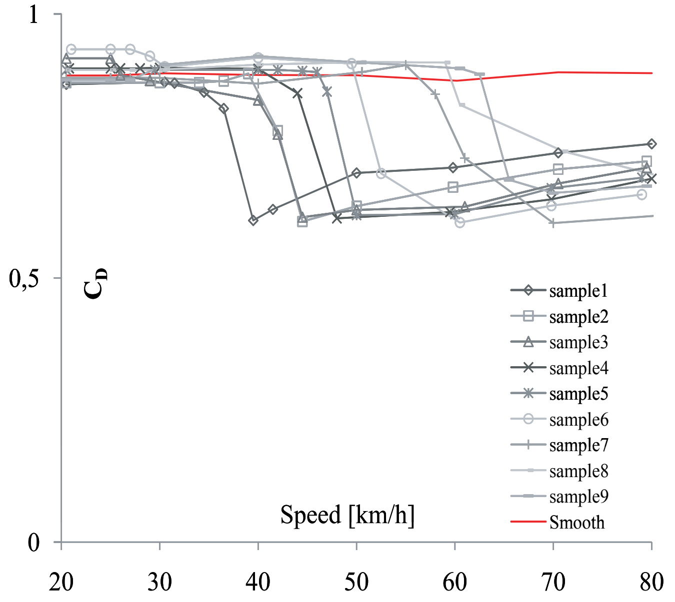


Figure 9.12: c_D-speed curves for technical back side of the textiles relatives to the cylinder model.

the best fabric for a chosen sport discipline, is the diameter of the cylinder (equivalent to e.g. the leg, arm or head of the athlete) where the fabric is going to be placed. The diameter affects the relative roughness r and it then in turn affects the aerodynamic properties of the fabric. In the present study, the effect of the diameter was not considered and the only parameter used in order to define the roughness was k_{TEX}.

The c_{DMIN} value varies from 0.592 to 0.692 for all the fabric samples tested. This gives a drag reduction of between 22% and 36% comparing to the drag on smooth cylinder at speeds ranging from 37 km/h to 70 km/h. The higher reduction in terms of drag was noted for speeds of up to 50 km/h (between 30% and 36%) while smaller gains were found for speeds greater than 50 km/h (drag reduction between 21% and 31%). For the front side of fabric samples, V_{TRANS} varies from a minimum value of 38 km/h to a maximum value of 61 km/h. It was decided in this study to use the speed value instead of the Reynolds number because it is easier to relate a certain speed value to the chosen sport discipline, and consequently to evaluate aerodynamic performance of fabrics in relation to that sport discipline. As can be seen in Fig. 9.13, the c_{DMIN} values are almost constant for both fronts and backs of the fabrics produced in this study. Slightly higher values were found for the lower roughness samples (1front, 2front 3front and for samples 1back and 2back). For all the other samples c_{DMIN} stabilizes to a value of 0.6. V_{TRANS} shows a much more linear relationship with k_{TEX} over the whole range studied (Fig. 9.14), for both, front and back sides of the fabrics with V_{TRANS} decreasing as k_{TEX} increases. This last correlation is particularly important because it provides the possibility of producing the 'right' fabric for each sport discipline if the average speed is known.

An unexpected trend for the c_D - speed curves was found for rougher samples (7, 8 and 9 for the front side and 8 and 9 for the back side of the fabrics) as shown in Fig. 9.11. The drop in c_D is smaller than found for the other (smoother) samples. A clear physical explanation of this phenomenon is not possible from the data acquired, and the data show a non linear correlation between c_{DMIN} and CF.

Uncertainties in c_D at low speeds are present in Figs 9.11. This is due to the higher relative error in the speed measurements at low values.

The wind tunnel tests in this study gave lower values of c_D (0.9 against the 1.1) for laminar flow around the smooth cylinder than reported by Fage and Warsap [Fage 1929]. This could be due to the high free stream turbulence present in the wind tunnel which has a major influence on the drag measurements. Another possible reason could be that the flow around the cylinder was not perfectly two dimensional due to the non infinite length of the cylinder. In order to avoid this effect, two dummy cylinders on both sides (upper and lower) of the cylinder model were introduced. However, the length of the dummy cylinders was not optimised.

9.3.2.2 Leg tests:

The effects of fabrics on the drag coefficient of the model show similar trends to those observed in the cylinder tests, Fig. 9.15 and Fig. 9.16. The rougher the textile is, the lower the value of $V_{TRANS}$is. However, c_D-speed curves acquired during tests on the leg model tend to show a much smaller range of V_{TRANS} values than for the cylinder model. As for the cylinder model, for both front and back sides of the fabric the largest change in V_{TRANS} values occurs from the smooth model to the roughest fabric (sample 1) and, as the roughness decreases, then the V_{TRANS} values increase back towards the smooth model value.

For the cylinder this change appears to be continuous but for the leg model no further changes are seen for roughness levels below k_{TEX} = 2.516 for the front and k_{TEX} = 3.328 for the back side.

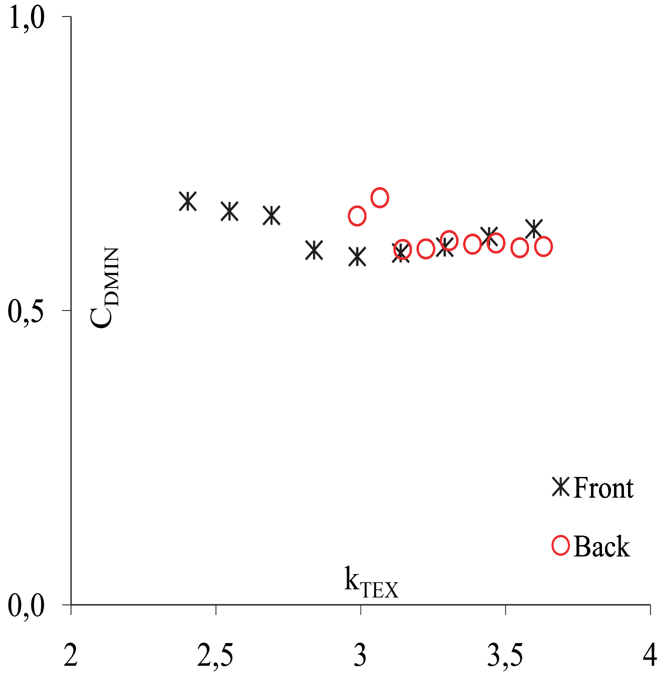


Figure 9.13: c_{DMIN} - k_{TEX} curves for technical front and technical back of the textiles relatives to the cylinder model.

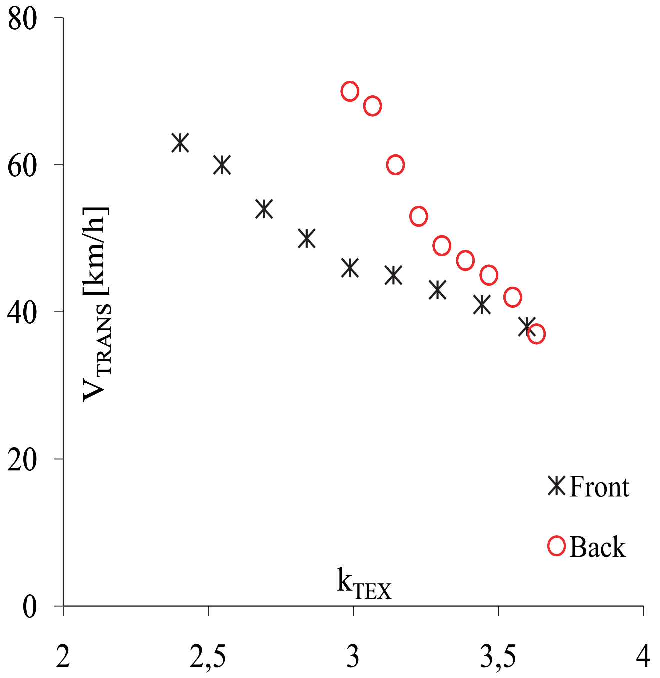


Figure 9.14: V_{TRANS} - k_{TEX} curves for technical front and technical back of the textiles relatives to the cylinder model.

The same behaviour was found for both, front and back side textiles. V_{TRANS} tend to stabilise around an asymptotic value of 54 km/h for the front side fabrics and 50 km/h for the back side fabrics. The approach to an asymptotic value suggests that there is another mechanism, in addition to surface roughness, acting for the leg model that is not apparent in the cylinder model. This may be an aspect of form drag where the non-uniform shape of the leg model disrupts the flow away from the 2D assumption more than in the case of the uniform section cylinder. Thus geometry would need to be considered along with surface roughness as the effect of the leg form is more dominant for the back side of the fabric than for the front side.

The drag reduction is higher than that found in the cylinder tests. The maximum drag reduction is about 55% for both, front and back side and it has been measured for the sample 9front (CF =1.4) at 59 km/h and for the sample 8back (CF=1.35) at 60 km/h (Fig. 9.15 and Fig. 9.16). The shape of the c_D - speed curves is similar to the one found for the cylinder. It can be divided in 3 different parts:

1. Laminar area (where the c_D is almost constant and its value is around 1. (Not all the curves start from the same value of 1. This might be due to uncertainties in the measurement due to the higher relative error on speed measurements at low speed. The error in speed measurements increases to ca.0.5 km/h from 0.25 km/h quoted above for higher speeds). In this part the flow is laminar and the separation point is probably placed at the front part of the model as is the case for the cylinder.

2. Transition area (where the flow pass from the laminar regime to the turbulent regime). In this part there is a drop in c_D and the value of c_D passes from 1 to a value of around 0.5. A similar trend is followed by all the different fabrics.However, fabrics with higher roughness or lower cover factor have a higher c_{DMIN}; this can be found in literature about rough cylinders as well [Achenbach 1977], Bearman [Bearman 1993], [Oggiano 2007].

3. Turbulent area (where the flow is fully turbulent). In this area the c_D is still lower than in the laminar part but it is slowly increasing its value while the speed increases.

Tests of the leg model indicate a fairly linear variation of c_{DMIN} with k_{TEX}, Fig. 9.17, whilst Fig. 9.18) shows the divergence in behaviour for cylinder and leg models. For the cylinder model the relation between k_{TEX} and V_{TRANS} is linear, whilst for the leg model the trend is not linear anymore but for low CF values, V_{TRANS} approaches a constant value.

This trend can be related to the different shape between cylinder and leg. The leg shape, in section, is closer to an ellipse than to a circle. Furthermore the leg is tapered while the cylinder has a constant round section along its length. However, as noted above there is an interaction between geometry and surface roughness resulting in the different behaviour between front and back sides of the fabric on the leg model.

Results obtained from the tests carried out on the cylinder model match results published by Achenbach [Achenbach 1977], Bearman and Harvey [Bearman 1993], and [Oggiano 2007]. It is clear that a higher k_{TEX} triggers the transition at a lower flow speed.

The samples between 1 and 5 (front) are the ones, which perform best at these ranges of lower

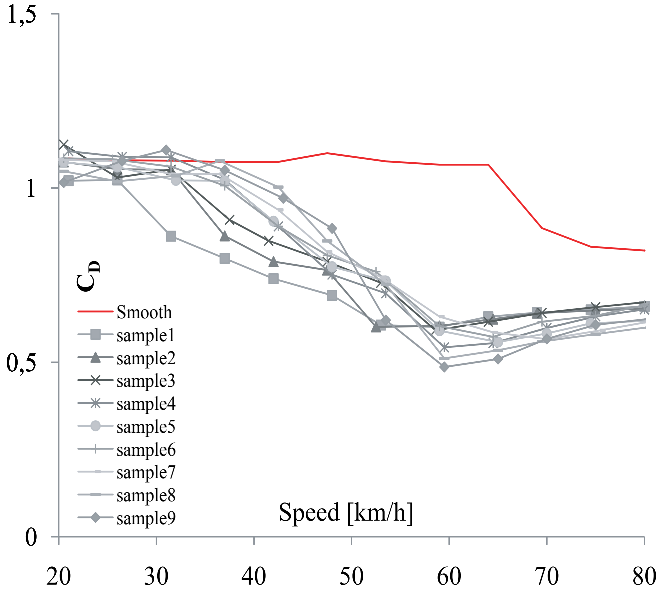


Figure 9.15: c_D - speed curves for techincal back side of the textiles using the leg model

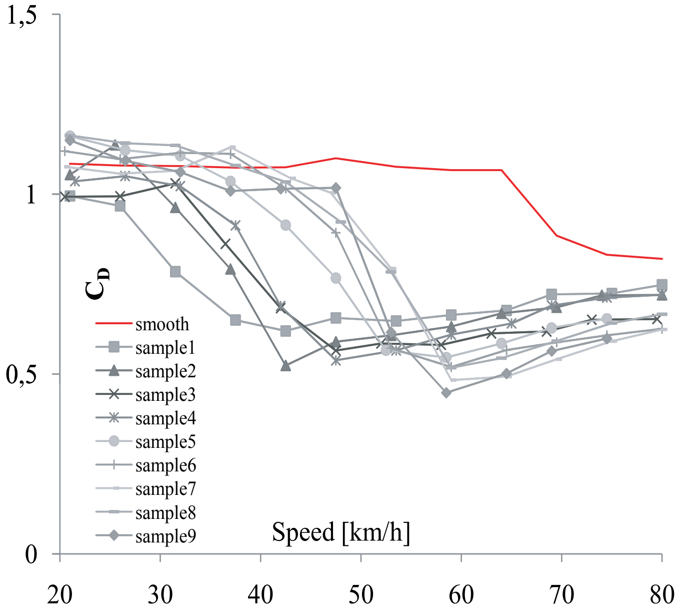


Figure 9.16: c_D - speed curves for techincal front side of the textiles using the leg model

speed. Sample 1, which is the roughest one, enters the transition at 35 km/h if placed on the leg model and at 38 km/h if placed on a cylinder. The c_{DMIN} measured for sample 1 is 0.620; it is greater than the c_{DMIN} measured for the next sample (sample 2 front. c_{DMIN} = 0.524).
For the front side of the fabrics: at k_{TEX} values > 2.5 the transition from laminar to turbulent occurs at similar speeds (V_{TRANS}) on both models (leg and cylinder) and the correlation is roughly linear, Fig. 9.18; the speed for the leg model is slightly below that of the cylinder model. If k_{TEX}<

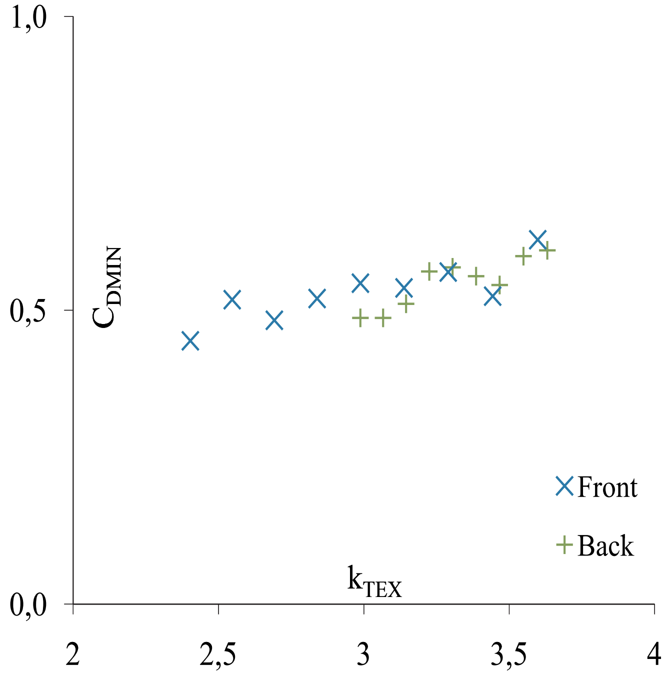


Figure 9.17: Variation of c_{DMIN} for the front side and the back side fabrics

2.5, two different behaviours are identifiable, Fig. 9.18. k_{TEX} and V_{TRANS} are linearly correlated when fabrics are tested on the cylinder model, while this linear correlation disappears when the fabrics are tested on the leg model. It is clear that it is possible to identify a limit in V_{TRANS} for the leg model. For k_{TEX}< 2.5, V_{TRANS} has a constant value (53 km/h).
Considering the back side of the fabrics: for k_{TEX}> 3.393 transition occurs at the same speed for the leg and the cylinder model, while, for smoother fabrics (k_{TEX}< 3.393), V_{TRANS} measured on the leg model stabilises at around 50km/h. While k_{TEX} increases, V_{TRANS} linearly decreases. For the front side textiles on cylinders, the linear equation which describes the relation between V_{TRANS} and k_{TEX} is V_{TRANS} = -20.478 k_{TEX} + 110.18 with a R^2 = 0. 954 while for the back V_{TRANS}= -50.928 k_{TEX} + 220.75 with R^2 = 0.956. R^2 values are high for both front and back side textiles.

9.4 Conclusions

In this research rough fabrics were shown to be able to reduce the drag by around 30% on the cylinder model and up to 50% on the leg model. Relationships between fabric CF, roughness and its aerodynamic properties were found. These provide a basis for selection of the most appropriate apparel fabric for specific sports discipline, but this will need expansion to consider the geometry - fabric interaction and full 3D flow. A distinctive trend has also been established through comparison of results obtained for the leg and the cylinder models. The relationship between k_{TEX} and V_{TRANS} is linear if the fabrics are tested on the cylinder (both for the front and the back side

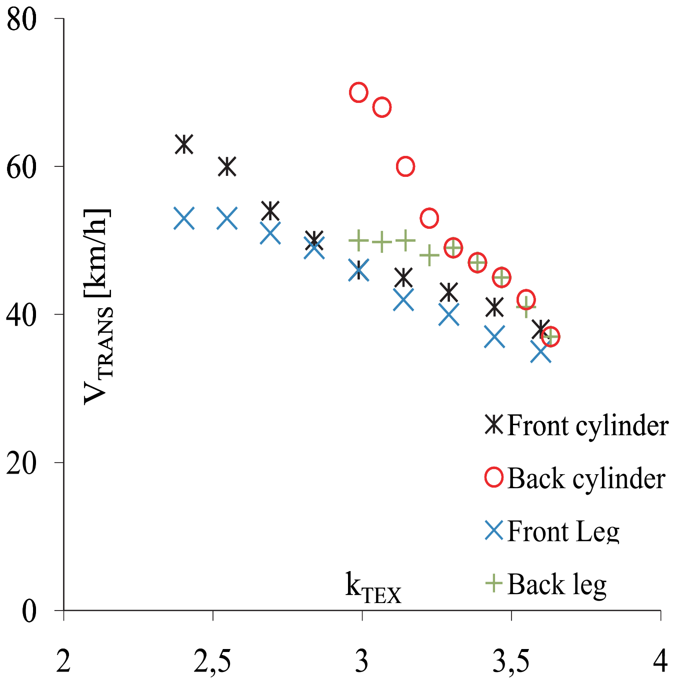


Figure 9.18: Variation of V_{TRANS} with k_{TEX} on leg model and cylinder model for the front side and the back side fabrics

of the fabric) but it is not linear if fabrics are tested on the leg model. A limit for V_{TRANS} of 53 km/h was identified for the leg model with the front side covered by the fabrics and 50 km/h for the leg model with the back side covered by the fabrics. This could be due to the different shape of the two models (the cylinder is bluffer than the leg). Thus the transition from the laminar flow to the turbulent flow on the leg permits the flow to be kept attached to the body creating a smaller wake than in case of the cylinder. Based on the results obtained, the following can be concluded:

- All the fabrics tested reach the transition from laminar to turbulent regime in the speed range of interest (between 30 km/h and 70 km/h)
- Fabrics show similarities in behaviour if placed on the leg model or on the cylinder model
- The minimum drag is almost constant for all the fabrics tested (front and back) on the cylinder model
- The minimum drag coefficient c_{DMIN} increases with k_{TEX} for all the fabrics tested (front and back) on the leg model

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CHAPTER 10

P5

Effect of different skin suits on speed skating performances

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Abstract:
Drag in speed skating is the most important frictional loss. This paper presents a numerical and experimental investigation on how rough textiles are able to affect the drag in competition speed skating suits. The attention has been mostly focused on the legs of the athletes. Methods: Experiments with a doll in scale 1:1 have been carried out. Drag at different speeds (from 4m/s to 17m/s) has been acquired and c_D-Speed curves for each suit have been plotted. A mathematical model based on the balance between the power generated and the power spent by the athletes has been used in order to estimate the final time in a 1500m long track competition for women and men. Results: Speed skating suits do affect speed skaters performances. A maximum difference in drag of about 10% has been acquired and a maximum difference in final time of about 3s has been estimated. Rough textiles on the suits legs are able to reduce the drag at low speeds (V<11m/s) but negatively affects performances at high speed (V>13m/s).

10.1 Introduction

Performances analysis in sports is complex since many factors linked together contribute to the final result thus a quantification of the effects of different suits on speed skating performances just with field measurements is a difficult task.

In fact, field measurements and competition results do not clearly show the effect of using different suits. Industries and Olympic committees have then been pushed to increase the number of laboratory tests on materials, apparels and equipments in order quantify the effects of different textiles on skating suits.

In some sports like cycling and speed skating the speed is entirely determined by the equivalence between external power and the power lost both by frictional losses and in order to increase the speed [DiPrampero 1976], [VanIngenSchenau 1982]. Forces acting against the athlete and power dissipated are related with the equation:

$$P = F \cdot V \tag{10.1}$$

Drag, in these sports, is the most important among the frictional losses. In cycling and speed skating, when the athlete reach a constant speed, D is about 80% of the total force while the frictional force is only about 20%. Drag acting on the athletes has been often represented as:

$$D = \frac{1}{2} A_p c_D \rho V^2 \tag{10.2}$$

K has been considered as constant both in cycling [DiPrampero 1979], and speed skating [DiPrampero 1979].

This was mostly due to the fact that the athletes were not able to reach the critical speed V_{TRANS} which cause the fall in c_D due to the change from laminar to turbulent regime and the consequent reduction of pressure drag.

Transition of the flow around the athlete from laminar to turbulent and the consequent drop in terms of drag has been predicted by Pugh [Pugh 1974]. However he has not been able to reach the critical speed value in his wind tunnel experiments in order to verify his prediction.

[DiPrampero 1979] showed that c_D is not constant but dependent on different factors. Among these factors also the speed is mentioned. The effect of different suits has not been taken into account in Van Ingen Schenau experiments but only effects of postures and speed have been analyzed. In the present paper then K will be considered as dependent on the speed and on the different suits.

$$K = K(V, suit) \tag{10.3}$$

The effect due to different postures has not been considered since it has been already discussed by Van Ingen Schenau [VanIngenSchenau 1982]. In the experiments carried out in the wind tunnel with a full scale mannequin model V_{TRANS} has been reached and the fall in c_D occurred. The target of this work is to give an overview on the effects of textiles with different roughness implemented in speed skater's suits with particular attention to legs.

A test on 6 different speed skaters suits and on the effect of different textiles on leg's athletes has been performed using a mannequin positioned in the wind tunnel. The position of the mannequin has been chosen in order to reproduce the position that speed skaters utilize during a 1500m race.

10.1.1 Forces acting on a skater

The total power (P_T) due to friction losses that a speed skater needs to overcome during his race is given by the sum of power spent to overcome the drag resistance (P_D) and power needed to overcome the skate-ice friction (P_F).

$$P_T = P_D + P_F \tag{10.4}$$

10.1.1.1 Aerodynamic forces

Aerodynamic forces are about 80percent of the total forces acting on a skater. Van Ingen Schenau [VanIngenSchenau 1982] showed that the intensity of the aerodynamic forces acting on a speed skater is related to the position assumed during the race. Defining the angles which characterize a speed skater's posture like shown in Fig 10.1, it has been shown that for both ϑ_2 and ϑ_3 there is a linear correlation between the angles and the drag. The greater the ϑ_2 or ϑ_3 are, the higher the drag is. From previous works [DeKoning 2005a] the average of the angle ϑ_3 is about 25degrees and the average of the angle ϑ_2 is about 115degrees. The total power spent in order to act against the aerodynamic resistance can be calculated as:

$$P_D = \frac{1}{2} A_P C_D(V, suit) \rho V^2 V \tag{10.5}$$

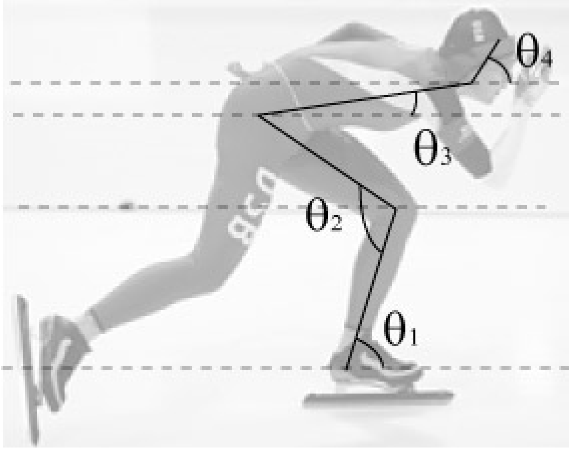


Figure 10.1: Angles which characterize a speed skater posture

10.1.1.2 Friction

The mean friction coefficients μ for the straights and curves are, respectively, 0.0046 and 0.0059 [VanIngenSchenau 1982]. The total power spent to overcome the friction losses can be written as:

$$P_F = \mu m g V \tag{10.6}$$

10.1.2 Speed

Data regarding 28 men athletes and 17 women athletes competing in a national Norwegian speed skating competition (Hamar 13-14 October 2007) have been acquired. For the 1500m race, the average speed for each interval has been calculated for each athlete and distance-speed curves regarding the averaged performances have been plotted for women and men competition. These data have then been compared to the data relatives to the world record in the 1500m.
Furthermore, the average speed for the different disciplines (500m, 1000m, 1500m, 3000m, 5000m, 10000m) have been calculated for the world records performances.
In short distance disciplines the speed is higher and increases and varies during the race while in long distance disciplines, where a constant speed during the whole race is important, the speed is lower. A difference of about 1.5m/s between ladies and men has been found.

10.2 The power balance model

In order to evaluate the effect of using different skin-suits, the power balance model developed by Koning

$$P_u = P_D + P_F + \frac{dE_mcb}{dt} \tag{10.7}$$

Where P_u is the total power in output generated by the athlete , P_D is the power lost with frictional losses due to drag P_F is the power lost with frictional losses due to friction between skates and ice and dE_{mcb}/dt is the power output spent to increase the kinetic energy. The efficiency of the power balance model in speed skating performance estimate has been shown by De Koning. [DeKoning 2005a], [DeKoning 1992b]; in these articles has been experimentally calculated measuring the oxygen uptake during the skating action.
The power balance equation 10.6 can be used to estimate a reference power output if friction coefficient (μ), drag coefficient (c_D) and the instantaneous velocity of the skater are known. In this case is the only unknown and it can be calculated as a function of time. The instant speed has been calculated from data acquired during a Norwegian national speed skating competition (Hamar 13-14 October 2007). A constant friction coefficient (μ = 0,005) have been used. A constant c_DA (c_DA=0.3) has been estimated using the data acquired by Van Ingen Schenau [VanIngenSchenau 1982]

10.3 Methods

10.3.1 Suit Test

Six different suits have been tested in the wind tunnel in order to evaluate the effect of each suit in a 1500m speed skating competition. Drag has been acquired using a six component balance. The suits tested have been numbered from 1 to 6 and some of them are currently used by top level athletes. Each suit has been mounted on a mannequin and the mannequin has been mounted in the wind tunnel (Fig. 10.2). The posture of the mannequin has been chosen following the data previously acquired about the average posture of a speed skater in a 1500m competition ($\vartheta_2 = 25°$, $\vartheta_3 = 115°$).

The drag of each suit has been measured in a range of speed (s) from 8m/s up to 18m/s and a c_DA-Speed curve has been then plotted for each suit. The c_DA-Speed curves acquired have been introduced in a Power balance model and a final time in the performance has been estimated for each suit. The suits tested are all different and produced by different manufactures. A level of

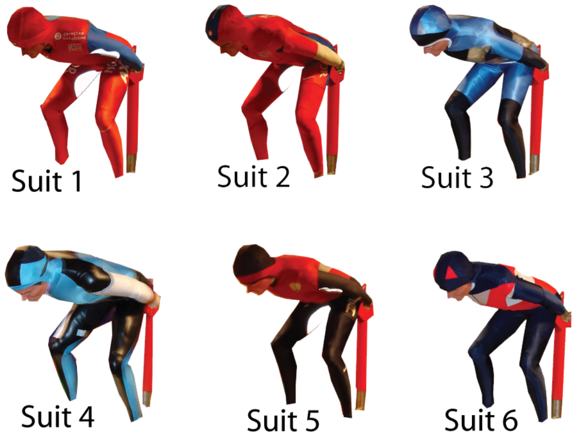
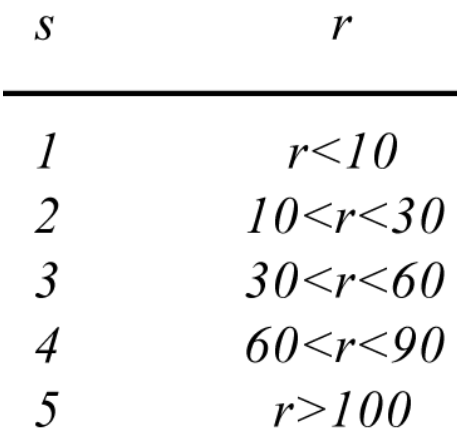


Figure 10.2: A picture of the 6 suits tested. All the suits have different patterns in the different parts of the body. Suits 1,3,5,6 have a moderate rough textile on their legs while suit 2 has an extreme rough pattern and suit 4 is totally smooth.

	Suit 1	Suit 2	Suit 3	Suit 4	Suit 5	Suit 6
Lower leg	3	5	3	1	3	3
Upper leg	2	1	2	1	2	2
Trunk	1	1	1	1	1	1
Head	3-1	1	3-2	1	3-2	3-2
Arms	1	3	2	2	1	2

Figure 10.3: Smoothness parameters for each suit



s	r
1	$r<10$
2	$10<r<30$
3	$30<r<60$
4	$60<r<90$
5	$r>100$

Figure 10.4: Relation between smoothness factor s and roughness coefficient r

smoothness (s) has been assigned for each textile. The smoothness level varies from 1 to 5 (1 = very smooth, 5 = very rough) (Fig 10.2, Fig 10.3, Fig 10.4) and it has been assigned to each part of the suit (lower legs, upper legs, trunk, hat, arms). Smoothness and roughness levels are important in order to reduce the drag. Considering the human body as composed by a series of spheres and cylinders and knowing that it is possible to shift the transition to turbulent regime (in spheres and cylinders) at different speeds by using rough textiles, it is then possible to sensible reduce the drag choosing the right textile. [Oggiano 2007] In order to give a more quantitative idea of the smoothness factor used, it is possible to correlate the smoothness factor with a roughness coefficient calculated for cylinders.

Based on structure width and depth, a surface parameter can be defined:

$$k_{surface} = \sqrt{w \cdot d} \tag{10.8}$$

The surface curvature (given by the cylinder diameter $Diam$) determines the pressure gradient that influences the flow separation conditions. It is possible to combine the two parameters in a dimensionless roughness coefficient.

$$r = \frac{k}{Diam} \cdot 10^3 \tag{10.9}$$

Equation 10.7 has been used to calculate the instant speed of the skater during the race using different skating suits A friction coefficient of 0.005 has been used. The final time for a 1500m race has been then estimated.

Suit 1 showed the best results while suit 4 showed the worst (Fig 10.5). This is due to the fact that the textiles adopted on suit 4 are too smooth and it has been impossible to reach the transition to turbulent regime on the legs and then reduce the drag. Suit 2 showed a different behaviour for girls and boys.

As predicted, the influence of the textile on the legs is quite high. Suit 2 which has a very rough textile reach the transition at lower speed while suit 4, which has a very smooth textile on the legs

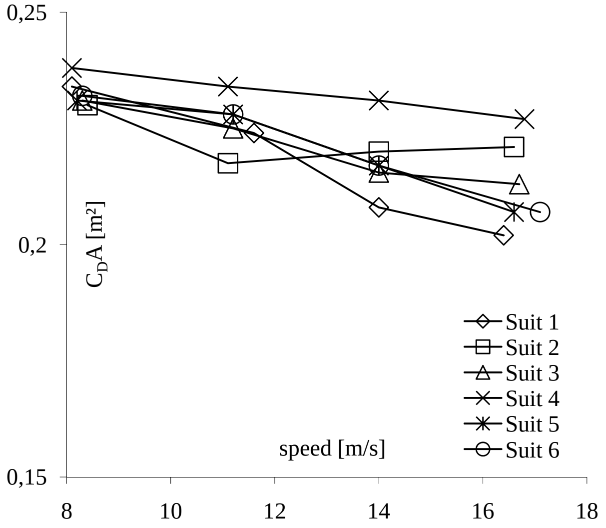


Figure 10.5: c_DA-Speed curves for the 6 different suits tested.

	Suit 1	Suit 2	Suit 3	Suit 4	Suit 5	Suit 6	Hybrid
Ladies	125,84	126,24	126,34	128,34	126,84	126,84	124,54
Boys	107,54	109,34	108,74	110,64	108,44	108,54	107,64

Figure 10.6: Results from the 1500m race simulation

can't reach the transition before 16m/s which is the maximum speed for a speed skater during a sprint competition.

This is due to the fact that the textiles used is on the legs are extremely rough and shift the transition at lower speed than any other of the suits tested, but at the same time increase the c_DA_{MIN} at higher speed. Considering that the maximum speed (during a 1500m competition) for the women is around 14m/s and for men is around 16 m/s suit 2 gives better performances if used by girls and permits to gain almost half of second. It is interesting to notice that the difference between the performances simulated with suit 1 and suit 4 is 3.31s for the men and 2.31 second for the women. Considering the Olympic Games in Torino 2006, a time difference of 3.1s for the men and 2.5s difference for the women was the difference between the 1st classified and the 23rd classified for the men and the 1st classified and the 5th classified for the women.

In order to evaluate the effect of the textiles on the legs a hybrid suit has been created. The legs of suit 2 has been covered with a smoother textile (s = 4) and the Drag has been acquired. A comparison between the c_DA curves for suit 2 and the hybrid suit shows that the introduction of a smoother textile on the legs gives better performances in terms of drag reduction. The final time calculated the hybrid suit is 1.7s lower than the one calculated using the suit 2.

10.4 Discussion and conclusions

The results presented above gives an indication of the effect, of the seven suits tested, on speed skaters performances on the 1500m race. It has been noticed that the effect of the textile used on the legs is the most important in terms of drag reduction. A rough textile can reduce the drag if compared to a smooth one but, if the smoothness coefficient is too high, it can affect the performances negatively. In order to understand how different parts of the body moves during a skating action, a deeper look into the skaters position assumed during a race is needed.

Size of different body parts and average speed are also two important parameters that should be considered in order to decide which kind of roughness gives the best results in terms of drag reduction. All these parameters should be considered in order to improve speed skating suits.

To conclude, results show that skin suits do affect speed skaters performances. A final time difference of about 3 seconds has been estimated (for both, women and men) if suit 1 and suit 4 are compared.

The test performed on the hybrid suit showed that textiles present on the legs have a central role in order to reduce the drag. Increasing the roughness of the textile means at the same time, decreasing of the drag at low speed but increasing of the drag at high speed. The strict correlation between roughness, drag coefficient and speed impose the use of different suits for different disciplines in order to have the best results. The average speed of a speed skater changes not only during the race but also from ladies to men competitions and it decreases when distance increase.

A rougher pattern on the legs should then be used for girls and for long distance competitions while a smoother textile is needed in men short distance competitions, where the average speed is higher. Possible suggestions are the use of a textile with s=3 or s=2 for short distance competition and in general when the average speed is larger than 12m/s and the use of a textile with s=4 for long distance competitions where the average speed is lower than 12m/s. These limits are not certain and future work is needed in order to have more precise values.

However, a correlation between the smoothness coefficient and the average speed is certain and it has been exposed. The use of totally smooth textiles on the legs (s=1) is not recommended in any case while they can be used for the trunk and the hat. The use of extremely rough textiles (s=5) is not recommended neither since they increase the drag at high speeds.

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CHAPTER 11

P6

Aerodynamic optimization and energy saving of cycling postures for international elite level cyclists

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Abstract:

Introduction: Drag in cycling counts for as much as 90percent of total resistance opposing motion in a normal time-trial course. A small gain in term of drag reduction can, over a longer timespan (30 - 60 minutes) give a large advantage to the cyclists in terms of power output saved or velocity gained. The aim of present study was to aerodynamically optimize the cycling posture for each cyclist and thereby improve the athletes' performances. We also wanted to quantify the power output saving, velocity gains and energy savings of this optimization. Methods: 11 elite cyclists with a maximal aerobic power output of 481 W were tested at 6 different positions on their time-trial bicycle in a wind tunnel with an air flow at 14.5 m/s. All positions were adjusted from their regular position and included both adjustment of seat and handlebar. All cyclists also went through an extensive physiological test, including lactate threshold and VO2max tests, allowing for individual efficiency calculations at several power outputs. Results: From the wind tunnel test individual power-output - velocity curves were plotted, showing the effect of the different positions in terms of saved power generation. Showing an average 21.9 W saving in power output and an average of 0.75 km/h gain in velocity at 500 W for the most aerodynamically position. Using each cyclist's efficiency we calculated the theoretical effect of oxygen consumption, Kcal/h and heart rate. Average results show a 0.34 l/min, 101.5 Kcal/h and 14 BPM for the heart, in saving, for the most aerodynamically position. Conclusions: The effect of small adjustments on elite cyclists can have large effect on performance and energy saving. However, care should be taken as the new position can negatively affect power generation and pedaling technique, which might become more energy consuming. Data on this is also collected in present study but needs further analysis.

11.1 Introduction

PPerformances in cycling are affected by a number of factors. Together with the important evaluations about physiology, biomechanics and all the possible research about materials, an accurate analysis of the forces acting against a cyclist during his motion is highly important. Considering a flat track, several forces act on a cyclist during his race (Fig 11.1). Using the second Newton's law, the force balance along the x-axis gives

$$F = ma_x + F_R + C + D \tag{11.1}$$

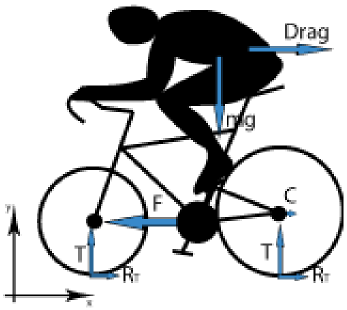

Figure 11.1: Forces acting on a cyclist

and along the y-axis:

$$mg = 2T \tag{11.2}$$

Where F is the total force produced by the cyclist during his cycling action, F_R is the rolling resistance is the inertia force, C is the transmission losses (which can be neglected), D is the aerodynamic resistance or drag, and T is the reaction force.

11.1.0.1 Rolling resistance

The rolling friction on the front wheel is different from the rolling friction on the rear wheel. This is due to the weight distribution on the bike. A simplified formula permits to consider the total rolling resistance as the sum of the front wheel rolling resistance (R_{TF}) and the rear wheel rolling resistance (R_{TR}).

$$F_R = R_{TF} + R_{TR} \tag{11.3}$$

Many studies have been carried out in order to determine . According and [KB1] ,can be written as follow:

$$F_R = c_{R1}mg + c_{R2}V \tag{11.4}$$

Where c_{R1} and c_{R1} are constants. In some studies the dependency of F_R on the speed has been neglected ([Capelli 1993], [Grappe 1997], [Davies 1980], [DiPrampero 1979],[Pugh 1974]) and thus F_D has been considered proportional to the rolling coefficient c_{R1}.
The non dependency of F_R on the speed gain importance when it comes to analyze the total forces resisting the motion of a cyclist. While D increase with the square of the speed F_R is constant. Thus, when the speed increases, the importance of rolling resistance compared to the drag decreases.

11.1.0.2 Drag

TAerodynamics has a central role. Drag resistance is in fact the major part of the total forces acting against a cyclist and it counts up to 90% at 14m/s (Fig. 11.2a). A gain in terms of drag reduction permits a sensible improvement in performances. (Fig. 11.2b)

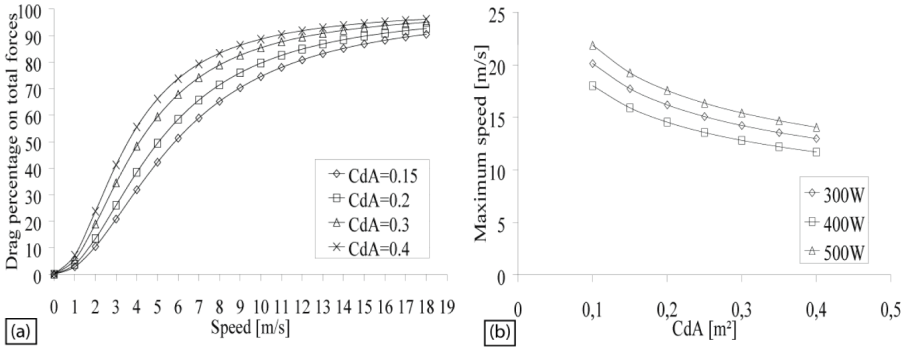

Figure 11.2: (a) Drag percentage on total force. (b) Maximum speed reachable with different power values.

$$D = \frac{1}{2} A_p c_D \rho V^2 \tag{11.5}$$

where A is the frontal area, c_D is the non dimensional drag coefficient and depends from the shape, r is the density of the air and V is the speed. The square dependency of the drag from the speed is significant because, a small reduction in c_D, at high speed, means a high reduction of the drag. This effect gain even more importance when it comes to analyze the power spent in order to overcome the drag. The power is in fact proportional to the cube of the speed

$$P_D = \frac{1}{2} A_p c_D \rho V^3 \tag{11.6}$$

However, cyclist posture is rigorously related to his anthropometric characteristics and, often, an aerodynamic optimized position do not give good results in terms of force production. Optimization between biomechanics and aerodynamics is then highly important in order to find postures which can gives some advantages. The cyclist posture has been studied and analyzed for many years. Di Prampero [DiPrampero 1979], Kyle [Kyle 2004], and Hennekam [Hennekam 1990] showed some postures are more efficient than others while Capelli [Capelli 1993] showed the importance of the bike itself in order to reduce the drag.

11.2 Methods

11.2.1 Subjects

After approval form the regional ethical committee 9 male and 2 female elite cyclists with an average age of 22.2 (5.9) years, signed an informed consent to participate in the study. Average height and weight was 181.6 (5.8) cm and 73.8 (7.4) kg. Subjects had a maximal aerobic power of 481 (75) W and an average VO2max of 4.66 (0.59) l/min. Average maximal heart rate was 198 (5.2) BPM. Their lactate threshold power (lactate = 4 mmol/l hemolysed blood) was 297 (47) W at an average VO2 consumption of 3.82 (0.53) l/min and a heart rate of 175 BPM (5.6). Average energetical efficiency was 21.8 (1.02)%.

11.2.2 Wind Tunnel

For the experiments, the wind tunnel of NTNU (Norwegian University of Science and Technology) in Trondheim has been used. The contraction ratio is 1:4.23, and the test section of the wind tunnel is 12,5 meters long, 1,8 m high, and 2,7 m wide. The wind tunnel is equipped with a 220KW fan that can produce a variation of speed between 0,5 - 30 m/s. The balance (Carl Schenck AG) used is a six components balance capable to measure the three forces and the three momentums around the three axes. Variations of forces and momentum are measured using strain gauges glued to the balance body. The voltage outputs are measured by a LABVIEW based PC program.

11.2.3 Aerodynamic test

All cyclists were tested and 6 different positions (table 1), starting for their natural position were tested. The test has been run at 14.5m/s and the drag acquired for each posture has been acquired 5 times and averaged. All positions were adjusted from their regular position and included both adjustment of seat and handlebar and were within the UCI rules for bicycle geometry in relation to body size. From the drag measurements at 14.5 m/s, the power output that each cyclist had to generate was calculated and a power - velocity curve was fitted down to 0 km/h for each cyclist.

11.2.4 Physiological methods

To define the individual performance level all subjects performed a lactate threshold protocol and a VO2max test. The lactate threshold protocol started at 200 W for men and 150 W for women. Each 4 min workload was increased by 25 W. Gas exchange (Jaeger Oxycon Pro - mixing chamber) was measured the last minute of each workload and blood lactate (Lactate Pro) and heart rate (Polar

Position	Seat	Handlebar
1	Normal	Normal
2	Up 15 mm	Normal
3	Down 15 mm	Normal
4	Normal	Down 20 mm + forward 20 mm
5	Up 15 mm	Down 20 mm + forward 20 mm
6	Down 15 mm	Down 20 mm + forward 20 mm

Figure 11.3: The six positions tested in the wind tunnel. All positions are adjusted form each cyclists normal position

s610i) at the end of each workload. The lactate threshold protocol was terminated when lactate was above 4 mmol/l haemolysed blood (lactate threshold)
From the gas exchange measurements on the sub-maximal workloads (lactate < 4 mmol/l blood) gross energetical efficiency was calculated using the correct energy equivalent for oxygen based on the respiratory exchange ratio (RER = VCO2/VO2). The energetical efficiency was used for calculating the individual energy saving for the different positions in the wind tunnel.
VO2max was tested starting at 300 W for men and 200 W for women with of 25 W increase in workload pr min. VO2max was defined as the highest average oxygen consumption over 1 min.
Both physiological tests were performed at freely chosen pedal rate (FCPR) at constant power outputs using a bicycle ergometer (Velotron) with an electro-magnetic brake mechanism creating resistance.
Subjects wore cycling shoes and the seat and handle bar position on the ergometer was adjusted to the preferred sitting position for each subject.

11.3 Results and discussion

Position 4 (Fig. 11.3) is resulted, in average, the position which gave the best performances in terms of drag reduction. This position has been obtained simply adjusting the handlebar. In order to evaluate the drag reduction per each athlete, a Drag reduction factor has been defined as:

$$Drag_{GAIN} = 100 \cdot \frac{Drag_{POSITION-X} - Drag_{POSITION-1}}{Drag_{POSITION-1}} \tag{11.7}$$

Position	%Gain	St.Dev
1	--------	-------
2	0.897	3.05
3	-0.864	2.06
4	-5.791	5.33
5	-4.078	4.00
6	-3.126	4.81

Figure 11.4:

However, not all the cyclists present in the test got the same improvement using the position 4 but results were quite scattered as confirmed by the standard deviation values.

This is due to the fact that the starting position for each cyclist is his normal cycling posture and some of them have already empirically optimized their position with the experience acquired during trainings and competitions. Thus, an individual analysis in order to achieve the best results is strongly recommended.

The physiological effects and benefits of each position have been estimated and calculated for each of the cyclist tested and then averaged. However, all cyclists told that the position tested did not affect pedalling technique. In fact, most of the subjects change their position permanently after these measurements. The physiological effects of each position have been estimated from the energetical efficiency for each of the cyclist tested and then averaged.

Results in Fig. 11.5, showing position 4 to give 21.9 W saving in power output at 50 km/h (this speed can be maintained for approximately 30mins). Or from a different perspective, position 4 gives a 0.75 km/h gain in velocity at 500 W. Calculated from the energetical efficiency of each cyclist, position 4 gives an average oxygen consumption saving of 0.34 L/min which is a 7.3 % reduction compared to the cyclists maximal aerobic capacity (VO2max). For elite cyclist an equal increase of their maximal oxygen consumption would be a whole year of training to give the same effect.

If we assume that heart rate and oxygen consumption are linear and that maximal heart rate and maximal oxygen consumption is synchronous, we calculate that position 4 in 50 km/h gives a heart frequency that is 15 BPM lower than at their normal position. This also gives an estimated 101.5 Kcal/h of energy saving, which is a substantial amount of energy. In conclusion, we have shown that adjusting the handlebar down 20 mm and forward 20 mm have a substantial effect on performance (gain in km/h at a given power output) or in energy saving (reduction in effort at a given velocity.

11.4 conclusions

The experiments carried out permits to affirm that a posture optimization is possible for each cyclist. However, even if a mean trend has been found, each athlete showed different results per each position tested.

A specific individual test is then mandatory in order to obtain advantages from the aerodynamic point of view. Furthermore, each athlete has different anthropometric values which should be taken into consideration in order to maintain high biomechanics efficiency with the postures tested.

In average, posture 4 is the one who gave the best results in terms of drag reduction with consequents advantages from the physiological point of view. At the same time, posture 2 resulted to be ineffective for most of the athletes tested.

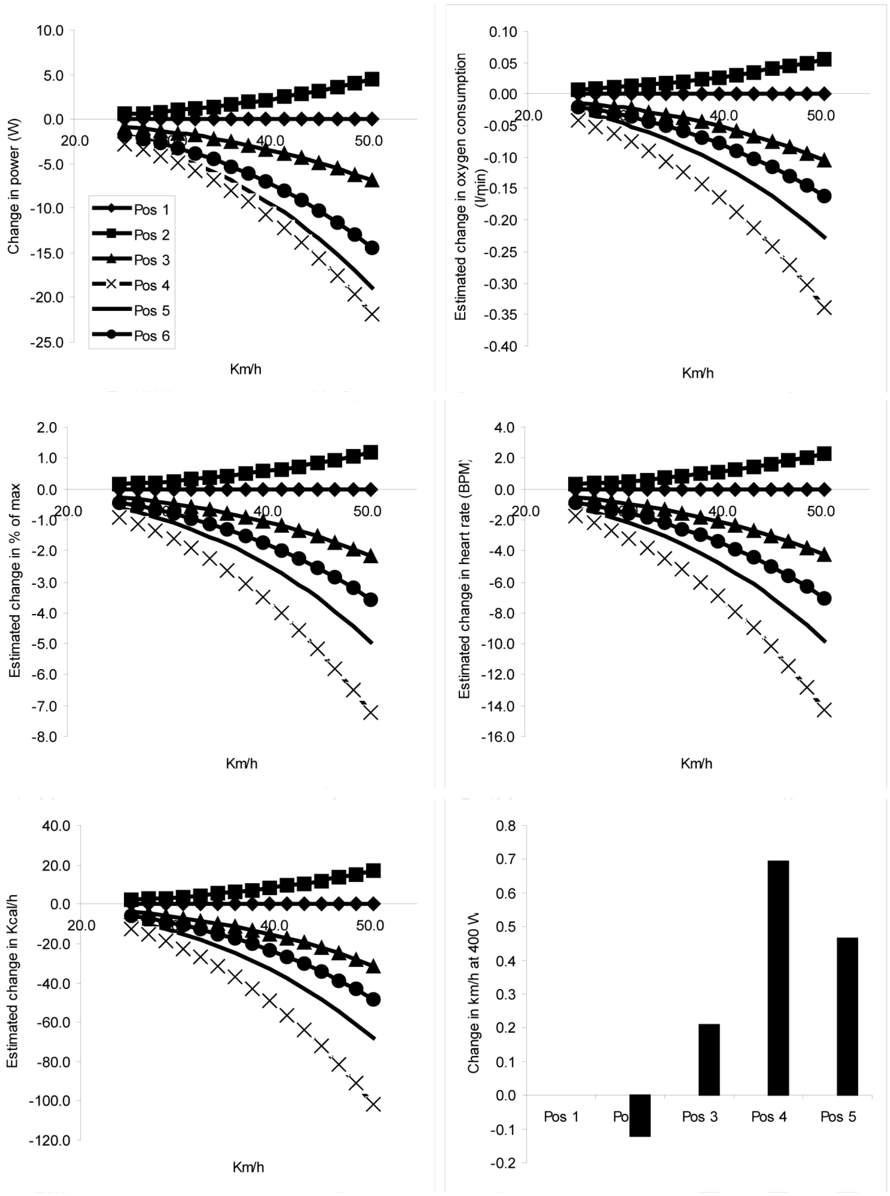

Figure 11.5: (a) Change in power output per velocity per position. (b) Estimated change in oxygen consumption per position per velocity. (c) Estimated change in % of maximal aerobic capacity per position per velocity. (d) Estimated change in heart rate per position per velocity. (e) Estimated energy saving per position pr velocity. (f) Estimated change in velocity pr position at 400 W power output.

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CHAPTER 12

P7

Effects of body weight on Ski Jumping performances under the new FIS rules

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Abstract:

Based on the results of several different experiments, it has been concluded that the weight of a ski jumper is crucial in performing a long ski jump. In response to this conclusion, many of the best ski jumpers in the world began dieting to reduce their weight, resulting in many underweight athletes and some incidents of anorexia. In order to deal with this problem the International Ski Federation (FIS) introduced a new rule where the ski length is determined by both the jumper's height and weight. An athlete with a Body Mass Index (BMI) of less than 20 must reduce the length of his or her skis.

To evaluate the effect of the new rules a numerical and experimental investigation on the effects of the BMI on ski jumper's performances has been done. A numerical model has been built in order to evaluate the effects of BMI on the final speed in the in-run path. The numerical results obtained from the model match experimental data present in the literature. Experiments in the wind tunnel have been made in order to evaluate the aerodynamic forces acting on the ski jumper and on the skis during the flight path according to the new FIS rules. Experiments have been carried out on a doll mounted on a 6 components balance and different positions and ski length have been tested. The data acquired have been introduced into a numerical model and the final jump length has been then estimated.

In conclusions it has been found out that the current FIS rules do reduce the problem addressed but experiments shows that it is still more advantageous to lose weight and consequently cut the skis, compared to gaining weight in order to keep the full ski length.

12.1 Introduction

Ski Jumping is a sport discipline which involves different engineering fields. In this paper we will focus on the effect that BMI (and then the body weight) has on ski jumper's performances and especially on the jump length.

The increase the BMI has 2 main effects on ski jumpers performances. It has a positive effect during the in-run (higher weight gives a higher speed at take-off) and it has a negative effect during the flight path (the higher the weight is, the shorter the jump is. The 2 effects are not balanced. The negative effect during the flight is much stronger than the positive one during the in run. The final effect of BMI increasing is a shorter jump length [Schmolzer 2002].

Because of this advantage of being light in terms of jump length, athletes began to lose weight, and many cases of underweight and some of anorexia athletica [Smith 1980] came up.

This alarming trend forced FIS to create new rules in order to reduce the problem with underweight ski jumpers. Under the old rules, an athlete's ski length was determined by the athlete's height only but, in 2004, the rules changed, and today the ski length is determined by both height and BMI.

Under the new rules, an athlete with a BMI of less than 20 must reduce the length of his skis according to a table made by FIS. Any athlete who has a BMI below 17.5 is not allowed to participate in the competitions. The rules change required underweight ski jumpers to use shorter skis than the jumpers' height had formerly allowed.

The intention was to reduce the positive lift forces acting on a ski jumper and his equipment during the flight, hence reducing the positive effect of being light.

When the new rules became operative, there was a general belief within the ski jumping community that it would be beneficial for the athletes to gain weight by building up their thigh muscles. The weight gained would cause an increase in BMI and the athletes could then keep their original ski length and, theoretically, increase the power generated at the jump.

The trend that the athletes followed it has not been the same that FIS expected. The average BMI among all the athletes present in the Olympic Games in Turin 2006 has been 19.41, 0.5 less than the average BMI measured in 2000 [Schmolzer 2002].

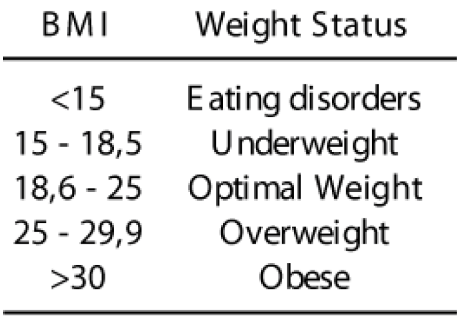
In order to determine whether the changes to the rules are justified, experiments have been conducted in a wind tunnel with 1:1 model of skis and ski jumper and a numerical model for In-run and flight-path has been made and used to compute the final jump length.

Different positions and angles for both jumper and skis have been analyzed and tested. Experimental data from previously studies and wind tunnel experiments [Schmolzer 2004] have been used in order to determine the position of skis and body angle. An adaptive numerical model has been built trying to describe as close as possible the real flight path.

12.1.0.1 BMI

The BMI is a relation between a person's weight and height. It's defined as:

$$BMI = \frac{Mass[kg]}{Height^2[m^2]} \tag{12.1}$$



BMI	Weight Status
<15	Eating disorders
15 - 18,5	Underweight
18,6 - 25	Optimal Weight
25 - 29,9	Overweight
>30	Obese

Figure 12.1: BMI compared to weight status

From results regarding the decrease of ski jumpers BMI acquired from 1973 to 2000 and shown by Vaverka [Vaverka 1994] and Müller [Schmolzer 2002] it has been noticed that the average BMI among ski jumpers dropped from a value above 23 in the past to a value under 20 in 2000 (Fig. 12.2).
The last data about 106 ski jumpers who participated to the Olympic Games in Turin 2006 give an average BMI of 19.41 (ca. 0.5 less than what was measured in 2000).
This shows that the trend of losing weight for obtaining better performances has not been stopped with the introduction of the new FIS rules.

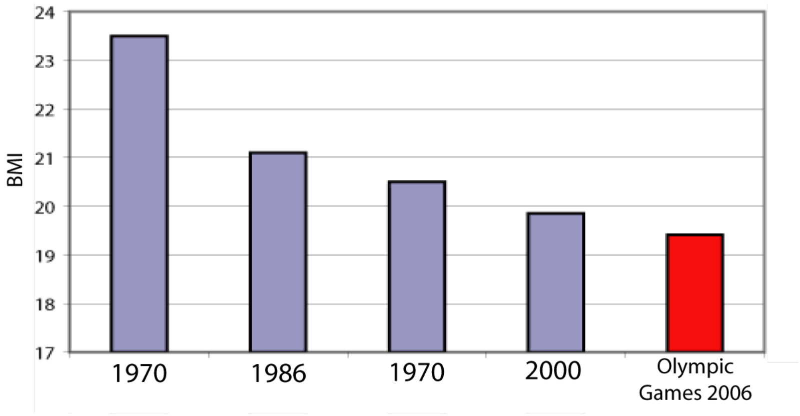


Figure 12.2: BMI trend in ski jumping competitions during the last 40 years

12.1.1 Forces acting on a ski jumper

Several forces act on a ski jumper during the three phases of the jump (in-run, take off, flight and landing). The combination of these forces will decide whether the ski jump is successful or not.
Roughly dividing the jump into 2 parts, the in-run and the flight, the main forces acting during these parts are drag, gravity, ski-snow friction during the in-run and drag, lift and gravity during the flight.

12.2 Experimental Setup

For the experiments, the wind tunnel of NTNU (Norwegian University of Science and Technology) in Trondheim has been used. The test section of the wind tunnel is 12.5 meters long, 1.8 m high, and 2,7 m wide. The wind tunnel is equipped with a 220KW fan that can produce a variation of speed between 0.5 - 30 m/s.The balance (Carl Schenck AG) used is a six component balance capable to measure the three forces and the three momentums around the three axes. Variations of forces and moments are measured using strain gauges glued to the balance body. The voltage outputs are measured by a LABVIEW based PC program.

12.3 Numerical simulation of the in-run

In order to evaluate the effect of BMI on the take off speed a numerical model has been built. The mathematical model here presented includes friction forces between ski and snow, mass forces due to gravity and aerodynamic drag forces acting on the ski jumper.

The simulation has been divided in three parts, following the different shapes of the in run path. The path (Fig. 12.3) is divided in three parts one straight part with a constant heeling-angle θ_1 (no curvature), one curved part with a constant radius of curvature r and then another straight part with constant heeling angle θ_2

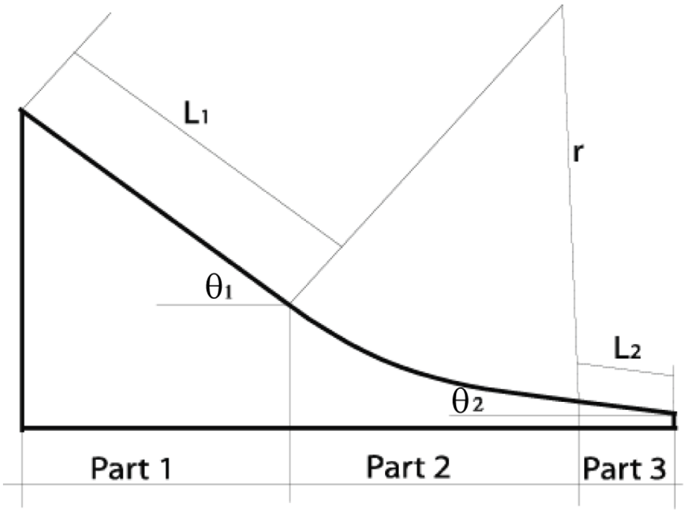


Figure 12.3: In-run path.

The results obtained applying the model to the Granåsen jumping hill in Trondheim show that the BMI does not have a huge influence on the speed at take off. The Granåsen jumping hill has the following parameters:L1=50m, L2=6.8m, r=110m, $\theta_1 = 34.5°$, $\theta_2 = 11°$, TOTlength=101.9m.

The difference between the take-off speed calculated for an athlete with a BMI around 30 (weight 85kg and height 170cm) and the speed calculated for an athlete with a BMI around 15 (weight 45kg and height 170cm) is about 1m/s (Fig. 12.4). Considering that most of the ski-jumpers have a BMI between 17 and 21, this difference is reduced and it has been calculated to be about 0.2 m/s.

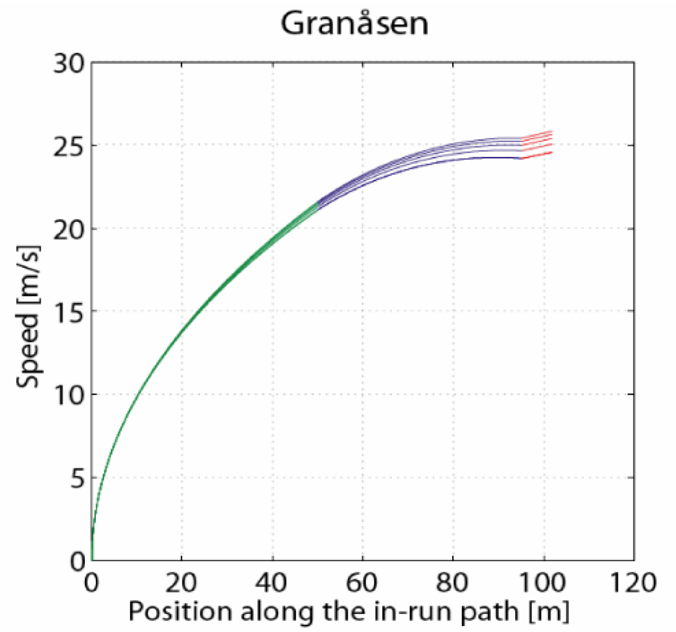


Figure 12.4: Effect of increase of BMI in the speed at take off calculated for the Granåsen jumping hill in Trondheim (Norway).

12.4 Experimental investigation on the aerodynamic forces

12.4.1 Ski and mannequin position in the wind tunnel

Skis and the doll have been tested separately since they can be considered as two separate systems. The ski's wake does not in fact interact with the ski jumper's body. This means that the 2 aerodynamic parameters (Lift and Drag) can be measured separately.

They were both connected to a shielded support connected to the 6 component balance. The doll used for the test is 170cm tall and his position has been varied from 10degrees to 60degrees. The suit used is the same suit used by the Norwegian ski-jumpers during the Olympic Winter Games in 2006.

The correct angles were adjusted using the joints on the support. Trying to model a ski jump in the most realistic way possible, the angles were adjusted in relation to the flying path, wind direction and the tilt of a skier's ankle. In the experiment, 3 different velocity levels have been used:13 m/s, 20 m/s and 27 m/s, respectively.

The ski-length is about 268cm and it has been tested at 6 angles relatives to 6 different flight positions. In order to evaluate the effect of the new FIS rules, the skis got cut in the back end for 5cm at a time and the same test has been done until a ski length of 248cm has been reached.

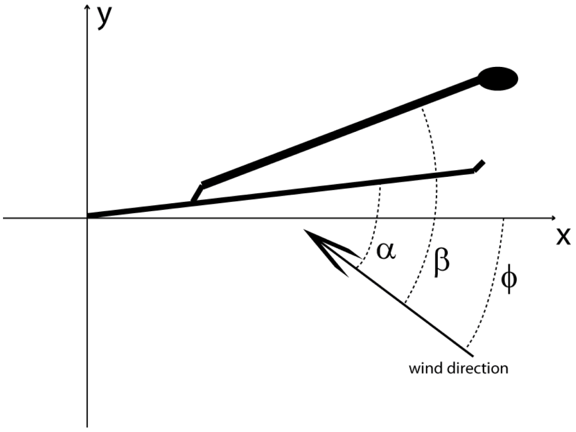


Figure 12.5: Different angles between ski jumper and wind direction. α is the angle between wind direction and skis, β is the angle between wind direction and ski jumper's body and ϕ is the angle between wind direction and horizon line.

12.4.2 The flight path

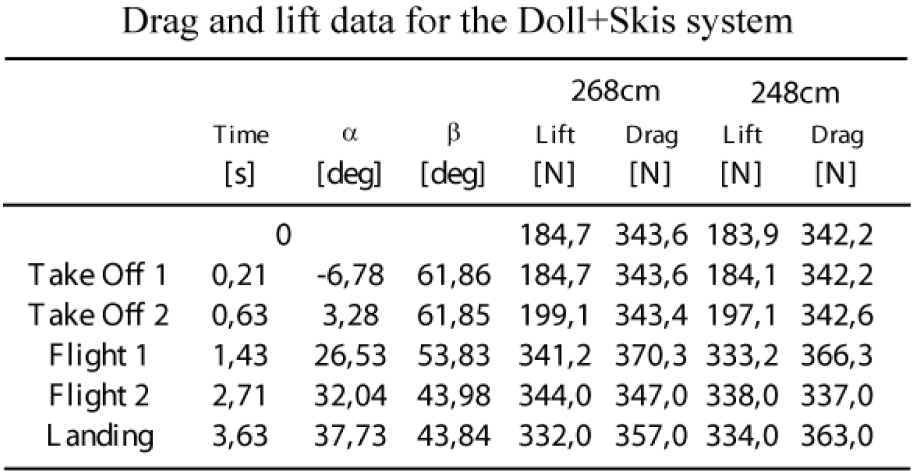
In order to evaluate the effects of the new FIS rules on the aerodynamic forces, data regarding the positions assumed by a ski jumper during his flying path were needed. These data have been acquired by Schmölzer and Müller [Schmolzer 2002].
The simplified flight path used for the model here presented has been divided in five different parts, assuming aero dynamical forces to be constant in each part. Forces during the flight path have been decomposed in vertical and horizontal forces [Remizov 1984].

- Take off 1 (t<0,21s) ($\alpha = -5°, \beta = 58°$)
- Take off 2 (0,21<t<0,63) ($\alpha = 5°, \beta = 58°$)
- Flight 1 (0,63<t<1.43) ($\alpha = 25°, \beta = 45°$)
- Flight 2 (1.43<t<2.71) ($\alpha = 30°, \beta = 45°$)
- Landing (t>2.71) ($\alpha = 35°, \beta = 52°$)

12.5 Results

The main goal of the aerodynamic test on skis is to evaluate the effects of the new rules on Lift and Drag. Lift and drag has been measured per each position α, with different ski length, from 248cm to 268cm.

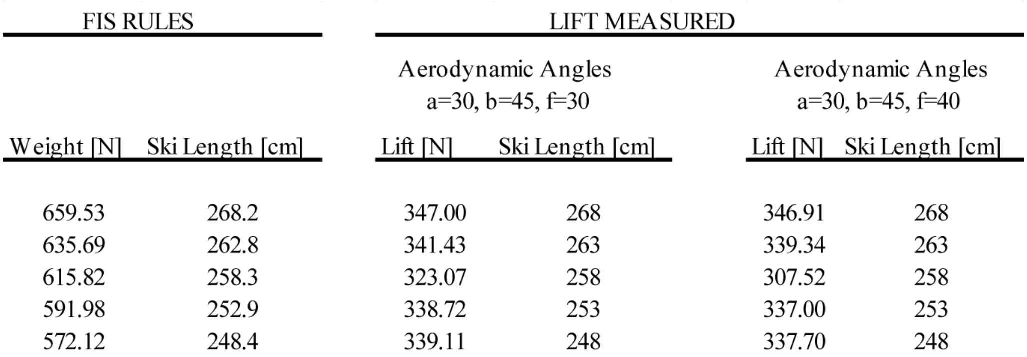
The ski jumper system has been obtained by summing the aerodynamic forces calculated separately for skis and doll. Wakes and possible interferences between doll and skis have been neglected.



Drag and lift data for the Doll+Skis system

	Time	α	β	268cm Lift	 Drag	248cm Lift	 Drag
	[s]	[deg]	[deg]	[N]	[N]	[N]	[N]
	0			184,7	343,6	183,9	342,2
Take Off 1	0,21	-6,78	61,86	184,7	343,6	184,1	342,2
Take Off 2	0,63	3,28	61,85	199,1	343,4	197,1	342,6
Flight 1	1,43	26,53	53,83	341,2	370,3	333,2	366,3
Flight 2	2,71	32,04	43,98	344,0	347,0	338,0	337,0
Landing	3,63	37,73	43,84	332,0	357,0	334,0	363,0

Figure 12.6: Experimental data for drag and lift



FIS RULES		LIFT MEASURED			
		Aerodynamic Angles a=30, b=45, f=30		Aerodynamic Angles a=30, b=45, f=40	
Weight [N]	Ski Length [cm]	Lift [N]	Ski Length [cm]	Lift [N]	Ski Length [cm]
659.53	268.2	347.00	268	346.91	268
635.69	262.8	341.43	263	339.34	263
615.82	258.3	323.07	258	307.52	258
591.98	252.9	338.72	253	337.00	253
572.12	248.4	339.11	248	337.70	248

Figure 12.7: Experimental data and FIS table

Comparing the curve obtained for the ski-jumper with the length-weight obtained from the new FIS rules (for a 180cm tall ski jumper) it has been obtained, for $\alpha = 30°$,$\beta = 45°$ (which is the position assumed for the longest period during the flight path). According to the flight path angles measured by Schmölzer and Müller [Schmolzer 2004] two angles have been chosen. $\phi = 40°$ and $\phi = 30°$ which represent the angles where the aerodynamic forces count more in the y direction and where ϕ is the angle between the wind direction acting on the skier and the vertical axis parallel to the gravity force (Fig. 12.8).

The flight path has been divided in 5 parts. Per each part, drag and lift of the ski jumper have been calculated using the experimental data. A vertical velocity at take off of 2.5m/s has been considered [Virmavirta 2001]. To evaluate the effect of the new FIS rules on a ski jumper's flight path, two different ski lengths, (248cm and 268cm) have been considered. A ski length of 248 cm correspond to a ski jumper (180cm tall) who weighs 58kg while 268 correspond to a ski jumper (180 cm tall) who weighs 65kg. Drag and Lift has been considered constant during each part of the flying path and the correction relative to the take off speed illustrated in par.1 has been taken into account.

The 2 curves presented in fig. 12.9 represent the flight path for 55kg ski jumper and a 67 kg ski jumper calculated using the new FIS rules. The solid curve is the path calculated for a 67kg ski

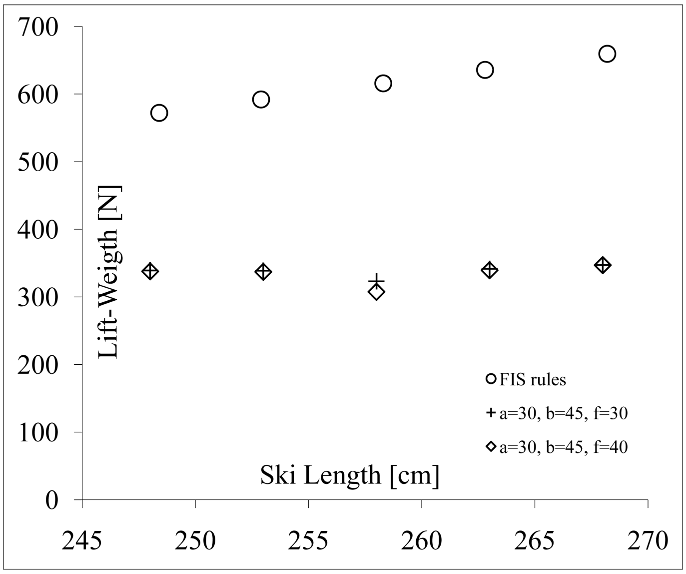


Figure 12.8: Comparison between the FIS rules and the data obtained with the wind tunnel experiments

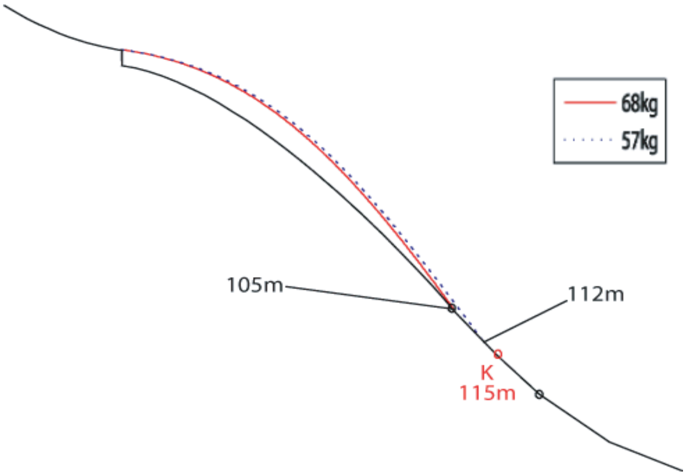


Figure 12.9: Simulated flight path

jumper and the dotted curve is the curve obtained for a 55kg ski jumper. The difference in jump length between the 2 jumpers has been estimated to be about 7 meters and the longest jump length has been obtained by the 55kg jumper.
The lighter jumper has then a big advantage due to his low body weight and this advantage is not enough compensated by the smaller aerodynamic forces acting on him during his flight.
It has been also estimated that, in order to compensate the disadvantage due to the higher weight, the ski jumper who weight 67kg has to increase his vertical take-off speed at up to 3m/s.

12.6 Conclusions

The new rules imposed by FIS have not solved the problem of low BMI in ski jumping. Athletes are in fact keeping loosing weight in order to improve their performances. It has been demonstrated that the negative effects due to higher weight can not be compensated with the adjustment imposed by the new rules. Furthermore, the increase of speed at take off is not enough to compensate the negative effect due to increase of BMI.
The possible solution proposed by some trainers, consisting on only increase the BMI by building up muscles in the thigh in order to obtain a higher vertical speed at take off could work but the vertical speed at take off sufficient to compensate the weight-effect should be around 3m/s, 20% higher than the normal vertical speed estimated by Virmavirta in 2.5m/s [Virmavirta 2001].
A better solution could be obtained by reducing the width of the skis instead of the length. This would not affect the stability of the jumper and at the same time will have a negative effect in terms of aerodynamic forces reducing the advantage of having a low BMI. New tests will then be carried out in order to evaluate this solution.

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CHAPTER 13

P8

Airfoiled design for alpine ski boots

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Abstract:
The aerodynamic effects in sport competitions increase with the speed. In some sports like skating, skiing or cycling the athletes have an average speed from 70km/h up to 150km/h. The aerodynamic drag coefficient increases with the square of the speed. This means that, by reducing the aerodynamic drag coefficient, it is possible to increase the athleteŠs speed and improve their performances. The drag of a human body when assuming the position of an alpine skier is divided approximately in 1/3 given by the legs, 1/3 given by shoulders an arms, 1/3 given by the chest. On bluff bodies like cylinders or spheres (we can consider the human body as a bluff body) the larger part of drag is given by the difference of pressure between the front and the rear part of the body [White 1991]. That is due to the boundary layer separation. In this paper we focus on the reduction of drag on skiers legs by modifying the shape of the boots from a cylindrical shape to an airfoiled one. Four different solutions with different designs have been studied, each solution has been experimentally analyzed and a $C_D A$-Speed curve has been obtained. By reattaching the boundary layer with a different design of the boot it has been possible to decrease from 10% up to 70% the drag coefficient. This means that a drag coefficient reduction of approximately 10% of the total drag of an alpine skier has been obtained.

13.1 Introduction

13.1.1 Introduction

The role of the air in sport can often be very important. In some disciplines like sailing or windsurfing, aerodynamics effects are used to generate lift and push the athletes. In some other disciplines like skiing, speed skating or cycling the air is an obstacle for the athletes and the aerodynamic

effects can mostly be reassumed into drag effects.
In the second category of sports mentioned above, a large part of the external power produced by the athlete is used to overcome the drag. From the experiments carried out by Grappe [Grappe 1997] about aerodynamic resistance in cycling, 90% of the total resistance opposing motion depends on drag. From a paper written by Thompson [Thompson 2001] about drag reduction in speed skiing, the aerodynamic loads contribute more than 80% of the total drag. Reducing the drag by improving materials can then sensibly improve the athlete's performances.

The drag can be defined with the formula:

$$D = \frac{1}{2} A_P c_D \rho V^2 \tag{13.1}$$

Where A_P is the frontal Area, V is the wind speed and c_D is the drag coefficient The position assumed by the athlete during is performance has an important role in determining the aerodynamic drag. As shown by Remondet [Remondet 1997] the position can affect the drag by influencing not only the frontal area but also the drag coefficient (c_D). The cd varies from 0.5 in downhill position to 1 in standing position.
Considering a classic downhill skiing position, the effect of each body part can be roughly divided in 1/3 given by the chest, 1/3 given by head and arms and 1/3 given by the legs. While reduce the drag on other body parts is quite hard (due to the position effect on aerodynamic resistance), reduce the drag on skier's legs is possible and 2 different solutions can be adopted:

- Trip the transition to turbulent regime using roughness. Many examples about that are present in literature especially about drag reduction drag on cylinders by using rough structures (this method is practically used in the speed skater's suits).

- Delay the separation keeping the flow in laminar regime. This can be done using an airfoil shape to surround the cylindrical shape of the legs. Shape the boots like an airfoil, reducing the wake dimensions and thus the drag component due to the pressure difference between front and back of the boot is what it has been done and exposed on this paper.

Some previous examples of airfoil shaped boots have been used in speed skiing, where rules are quite strict and they have been presented by Thompson.

13.1.2 Forces acting on a downhill skier

There are 4 forces acting on a skier: the friction force between the skis and the snow, the gravity force gravity, the aerodynamic drag and the centripetal acceleration (this last force is 0 for on a straight path).
Considering the relations who link of all these forces, it is possible to estimate the total resistance

(drag and friction) and then find a correlation between the respective influences of the two parameters mentioned above.
Considering a straight path (S=0) with 35% inclination, the influence of the aerodynamic drag is higher (55%) than the one given by the friction force (45%).

13.2 Experimental Setup

13.2.1 Wind tunnel

The test section of the wind tunnel is 12.5m long, 1.8m high and 2.7m wide. The convergent has an initial section of 20.59m^2 and final section of 4.88m^2 with a contraction ratio of 4:22. The wind tunnel is equipped with a 220KW engine that drives a fan which produces a speed range between 0.5m/s and 30m/s.

13.2.2 Balance

The balance which has been used is a six components balance, produced by Carl Schenck AG, which can measure force and momentum along three directions of a preset frame of reference.

13.2.3 Different design tested

5 different versions of the boots have been tested (Fig. 13.1)

- Normal boots (1)
- Small spoiler down (2-b)
- Small spoiler up (2-a)
- Big spoiler (3)
- Airfoil (4)

The methodology used for the design followed the theoretical backgrounds about flow around bluff bodies and streamlined bodies. It has been tried to find the shape which minimize the wake (and then gives lowest drag) and at the same time the length of the spoiler.

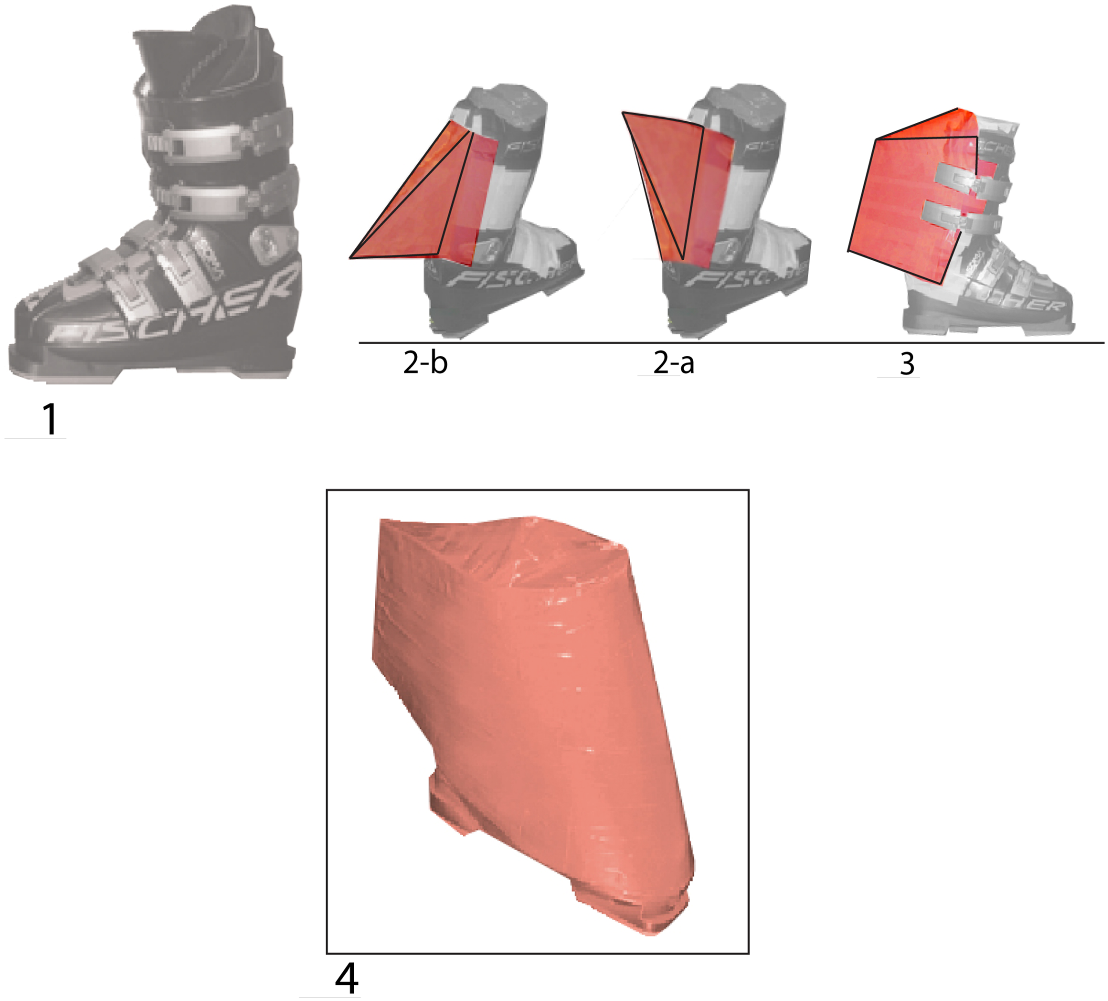

Figure 13.1: The 5 different versions tested.

13.3 Results

13.3.1 Normal boots

A preliminary test to evaluate the drag of the normal boots has been carried out.
The boots have been tested with and without clamps to evaluate the effect of the clamps on the aerodynamic performances. The effect of the clamps is quite important. Just removing the clamps it has been possible to reduce the drag of about 7% at 25m/s.

13.3.2 Short spoiler (2-a and 2-b)

The first attempt to improve the aerodynamic efficiency of the boots has been done adding a small spoiler behind the boots. 2 different configurations with the spoiler positioned in 2 different ways

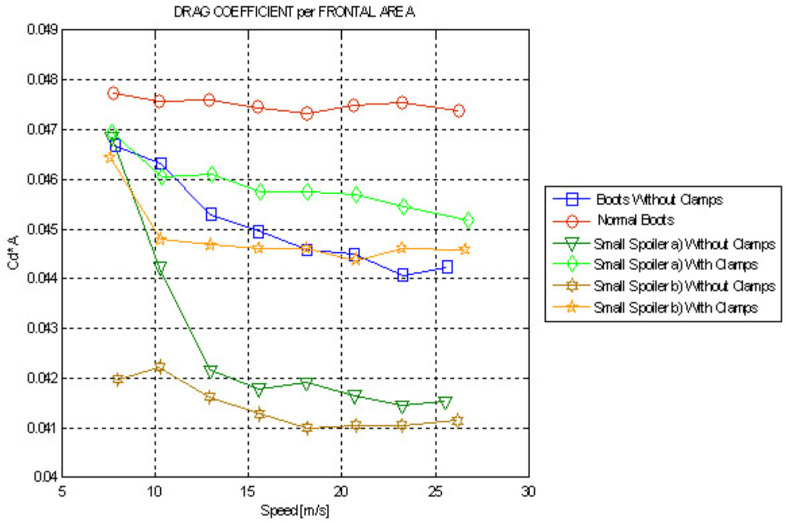

Figure 13.2: Short spoilers

have been tested. The target was trying to split the wake into two smaller wakes in order to reduce the aerodynamic resistance. This test, like the previous one, has been carried out with and without clamps for both configurations. A drag reduction of about 15% has been obtained using this small spoiler in the configuration (b) without clamps and the same result has been obtained for the configuration (a), testing both configurations without the clamps on.

13.3.3 Long Spoiler (3)

The final target of the designing process is to get as close as possible to the airfoil shape. A bigger spoiler has been made to reduce the separation effect present in all the bluff bodies and to try to keep the flow attached to the boot, reducing the pressure drag and then reducing the total drag.
The test carried out using the balance show a drag reduction of 45% at the maximum speed for the configuration without clamps.
The aerodynamic effect of the clamps in this configuration is much higher than in the previous ones. The clamps in this case affect the flow around the boot inducing a early stage flow separation. The flow separation produces a loss in term of drag of about 35% due to the increase of the wake size and consequently due to the increase of the pressure drag.

13.3.4 Airfoiled shape (4)

To avoid the problem described above (earlier separation induced by the clamps) it has been chosen to surround the boots and the clamps with a rigid cover shaped as an airfoil. The results obtained with this configuration show a drag reduction of about 70% comparing the airfoil design to the normal boots.
To evaluate the reduction on the total drag of a skier, a supplemental test mounting both the normal

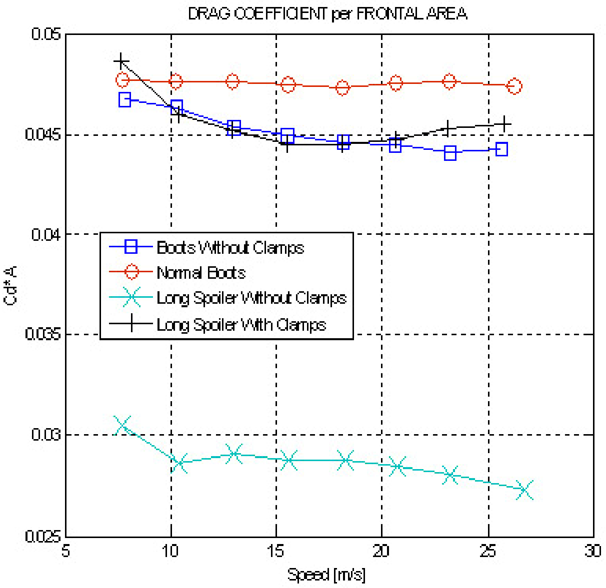

Figure 13.3: Long Spoilers

boots and the airfoil boots on a mannequin has been done. A drag reduction of about 10% in drag has been obtained.

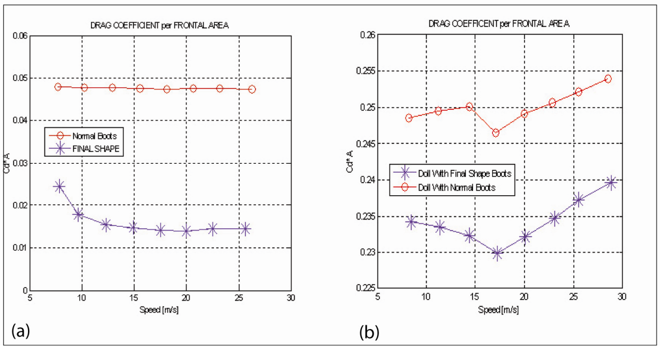

Figure 13.4: (a)Airfoiled shape. (b) Mannequin test

13.4 Conclusions

Comparing the results obtained for the airfoil shape (4) with the results obtained by Thompson [Thompson 2001], the drag has been reduced of about 50%. Fig. 13.3 shows the improvement obtained in the design and in the performances of the boots. With the airfoil shaped boots it has been possible to decrease the aerodynamic resistance of 70% if we compare this configuration with the normal boots.

An estimate of the influence of this reduction in terms of performances on a normal downhill competition has been done. With some simple calculations it is possible to evaluate if a reduction of 10% on the total drag can influence the performances of the athletes.

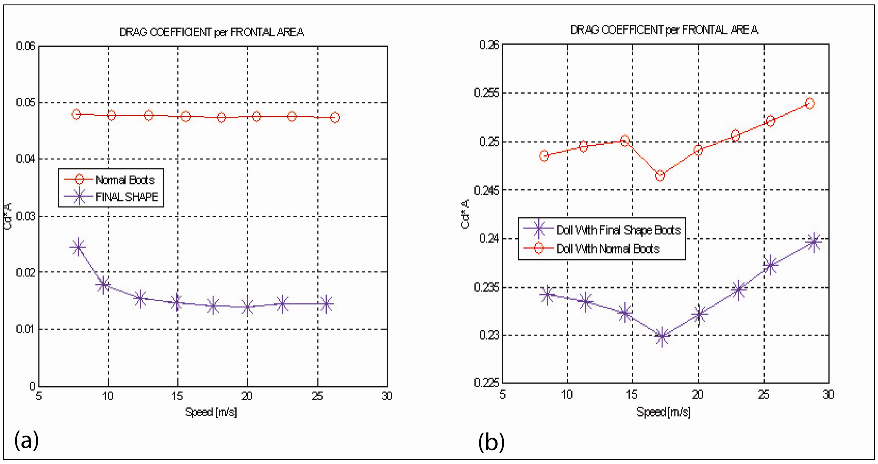

Figure 13.5: Drag coefficient reduction for the different boot versions at 25m/s

Taking as reference the downhill slope Kandahar Banchetta G. Nasi used for the downhill competition in the Winter Olympic Games in Turin
(which has a length of 3.299 m and a height difference of 914m, with an average slope angle of 20% and a maximum slope angle of 58.5%) and considering that the best time of the challenge was 1:48:80, it results a average speed of about 30.32m/s. Reduce the total drag of about 10% means, in terms of speed gain, increase the speed of approximately 0,5m/s. This increase of speed could consent to the skier to finish his run with a time of 1:47:04 instead of 1:48:80. The gap between the real performance and the calculated performance is 1'76" that is the difference between the first and the 13th classified.

13.5 Acknowledgments

The authors wish to thanks S.Løset and R.Winther for their help, suggestions and advices during the experiments.

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CHAPTER 14

P9

Aerodynamic and Comfort Characteristics of A Double Layer Knitted Fabric Assembly for High Speed Winter Sports

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Abstract:

In this paper, the double layer concept of knitted fabrics suitable for performance sportswear, where each layer is unique in that it is completely separate from the other layer,, was studied. Aerodynamic properties of this double layer fabric assembly, where the base layer is made of 100% wool and an external layer made of 100% continuous filament polyester were determined. Each fabric layer was produced with varying geometrical parameters and tested for their aerodynamic properties separately as well as a double layer assembly.

All fabric samples were placed over a single diameter cylinder that was used to imitate the leg, using the approximation that arms and legs are cylindrically shaped. All aerodynamic tests were performed in the wind tunnel, equipped with a 220KW fan that can produce a variation of speeds between 0.5 - 30 m/s. The aerodynamic resistance was acquired at different incremental speeds relevant to sports such as cycling or speed skating.

In addition, evaluation of the comfort properties of each layer as well as a double layer assembly was carried out. Measurements of dynamic comfort properties of the each layer and a double layer knitted fabric assembly were obtained. As part of this evaluation fabrics' liquid moisture transport properties in multi-dimensions (moisture management properties) were acquired. The moisture management capacity of double layer fabric assembly was assessed and classified by simulation of the liquid sweat on the skin absorbed and transferred to the outside of the fabric.

Results from the series of aerodynamic tests demonstrated that the base layer influences the aerodynamic characteristics of the entire double layer knitted fabric assembly. Correlations between

the geometrical parameters of double layer single jersey fabric assembly and comfort and aerodynamic properties were also established.

14.1 Introduction

For most speed sports, the top competitor is generally the one who can sustain the greatest power output to overcome resistance to drag. The criterion for success in many sports, including those involving running, swimming, bicycling, speed skating, rowing, and cross-country skiing, is the time required to propel the athlete's body for a given distance and success depends on a complicated application of a simple principle–the champion is the athlete best able to reduce the resistance to movement or drag that must be overcome in competition [Lamb 1995].

There have been a number of research studies conducted over the last two decades that identified the factors that contribute to the reduction of the aerodynamic resistance (drag) and the associated energy loss during the sport events. These factors include: posture and weight of the athlete's body; the weight and aerodynamic properties of the equipment used; the surface characteristics of the textile materials (fabrics) used in sports garments; fit, style and design of the sports garments worn [Lamb 1995],[Oggiano 2007],[Oggiano 2007],[Kyle 1986]. It is well recognized that advances in aerodynamic properties of fabrics used in sports garments contribute significantly to the improved performance of an athlete. Garments are often constructed of multiple layers or are worn as one on top of another creating a layered assembly. Under such situations, many of the resultant properties are affected, some obviously such as mass of an assembly increasing with an increasing number of layers, which in turn affects the overall fit and drape. Some effects are less apparent such as air spaces between layers of fabric, known to affect air and thermal permeability, and transfer of liquid moisture, thereby affecting overall comfort of the garments worn [Nielsen 1989]. In addition, fabric surface roughness (surface unevenness) of each layer in the fabric assembly has its own significant affect on both the comfort of the garment worn as well as the amount of the resultant aerodynamic drag employed on the athletes. In terms of comfort, using fabrics that have relatively uneven surface for next to skin (inner) layer means less direct contact points with the skin which makes them more comfortable than smooth surfaced fabrics [Higgins 2003]. In terms of aerodynamics, research shows that using fabrics with the increased fabric surface roughness in outer (external) layer reduces aerodynamic drag (particularly for low speeds) thereby increasing the speed of athletes [Oggiano 2007],[Achenbach 1977],[Bearman 1993].

The clothing assembly does not operate as an individual entity but in dynamic relationship with the wearer, activity and the environment. It should aim to essentially help the performance of the athlete and not to generate additional negative physical forces or have a negative effect on the athlete's performance by causing discomfort, which reduces the performance efficiency and restricts the range of motion [Scott 2001].

Since the purpose of the present work was to determine the aerodynamic and evaluate some of the comfort properties of the double layer knitted fabric assembly, both need to be defined.

Aerodynamic drag is the retarding force that acts on moving aerodynamic body in the direction of the free stream flow and can be often represented as [Kamen 2001]:

$$Drag = \frac{1}{2}\rho A_p c_D A V^2 \tag{14.1}$$

Where A_p is the frontal area of the cylinder, c_D is the drag coefficient, ρ is the air density and V is the air velocity. The drag coefficient c_D is a dimensionless parameter that describes how much drag is caused by a flow on an object.

A larger c_D value implies that the object has more drag and less speed. This parameter is not constant and is influenced by different factors. In general, it is established that the surface roughness has an important effect on the drag coefficient, yet significant drop in the aerodynamic resistance (drag) can be achieved shifting the transition to turbulent regime and consequently reducing the drag. Garment surface roughness depends on combination of factors such as fibre choice and fabric construction; porosity (openness/tightness) and thickness of fabric assembly. All of these factors, in turn, depend on fabric's cover factor (CF). Cover factor is the most important factor for the definition of fabrics physical properties. It expresses the tightness of a fabric and is directly related to the appearance, weight per unit area, thickness, porosity and other attributes of any fabric [Spencer 2001].

In addition, it has been recognized that the performance of the athletes can be significantly influenced by the comfort of the garment/s worn. The wearer comfort can enhance or suppress their performance and efficiency. Comfort is a complex concept influenced by the multitude of various factors, including thermo physiological, sensorial and ergonomic [Elshner 2003]. Thermo physiological comfort relates to heat and moisture interaction between the human body and clothing worn. Sensorial comfort is a function of the feel of garment against the skin. Ergonomic comfort relates to the fit of the garment and may be influenced by factors such as a tendency to stick to the skin.

In recent years, there have been considerable research and studies conducted to evaluate the comfort of sports garments [Higgins 2003], [Thumm 2000], [Wardiningsih 2009]. It has been established that fabrics used to create sports garments should provide the control of the movement of body moisture (e.g. sweat) in such a way that it is transported away from the skin to the external surface of fabric, where it can evaporate quickly. This is essentially a definition of the m̈oisture managementöf textile materials. Garments produced from fabrics with high moisture management performance keep the skin dry and provide the maximum comfort to the wearer. For active sportswear, the moisture management properties of the constituent fabrics are critical in keeping the skin dry. The factors that are important in maintaining the m̈oisture managementp̈roperties of the fabrics and fabric assemblies are: fiber choice, yarn and fabric construction, fabric/fabric assembly porosity and applied fabrics finishers/treatments.

The purpose the present work was to study and assess the aerodynamic properties, the surface roughness (texture) and the corresponding size of openings, created by interlooping of yarn within the knitted structure of the double layer fabric assembly as well the moisture management capability of these assemblies. It was also aimed at establishing the relationship between the cover factor (CF) of the double layered knitted fabric assemblies and their aerodynamic and moisture management properties.

14.2 Experimental

The base layer fabric lies on the surface of the athlete's skin and remains in direct contact with the body, therefore the fibres used to produce next to skin fabrics need to be relatively soft and smooth, while the fabric assembly with an external layer being on top of the base layer, needs to be able to transport the moisture away from the skin without restricting the comfort of the wearer and the body movement. At the same time this fabric assembly and especially external layer, should provide optimum level of aerodynamic drag in order to be suitable for use in high-speed sports garments. To satisfy these criteria, fabric samples intended for inner layer were produced using 20 Tex 100% extra fine Merino wool (18.5μ fibre diameter) and fabrics intended for outer layer were produced using, 100% Polyester (PET), 1/150D/48f, flat, optically bright filament yarn.

The experimental measurement of aerodynamic properties of all fabric assemblies was conducted at NTNU (Norwegian University of Science and Technology) wind tunnel in Trondheim.

Structure analysis of the fabrics was performed with an Epson Perfection 4990 desktop scanner.

Liquid moisture management performance of all fabric assemblies was tested at RMIT University, Melbourne, Australia by using SDL Moisture Management Tester (MMT).

14.2.1 Structure of instruments used and principle of the test methods

Wind tunnel: the experiments have been carried out in the NTNU (Norwegian University of Science and Technology) wind tunnel in Trondheim. The test section of the wind tunnel is 12.5 meters long, 1.8 m high, and 2,7 m wide. The wind tunnel is equipped with a 220KW and the maximum speed reachable is 30 m/s

Force balance: The balance (Carl Schenck AG) used is a six component balance capable to measure the three forces and the three momentums around the three axes. Variations of forces and moments are measured using strain gauges glued to the balance body. The voltage outputs are acquired with a USB acquiring card produced by National Instruments. The acquiring card is divided in two parts, a NI cDAQ-9172 chassis and a NI-9205 module.

The cDAQ-9172 is an eight-slot NI CompactDAQ chassis that can hold up to eight C Series I/O modules. The NI 9205 features 32 single-ended or 16 differential analog inputs, 16-bit resolution, and a maximum sampling rate of 250 kS/s. Each channel has programmable input ranges of ±200 mV, ±1, ±5, and ±10V. Two channels have been used, one for the drag and one for the speed. The acquiring rate was set to 300Hz and 5 samples of 5seconds each were taken per each sample and each speed.

Cylinder model: A vertical 16cm diameter cylinder made of rigid plastic material was used, using the approximation that arms and legs are cylindrically shaped. The cylinder is connected to the force balance with a rigid metal support placed in the back of the cylinder in order to avoid any interference with the flow.

Scanner: the scanner used was a Epson Perfection 4990 desktop scanner used in transmission and reflection modes. Digital images were acquired with a resolution of 2400 dpi, giving a pixel size of approximately 10.6±m. Image processing and analysis were performed with the ImageJ program [Rasband 1997] and utilizing the Shape descriptor plugin [Syverud 2007]. *Moisture management* *tester (MMT)*; The MMT instrument was used to test the liquid water transfer and distribution of knitted fabric sample assemblies The principle utilized by the MMT [Dias 2008] is based on the fact that when the moisture travels through a fabric, the contact electrical resistance of the fabric will change. The fabric is in contact with the sensor rings, which determine the liquid content and the liquid moisture transfer behavior between the fabric surfaces, where the top surface on the instrument is normally the surface in contact with the skin (base layer) and bottom surfaces of the fabric is the surface exposed to the atmosphere (external layer). On the basis of the measured voltage charges, the variation of water content with time on the fabric top and bottom can be quantitatively measured.

Fabric assembly: 9 knitted fabric assemblies variations were manufactured and analyzed, using 3 fabric samples with varying CF, produced from natural 100% wool spun yarn, as a base (bottom) layer and 3 fabric samples with the same variations in CF, produced from 100% polyester filament yarn, as a external (top) layer. For aerodynamic assessment, fabric samples were fabricated to fit the cylinder model and placed over the cylinders without any distortion.

All knitted fabric samples were produced on a Lawson Hemphill FAK - S, Fabric Analysis Knitter in 24 gauge, 8.9 cm diameter, with total number of needles being 260 knitting. Single jersey knitted fabric construction was selected in all the knitted fabric samples due to its simplicity and inherent stretch/ recovery properties. Details of the fabric sample assemblies and matrix of the tests conducted presented in Figure 10.1 below:

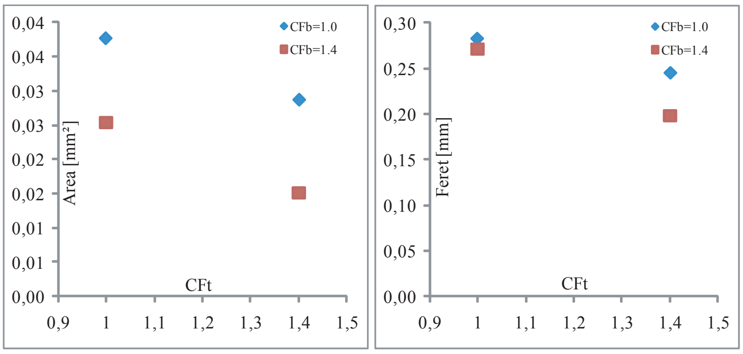
Sample N	**Base layer**	**External layer**	**Tests**		
	Top	**Bottom**			
	wool	*polyester*	*Comfort*	*Aerodynamic*	*Surface*
	CFt	*CFb*			
1	1.00	1.00	x	x	x
2	1.20	1.00	x	x	
3	1.40	1.00	x	x	x
4	1.00	1.20	x	x	
5	1.20	1.20	x	x	
6	1.40	1.20	x	x	
7	1.00	1.40	x	x	x
8	1.20	1.40	x	x	
9	1.40	1.40	x	x	x

Figure 14.1: Fabric assemblies' details and matrix of test conducted

14.3 Methods

14.3.1 Surface analysis of double layer knitted fabric assemblies by using optical image technique

The images were thresholded automatically with particles less than 50 pixels been removed. The following shape descriptor was considered: area (Fig. 14.2a) and, ii feret diameter (Fig. 14.2b). The area is given by the total number of black pixels within each opening. The feret diameter corresponds to the longest axis within a given object. The results show that the base layer influences the overall structure of the fabric assembly. From the scattered plot in figure 1a, the higher CFt is, the smaller the openings in the fabrics are. This behavior is shown for both the external layers tested (CFb=1.4 and CFb=1.0). The same trend can be seen in Figure 10.2b for the feret diameter: the higher CFt is, the smaller the feret diameter is.



a) b)

Figure 14.2: (a) area and (b) feret diameter, measured with the optical scanner technique

14.3.2 Aerodynamic performances of double layer knitted fabric assemblies

Testing of aerodynamic properties of all fabric assemblies was carried out on cylinder model in order to simulate the human body shape. The advantage of carrying out tests on cylinders is the possibility to compare the results (c_D-*Speed* curves, V_{TRANS} , C_{DMIN}) with the test results obtained from number of experiments previously conducted by various researchers [Oggiano 2007], [Oggiano 2008], [Achenbach 1977], [Bearman 1993]. The typical c_D-*Speed* curve can be divided into three main regions: pre critical zone, critical zone and post critical zone, depending if the flow around the cylinder is laminar (pre-critical), fully turbulent (post critical), shifting from laminar to turbulent (critical). In the critical area, a drop in c_D occurs with a consequent drop in terms of drag. The speed where the shift from laminar to turbulent regime occurs is called V_{TRANS} and it can be defined in order to give an approximate description of where transition occurs and it is defined as the velocity where the c_D curve has gone through half its drop ($\Delta c_D/2$)[Oggiano 2007]. The main purpose of covering the cylinders with materials (fabrics) is to add some roughness to

the surface and then be able to shift the drag crisis at the desired speed. Wearing a garment made out of the fabric with the specified surface roughness, leads to a lower drag employed on an athlete at this speed and therefore an improvement in athlete's performance could be achieved.
In the case of double layer assembly, the effect of the base layer and external layer on the V_{TRANS} parameter was evaluated. A comparison between figure 14.3a and 14.3b shows that the top layer has a higher impact in terms of affecting the drag.
In order to quantify the impact of each layer on the aerodynamic performances a parameter Δ*Tr* was defined as:

$$\Delta Tr = \frac{\Delta V_{TRANS}}{\Delta CF} \tag{14.2}$$

ΔTr indicates how much each layer influences the shifting of the V_{TRANS} being the angular coefficient of the first order trendline in a plot V_{TRANS}-CF.A higher value of δTr corresponds to a higher influence of the fabric in shifting the V_{TRANS}.
In other words, the higher ΔTr is, the less change in *CF* is required in order to shift V_{TRANS} to the desired speed. Using the suffixes b and t respectively for bottom and top layer, two Δ*Tr* can be defined: Δ*Tr -b* which refers to the external (bottom) layer and ΔTr -t which refers to the base (top) layer.
From the analysis of scattered plot figure 14.3c it is evident that the bottom polyester layer plays a major role in terms of modifying the aerodynamic parameters, however, the base (top) layer has a significant impact as well.
The scatter plot in figure 14.3c indicates that the base layer gains more importance (Δ*Tr-t* increases) in terms of aerodynamic performance when CFb increases.

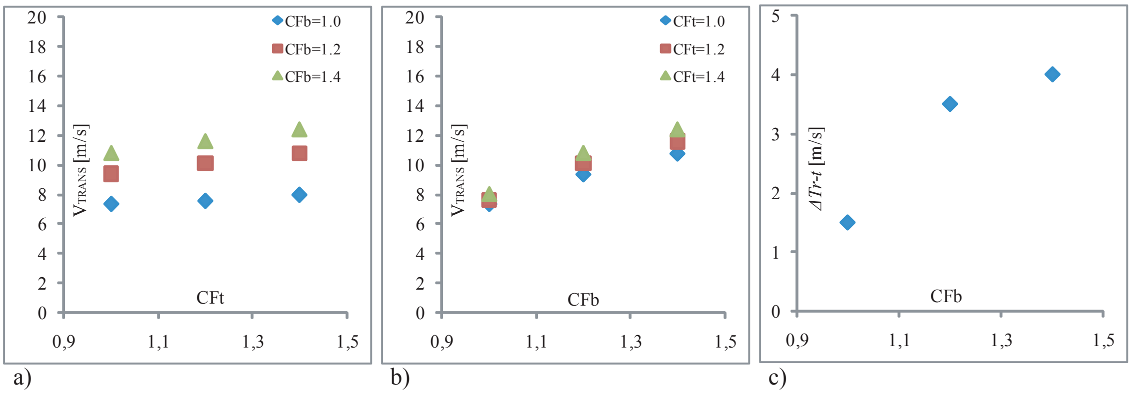


Figure 14.3: (a) V_{TRANS}-CFt plot; (b) V_{TRANS}-CFb plot; (c) ΔTr-CFb plot

The scatter plot in figure 14.3a shows that the lower the CFt is, the lower V_{TRANS} is. The same effect can be noticed for the bottom layer but a change in CFb affects V_{TRANS} more than a change in CFt.
The scatter plots in figures 14.3a and 14.3b shows that there is a linear correlation between CF and V_{TRANS} for both top and bottom layers with the regression coefficient R^2 varying from a minimum of 9.753 to a maximum of 1. These results are in agreement with the results previously

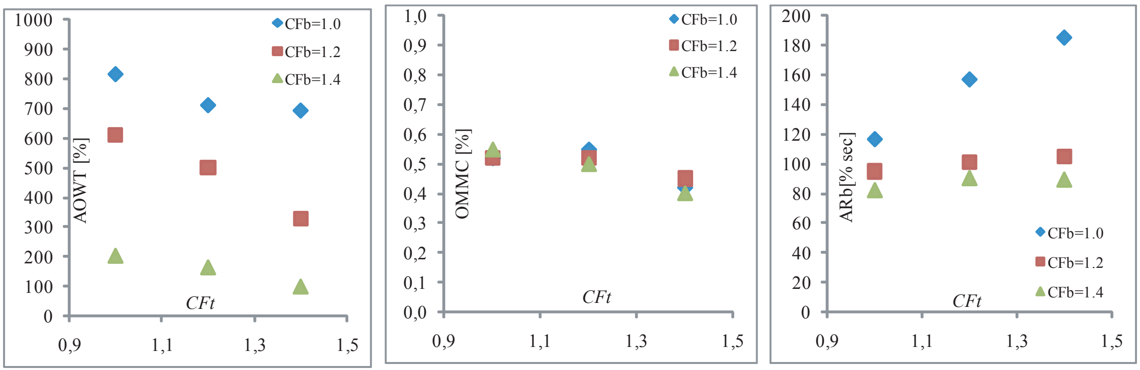
obtained by Oggiano [Oggiano 2007].

14.3.3 Moisture management properties and Cover Factor relationship of double layer knitted fabric assemblies

Moisture management capability of the fabric/fabric assembly to manage the transport of liquid moisture is mainly assessed on the basis of three criteria's:

a) one way liquid transport capability;
b) overall moisture management capacity (OMMC);
c) average moisture absorption rate at the bottom surface.

Figure 14.4 shows the relationship between CF of double layer assembly and main aspects of moisture management properties.



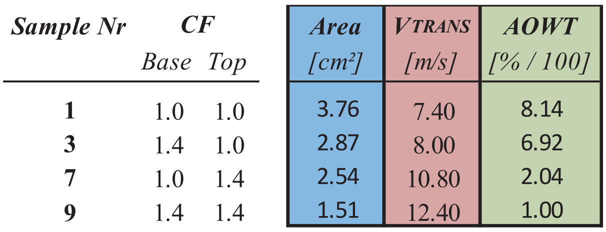
a) b) c)

Figure 14.4: a) accumulative one way transport index vs CF; (b) overall moisture management capacity vs CF; (c) average moisture absorption rate at the bottom surface vs CF

The scatter plot in figure 14.4a illustrates that one way moisture transport capability (AOWT) of the fabric assembly decreases as CF of both layers increases, confirming that the looser the construction in both layers the easier it is for the moisture to diffuse through the fabric layers. This indicates that the fabric assembly with the higher values of AOWT could transport the liquid sweat quicker from the skin layer to the external surface of the assembly, keeping the skin dryer.
OMMC versus cover factor (fig 14.4b) depicts that the tightness of the overall assembly negatively influences the overall moisture management capability. It is evident that sample 9 (CFt=1.4 and CFb=1.4) has the lowest value of OMMC, but nevertheless, due to the fact that the values of OMMC for all of the assemblies are in a range of 0.4 to 0.6, they can be still classified as good.
It was also established and is evident from the scatter plot in figure 14.4c that as CF factors of both layers increase, the absorption rate of external surface decreases, indicating that the tighter construction of the overall assembly negatively influences the absorption rate.

14.4 Conclusion

It is well recognised that aerodynamic and comfort properties of knitted fabrics used to construct performance garments play a significant role in improving the performance of an athlete. Based on the obtained results the following can be concluded:
Each layer in the fabric assembly has its own significant impact on the aerodynamic and moisture management properties of the entire assembly, However the results from the series of aerodynamic tests demonstrate that the base layer gains more importance in terms of aerodynamic performance when CF of the top layer increases. In regards to the moisture management performance, it is evident that the looser the construction (lower the CF) of each of the constituted fabrics in the assembly, the easier it is for the liquid moisture to diffuse thorough the fabric and then to evaporate to the surrounding environment.
It was also established that the decrease in the size of the openings within the knitted structure of the layered assembly leads to the increase of the V_{TRANS} and decrease in one way moisture transport capability (AOWT), proving a strong correlation between these parameters (Fig. 14.5). The results presented here could be used for a selection of suitable fabrics for the performance garments with optimised aerodynamic and moisture management performance.



Sample Nr	*CF*		*Area*	*VTRANS*	*AOWT*
	Base	*Top*	*[cm^2]*	*[m/s]*	*[% / 100]*
1	1.0	1.0	3.76	7.40	8.14
3	1.4	1.0	2.87	8.00	6.92
7	1.0	1.4	2.54	10.80	2.04
9	1.4	1.4	1.51	12.40	1.00

Figure 14.5: Correlation between Area, Vtrans and AOWT

14.5 References

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CHAPTER 15

P10

A Low Drag Suit For Ski-Cross Competitions

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Abstract:

Ski cross is a modern discipline which will be included in the Winter Olympics events from Vancouver 2010. In a ski cross competition, a group of four skiers take simultaneously part of the race and attempt to reach the end of the course. The first two to cross the finish line will advance to the next round.
It is then not a timed racing event like the other ski competitions.
Since it has been proved that low drag apparels have a major role in sports where high speeds are involved and speeds in ski cross can vary from 50km/h to 100km/h (depending on the track), a low drag suit could give an advantage to the athletes. Knowing that it is possible to design suits which are capable to shift the transition from laminar to turbulent regime (giving a great advantage in terms of drag reduction) it has been chosen to use different textiles with different roughness in different parts of the body to minimize the aerodynamic drag.
This had to be matched with the rules about how the suits should be made. The rules present in the FIS regulation states that skin suits like the one used in Skiing and Speed Skating can not be used and that *The gap in the material must be a minimum of 80mm, measured everywhere around the circumference of the thigh of each leg from the mid thigh to the top of the ski boot and 60mm everywhere around the elbow and the bicep*. The flappin" effect should then be taken into consideration. The suit design has been carried out in following steps:
1-A preliminary wind tunnel test on a athlete from the Olympic team has been carried out and different suits have been tried. The major parameters which influence the drag have been addressed
2-12 textiles have been chosen basing the choice on the different patterns present on the textile and on the experience. All the textiles had different roughness and thickness.
3-A preliminary wind tunnel test on cylinder models has been carried out on the textiles and 8 textiles have been discarded. 4 different pants and 3 different jackets design have been suggested.

15.1 Introduction

In the past years, high speed sports such as speed skating, cycling and skiing have been extensively studied from the aerodynamic point of view [DeKoning 2005a], [DeKoning 1992a], [DiPrampero 1979], [Thompson 2001], [VanIngenSchenau 1982], [VanIngenSchenau 1983].
However, new sports are gaining more and more attentions and a large margin of improvement in terms of aerodynamic performances is still possible. Considering that the aerodynamic loads (D) in a speed skiing competition contribute to more than 80% of the total drag [Shanebrook 1974], a reduction of D can sensibly improve athletes performances. The aerodynamic resistance (D) is defined as:

$$D = \frac{1}{2}\rho A_p c_D A V^2 \tag{15.1}$$

Where A is the frontal Area, V is the wind speed cd is the drag coefficient and ρ is the air density.
In order to reduce the Drag, the parameters in equation 1 need to be reduced.
The frontal area A can be reduced adjusting the athlete's posture. A lower posture corresponds in fact to a lower value of A. Furthermore, previous studies [Remondet 1997] showed that the position assumed by the athlete during its performance can affect the drag by influencing not only the frontal area (A) but also the drag coefficient (c_D). The cD varies from 0.5 in downhill position to 1 in standing position.
Another method used in order to reduce D consists in using rough textiles in order to trip the transition to turbulent regime around the body and consequently create a drop on the c_D parameter at certain speeds. Considering the human body as a series of cylinders with different shapes and inclinations, each body part can be considered separately [Shanebrook 1974].
How surface roughness affects the drag cylinders have been previously studied by a number of authors [Achenbach 1977],[Bearman 1993],[Brownlie 1992],[Oggiano 2007],[Oggiano 2008]). Some of them ([Brownlie 1992],[Oggiano 2007],[Oggiano 2008]) focused their attention on surface roughness created with textiles and on how drag reduction can be achieved using the right textile in each body part.
These findings have been already used in speed skating suits where Nike first [Brownlie 1992] and then all the other manufactures (Mizuno, Craft, Asics) produce suits with different textile patches in different areas of the body.
In some other sports, especially new disciplines like Ski-cross, a large margin of development in terms of aerodynamic apparel is possible.
Ski-Cross is a recent sport, the first Ski Cross event was held at the Winter X Games in 1999 gained popularity shortly thereafter in Europe.
In 2002 Ski-Cross was adopted by FIS as a Freestyle event. FIS sanctioning was key to its pathway to the Olympics. In the Olympic games of 2010 in Vancouver, Ski-Cross made its first appearance amongst the Olympic events. In contrast with speed skating, cycling or other skiing disciplines where the athletes are allowed to wear skin suits in order to improve their aerodynamics, in Ski-

Cross this is not possible.
The International Ski Federation (FIS) rules for ski-Cross suits states that Ski-Cross suits must be two pieces; pants and a separate top. Suits worn in the Alpine events of Downhill, Super-G, Giant Slalom, Slalom, and Speed Skiing are not allowed. Suit base material shall be textile fabrics and fastening devices shall not be used to tighten the suit material closer to the body or prevent the natural fall of the clothing.
The gap in the material must be a minimum of 80mm, measured everywhere around the circumference of each leg from the mid thigh to the top of the ski boot and 60 mm everywhere around the elbow and the bicep.
This leads to the fact that the flapping effect of the textile should be taken into consideration when chosing the textile which minimize the drag on each body part.

15.2 Methods

15.2.1 Wind Tunnel

Wind tunnel: the experiments have been carried out in the NTNU (Norwegian University of Science and Technology) wind tunnel in Trondheim. The test section of the wind tunnel is 12.5 meters long, 1.8 m high, and 2,7 m wide. The wind tunnel is equipped with a 220KW and the maximum speed reachable is 30 m/s
Force balance: The balance (Carl Schenck AG) used is a six component balance capable to measure the three forces and the three momentums around the three axes. Variations of forces and moments are measured using strain gauges glued to the balance body. The voltage outputs are acquired with a USB acquiring card produced by National Instruments. The acquiring card is divided in two parts, a NI cDAQ-9172 chassis and a NI-9205 module.
The cDAQ-9172 is an eight-slot NI CompactDAQ chassis that can hold up to eight C Series I/O modules. The NI 9205 features 32 single-ended or 16 differential analog inputs, 16-bit resolution, and a maximum sampling rate of 250 kS/s. Each channel has programmable input ranges of ś200 mV, ś1, ś5, and ś10 V. Two channels have been used, one for the drag and one for the speed. The acquiring rate was set to 300Hz and 5 samples of 5seconds each were taken per each sample and each speed.
Mannequin model: A real size model mannequin has been used to test the pants and jackets produced. The mannequin is 170cm tall and weights 70kg. All the joints are adjustable. The mannequin was connected to the force balance with a steel support placed in the back of the model in order to avoid interferences with the flow
Yaw Cylinder model: In order to simulate the effect of yaw angle, a horizontal cylinder model was mounted in the wind tunnel. The cylinder has a diameter of 11cm. Two dummy cylinders were mounted at the 2 extremities of the cylinder in order to simulate a infinite cylinder. The model is able to rotate along the vertical axis giving the possibility to measure the drag force at different yaw angles.
Tandem cylinder model: in order to simulate the effect of the athlete legs, a tandem cylinder model has been used. The model consists in two plastic 11cm diameter cylinders vertically mounted on a

support connected to the force plate balance. The distance and the angle between the two cylinders can be manually adjusted. Two dummy cylinders have been added in order to simulate the infinite effect.

15.2.2 Textiles

Thirteen textile samples have been analyzed. All the textiles tested were different in terms of thickness and roughness. The samples consisted in two cylindrically shaped pieces of textiles, each 40cm long and with a 13cm diameter. The diameter of the samples has been chosen so that the fabrics, when mounted on the models, were conform to the FIS rules.
In order to classify the textiles, a basic classification has been made. The two parameters chosen were thickness and roughness. **Thickness:** It affects the flapping effect of the textile. A thicker textile tends to have a stiffer shape and it oppose a higher force to the flow. The recirculation area placed behind the cylinder leads also to the fact that thicker textiles show a larger frontal area if compared with a thinner textile. The thickness has been measured in 10 different parts of the textile

- Thick: textiles with a thickness value larger than 0.8mm

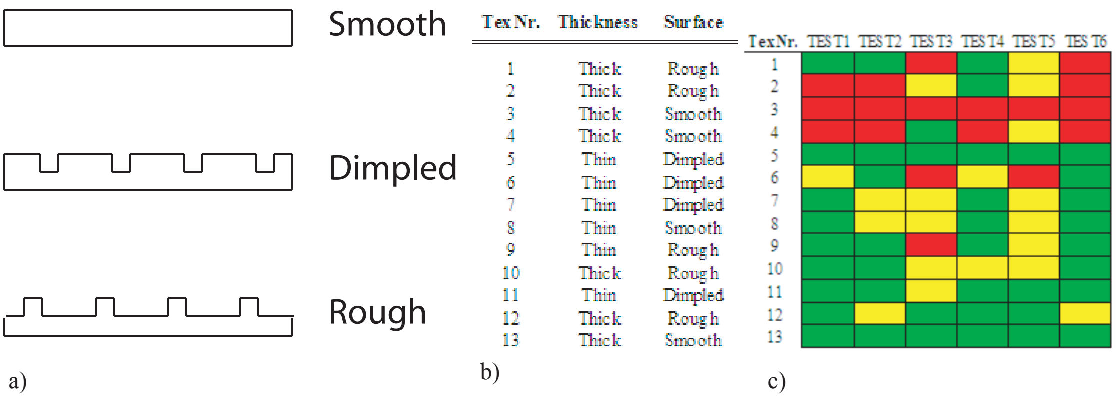
- Thin: Textiles with a thickness value smaller than 0.8mm

Roughness: As showed by a number of authors ([Achenbach 1977], [Bearman 1993], [DiPrampero 1979], [Oggiano 2007]), the roughness placed on the surface of a cylinder is able to modify the aerodynamic properties of the cylinder model by trigging the transition to turbulent regime at lower speed thus reducing the drag [Oggiano 2007]. In principle, all the textiles tested can be considered as rough. However, a basic description of the surface texture has been made and the textiles have been divided into three categories: Rough, Dimpled, Smooth.

- Smooth: Only a minimal roughness due to the knitting process of the textile is present on the surface of the textile. No holes, dimples or excrescences are present.
- Dimpled: The textile can be considered basically smooth with some structured holes present on the surface.
- Rough. The textile is rough and excrescences are present on the surface of the fabric.

15.2.3 Preliminary test: cylinder tests

In order to minimize the errors and reproduce random effects due to different positions assumed by the body during 6 different tests on 2 different models have been carried out: 3 tests on a tandem cylinder model and 3 tests on a horizontal cylinder model. All the results were then resumed in a



TexNr.	Thickness	Surface
1	Thick	Rough
2	Thick	Rough
3	Thick	Smooth
4	Thick	Smooth
5	Thin	Dimpled
6	Thin	Dimpled
7	Thin	Dimpled
8	Thin	Smooth
9	Thin	Rough
10	Thick	Rough
11	Thin	Dimpled
12	Thick	Rough
13	Thick	Smooth

TexNr.	TEST1	TEST2	TEST3	TEST4	TEST5	TEST6
1	🟩	🟩	🟥	🟩	🟨	🟥
2	🟥	🟥	🟨	🟩	🟨	🟥
3	🟥	🟥	🟥	🟥	🟥	🟥
4	🟥	🟥	🟩	🟥	🟨	🟥
5	🟩	🟩	🟩	🟩	🟩	🟩
6	🟨	🟩	🟥	🟨	🟥	🟩
7	🟩	🟨	🟨	🟩	🟨	🟩
8	🟩	🟨	🟨	🟩	🟨	🟩
9	🟩	🟩	🟥	🟩	🟨	🟩
10	🟩	🟩	🟨	🟨	🟨	🟩
11	🟩	🟩	🟨	🟩	🟩	🟩
12	🟩	🟨	🟩	🟩	🟩	🟨
13	🟩	🟩	🟩	🟩	🟩	🟩

Figure 15.1: (a) The three different types of textiles used (smooth, rough and dimpled) (b) List of the 13 textiles tested. (c) Schematical results from the preliminary tests carried out on cylinder models

simplified comparison table (Fig 15.1c).
Some simplifications were made in order to create the table: It was chosen to use the drag measurements relative to the *speed*>15m/s. The speed has been varied from 15 to 25m/s with 1m/s interval. 5 drag measurements have been acquired per each speed, the highest and lowest measurements have been discarded and the remaining 3 have been averaged. A total average representative of the behaviour of the textile for speeds higher than 15m/s have been calculated averaging the 11 drag measurement acquired per each speed.
Defining per each test c_{DMAX} as the maximum c_D value measured for textile a and c_{DMIN} as the minimum c_D value measured for textile, a colour has been used in order characterize the performance of each textile.
Green: low average drag for V>15m/s. (c_{DMIN}< cD< c_{DMIN}+1/3(c_{DMAX}- c_{DMIN})
Yellow: medium average drag for V>15m/s. (c_{DMIN}+1/3(c_{DMAX}- c_{DMIN} < c_D< c_{DMIN}+2/3(c_{DMAX}- c_{DMIN})
Red: The high average drag for V>15m/s. (c_{DMIN}+2/3(c_{DMAX}- c_{DMIN})< c_D< c_{DMAX})
Each test have been repeated twice in order to validate the results.

Tandem Cylinder Test
The tandem cylinder model consists in 2 vertical 11cm diameter (Diam=11cm) cylinders placed side by side in order to simulate the legs of the athlete. The distance between the cylinders can be varied.
The tests have been carried out at L=22cm and L=33cm and, for L=33cm a third test have been carried out with a 20 degrees angle between the model and the flow:
TEST 1 : Diam=11cm, L=22cm, $\beta = 0°$
TEST 2 : Diam=11cm, L=33cm, $\beta = 0°$
TEST 3 : Diam=11cm,L=33cm, $\beta = 20°$

Yawed Cylinder Test
The cylinder model has been used in order to evaluate the effect of the wind angle on the model.

This is due to the fact that the wind is almost never coming from a direction normal to the athlete's arms and legs, thus it is important to evaluate the effect of the side wind combined with the use of rough textiles. Three tests have been carried out using this model:

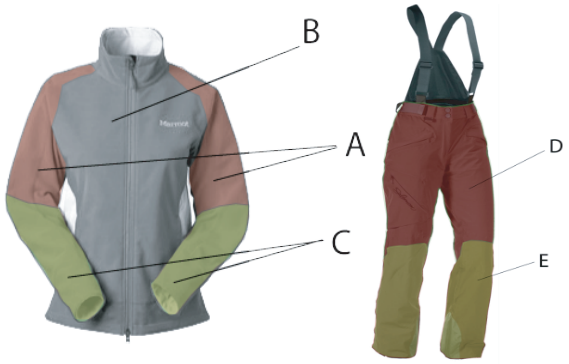
TEST 4 : $\alpha = 0°$
TEST 5 : $\alpha = 10°$
TEST 6 : $\alpha = 30°$

From the preliminary test carried out on cylinder models, some conclusions can be stated:

o Textile 5 was the one which reduced the drag the most in average.
o Textiles 1 or 12 performed better than textile 5 at high speed (90km/h) and no angle.
o THICKER textiles have HIGHER drag in average.
o ROUGHER textiles have lower drag than the SMOOTHER ones only if the flow is coming perpendicular.

15.2.4 Suit design

From previous experiments it's known that legs counts up to 1/3 of the total drag of the body when the body is in a tuck position. High attention needs then to be given to the legs.



a) b)

Jacket

Area	1 (long)	2 (short)	3 (REF)
A	5	5	12
B	13	13	12
C	5	5	12

Pants

Area	1	2	3	4	5 (REF)
D	5	5	5	13	12
E	1	12	5	5	12

c)

Figure 15.2: ((a) Jacket prototype with different patching areas b) Pants prototype with different patching areas (c) Tables showing the type of textiles used on the different patching areas

15.3 Results

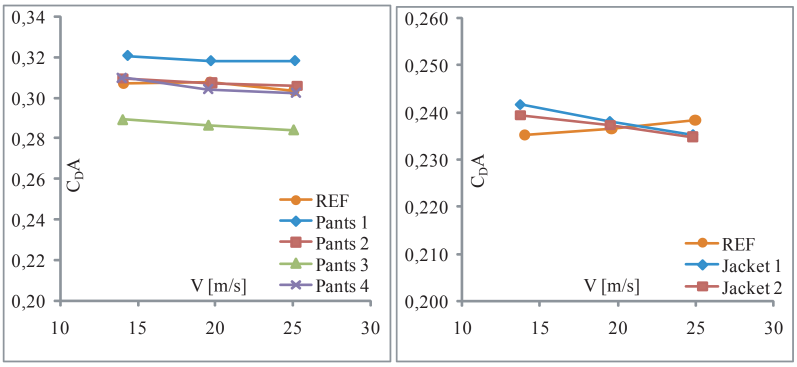
Five different models of pants and three different model of jackets have been made. (Fig 15.2) The pants have been designed with two different textiles: a rougher textile for the lower part of the legs (E) and a smoother textile for the higher part of the legs (D) and the jackets have been designed in order to have rougher textiles in the arm (A) and (C) and smoother and elastic textile on the trunk in order to adjust itself to the athlete's shape during the race.

Parts A, B , D and E have been modeled following the FIS rules which state that the gap in the material must be a minimum of 80mm, measured everywhere around the circumference of the thigh of each leg from the mid thigh to the top of the boot and 60 mm everywhere around the elbow and the bicep.

A tighter fit has then be used on part E and B.

The test has been carried out on a mannequin model which is 170cm tall and it has human proportions. The skiing position was chosen referring to the body angles defined by Van Ingen Schenau [VanIngenSchenau 1982]. $\vartheta 1$ =15 and $\vartheta 2$ =100 has been chosen where $\vartheta 1$ is the angle between the upper and lower leg and the angle and $\vartheta 2$ is the trunk angle (the line between the hip joint and the middle of the neck with respect to the horizontal).

In order to reduce coupling effects, when the pants were tested, no jacket was worn by the mannequin and the other way around then the jackets were tested.



a) b)

Figure 15.3: (a) - CDA-speed curve for the pants tested on the mannequin model . (b) CDA-speed curve for the different jackets teted on the mannequin model

From the tests carried out pants 3 showed a high improvement if compared with the reference pants. A drag reduction of ca. 10% has been obtained for the whole range of speed from 15m/s to 25m/s.

No sensible improvements have been found for the jackets but this might be due to the fact that the posture chosen had both arms placed around the trunk. However, the trend plot in fig 3b shows that both jacket 1 and 2 have lower drag for a speed higher than 20m/s than the reference jacket.

15.4 Acknowledgements

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