We are IntechOpen, the world's leading publisher of Open Access books
Built by scientists, for scientists

6,000
Open access books available

147,000
International authors and editors

185M
Downloads

154
Countries delivered to

Our authors are among the

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Sport Aerodynamics:
On the Relevance of Aerodynamic Force
Modelling Versus Wind Tunnel Testing

Caroline Barelle
National Technical University of Athens
Greece

1. Introduction

In sports events, performance analysis is not an easy task since multiple factors, such as physiology, psychology, biomechanics, and technical progress in equipment are simultaneously involved and determine the final and ultimate outcome. Identification of individual effects are thus complicated, however from a general point of view, aerodynamics properties are recognized to play a determinant role in almost every sports in which the performance is the result of the optimal motion of the athlete (multi-jointed mechanical system) and/or is equipment (solid system) in the air. From ball games like golf, baseball, soccer, football and tennis to athletics, alpine skiing, cross-country skiing, ski jumping, cycling, motor sport and many others, the application of some basic principles of aerodynamic can make the difference between winners and losers.

If the general shape of the athlete/equipment system in terms of postural strategies and equipment customization is not optimized, it can either be made to deviate from its initial path, resulting in wrong trajectories and/or loss of speed and leading to failure in terms of performance. Coaches should thus be able to assess the aerodynamic efficiency of the motor task performed by the athlete with accuracy and in almost real time. Indeed, quick answers and relevant information can help the athlete to focus on specific aspects of his technical behaviour to improve his performance. So far for this purpose, two solutions are available i.e. dedicated wind tunnel testing or implementation of aerodynamic force models during the athlete training sessions. According to the complexity of sport performance and the necessity of almost real time answers for stakeholders, issue concerning the relevance of aerodynamic force modelling versus controlled experiments in wind tunnel must be discussed. In particular when searching to optimize athletes' performances, what are the advantages to develop and implement aerodynamic models comparing to controlled experiments in wind tunnel and for which purpose?

After a short description in section 2 of the aerodynamic principles commonly applied in sport to help optimize performance, the current chapter will document in section 3 both approaches (wind tunnel testing and aerodynamic force modelling) to assess the aerodynamics properties of a particular mechanical system: the athlete with or without his equipment. It will among others present a review of particular wind tunnel setting and modelling methods dedicated to specific sports such as cycling and skiing as well as shows

in section 4, how appropriate applications of them can lead to an increase of athletes' performances.

2. Aerodynamic principles applied to help optimize performance in sport

2.1 The performance in sport

Athletic performance is a part of a complex frame and depends on multiple factors (Weineck, 1997). For sports such those involving running, cycling, speed skating, skiing … where the result depends on the time required to propel the athlete's body and/or his equipment on a given distance, the performance is largely conditioned by the athlete technical skills. Success then is the outcome of a simple principle i.e. the winner is the athlete best able to reduce resistances that must be overcome and best able to sustain an efficient power output to overcome those resistances.

In most of the aforementioned sports, those resistances are mainly the outcome of the combination of the contact force and the aerodynamic force acting on the athlete (Fig. 1.) The goal in order to optimise the performance consists to reduce both of them as much as possible.
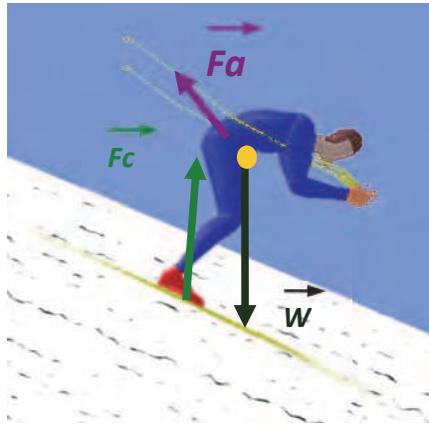

Fig. 1. Force acting on a downhill skier. With $\overrightarrow{W}$ the weight of the skier, $\overrightarrow{Fc}$ the ski-snow contact force and $\overrightarrow{Fa}$ the aerodynamic force.

However, whether cycling, speed skating, skiing, given optimal physical capabilities, it has been shown that the main parameters that can decreased the race time considerably is the aerodynamic behaviour of the athlete and/or his equipment. Indeed, in cycling, the aerodynamic resistance is shown to be the primary force impeding the forward motion of the cyclist on a flat track (Kyle et al., 1973; Di prampero et al., 1979). At an average speed close to 14 ms^{-1}, the aerodynamic resistance represents nearly 90% of the total power developed by the cyclist (Belluye & Cid, 2001). The statement is the same in downhill skiing. The aerodynamic resistance is the parameter that has the greatest negative effect on the speed of the skier. For a skier initially running with a speed of 25 ms^{-1}, the transition from a crouch posture to a deployed posture can induce in 2 seconds (1.8% of the total run) almost a decrease of 12% of the skier speed whereas in the same condition, the ski-snow contact force only lead to a decrease of 2.2% (Barelle, 2003).

It is thus obvious that in such sports where a maximal speed of the system athletes/equipment is needed in order to reduce as much as possible the racing time, an optimisation of the system aerodynamic properties is crucial compare to the optimization of its contact properties.

2.2 Fundamentals of aerodynamic

Aerodynamics in sport is basically the pressure interaction between a mechanic system (athlete and/or his equipment) and the surrounding air. The system in fact moves in still or unsteady air (Fig.2.).

Fig. 2. A downhill skier passing over a bump (photo: Sport.fr).

By integrating the steady and static pressure field over the system, the resulting aerodynamic force acting on this system can be obtained (Nørstrud, 2008). This force is generally divided into two components, i.e. the drag force $\vec{D}$ and the lift force $\vec{L}$ (Fig.3.).
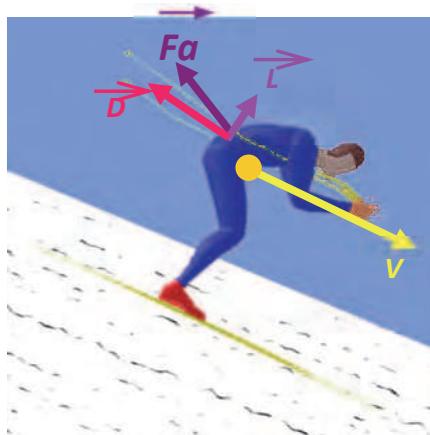

Fig. 3. Aerodynamic force applied on a skier and its two components: $\vec{D}$ the drag (axial component) and $\vec{L}$ the lift (normal component). V represents the speed of the skier.

The drag $\vec{D}$ is defined as the projection of the aerodynamic force along the direction of the relative wind. This means that if the relative wind is aligned with the athlete/equipment system, the drag coincide with the aerodynamic force opposite to the system motion. $\vec{D}$ depends on three main parameters: (i) the couple athlete/equipment frontal surface area (defined as the surface area of the couple athlete/equipment projected into the plane perpendicular to the direction of motion), (ii) the drag coefficient depending on the shape and the surface quality of the system and (iii) the athlete speed. The drag is thus expressed using the following equation (1).

$$D = {}^{1}\!/_{2} \cdot \rho \cdot A \cdot C_{D} \cdot V^{2} \qquad (1)$$

Where D denotes the drag (N), ρ is the air density (kgm^{-3}), A is the projected frontal area of the couple athlete/equipment (m²), C_D is the drag coefficient and V is the air flow velocity (ms^{-1}) equivalent to the athlete speed.

The drag is essentially proportional to the square of the velocity and its importance grows more and more as the speed increases. If speed is doubled, the drag increases by four-fold. The drag coefficient C_D is dimensionless and depends on the Reynolds number (ratio of inertial forces and forces due to the viscosity of air) and the speed of the airflow. If C_D varies for law speed values (Spring et al., 1988), in most of the sports considered in this chapter, it can be considered as constant (Di Prampero et al., 1979 ; Tavernier et al., 1994). In fact, the athletes never reach the critical speed which cause the fall in C_D due to the change from laminar to turbulent regime. So at a steady and relatively high speed, variations of drag are mainly induced by variations of the projected frontal area of the couple athlete/equipment, thus by posture variations (Watanabe & Ohtsuki, 1977; 1978). The figure 4 shows in which proportion the A.C_D factor of a downhill skier varies with changes in posture.

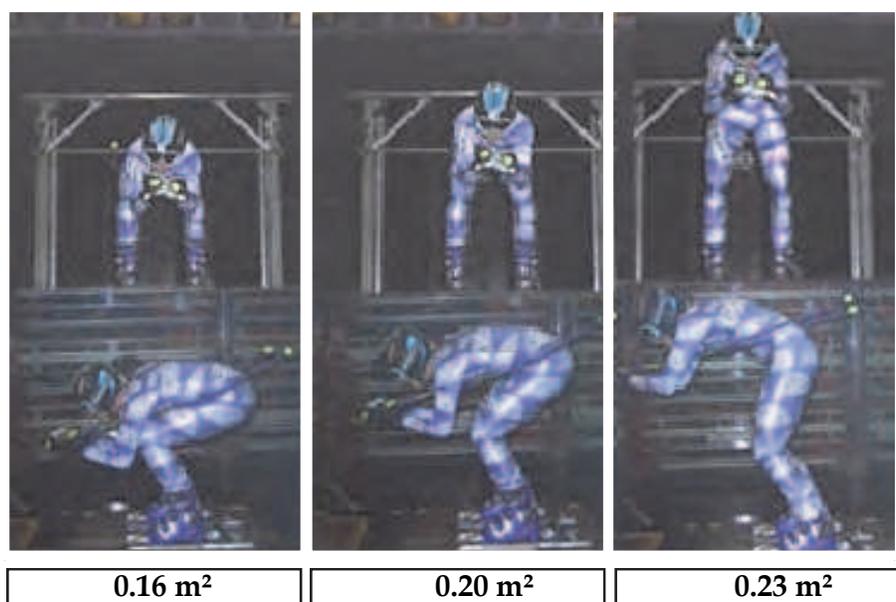| 0.16 m² | 0.20 m² | 0.23 m² |

Fig. 4. Variation of the A.C_D factor of a downhill skier according to posture variations (Wind tunnel of IAT, France).

The lift $\vec{L}$ is the component of the aerodynamic force that overcomes gravity. It is acting normal to the drag component. As the drag, it depends also on three main parameters: (i) the couple athlete/equipment frontal surface area (defined as the surface area of the couple athlete/equipment projected into the plane perpendicular to the direction of motion), (ii) the lift coefficient depending on the shape and the surface quality of the system and (iii) the athlete speed. The lift is thus expressed using the following equation (2)

$$L = {}^1\!/_2 \cdot \rho \cdot A \cdot C_L \cdot V^2 \tag{2}$$

Where L denotes the lift (N), ρ is the air density (kgm^{-3}), A is the projected frontal area of the couple athlete/equipment (m²), C_L is the lift coefficient and V is the air flow velocity (ms^{-1}) equivalent to the athlete speed.

Bernoulli's law explains the phenomenon of lift from pressure differences between the lower and upper surfaces of the profile of a mechanical system (Fig. 5).
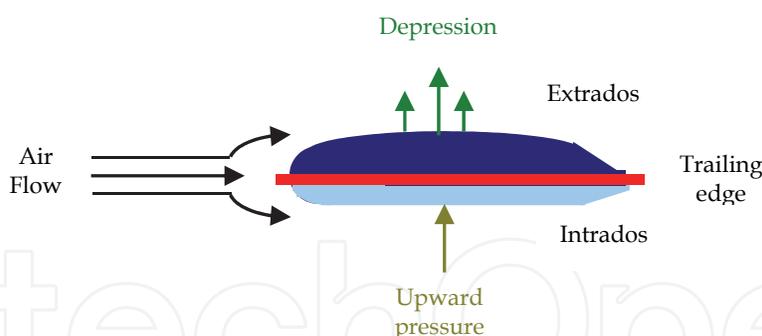
Fig. 5. The lift effect according to Bernoulli's law.

The distance travelled by the air flow is more important above the extrados than below the intrados. To avoid creating a vacuum of air at the trailing edge, the air flow following the extrados must move faster than the one following the intrados. An upward pressure is thus formed on the intrados and a depression appears on the extrados, thereby creating a phenomenon of lift. The shape of the mechanical system and its surface quality have thus, an effect on the lift intensity. However in the same manner as the drag coefficient C_D, the lift coefficient can be considered constant for the ranges of speed practiced during the aforementioned sports. Variations of the surface opposing the airflow induced by variations of the angle between the system chord line and the longitudinal axis (Fig.6.) namely the angle of incidence (i), impact the variability of the lift (Springings & Koehler, 1990). For an angle of incidence greater than 0 °, the lift will tend to increase while for an angle of incidence lower than 0 °, a phenomenon of "negative lift" will appear (down force).
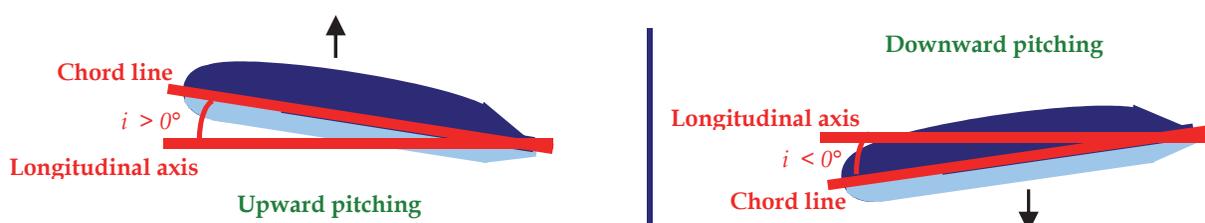
Fig. 6. Profile of an object according to its angle of incidence. i correspond to the angle of incidence.

In the aforementioned sports (running, cycling, skiing, skating), the equipment surface is rather small with respect to the athlete surface and therefore the main part of the aerodynamic force acts on the athlete who can be regarded as bluff body (non streamed line body). The bluffness leads to the fact that the aerodynamic resistance is mainly pressure drag instead of friction drag and thus, on a general point of view, it's more important to reduce the frontal area than to reduce the wet area. Then as lift is generally not required, it's better to keep it as small as possible in order to avoid the production of induced drag. However, in particular sport like ski jumping, it is obvious that the flight length is sensitive both to lift and drag. Small changes in the lift and or drag can have important effect for the jump quality and the skier must find the right compromise between an angle of incidence that will lead to an increase of the lift but not to an increase of the drag. The athlete must thus produce an angular momentum forwards in order to obtain an advantageous angle of incidence as soon as possible after leaving the ramp (Fig.7.). If the forward angular

momentum is too low, the flight posture will induce a high drag thus a law speed and a low lift, resulting in a small jump. Too much forward angular momentum on the other hand can increase the tumbling risk.
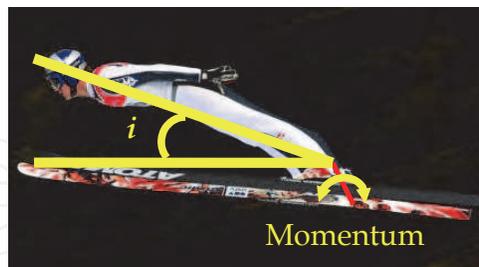

Fig. 7. A ski jumper during the flight phase just after leaving the ramp (photo: Photo by Jed Jacobsohn/Getty Images North America).

2.3 Reducing the aerodynamic force to optimize the performance

Reducing the air resistance in sport events typically involved improving the geometry of the athlete/equipment system. Optimisation of the athlete postures as well as the features of his equipment is generally required since they have a pronounced impact on the intensity of the aerodynamic force.

Firstly, by proper movement of the body segments (upper limbs, trunk, lower limbs) in order to minimize the frontal surface area exposed to the air flow, the posture can become more efficient aerodynamically. For example, in time trial cycling, it is now well known that four postural parameters are of primary importance in order to reduce the drag resistance i.e. the inclination of the trunk, the gap between the two elbows, the forearms inclination with respect to the horizontal plan, the gap between both knees and the bicycle frame (McLean et al., 1994). The back must be parallel to the ground, the elbow closed up, the forearms tilted between 5° and 20° with respect to the horizontal and the knees closed up to the frame (Fig.8.). Such a posture (time trial posture) can lead to average reduction of the drag resistance of 14,95 % compared to a classical "road posture" (37.8 ± 0.5 N vs. 44.5 ± 0.7 N; $p<0.05$) and that merely because of significantly lower frontal area (0.342 ± 0.007 m2 vs. 0.398 ± 0.006 m2; $p<0.05$) (Chabroux et al., 2008).

Fig. 8. An optimal aerodynamic posture in time trial cycling.

In downhill skiing, the principle is the same. The intensity of the aerodynamic resistance is even lower that the skier adopts a compact crouched posture for which the back is round and horizontal, the shoulders are convex and the upper limbs do not cross the outer contour of the skier and especially do not obstruct the bridge created by the legs.
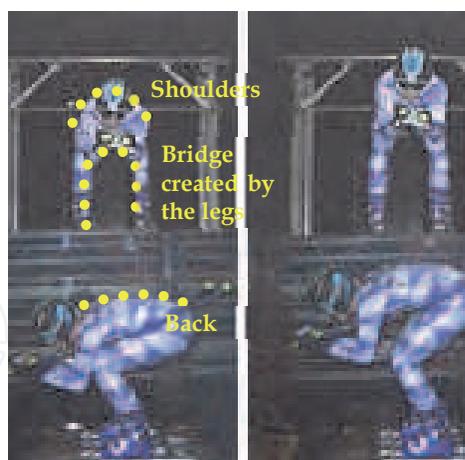
Fig. 9. An optimal aerodynamic posture in downhill skiing on the left compare to a posture a little bit more open on the right (Wind tunnel of IAT, France).

For an initial skier speed of 25ms^{-1}, such a crouched posture can lead to a gain of 0,04 second after a straight run of 100 meters thus to a victory compared to a posture a little bit more open (Barelle, 2003).

Secondly suitable aerodynamic customisation of the equipment can also strongly reduce the negative effect of the aerodynamic resistance. Indeed as example, in cycling, the comparison between time trial helmet and normal road helmet shows a drag resistance improvement that can range from 2,4 % to 4 % according to the inclination of the head (Chabroux et al., 2008).
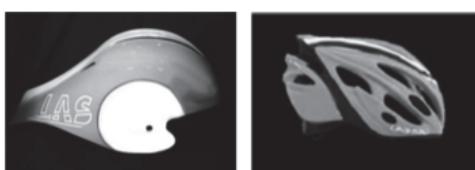

Fig. 10. Two cycling helmets, one aerodynamically optimised for time trial event (left) and the other a simple road helmet (right).

It is worth noting that an efficient optimisation of the aerodynamic properties of the athlete/equipment system must take into consideration precisely the interaction between the posture features and the equipment features. The aerodynamic quality of the equipment is totally dependent of the geometry characteristics of the athlete during the sport activity. An efficient optimization cannot be done without taking this point into consideration. In particular in time trial cycling, the interaction between the global posture of the cyclist and the helmet inclination given by the inclination of the head is significant from an aerodynamic point of view. The drag resistance connected with usual inclination of the head (Fig.11) is lower (37.2±0.6 N) than the one related to the low slope of the head (37.8±0.5 N), which is itself significantly lower than the one generated by a high slope of the head (38.5±0.6 N). In fact according to the helmet shape, the inclination of the head can have different impact on the projected frontal area of the couple helmet /athlete head thus on the aerodynamic drag.

Hence, it is also important for coaches and athletes to optimize postures in a way that it will not affect the athlete physical power to counteract the resistance. In most of the sport and

Fig. 11. Inclination of the head in time trial and corresponding inclination of the helmet (Wind tunnel of Marseille, France).

for aerodynamic purposes, athletes are asked to adopt a tightly crouched posture to reduce their frontal areas exposed to the air stream but if it is not well done, it can also have bad biomechanical and physiological consequences for the athlete performance such as a decrease of physiological qualities. Everything is a compromise. In ice skating for example, although a tightly crouched posture reduces leg power, it reduces air drag to an even greater extent and thus produces higher skating velocities.

3. Methods for assessing the aerodynamic force applied on an athlete with or without his equipment

To assess the aerodynamic performance of an athlete and/or his equipment, two methods are available, i.e. either to perform wind tunnel testing to single out only one specific determinant of the performance in this case aerodynamic properties of the athlete or/and his equipment, or to develop and implement aerodynamic force models that can for example be apply in a real training or competitive conditions which mystifies the role of other factors such as for instance mental factors. The real question here, concern the relevance of the inferences drawn from the results obtain with this two methods according to the fact that the performance in sport is the outcome of the efficient interaction of multiple factors at the right time. Indeed, "a fact observed in particular circumstances can only be the result of particular circumstances. Confirming the general character of such a particular observation, it is taking a risk of committing a misjudgement." (Lesieur, 1996). Both approaches are further detailed below as well as their relevance according to the performance goal pursue by the principles stakeholders i.e. athletes and coaches.

3.1 Wind tunnel testing

Wind tunnel tests consist in a huge apparatus used to determine the complex interactions between a velocity-controlled stream of air and the forces exerted on the athlete and his equipment. The tunnel must be over sized compare to the athlete to be assessed in order to avoid side effects that may disturb the measurement of the aerodynamic force. The athlete with or without his equipment is fasten on a measured platform (6 components balance) in the middle of the test section. The athlete is thus stationary in the flow field and the air stream velocity around him generally corresponds to the ones observed during the sport practice (e.g. 14ms^{-1} in time trial cycling, 25 ms^{-1} and more in alpine skiing.). The aerodynamic balance enables to measure the smallest aerodynamic force imposed on the athlete/equipment system in particular its axial (drag) and normal (lift) components (Fig.12).
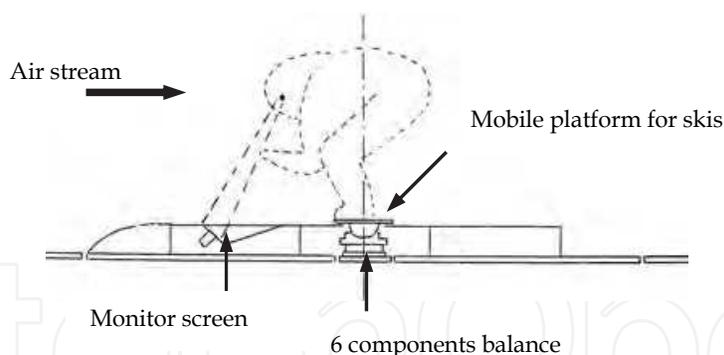
Fig. 12. Diagram of a data acquisition system for the assessment of the aerodynamic properties of a downhill skier (Wind tunnel of IAT, France).

For a better understanding, the path of the air stream around the system can be made visible by generating smoke streams (Fig.13).

Fig. 13. Smoke stream around a time trial cyclist and his equipment (Wind tunnel of Marseille, France).

A tomography gate can also be installed in the wind tunnel behind the athlete to explore the air flow wake behind him (Fig.14).

The figures below shows different wind tunnel settings that have been used for the measurement of the aerodynamic force applied on downhill skiers and time trial cyclists.

In alpine skiing, most of the time, the skier is in contact with the snow and only an accurate assessment of the drag applied on him is necessary. However in particular conditions and especially when he passes over a bump (Fig.2), it is interesting to quantify the lift applied on him. It has to be the smallest as possible since the skier as to be as soon as possible in contact with the snow to manage his trajectory. The length of the jump must be very short according to the initial and following conditions and the goal for the skier is to adopt in the air a posture that will generated the smallest lift. For both purposes i.e. measuring accurately the drag and the lift, two wind tunnel setting must be considered (Barelle, 2003; 2004).

On Fig.15, the goal is only to measure the aerodynamic drag applied on a skier adopting a crouched posture. The measuring device is the one of the Fig.12. The skier is fastening in the middle of a wind tunnel (rectangular section, 5 meters wide by 3 meters in height and 10 meters length) on a 6 components balance that enables ones to have access to multiple variables, among other the aerodynamic drag. Wind-less balance signals acquisition (during which the skier has to keep the crouched posture) are generally performed before each
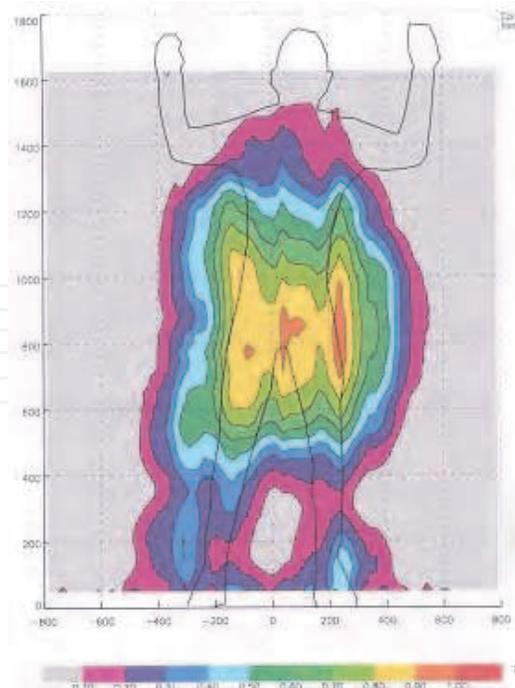
Fig. 14. Mapping of the air flow behind a cross country skier (Wind tunnel of IAT, France). The more colours are warm, the more the aerodynamic resistance is important.

aerodynamic measurement trial, in order to correct the measurements for zero drift and mass tares. After the zeros acquisition, the wind tunnel is started and when the required speed of the air flow is reached, the athlete can optimized is posture according to the strategy build with his coach. A mobile platform allowed him to adjust the posture of his legs whenever he wants according to the information he can read on the monitor screen.

Fig. 15. Measuring device for the assessment of the drag applied on a downhill skier (Wind tunnel of IAT, France).

If the skis have not a great impact on the variability of the drag intensity, their contribution to the variability of the lift has to be taken into account. It is therefore necessary to position the skis outside the boundary layer which is near the ground. Although it is relatively thin, the velocity of the airflow in this area varies significantly and disturbs the measurement of the lift. Sections of boat masts (Fig.16) located under each skis have thus allowed to overcome this problem and allowed to remove the skis from this thin layer where the air stream can transit from a laminar to turbulent conditions.

In time trial cycling, in order to determine the drag force of the system bicycle /cyclist, a cycletrainer is fastened on a drag-measurement platform mounted in the middle of the test-
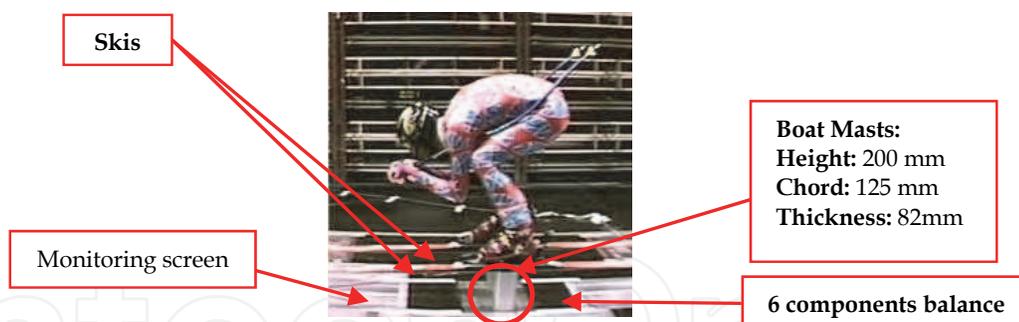
Fig. 16. Measuring device for the assessment of the lift applied on a downhill skier (Wind tunnel of IAT, France).

section of a wind tunnel which dimensions (octagonal section with inside circle of 3 meters in diameter and 6 meters length) allowed to avoid walls boundary layer effects that can interfering measurements (Fig.17). This platform is equipped with ball-bearing slides in the direction of the wind tunnel as well as a dynamometer measuring the drag force. As for assessing the aerodynamic properties of a skier, the general procedure for a cyclist is the same. A preliminary measurement without wind is performed in order to correct the measurements for zero drift and mass tares. Then a second measurement with wind but without the athlete allowed obtaining the drag force of solely the platform equipped with the cycletrainer. Finally, the drag force of the couple bicycle/cyclist can be measured while the cyclist adjusted his posture with a wind speed similar to that found in race conditions (around 14 ms^{-1}).

Fig. 17. Measuring device for the assessment of the drag applied on a time trial cyclist.

If such a measurement tools provides accurate recording of the aerodynamic force apply on the athlete, it has the disadvantages of not being able to be used anytime it is needed. Specific and dedicated wind tunnel program has to be perform and sometimes far away from the athletes current concerns. Moreover, the usual environmental conditions of the sport practice are requirements that cannot be taken into account in a wind tunnel setting.

3.2 Modelling methods
For numerical models, the method consists in computing correlation between postural parameters observe during the practice as well as equipment characteristics when or if needed and the value of the aerodynamic force. It requires most of the time and previously wind tunnel data of the aerodynamic characteristics of the athlete according to various postures and if necessary within a wide range of orientations relative to the air flow (Fig.18). Indeed, the functions are generally determined with athletes or model of athletes positioned in a wind tunnel in accordance with postures observed during competition in the field.
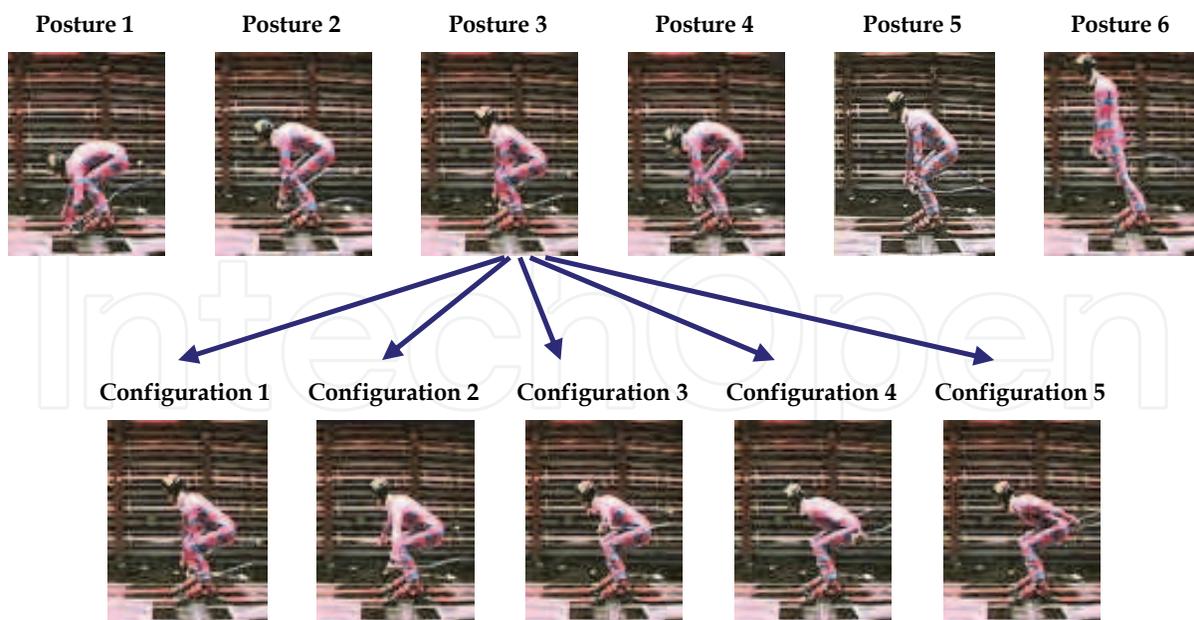
Posture 1   Posture 2   Posture 3   Posture 4   Posture 5   Posture 6

Configuration 1   Configuration 2   Configuration 3   Configuration 4   Configuration 5

Fig. 18. 30 postures assed in wind tunnel prior the development of a model of the aerodynamic lift applied on a downhill skier when passing over a bump. These postures correspond to postures observed in real conditions (Barelle, 2003).

The results of such models can then serve for example as input for simulations based on the Newton laws to estimate variations in time, loss in speed performance induced by different postural strategies as well as equipment interactions. When dedicated simulators integrating such models already exist, an almost real time feedback can be provided to the stakeholder on the aerodynamic properties of the athletes' posture. This can be a cost effective solution since it needs few human and material resources and it can be performed anytime it is needed during normal training sessions.

Examples of the development approach of some models for the evaluation of the aerodynamic performance in running, skiing, cycling are presented and discussed below.

3.2.1 Modelling of the aerodynamic force in running

Shanebrook & Jaszczak (1976) have developed a model for the determination of the drag force on a runner. They have considered the human body as a multi-jointed mechanical system composed of various segment and showed that the drag assessment applied on an athlete could be realized by considering the athlete's body as a set of cylinders. Their model is thus composed of a series of conjugated circular cylinders, to simulate the trunk and the lower and upper limbs, as well as a sphere to simulate the head. Projected surface area was measured for each segments (head, neck, trunk, arm, forearm, tight, shank) of the body of three runners representing respectively, adult American males in the 2.5, 50 and 97.5 percentiles of the population. Then the drag coefficient of cylinders and sphere representing these segments has been measured in a wind tunnel. The results for the 50 percentiles are proposed in the table here after (Table 1).

If such a model has the merit to enable one to reach the drag coefficient of the body segments of a runner, it doesn't consider the athlete body has a whole as well as the succession of body segments orientations that can generate different projected surface area and thus variation of the air resistance throughout the global motion of the runner.
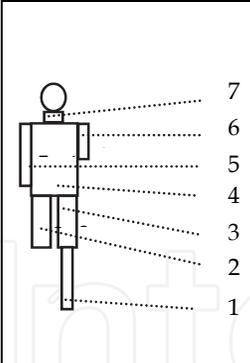
	Cylinders	A (in²)	C_D
	1	64.5	1.2
	2	67.7	1.2
	3	67.7	1.2
	4	312	1.1
	5	78.1	1.2
	6	43.2	1.2
	7	11	1.2
	sphère	48.3	0.43

Table 1. Models to determine the drag coefficient of the body part of a runner according to their projected surface area according to Shanebrook & Jaszczak (1976).

Moreover the adaptation of such model to different runners or to different kind of sportsmen during their practice is time consuming and not in accordance with the stakeholders (coaches, athletes) requirement of a quick assessment of the aerodynamic performance of an athlete.

3.2.2 Modelling of the aerodynamic force in skiing

The aerodynamic resistance in alpine skiing has been largely investigated, leading to different approaches to model the aerodynamic force. Luethi & Denoth (1987) have used experimental data obtained in a wind tunnel in their approach of the aerodynamic resistance applied on a skier. They have attempted to assess the influence of aerodynamic and anthropometric speed skier. By combining the three variables most influencing the speed of the skier i.e. his weight, is projected surface area (reflecting its morphological characteristics), and the drag coefficient C_D, they established a numerical code (ACN: Anthropometric Digital Code) representing the aerodynamic characteristics of skiers. The model is written as follow (3):

$$ACN = \left(\frac{mg}{A.\,C_D}\right)^{1/2} \tag{3}$$

Where m is the skier mass, A is the projected frontal area, C_D is the drag coefficient.
If the factors mg and C_D (invariable for skiers dressed with the same race clothes) are easily accessible, this model set the problem of assessing the projected frontal area of the skier in real condition. The observer (coaches) because of its placement on the side of the track can hardly have a front view of the athlete in action and even if he had it, it would not allow him to determine directly and easily the A. The model of Springings et al. (1990) for the drag and lift lead to the same problem. For this purpose, Besi et al. (1996) have developed a an images processing software to determine A but the processing time is once again too important for field application.
Spring et al. (1988) uses the conservation of energy principle in order to model the term $A.C_D$ (4).

$$A.\,C_D = \frac{m(V_D^2 - V_F^2) - 2k.\,V.\,mg.\,d}{V^2.\,\rho.\,d} \tag{4}$$

Where m is the skier mass, A is the projected frontal area, C_D is the drag coefficient, V_D is the initial speed of the skier, V_F is the final speed of the skier, V is the mean speed of the skier, k the snow friction coefficient and ρ the air density, d the distance travelled by the skier.

While this model takes into account as input data, field variables (speed of the skier, travelled distance), it does not incorporate the influence of postures variations. Once again the results obtained from this model can only be an approximation for use in real conditions since it cannot explain with accuracy the performance variations induced by changes in posture.

The modelling of the aerodynamic force as it is described above is not relevant and efficient for rapid application in real conditions. If in straight running, skiers can easily maintained an optimal crouched posture, in technical sections (turns, bumps, jumps), they must manage their gestures to ensure an optimal control of their trajectory, while minimizing the aerodynamic effects. To be relevant for such real conditions applications, posture variations must be taken into account in the modelling and thus whatever the considered sport.

3.2.3 Modelling of the aerodynamic force in cycling

As cyclists' performances depend mainly on their ability to get into the most suited posture in order to expose the smallest area to the air flow action, the knowledge of their projected frontal area can be useful in order to estimate their aerodynamic qualities. By the way, several authors have either reported values of A or developed specific equations to estimate the projected frontal area (Gross et al., 1983; Neumann, 1992; Capelli et al., 1993; De Groot et al., 1995; Padilla et al., 2000; Heil, 2001). However, this has been generally done only for riders of similar size and adopting the same posture on a standard bicycle. Such estimations have then shown large divergences and methodological differences may have widely contributed to such variability. Thus to be useful, models mustn't be developed as black boxes but by indicating accurately why they have been develop for and in which condition they can be used, by being transparent on the variables that have served to its construction and the results accuracy it can provided.

For example, Barelle et al. (2010) have developed a model estimating accurately A as a function of anthropometric properties, postural variations of the cyclist and the helmet characteristics. From experiments carried out in a wind tunnel test-section, drag force measurements, 3D motion analysis and frontal view of the cyclists were performed. Computerized planimetry measurements of A were then matched with factors related to the cyclist posture and the helmet inclination and length. A Principal Component Analysis has been performed using the set of data obtained during the experiment. It has shown that A can be fully represented by a rate of the cyclist body height, his body mass, as well as the inclination and length of his helmet. All the above mentioned factors have been thus taken into account in the modelling (5).

$$A = 0.045 \times h^{1.15} \times m_b^{0.2794} + [0.329 \times (L \times \sin \alpha_1)^2 - 0.137 \times (L \times \sin \alpha_1)] \tag{5}$$

where h is the height of the cyclist, m_b *the body mass of the cyclist,* L the length of the helmet, and α_1 the inclination of the head.

The prediction accuracy was then determined by comparisons between planimetry measurements and A values estimated using the model. Within the ranges of h, m_b, L and α_1

involved in the experiment, results have shown that the accuracy of the model is ± 3%. Within the objective to be easy to use, this accuracy can be considered sufficient enough to show the impact of postural and equipment changes on the value of the frontal area of cyclists. This model is explicit and it has been developed to take into consideration variation of posture i.e. inclination of the head. It can easily be applied to a variety of cyclists with different anthropometric characteristics since the height and body mass are input data. Moreover it can also considered the shape characteristic of the helmet including (L) its interaction with the inclination of the head (α_1). Finally its conditions of use are specified since its accuracy can only be guaranteed for input data that are within the ranges of h, m_b, L and α_1 involved in the experiment. It can thus provide pertinent indications useful for both coaches and cyclists.

3.3 On the relevance of aerodynamic force modelling versus wind tunnel testing

Individual and accurate optimization of the aerodynamic properties of athletes on very details modifications by means of wind tunnel measurements is essential for high performance. However, such comprehensive experiments in large scale wind tunnels lead to excessive measurement time and costs and require the disposability of athletes over unreasonably long periods. Even if accurate, wind tunnel tests have the disadvantage of not being able to be used anytime it is needed as it is required for high level sport. Moreover, the usual environmental conditions of the sport practice that can widely influence the performance are requirements that cannot be taken into account in a wind tunnel setting.

Instead, the computer modelling approach if well oriented allows studying the impact of all variables, parameters and initial conditions which determine the sport performance. In terms of aerodynamic, models implemented in the years 1980 and 1990 (Shanebrook, 1976; Watanabe & Ohtsuki, 1978; Luethi et al., 1987; Springings et al., 1990 ...), do not report the low dispersion of athletic performance neither because of the technical means available for their implementation nor because they were not designed for this purpose.

Several authors have tried to formalize the different steps to develop useful model (Vaughan, 1984; Legay, 1997) but this process is not as linear as it seems. The first stage involves identifying the system under study. This is a situation analysis which will determine and describe the framework within which will take place all the work ahead. When the frame is set, it is about to implement procedures to collect data relating to the objective pursued. The choice of tools for collecting and processing experimental data must be consistent with the model and the desired accuracy. Wind tunnel testing can thus in this case be useful if it takes into consideration postures observed during training and racing, athlete/equipment interactions, boundary conditions. Then to build the model, dependencies between different recorded variables are considered. These relationships are then translated in the form of equations giving the model structure. According Orkisz (1990), it must be hierarchical and give the possibility to adapt to all levels of complexity, depending on the nature of the results to be obtained. Such models have an important value in the quest for performance if their results are express in term of objective benchmarks (time, speed, trajectories ...) that can extend the observation of the coaches.

They could have two exploitation level i.e. analytical or global since they enable stakeholders respectively to focus on a particular aspect of performance such as the specific influence of the aerodynamic resistance (analytical approach of the Newton's law) or on the interaction of factors determining the performance (global approach of the Newton's law)

with the aerodynamic resistance among others (Barelle, 2003). When such models are used for simulation, they allow stakeholders to go further than the simple description. Beyond the fact that they can be used anytime it is needed, they have also predictive capacities and that, at a lower cost.

4. Application and valorisation: towards an optimization of downhill skiers' performances when passing over a bump

For each discipline in Alpine skiing (downhill, slalom, giant slalom ...), the difference in performance among the top world skiers is lower than one percent. Taking into account this low variability, coaches are confronted with the problem of assessing the efficiency of different postural strategies. Numerical models may provide an adequate solution. The method consists in computing a correlation between skiers' kinematics and postural parameters observed during training and each of the forces involved in the motion's equation (Barelle, 2003, Barelle et al., 2004; Barelle et al.; 2006). For postural strategies such as pre-jump or op-traken in downhill, models of the projected frontal area for the lift (6) (Barelle, 2003) and for the drag (7) (Barelle et al., 2004) are calculated based on postural parameters (length and direction of skier's segments).

$$A_{L=}0.1167\sin(\gamma) + 0.0258\sin(\beta) + 0.0607 + 0.024E_T((\sin(2.\theta_3) - \cos(\theta_4)) \qquad (6)$$

Where A_L is the projected frontal area, γ is the orientation of the trunk, β is the orientation of the tight in the sagittal plan, θ_3 and θ_4 are the arms orientation respectively in the frontal and horizontal plan.

$$A_D = 0.0003(L_1\sin(\alpha) + L_2\sin(\beta) + L_3\sin(\gamma)) - 0.026 + 0.041(|sin\theta_1| + |sin\theta_2|) \qquad (7)$$

Where A_D is the projected frontal area, γ is the orientation of the trunk, β is the orientation of the tight, α is the orientation of the shank in the saggital plan, θ_1 and θ_2 are both arms orientations in the horizontal plan.

Ground reaction and skis-snow friction are computed according to skiers' postural kinematics (skier's amplitude variation and duration of spread movements). Skiers' weight is easy to obtain. Thus the external forces exerted on the skis-skier system (Fig.1) are known, the motion's equation can be solved and simulations performed (Fig.19). These can be used to estimate variations in time and loss in speed performance induced by different postural strategies.

Such simulations find an application in the field of training as they enable to assess the impact on performance of a given strategy compared with another (Barelle, 2003; Barelle et al., 2006). Simulation results can be presented in the form of animations, using DVD technology. Such tool enables trainers to show skiers very quickly the variability of performance induced by different postural strategies (Fig.20.).

Broken down in this form, the simulation becomes a way of learning transmission. The aerodynamic drag model (7) can be used directly, if the coach chooses to particularly focus his attention on the aerodynamic effects. A first level of use is then given to the model. Then the model can have a second level of use, if the coach wants to have a general view of the skier performance since it is also designed to be an integral part of the modeling of the postural strategies implemented by skiers when passing over a bump in downhill skiing (simulator, Fig.19.).
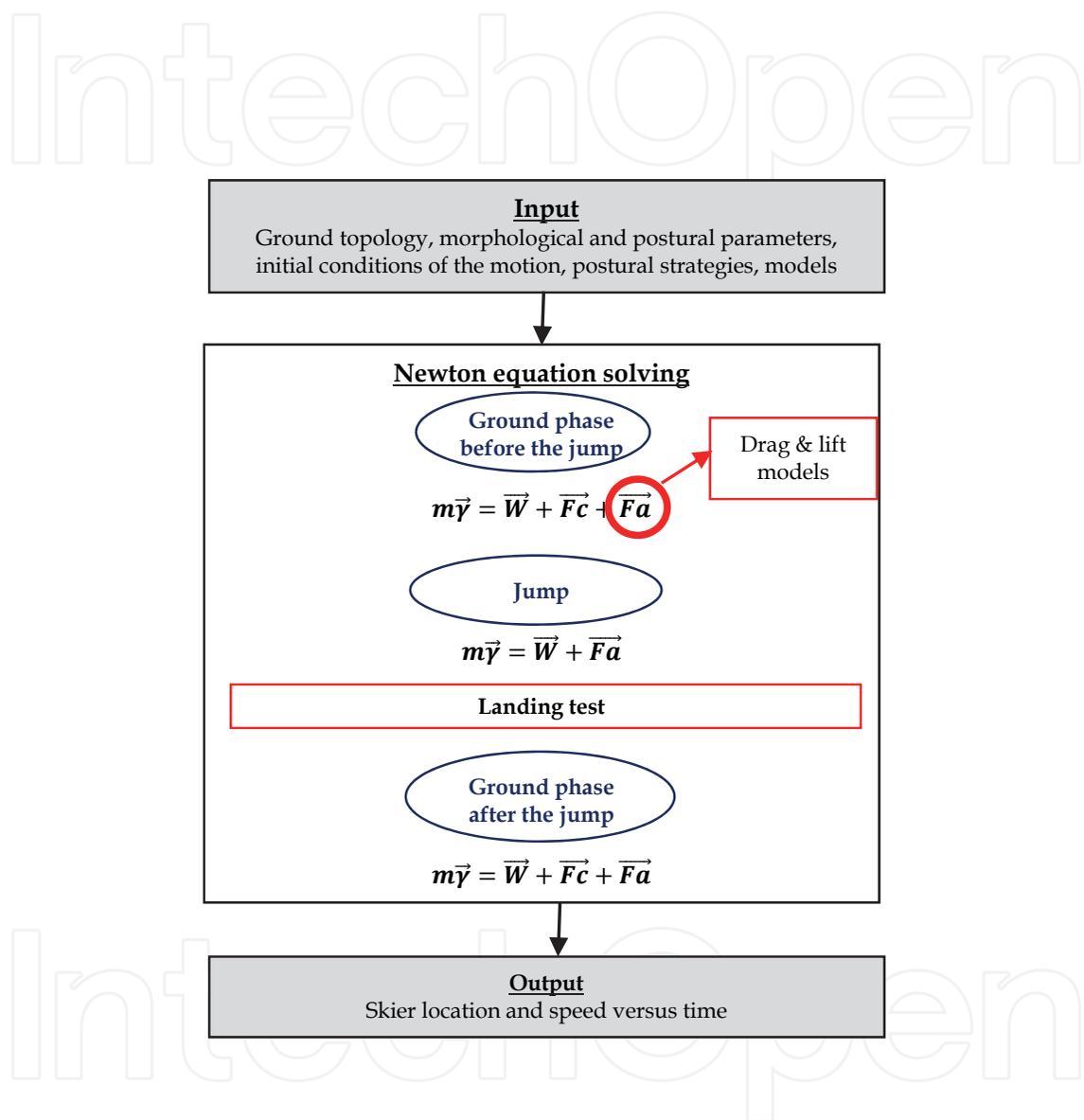
Fig. 19. Structure overview of the simulator of the trajectory of the centre of mass of a skier according to his anthropometric characteristics and his postural strategy as well as the topology of the downhill slope.
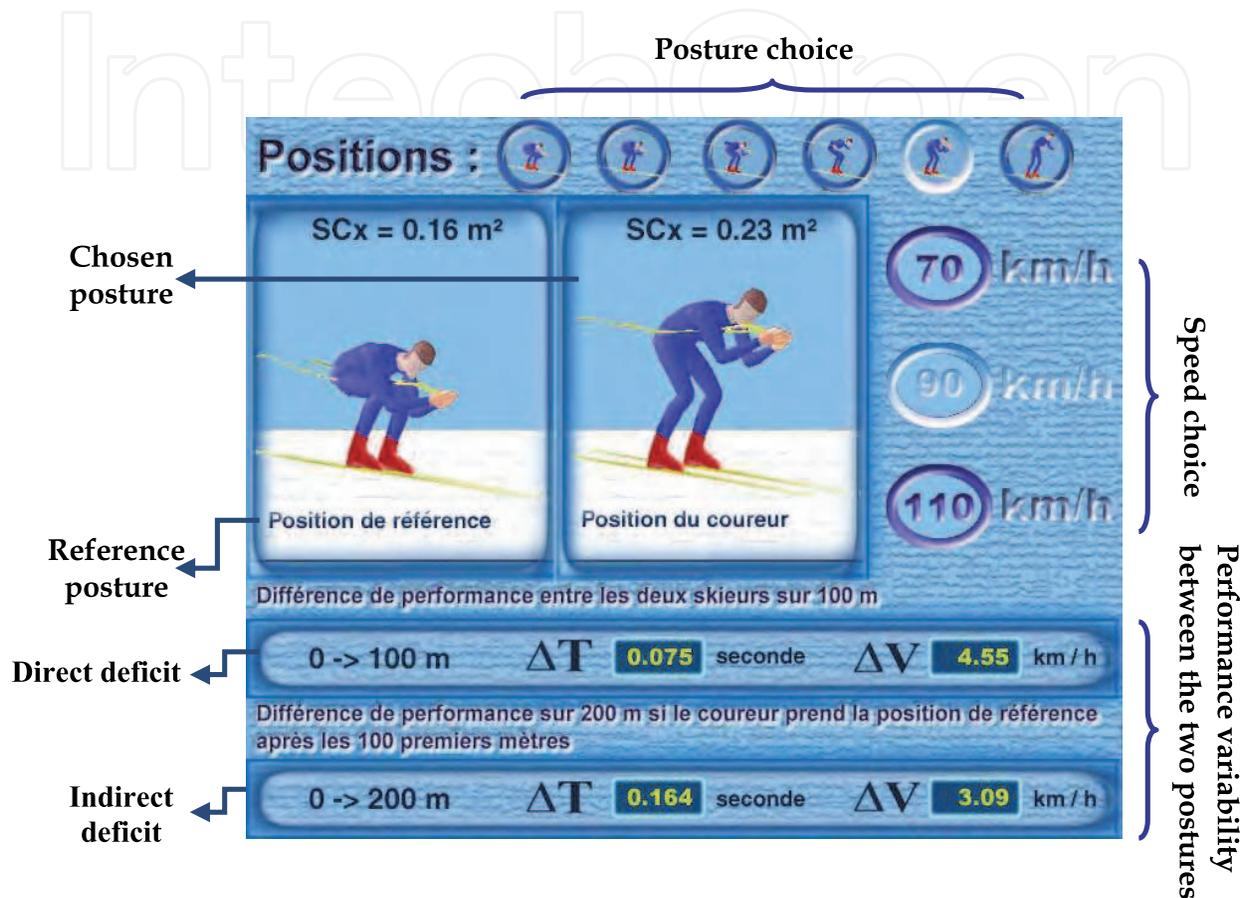
Fig. 20. Overview of DVD application built for the downhill skiers of the French Ski Federation. The choice of a posture enables ones to see the aerodynamic drag impact on performance for three input speed. The choice of a particular input speed enables to see the aerodynamic drag impact according to six different postures usually observed during races. The direct performance variability in terms of time deficit and loss of speed between the reference posture and the chosen posture is given after 100 meters of straight running (Direct deficit). Then stakeholders can visualize the indirect deficit generate 100 meters further (200m) even if the skier adopt again an aerodynamic crouched posture (like the reference one) on the last 100 meters (Indirect deficit).

6. Acknowledgment

7. Reference

Barelle, C. (2003) Modélisation dynamique du geste sportif à partir de paramètres posturaux. Application à l'entraînement en ski alpin. *PhD Thesis*, Claude Bernard University, Lyon, 99-102.

Barelle, C.; Ruby, A.; Tavernier, M. (2004). Experimental Model of the Aerodynamic Drag Coefficient in Alpine Skiing. *Journal of Applied Biomechanics*, No.20, pp167-176.

Barelle, C.; Ruby, A.; Tavernier, M. (2006). Kinematic analysis of the performance based on simulations of the postural strategies produced by the alpine skiers. Science et Motricité, Vol.3, No.59, pp.99-111.

Barelle, C.; Chabroux, V.; Favier, D. (2010). Modeling of the Time Trial cyclist projected frontal area incorporating anthropometric, postural and helmet characteristics, *Sports engineering*,Vol.12, No. 4, pp.199-206.

Belluye, N. & Cid, M. (2001). Approche biomécanique du cyclisme moderne. *Science et Sports*, No.16, pp. 71-87.

Besi, M. Vedova, D.D., Leonardi, L.M. (1996) Sections : un programma di analisi dell'immagine applicato allo sport. *Scuola dello sport*. No.34, pp. 72-77.

Chabroux, V.; Barelle, C.; Favier, D. (2008). Aerodynamics of time trial bicycle helmets. The engineering of sport, No. 7, pp.401-410.

Capelli, C.; Rosa, G.; Butti, F.; Ferretti, G.; Veicsteinas, A.; Di Prampero, P.E (1993) Energy cost and efficiency of riding aerodynamic bicycles. *European Journal of Applied Physiology*, No.67, pp.149-165.

De Groot, G.; Sargeant, A.; Geysel, J. (1995). Air friction and rolling resistance during cycling. *Medecine and Science in sports and exercise*, pp.1090-1095.

Di prampero, P.E.; Cortili, G.; Mognoni, P. & Saibene, F. (1979). Equation of motion of a cyclist. *Journal of applied physiology*, No.47, pp.201-206.

Gross, A.C; Kyle, C.R; Malewicki, D.J (1983) The aerodynamics of human-powered land vehicles. *Scientific American*, No.249, pp. 126-134.

Heil, D.P (2001). Body mass scaling of a projected frontal area in competitive cyclists. *European Journal of Applied Physiology*, No.85, pp. 358-366.

Kyle, C.R.; Crawford, C. & Nadeau, D. (1973). Factors affecting the speed of bicycle. *Engineering report 73-1*. California State University. Long Beach, California.

Legay, J.M. (1997) L'expérience et le modèle : un discours sur la méthode. *Sciences en question. INRA éditions*.

Lesieur P. (1996) L'étude de cas : son intérêt et sa formalisation dans une démarche clinique de recherche. *Colloque interface INSERM / FFP*.

Luethi, M.S., Denoth J. (1987). The influence of aerodynamic and anthropometric factors on speed in skiing. *International journal of sport biomechanics*, No.4, pp.345-352.

Padilla, S.; Mujika, I.; Angulo, F.; Goiriena, J.J. (2000). Scientific approach to the 1h cycling world record : a case study. *Journal of Applied Physiology*, No.89, pp.1522-1527.

McLean, B.D.; Danaher, R.; Thompson, L.; Forges, A.; Coco, G. (1994). Aerodynamic characteristics of cycle wheels and racing cyclists. *Journal of Biomechanics*, Vol. 27, pp.675.

Neumann, G. (1992) Cycling. Endurance in sport. *Edition R.J. Shepard and P.O. Astrand, London : blackwell*, pp.582-593.

NØrstrud, H. (2008). Basic Aerodynamics. *Sport aerodynamics. CISM International centre for mechanical sciences*, Vol. 506, pp.1-8.

Orkisz M. (1990). Traitement d'image pour l'analyse du mouvement humain. *Cinesiologie*, No.29, pp.133-140.

Shanebrook, R.J., Jaszczak R.D. (1976) Aerodynamic drag analysis of runners. *Medecine and science in sports*, Vol. 8, No.1, pp.43-45.

Spring, E.; Savolainen, S.; Erkkilä, J.; Hämäläinen, T.; Pihkala, P. (1988). Drag area of a cross country skier. *International journal of sport biomechanics.* Vol.4, pp.103-113.

Springings, E.J. & Koehler, J.A. (1990). The choice between Bernoulli's or Newton's model in predicting lift. *International Journal of sport biomechanics*, No. 6, pp.235-245.

Tavernier, M.; Cosserat, P.; Joumard, E.; Bally, P. (1994).Influence des effets aérodynamiques et des appuis ski – neige sur la performance en ski alpin. *Science et motricité*, No.21, pp.21-26.

Watanabe, K. & Ohtsuki, T. (1977). Postural changes and aerodynamic forces in alpine skiing. *Ergonomics*, Vol. 20, No.2, pp.121-131.

Watanabe K. & Ohtsuki T. (1978). The effect of posture on the running speed of skiing. *Ergonomics*, Vol. 21, No.12, pp.987-998.

Vaughan, C.L. (1984). Computer simulation of human motion in sports biomechanics. *Exercice and sport sciences reviews*, No.12, pp. 373-416.

Weineck, J. (1997). *Manuel d'entraînement*. Vigot, collection Sport + Enseignement. 4ème édition.
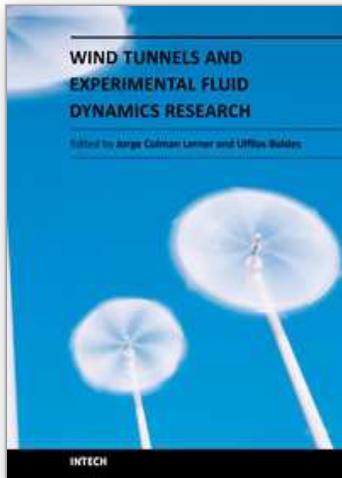
Wind Tunnels and Experimental Fluid Dynamics Research

Edited by Prof. Jorge Colman Lerner

The book "Wind Tunnels and Experimental Fluid Dynamics Research" is comprised of 33 chapters divided in five sections. The first 12 chapters discuss wind tunnel facilities and experiments in incompressible flow, while the next seven chapters deal with building dynamics, flow control and fluid mechanics. Third section of the book is dedicated to chapters discussing aerodynamic field measurements and real full scale analysis (chapters 20-22). Chapters in the last two sections deal with turbulent structure analysis (chapters 23-25) and wind tunnels in compressible flow (chapters 26-33). Contributions from a large number of international experts make this publication a highly valuable resource in wind tunnels and fluid dynamics field of research.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Caroline Barelle (2011). Sport Aerodynamics: on the Relevance of Aerodynamic Force Modelling versus Wind Tunnel Testing., Wind Tunnels and Experimental Fluid Dynamics Research, Prof. Jorge Colman Lerner (Ed.), ISBN: 978-953-307-623-2, InTech, Available from: http://www.intechopen.com/books/wind-tunnels-and-experimental-fluid-dynamics-research/sport-aerodynamics-on-the-relevance-of-aerodynamic-force-modelling-versus-wind-tunnel-testing-

INTECH

open science | open minds