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Aerodynamics and Hydrodynamics in Sports

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ABSTRACT
Aero/hydrodynamics plays a vital role in speed sports (athletes, athletes' outfits, sports balls, sports equipment, etc.). Sports balls (spherical - golf, cricket, tennis, soccer, baseball, softball, etc. and oval shape - rugby, American football, Australian football), sports garments (swimsuits, ski jumping & alpine skiing suits, cycling skin suits, skating suits) are affected by aerodynamic and hydrodynamic behaviour of fluids (air and liquids). The aero/hydrodynamics dictates the curved flight path of a soccer, tennis, cricket, baseball or golf ball and the course of a surfboard and sailboat through water. It affects speed, motion (position and placement) and ultimately athlete's performance. Ignoring the effect of aerodynamic and hydrodynamics, it is almost impossible to achieve the desired success in any competitive speed sports. Due to stiff competition, the outcome of most sports aero/hydrodynamics research work undertaken by commercial organisations as well as individual sports teams/organisations are kept in-house and scant information is available in the public domain. The RMIT University's Sports Aerodynamics Research Group has been active in aerodynamics and hydrodynamics research related to some popular speed sports. This paper highlights some research work on sports aerodynamics and hydrodynamics undertaken at RMIT University.

Keywords: Sports aerodynamics, cycling, ski jumping, swimming

1. Introduction
Aerodynamics and hydrodynamics have a major impact on speed sports (ski jumping, alpine skiing, cycling, bobsleighing, javelin, discus, speed skating, sprint, etc.), ball sports (soccer, tennis, cricket, golf, baseball, softball, rugby, Australian rules football, American football) and projectile sport (badminton), equipment and ultimately athlete's performance [1-8]. The pattern design of dimples on a golf ball, engineered outfits (swimming, cycling, skiing, speed skating, etc.), smart designs of racing helmets, the curved flight path of soccer, cricket, tennis, baseball, rugby, American football; and Australian rules football- have significant effect on athlete's motion (position and placement) and performance [1, 2-5,22-23]. The winning time margin in all speed sports is progressively being reduced with the better integration of aerodynamic understanding, advanced technologies and athlete training regimes. Scope for further improvement clearly lies with the in-depth understanding of aero/hydrodynamic behaviour of athletes' sports equipment, physical body posture and their outfits. In most water sports (swimming, rowing, sailing, water skiing, and powerboats), the equipment or the athlete is affected by the dual fluid medium of both water and air simultaneously [5,8-16].

The forces such as aerodynamic drag, lift/down force, side force, buoyancy acting on athletes and their equipment and outfits are highly dependent on speeds, shape, position, flow types (laminar or turbulent regimes) and sports gears' surface morphology. The Sports Aerodynamics Research Group at RMIT University is well known for its wide range of aero/hydrodynamics research on spherical and oval shape sports balls, winter sports (ski jumping, downhill/alpine skiing, bobsleigh, speed skating), summer sports (cycling, sprint), water sport (swimming), sports garments (athlete's outfits), aerodynamics and thermal comfort of racing and recreational helmets as well as projectile (badminton shuttlecock). Due to current limitation of Computational Fluid Dynamics (CFD) modelling, experimental (wind tunnel and field trial) studies are still the main tools used to enhance scientific understanding on aero/ hydrodynamic behaviour. In this paper, special focus is made on aerodynamic behaviour of soccer ball, cycling, ski jumping, and sports garments that are widely used in speed sports.

2. Football (Soccer Ball)
The centre piece of world's most popular game football (soccer) is the spherical ball. The growing popularity and financial strength of the game have driven a number of technological changes to the ball. The FIFA World Cup has become a launching pad for a new ball in every four years. The ball has undergone through incredible changes since 2002. The advancement of technology, popularity and economic interest have made possible to introduce new changes on the ball design. An epoch-making design change of Adidas made FIFA World Cup football is illustrated in Fig. 1 since 2002.

Fig. 1 Transformation of FIFA World Cup balls from 2002 to 2018.

All FIFA World Cup balls were made of 32 panels (20 panels-hexagonal & 12 panels-pentagonal) from 1970 to 2002. A significant deviation from the traditional leather

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made panel to the synthetic panel was introduced by Adidas for the FIFA 2002 World Cup ball. However, Adidas introduced more radical design change in its 14-panels Teamgeist ball in FIFA 2006 World Cup. The smooth synthetic panels were bonded together instead of stitching. The 8-panels 'Jabulani' ball along with its asymmetrical orientation and pattern of grooves was introduced in 2010 FIFA World Cup by Adidas. The Jabulani ball drew huge criticisms and comments from players and experts alike for its erratic flight behaviour. In 2014 FIFA World Cup, Adidas unveiled a 6-panels Brazuca (meaning Brazilian way of life) ball which aerodynamically behaved better than Jabulani ball. Adidas has introduced a designed 'Telstar 18' ball in 2018 FIFA World Cup. The outer skeleton of Telstar 18 ball is made of 6 synthetic panels as Brazuca ball but with different panel shape.

Is Telstar 18 aerodynamically better than Brazuca? Can player predict its anticipated flight trajectory? To answer these questions, the Sports Aerodynamics Research Group at RMIT University undertook an aerodynamic study of Telstar 18 ball along with Brazuca, Jabulani, Teamgiest and Fevernova balls using RMIT Industrial Wind Tunnel. A Telstar 18 ball and RMIT Wind Tunnel are shown in Fig. 2. The study showed that the variation of drag coefficient (an indicator of aerodynamic efficiency, lower the coefficient, better the aerodynamic efficiency) between the two sides of Telstar 18 ball is less than 2% compared to Brazuca (3%), Jabulani (9%), Teamgeist (5%) and Fevernova (2%). The Telstar 18's sideway aerodynamic behaviour is very close to Fevernova ball used in FIFA 2002 World Cup in Korea and Japan. Therefore, Telstar 18 is expected to have more predictable flight in calm wind and non-spinning conditions than its predecessors Brazuca, Jabulani and Teamgeist balls.

For short pass, the Telstar 18 needs harder kick as its aerodynamic drag is higher at low speeds (below 60 km/h) than Brazuca ball. For mid-range distance, the Telstar 18 needs to be kicked softer (60 to 90 km/h range) due to its lower drag. However, for long distance, the ball requires slightly greater force-kick than Brazuca ball.

For goalkeeper, Telstar 18 will be slightly hard to grip compared to Brazuca ball due to its orderly square flat pimples in contrast to Brazuca's prominent wavy patterned rectangular pimples. Telstar 18 has longer seam length (~4.2 m) and shorter seam depth and width than Brazuca ball.

Fig. 2 Telstar 18 ball and RMIT Industrial Wind Tunnel

3. Ski Jumping and Cycling

Ski-jumping is one of the most complex acrobatic winter sports. In ski jumping, skiers go down a hill with a take-off ramp with a view to travel as far as possible. Points are allocated predominantly for the length; however, some points are also allocated for style on a scale from 1 to 20 skipping the highest and the lowest marks allocated by the judges. The skis used for ski jumping are wide and long, with parallel sides. Ski jumping consists of four main phases: a) In-run, b) Take-off, c) In-flight, and d) Landing. During the in-run and take-off phases ski-jumper tries to reach maximum velocity. In the flight phase, the ski-jumper wishes to keep favourable body position in relation to wind direction to maximise the lift and minimise the drag to achieve the maximum jump distance possible. In landing phase, the aerodynamic drag needs to be maximised and lift to be minimised in order to achieve the maximum range, safe and artistic landing. It is no doubt that several factors including the initial ski jumper's body position and its changes at the transition to the flight phase, the magnitude and the direction of the velocity, the jumper's centre of mass, the magnitude of the aerodynamic drag and lift forces determine the trajectory of the ski jumper hence the total distance of the jump. Using the modern V-technique to maximise lift and minimise drag, pioneered by Jan Boklöw of Sweden, elite level skiers can exceed the distance of the take-off hill by about 10 percent compared to the previous technique with parallel skis. Athlete's outfits and geometric dimensions of ski are highly regulated by FIS (an International ski regulatory body). Within the regulations, there are still scopes to enhance ski jumper's performance further. The ski jump length greatly depends on the in-run velocity, the velocity perpendicular to the ramp due to the athlete's jumping force, the lift and drag forces acting during the take-off and in flight, and the masses of the athlete and his/her equipment (eg, ski, helmet, goggles, suit, hand gloves, boots etc). The aerodynamic forces experienced by the skier directly depends on the projected frontal area of the athlete's body, body position in flight, equipment and their positions and features.

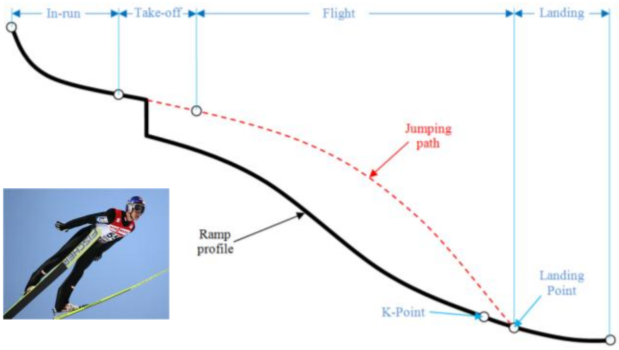


Fig. 3 Different phases of ski jumping [11-12].

A series of studies has been undertaken by Mueller et al. [23-24] and Seo et al. [21] predominantly looked at the biomechanical, body orientation and equipment of the ski jumper on aerodynamic effects using simulation, wind tunnel and in-situ measurements. It is beyond doubt that these aspects are important to understand the flight trajectory of the athlete. A close look indicated that an aerodynamically smart ski jumper's suit can provide some aerodynamic advantages. Despite having potential, the effects of ski garments on aerodynamic performance of the athlete have not been well studied and/or understood. Since 2008, a large research program on textile aerodynamics has been undertaken at RMIT University. As part of this research program, Chowdhury et al. [9-12] undertook a series of studies on aerodynamic performance of sports textiles widely used in ski jumping and cycling suits. Figure 3 shows the four phases of ski jumping. In these studies, Chowdhury et al. demonstrated that an engineered ski jumping suits can minimise aerodynamic drag and maximise lift thereby enhancing a considerable jumping length.

Over the last 50 years a number of publications have been reported in the public domain on cycling aerodynamics primarily focusing on athlete's physiological aspects and cycling accessories. Several studies (see Kyle et al. [17], Chowdhury et al. [9-11]) were conducted on the cyclist body configuration. On the other hand, studies by Kyle et al. [17], Brownlie et al. [20], and more recently by Chowdhury et al. [10-11] indicate that the sports apparel can make impact on the aerodynamic drag reduction.

In cycling, in addition to cyclist, a bicycle is comprised of the frame, forks, wheels, drive train, brakes, handlebars, water bottles, etc. that interact with the oncoming airflow. The bicycle accounts around 31% to 39% of the total aerodynamic resistance (drag) depending on the bicycle type [9-12, 20] and a small contribution comes from various add-ons such as cycling suit, helmet and so on. Prior studies [10-11] reported that the cyclist body position along with a helmet and suit can significantly minimize aerodynamic drag experienced by the cyclist at all stages of racing (road racing and time trial). There are three main positions commonly used by professional cyclists depending on the type of race and profile of the terrain. These positions are: a) Upright Posture, characterized by the hands on the upper part of the handlebars, is mainly used when pulling up on the handlebars to ride in hill terrain (see Fig. 4a), b) Dropped Posture, the hands on the bottom of the handlebars, is adopted at high speed to minimize projected frontal area (see Fig. 4b) and c) Time Trial Posture, when the elbows are placed on the pads of the aero-handlebars, is believed to be the best aerodynamic position to overcome the aerodynamic drag (see Fig. 4c).

Table 1 shows the average speed of various stages of 2010 Tour de France cycling racing. The average speed (of all 21 stages) was around 42 km/h. However, the speed in the Time Trial stage is over 55 km/h. Although the average speed in mountain stages is slightly below 40 km/h, the maximum speed in downhill stages can easily exceed to 100 km/h.

Table 1 Data from Tour de France 2010

Stage Type	No. of Stages	Average Speed (km/h)
Individual time trial	2	52.30
Flat stage	11	42.37
Medium mountain stage	2	36.16
Mountain stage	6	37.11
Total	**21**	**41.98**

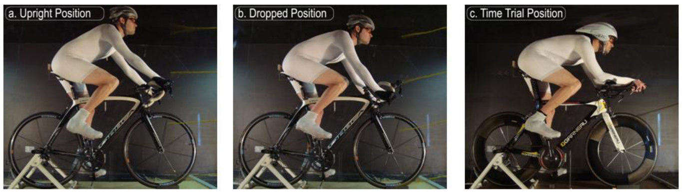
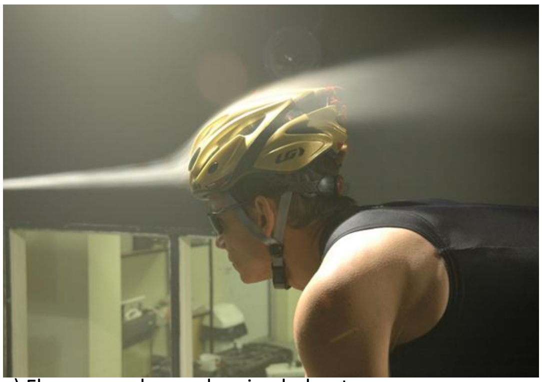


Fig. 4 Three popular cycling positions in RMIT Industrial Wind Tunnel [11]

Figure 5 illustrates the C_D values for the positions of recreational/non-professional bicyclist and professional bicyclist. The figure shows that C_D values are almost independent of speeds for the upright and dropped positions of the professional and the recreational cyclists at all speeds (20-70 km/h). A slight variation in C_D value at low speeds for the time trial position is evident. A minor difference of C_D value between the upright and drop position of the professional cyclist is also noted. It is clearly evident that the upright position generates more drag compared to other widely used positions especially the time trial positions. As expected, the C_D value for the upright position of the recreational cyclist is notably higher compared to the same position of the professional cyclist primarily due to the cycling accessories (bicycle, suit, helmet, shoes, etc.) and the casual posture. The average reduction of drag for upright, dropped and time trial position of the professional cyclist was found to be approximately 30%, 32% and 45% compared to the upright position of the recreational cyclist respectively. In the case of the professional cyclist, the average reduction of drag for dropped and time trial positions is around 3% and 21% respectively compared to the upright position.

Additionally, studies by Alam et al. [1,3-5] looked at the aerodynamics and thermal comfort of different bicycle helmets. The study by Alam et al. [5] showed that the helmet can produce up to 8% of the total aerodynamic drag depending on the shape and venting features of the helmet. Complex flow pattern around two racing helmets are shown in Fig. 6.


a) Flow around a road racing helmet


b) Flow around a time trial racing helmet

Fig. 6 Complex flow pattern around racing helmets.

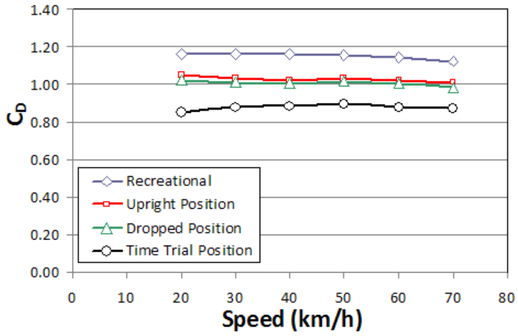


Fig. 5 Drag coefficient as a function of speed (for cyclist and the bicycle in different cycling positions) [11-12]

4. Sports Garments (Outfits)

As mentioned earlier, aerodynamics plays a vital role in sports textiles used in a wide variety of sports including cycling, ski-jumping, speed-skating and bobsleighs. Outfits of some high speed sports are shown in Fig. 7. Competition in the elite usually incorporates very short winning time margins. Prior researches have shown that a two-fold rise in athlete's velocity brings forth a four-fold rise in the drag force that needs to be overcome (Ogiano et al. [18-19], Konopov et al. [16]). Recently Moria et al. [13-15] and Chowdhury et al. [9-12] carried out systematic studies of textile aerodynamics using a unique RMIT developed testing methodology. The studies showed that test surface having several types of textile fabrics exhibited sufficiently less aerodynamic drag than the smooth surface due to the flow transitional effect caused by the textile fabrics. They also hypophyses that in speed sports, various sports garments made of knitted and woven fabrics with various degree of stretchability may have different aerodynamic behaviour. To understand more detail aerodynamic behaviour of knitted and woven fabrics under variable stretch conditions, Moria et al. [13-15] undertook a comprehensive study of ten textile fabrics (5 knitted and 5 woven) that are widely used in different speed-sport garments including swimming. The study focused on aerodynamic behaviour of all these textile fabrics under various stretches as under the stretch, the surface morphology (structure, roughness, fibre orientation, etc.) changes significantly. Moria et al. investigated both drag and lift generation capabilities of all these fabrics. Their study included comprehensive surface characterisation using tensile, electron microscopic and roughness analyses under various degrees of stretches.

Some major findings of Moria et al. [13-15] on knitted and woven fabrics are shown in Figs. 8-11 respectively. For knitted fabrics, the surface roughness increases under the increasing stretch. These changes make the airflow turbulent at a much lower speeds compared to the un-stretch surface of the textile fabrics. The findings also indicate that the aerodynamic properties are highly dependent on fabrics surface roughness, distance and gap area between courses. With elongation of knitted fabric, the increment of C_{Dmin} values increases respectively without any sudden change. However, the knitted fabric with lower relative roughness, distance and gap area between courses creates an advantage in aerodynamic properties by reducing the drag at higher speeds. In contrast, the higher relative roughness, distance and gap area between courses provide an aerodynamic advantage by reducing drag at lower Reynolds numbers (lower speeds). The surface texture can be utilized to maximize the aerodynamic benefit for various speed ranges. By increasing the surface roughness of knitted fabrics by stretch, the flow can be tripped into turbulence at lower Reynolds numbers, potentially decreasing drag. It also shows however, that after the initial reduction in drag coefficient the drag then increases quickly with increasing Reynolds number due to high levels of friction drag associated with turbulent flow. Thus increasing the surface roughness can significantly increase the total drag if the flow is tripped prematurely due to increasing the roughness of the surface already in turbulent flow. A suitable selection of stretchable sport knitted fabric and garment fit for elite athletes is vital for achieving aerodynamic advantages. Similarly, the angle of attack is crucial in term of speed sport applications to maintain the maximum glide ratio and obtain the appropriate posture for the elite athlete.

Fig. 7 Sports outfits for various speed sports.

Regarding oven fabrics, the roughness decreases with the increase of stretches as woven fabrics structural patterns and physical properties are different than those of knitted fabrics. The findings of Moria et al. [13-15] clearly demonstrated that woven fabric undergoes a sudden drop in C_{Dmin} values at a small elongation and at further elongation followed by linear increment to the maximum stretch. At normal fit (under no stretch), the fabric with a lower relative roughness, distance and gap area between wefts provides an aerodynamic advantage by reducing drag at higher speeds. On the other hand, the higher relative roughness, distance and gap area between wefts also provide a benefit in aerodynamic properties by reducing the drag at lower speeds. Also, the surface texture can be utilised to maximise aerodynamic properties for various speed ranges. Optimal selection of speed sports woven fabric and garment fit for the elite athletes is of utmost important for achieving aerodynamic advantages. In addition, the angle of attack is vital in terms of speed sport applications to maintain the maximum glide ratio.

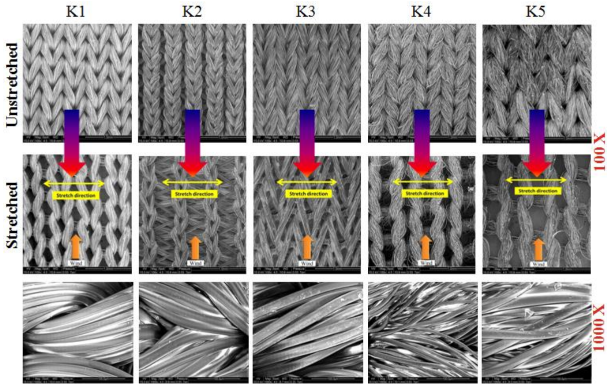


Fig. 8 Electron Microscopic Analysis: Knitted Fabrics [13-15].

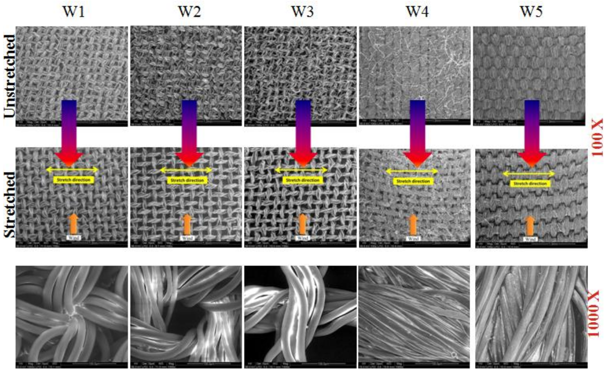


Fig. 9 Electron Microscopic Analysis: Woven Fabrics [13-15].

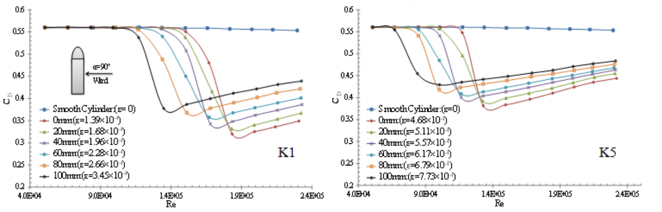


Fig. 10 Knitted Fabrics: Effect of Surface Roughness, angle of attack α = 90° [13-15].

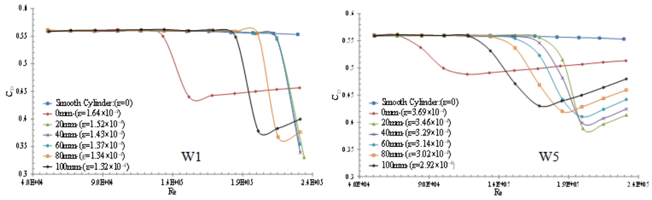


Fig. 11 Woven Fabrics: Effect of Surface Roughness, angle of attack α = 90° [13-15].

5. Conclusions

The surface morphology and physical shape determine aero/hydrodynamic behavior and flight trajectory of all speed sports balls.

The aero/hydrodynamic understanding of athlete's body orientation and sports textile is paramount for achieving high performance in speed sports such as ski jumping, alpine skiing, speed skating, cycling, sprint, swimming, bobsleigh and skeleton.

Appropriate selection of textile fabrics based on athlete's speed regime is important as knitted and woven fabrics behave aerodynamically differently due to their surface morphology.

For knitted fabrics, the minimal drag coefficient (C_{Dmin}) is directly proportional to the relative roughness whereas the critical Reynolds number (Re_{crit}) is inversely proportional to relative roughness. For woven fabrics, the C_{Dmin} is proportional to the relative roughness and Re_{crit} relationship with relative roughness is non-linear.

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