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Factors affecting the aerodynamic drag of alpine skiers

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Abstract

This paper documents a five year testing program that identified factors affecting the aerodynamic drag (F_d) of alpine skiers. Wind tunnel F_d measurements of world class alpine skiers and air permeability measurements of ski suits were conducted to determine the effect of fabric permeability on suit F_d. Frontal area (Ap) measurements were combined with F_d data to determine the drag coefficient (C_d) of the athletes in various skiing positions. Differences in F_d of ski suits were most pronounced between downhill (DH) race suits and those designed for Giant Slalom (GS) competition where protective padding increased F_d by up to 7.1%. In general, suits that were stretched from multiple wearing or that were undersized had greater permeability and higher F_d. Alternatively, skiers who wore a loose fitting suit or multiple suits that increased the skier's Ap experienced up to 5.2% of additional F_d, estimated to slow a skier by 0.19 sec over a 250 m straight glide section of a downhill race course. Pre-season wind tunnel testing to optimize body positioning and ski suit size selection, followed by custom suit fitting have been important to the competitive success of the Canadian Alpine Ski Team.

keywords: aerodynamic drag; alpine ski apparel; fabric permeability; skier drag coefficient, plomb test

1. Introduction

Alpine Downhill, Super G, Slalom and Giant Slalom ski racing are high speed winter sliding sports with race times measured to one one-hundredth of a second. Small differences in the aerodynamic drag of a skier's apparel or equipment can have a major impact on race placing. For example, in the Super G races at the 2006 Torino Winter Olympics, the difference between a third place podium finish and fourth place was 0.10 seconds (0.11%) in the

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Men's event and 0.03 seconds (0.03%) in the Women's race. Given the highly competitive nature of alpine skiing,there has been little research published on the effect of skier body positioning and ski suit parameters such as air permeability, sizing and wear on skier F_d. Watanabe and Ohtsuki [1] performed a detailed analysis of the effect of postural changes on a downhill skier's F_d however this work was conducted in 1977 with ski suits, boots and helmets that are not comparable to the equipment currently used by world class alpine skiers. The Fédération Internationale du Ski (FIS), has mandated that all suits worn in competition must pass a permeability test conducted with an approved permeability meter [2]. The requirement for a minimum suit permeability (30 litres per m^2/sec under 10 mm of water pressure) arose as a means to prevent the use of impermeable polyurethane coated (plastic) suits since skiers wearing these suits were observed to slide on the snow at high speed after a fall and to then suffer more severe injuries when they impacted course barriers or fences. While an air permeability standard might prevent the use of totally impermeable fabrics in ski apparel, there has been no published reports that correlate suit permeability and skier F_d.

To assist its athletes in the selection of aerodynamically optimized apparel and body positions, the Canadian Men's and Women's Alpine Ski Teams have had an ongoing wind tunnel test program that was expanded in preparation for the Vancouver 2010 Winter Olympics to include a study of factors such as skier body positioning, ski suit air permeability, sizing and padding that might affect the F_d of skier. The results of this study, compiled through twelve days of wind tunnel testing over a five year period, provide insight into the factors that lead to reduced F_d in alpine skiing.

2. Materials and Methods

2.1. Wind tunnels

Tests were conducted at the General Motors (GM) Wind Tunnel located on the grounds of the General Motors Technical Center in Warren, Michigan, USA and the National Research Council of Canada (NRC) 2 m x 3 m Wind Tunnel, located in Ottawa, Ontario, Canada. Both tunnels are of a closed circuit design with temperature control of the recirculated air. The NRC tunnel has a 1.94 m x 2.7 m x 5.2 m test section with a cross-sectional area of 5.03 m^2 while the GM wind tunnel has a 5.5 m x 10.4 m test section with a cross-sectional area of 57.2 m^2. Boundary layer control at the GM is provided by a primary suction slot in the test section floor ahead of the model.

2.2. Skier Positioning

In general, the skier was placed in either a simulated downhill "tuck" (Figure 1a) or a more upright position on the wind tunnel balance (Figure 1b). All skiers wore their normal racing equipment (helmet, goggles, gloves, back protectors, boots, underwear and ski poles) during each test session. Aerodynamic strut supports and anchor points for the tips of the ski poles helped the skiers remain in a static position for extended periods of time. A side view video image of the skiers, projected on to the wind tunnel floor, was used as a positioning reference by each skier. Communication with the skiers at NRC was by a computer display projected onto the tunnel floor while at GM a spotlight was activated to inform the skier that a data collection window had begun or ended.

2.3. Frontal Area

A digital frontal view photograph of each skier was taken with a 10 cm x 10 cm grid reference board in the background and a reference post in the foreground. The frontal area of the skier in each photograph was measured by digital planimetry. The average of the reference board and support post areas was used to provide the reference area for the skier's Ap. The skiers had Ap of approximately 0.34 to 0.6m^2, equivalent to 0.59 to 1.0% of the GM tunnel cross-sectional area and 6.7 to 11.9% of the NRC tunnel cross-sectional area. In general wind engineering practice, a blockage correction factor is applied if the model blockage to tunnel cross-sectional area ratio exceeds 2%; however, due to the A-B comparative nature of the tests, no correction factor was applied to the data.

2.4. Velocity and Drag Measurements

At NRC, F_d measurements were recorded at four air velocities (v) of 80, 90, 95 and 100 km/h (22.2 to 27.8 m sec^{-1}) with each measurement averaged for 7 seconds at a rate of 7 Hz, yielding 49 samples for a given F_d measurement. The NRC balance has a resolution of +/-1.7 g (0.017 N), with a maximum capacity of 4.4 KN. Pre-test wind-off F_d measurements (tares) were recorded for all tests and subtracted from test run F_d data. At GM, four v set points were selected in the range of 60 to 100 km/h, depending on the skier's position, with the higher v reserved for more streamlined positions. At GM, F_d measurements on the skiers were made with a custom built six-component strain gauge balance programmed to collect F_d measurements at a rate of 100 Hz for 30 seconds to yield 3000 samples for a given F_d measurement.

2.5. Suit Permeability Measurements

Suit permeability measurements were conducted with a Steinel porosity meter [SteinelElektronik GmbH & Co., Betriebsstatte Molkau, Sommerfelder Str. 120, D-04316 Leipzig, Germany, www.steinel.de] which is the approved Fédération Internationale du Ski (FIS) porosity test meter for ski suits. The official test procedure involves measuring the permeability of each suit after manufacture in six places (right front panel – mid waist; left front panel – mid waist; right rear shoulder; left rear shoulder; right thigh; left thigh) with each panel required to exceed the minimum permitted air permeability. Suits that have passed this standard are then fitted with a numbered lead stamp and are referred to as having been "plombed". To compare the porosity of ski suits in the current work, four torso permeability measurements were averaged to provide a single suit permeability value.

Fig. 1 (a) skier in full tuck position at NRC wind tunnel; (b) skier in upright position at GMAL wind tunnel

3. Results and Discussion

3.1. Data Analysis and Experimental Repeatability

A linear regression equation was fitted to the F_d and v^2 data from each test run. At NRC, an extended v sweep was performed with a skier in a full tuck position and his F_d was measured at 10 dynamic pressures (q) which equated to v of 40 to 130 km/h, increased in steps of 10 km/h. The linear regression coefficient (R^2) for this data set was 0.99987, suggesting that the C_d was constant with no whole body flow transition occurring in the range of q tested and confirming that the F_d data could be analyzed with linear regression. In all tests reported herein, the R^2 value ranged from 0.9999 to 0.9959 in the v range of 60 to 100 km/h. For comparative purposes, the regression equation for each test was utilized to calculate the F_d at a v of either 80 (upright position) or 100 km/h (full tuck position) (22.2 to 27.7 m sec^{-1}) under standard atmospheric conditions (pressure = 101.1 kPa; temperature = 15^{oC}). Through the various test sessions, repeat tests of the same skier with the same suit and body position provided a 95% confidence interval of from +/-1.089 N or +/- 1.10% to +/- 1.51 N or +/- 1.54%.

3.2. Effect of Body Position on skier F_d and C_d

At NRC, a male skier experimented with various body positions while the tunnel v was maintained at 100 km/h (Table 1). The main observation from these measurements is that a skier who "opens up" by spreading his or her arms and becomes more upright causes a large increase in Ap and F_d. For example, a skier who transitions from position 4 to 5 would experience a 41% increase in F_d. For this reason skiers are coached to keep their arms close to the body during a jump, thereby significantly reducing their F_d.

Table 1. Drag of a skier in various racing positions

Body Position Number	Description of body position	F_d (N) at 100 km/h	F_d Difference from best tuck position (N)	% Difference from best tuck position
1	Best tuck	88.8	0	0
2	Mid to high tuck	104.4	15.5	17
3	High knees	119.7	30.9	35
4	Pre-jump/ arms in	147.1	58.3	66
5	In air/ arms out	183.5	94.6	107
6	Standing	289.5	200.6	226

Given the dynamic nature of alpine skiing, a downhill racer will spend the majority of a race in a non-tuck position so that the test protocol was developed to test all ski suits in both a full tuck and upright position (Figure 2), where more of the suit is exposed to the air and F_d is approximately 50% higher than in a full tuck.

At GM, the Ap and F_d of eight skiers were used to calculate the skiers' C_d and drag area (Ad) (Table 2). There are few published reports of the C_d of a downhill skier in a tuck position however Watanabe and Ohtsuki [1] reported Ad values for similar body positions that were consistent with the current values. Paps, Nachbauer and Mossner [3] cited unpublished Austrian Ski Federation studies where the Ad of male world class skiers was between 0.13 and 0.19 m^2. Paps, Nachbauer and Mossner [3] suggested that the C_d is independent of body position in straight line skiing at racing velocities in excess of 20 m sec^{-1} however a range of C_d from 0.46 to 0.60 was observed in the current study.

3.3. The drag of ski suits – effect of age, size and type

Canadian national team skiers normally receive a new suit before each race because of anecdotal evidence that suits that have been worn previously create additional F_d and lead to slower race times. Over the course of the study, we compared the F_d created by GS and DH suits, different sizes of the same suit, worn and new suits and combinations of suits to determine the ensembles that provide the least F_d. Table 3 provides representative F_d measurements recorded during the study. These data illustrate the following ski suit selection principles:

- A DH suit will create much less F_d than a GS suit, so skiers should wear the DH suit whenever possible (Example #1);

- The addition of GS protective padding under a DH suit invariably leads to an increase in Ap and F_d (Example #2);
- If the skier wears an undersized suit, the suit may overstretch and create a higher F_d (Example #3);
- If a skier wears an oversized suit, the suit may be baggy and induce increased F_d (Example #4);
- A suit that is worn repeatedly rapidly loses elasticity, becomes too porous and will cause more F_d than a new suit (Examples #5 and 6); and
- Overlaying suits increases the Ap of the skier and creates air pockets between the suit layers, increasing F_d (Example #7).

As suit fit is so important and is also such an individual matter, Alpine Canada arranged for a seamstress to be present at the wind tunnel to ensure that suits are custom fitted prior to the start of the competitive season. This is particularly critical for female skiers who may not fit the unisex ski suit pattern and limited sizes originally developed to fit the body dimensions of male skiers.

3.4 Effect of suit permeability on skier drag

The permeability of seven DH ski suits was recorded and compared to the F_d of three skiers who took turns wearing the suits in either the upright or full tuck position. The results of this comparison (Table 4) suggest that there is a correlation between high fabric permeability and F_d however other factors, such as the skier's body position, body size, the suit size and the number of times the suit has been worn will affect the F_d of the suit as much as the air permeability.

3.5 Drag reduction and time savings in Alpine skiing

Broker [4] developed a mathematical model of the effect of F_d reduction on downhill race performance. In his model, Broker assumed that a skier with a 1.48 N reduction in F_d would save 0.069 seconds or 2.521 m in a 250 m straight glide down a 15^o slope at a v of 30 m sec^{-1} (108 km/h). While 0.069 seconds is a small difference, extrapolated over the straight stretches of an entire race, the benefit of reduced F_d is sufficient to change the finish order of a highly competitive race. As the magnitude of F_d differences noted in Table 3 can be two to three times greater than the 1.48 N example cited, apparel related F_d is undoubtedly a significant factor in ski race performance.

4. Conclusions

The benefits of an annual, pre-season program of wind tunnel testing of elite skiers have been clearly demonstrated as a screening tool to ensure proper sizing and fit of apparel. Properly fitted new suits with permeability values near the minimum standard of 30 l /m^2 sec^{-1} provide Alpine racers with the lowest F_d apparel available. This emphasis on apparel selection has helped the Canadian Alpine Ski Team obtain three World Championship medals and 34 World Cup podium finishes (including three victories) since the 2006 Winter Olympics.

Acknowledgements

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Table 2. Drag coefficient (C_d) of skiers in upright or tuck position

Skier	Sex	Body Position	Frontal Area (m^2)	Drag (N) at 80* or 90** km/h	Drag Area (Ad) m^2	Calculated Drag Coefficient (C_d)
1	F	Tuck**	0.34	65.0	0.17	0.51
2	F	Tuck**	0.34	69.8	0.19	0.54
3	M	Tuck**	0.38	76.2	0.20	0.54
4	M	Tuck**	0.38	86.5	0.23	0.60
5	F	Upright*	0.55	73.4	0.25	0.46
6	F	Upright*	0.60	87.7	0.29	0.50
7	M	Upright*	0.62	98.0	0.33	0.54

Table 3: Effect of ski suit size, type and wear on skier drag in upright or tuck position

Test Example Number	Skier	Body Position	Change from Suit 1 (original)	To suit 2 (new)	Drag Difference (N) at 80*, 90** or 100*** km/h	Difference %
1	8	Full tuck	2004/5 GS (large)	2004/5 DH (large)	-4.69***	-4.9
2	6	Upright	2006/07 DH (small)	same, with hard padded GS top	+5.24*	+7.1
3	2	Tuck	2006/7 DH (medium)	2006/7 DH (large)	-3.03**	-4.1
4	1	Tuck	2006/7 DH (medium)	2006/7 DH (large)	+1.84**	+2.5
5	7	Upright	2005/06 DH (large) - worn	2006/7 DH (large) - new	-2.83*	- 2.7
6	3	Upright	2005/06 DH (XL) - worn	2006/7 DH (large) - new	-2.88**	- 3.7
7	3	Upright	2006/7 DH (large)	2006/7 DH (large) on top of identical suit	+4.10**	+5.2

Table 4. Comparison of ski suit air permeability, size, and wear on skier drag in upright or tuck positions

Skier	Body Position	Suit description	Suit Number	Suit size	F_d (N) 80* or 90** km/h	Permeability (L per m^2 sec^{-1})	Rank based on F_d	Rank based on Permeability
5	Upright	2006/07 worn DH	11406	XXL	126.9*	53.8	9	6
5	Upright	2007/08 new DH	42507	XXL	123.3*	38.7	7	3
5	Upright	2007/08 new DH	45107	XL	123.4*	35.3	8	1
9	Tuck	2006/07 worn DH	128606	L	91.3**	43.9	4	4
9	Tuck	2007/08 new DH	46807	L	92.9**	35.4	5	2
9	Tuck	2007/08 new DH	45107	XL	94.4**	35.3	6	1
10	Tuck	2006/07 new DH	1516	L	88.5**	48.6	2	5
10	Tuck	2007/08 new DH	46807	L	86.8**	35.4	1	2
10	Tuck	2007/08 new DH	45107	XL	88.7**	35.3	3	1