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The use of vortex generators to reduce the aerodynamic drag of athletic apparel

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Abstract

In world-class athletic competitions the margin of victory is often exceedingly small and in a range that maybe influenced by aerodynamic drag (F_d). Vortex generators (VG) are small triangular or vane shaped protuberances that have been used successfully in automotive and aerospace applications to stir the boundary layer and delay flow separation over a wing or body surface. To determine if VG would reduce the F_d of a sprinter or marathon runner, a series of F_d measurements were conducted on circular cylinders, mannequin limb segments and full-scale mannequins in wind tunnels at the University of British Columbia and University of Washington. A large variety of VG shapes, sizes and patterns were developed using computer-aided design and rapid prototype printers. In total, the test program involved 1,540 discrete multi-velocity test runs requiring 56 days of wind tunnel time. The test program successfully identified specific arrangements of VG that, in combination with well-fitted garments, would reduce the F_d associated with running apparel by up to 6.8%, compared to the previous generation of advanced race apparel. Specific body maps based on race distance and gender were created to optimize the application of VG to different types of running apparel. Unlike previous apparel based drag reduction strategies that utilized multiple textured fabrics to reduce F_d, the VG based F_d reduction strategy provided three key advantages: (i) it became effective at a very low velocity and so can be used on apparel designed for either higher velocity (sprint) or lower velocity (marathon) running activities; (ii) it did not undergo a post-flow transition increase in F_d; and (iii) only a few rows of VG were normally required so that the weight and complexity of manufacturing the apparel were reduced. Mathematical modelling of sprint, middle distance and marathon performances at a world-class level suggest that aerodynamic apparel with VG could provide time savings of 0.013 seconds in 100 m, 0.50 seconds in 1500 m and 10.9 seconds in the marathon for male athletes wearing apparel with VG versus those wearing 2012 Olympic apparel without VG. The results of this study suggest that appropriate sizes and patterns of VG can provide a significant reduction in the F_d of running apparel.

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1. Introduction

In world-class athletic competitions, extremely small performance differences between competitors can profoundly affect race outcomes. For example, only 5 seconds (0.058%) separated first and second place in the Women's marathon at the 2012 London Olympics. Such small differences in performance are within the range of performance benefits that may be attainable by wearing aerodynamic apparel. Previous work by the authors and others have demonstrated that apparel constructed from suitably textured fabrics can trigger a "drag crisis" (DC) on the torso and limb segments and reduce the pressure drag on the body by up to 10% [1,2,3,4,5]. The DC can be explained as a reduction in pressure drag through an induction of premature

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turbulent airflow over a limb that leads to boundary layer (BL) mixing with the overall air flow then remaining attached to the limb for a larger proportion of the circumference of the limb, with separation of the flow from the limb delayed and the resulting low pressure wake area behind the limb reduced in size. On a circular cylinder the phenomenon can occur at a Reynolds number (Re) of less than 1×10^5 and the DC will cause up to a 50% reduction in F_d. With the human body, due to the variable diameter and tapered shape of the limbs, a uniform DC does not occur at one particular velocity (V) so the maximum reduction in drag of a fabric covered limb segment is less than that of a uniform diameter cylinder [6].

After 14 years of development of performance apparel that rely on textured fabrics to reduce F_d, the authors have observed that there are other characteristics of textured fabrics that limit the application of this technology to athletic apparel. Textured fabrics are typically not effective at the relatively low V encountered in middle and long distance running events. Moreover, roughly textured fabrics that are capable of inducing a DC on a small limb segment typically have a very sharp decline in drag coefficient, followed by a rapid post - transition increase, due to increased frictional drag. Thus matching the texture of the fabric to the limb speed and limb diameter can be difficult. There are also weight and thermoregulatory limitations with wearing complete bodysuits in hot climates and for extended duration races.

Due to these concerns, the authors began to investigate discrete texture elements that could be printed on garments to provide the necessary surface roughness to cause a DC and reduce the F_d of athletic apparel. The initial products of this research were sprint garments that were covered in silicone dots and “doughnuts” and that were worn by many sprinters at the 2012 London Olympics. The use of silicone dots was constrained by technical limits on the precise height and shape of the applied dots. Following the London Olympics, the authors determined that they could create a very large number of different discrete roughness elements by combining computer aided design programs and rapid prototype printers.

The texture elements could either be printed on a flexible substrate or directly on a fabric and the resulting material could then be wind tunnel tested on cylinders, limb segment models and ultimately full scale mannequins. Early in the research the authors discovered that the VG form of texture element could be quite effective in reducing cylinder drag. VG are small triangular vane or ramp shaped protuberances that are routinely used in in the aerospace industry to assist in maintaining attached flow over the control surfaces of wings, allowing an airplane to climb more steeply without encountering stall conditions [7]. Unlike roughly textured fabrics, which creates a series of random and poorly organized vortices on the surface of the body, VG are believed to reduce drag by creating a series of orderly vortices that stir the BL of air next to the body. The cultivated vortices are more durable and can exist over a wider range of V than randomly created vortices [7].

This report details the results of the texture research and the development of a novel approach to trigger flow transition in athletic apparel.

2. Methods

2.1. Development of Texture Elements

The designs of the texture elements included pointed protuberances, negative height dimples, dots, spikes, paddles and various iterations of vane and ramp VG with the height, pattern and spacing of each element tested in a systematic matrix. The resolution of the printed textures was on the order of 0.1 mm, allowing for the repeatable printing of very fine details. The ease of construction and the printing resolution provided by 3D printing allowed major advances in texture design, production and testing that would have not been heretofore possible. Given that the boundary layer of air over moving limb segments was estimated to be less than 2 mm in thickness, the height of the texture elements was generally constrained to less than 2 mm. With the vortex generators, there is some evidence [7] that they can be effective in stirring the BL and creating systematic vortices when they are either submersed or extending above the BL, so 30 cm x 45 cm sheets of VG with heights from 1 to 5 mm were printed and tested. The initial aerodynamic screening was conducted by fixing the sheets on 10 and 20 cm diameter vertical cylinders with double-sided tape. Suitable textures were then tested on full-scale arm, leg and torso body segments.

2.2.Wind Tunnel Tests and Test Models

Between 2013 and 2015, the authors conducted 1,540 discrete multi-velocity test runs that required 56 days of wind tunnel time. The F_d of cylinders and other body segment models was measured in the 69 x 92 cm Parkinson wind tunnel of the Mechanical Engineering Department, University of British Columbia while full-scale tests were conducted in the 244 x 366 cm Kirsten Wind Tunnel, University of Washington Department of Aeronautical and Astronomical Engineering.

Test fabric sleeves or sheets were taped to either a 10 cm or 20 cm diameter aluminum or plastic tube. The 10 cm diameter cylinder extended vertically 59 cm from the floor of the 69 cm high wind tunnel while the 20 cm diameter cylinder spanned the entire height of the test section and through the roof of the tunnel. Three dimensional laser scans of world class athletes were averaged and converted into straight limb segment and torso models and then into four full scale lightweight foam mannequins, representing Men’s and Women’s sprint and middle distance athletes. Five to ten cm wide strips of the texture sheets were adhered to the limb and torso segment models with a double-sided adhesive tape.

All drag measurements were made with metric balances which collected and averaged either 1,000 or 2,000 drag samples for a given dynamic pressure over 15 to 30 seconds. The balances have resolutions of between 1.2 and 5.9 gm. In all wind tunnels, air velocities were set to pre-determined dynamic pressures, q, where:

$$q = 0.5 \cdot \rho \cdot V^2 \quad (1)$$

and V is the relative velocity (defined as the vector sum of model and wind velocities) ($m \cdot sec^{-1}$) and ρ is the air density in ($kg \cdot m^{-3}$).

In each experiment q was varied by altering tunnel fan rotation speed. All F_d measurements were recorded at between four and nine q equivalent to V of between 5 and 31.5 m/sec. These V were designed to match and exceed the maximum body segment velocities of sprinters and distance runners as determined from kinematic analyses. For the cylinder tests, F_d and V measurements were converted to non-dimensional Re and drag coefficient (C_d) values to determine the DC characteristics of each texture. For the limb segment and mannequin models, a linear regression equation was fitted to the Fd and V^2 data from each test run. The correlation between V^2 and F_d was linear and R^2, the regression coefficient, was essentially 1.00 for all model conditions that did not undergo flow transition, indicating that C_d was constant. This relationship was utilized to compare the F_d of each model at a reference V that matched the world record velocity for Men and Women 100 m sprinters, 1500 m middle distance and marathon runners.

3. Results

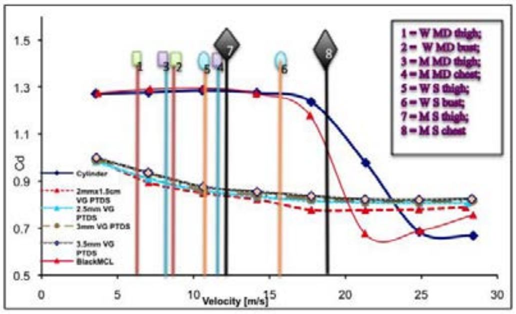
3.1. Data repeatability

As the cylinder and limb segment tests were mainly designed to rapidly select textures with the greatest potential to reduce whole body drag, most textures were only tested once on the cylinders and limb segments. With the full scale tests, the bare mannequin would be tested between three and ten times over the course of a test session. A 95% confidence interval (CI) was calculated for the F_d of each mannequin. The 95% CI ranged between +/- 4 g (0.36%) to +/-14 g (0.56%) for the female distance and female sprint mannequins, respectively. The 95% confidence interval varied from +/- 6 g (0.41%) to +/- 9 g (0.28%) for the male distance and male sprint mannequins, respectively. Confidence intervals were also determined for the female sprint and male sprint mannequins after three to five repeat tests of a particular clothing ensemble and in these cases, the 95% CI was between +/- 3 g (0.32%) and +/- 7 g (0.23%). This high level of data repeatability suggests a very reliable model and test system.

3.2. Effect of VG on F_d of a cylinder or limb segment

With the large number of tests conducted in the project, only the most salient comparisons can be considered in this paper. In virtually all cylinder and limb segment tests, Wheeler style VG [8] with the point orientated in the downstream direction (Figure 1) provided substantially less drag than any other texture element.

Fig. 1 Showing an array of 3.5 mm high Wheeler style vortex generators (VG) with 1 cm half step offset spacing



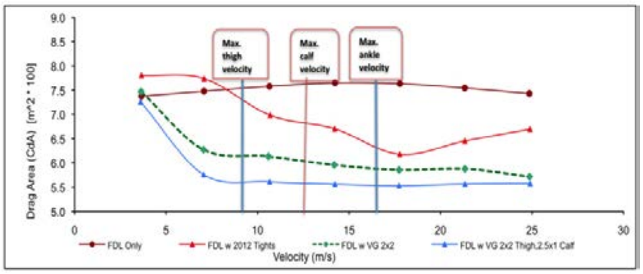


Fig. 2: Showing equivalent maximum limb segment velocities for Men's and Women's middle distance (MD) and Sprint (S) events for a 10 cm diameter cylinder covered in various VG and fabric textures; Fig. 3: Showing the effect of VG on the drag area of a female middle distance runner leg

The effect of different heights of VG on the C_d and V of a 20 cm diameter cylinder are shown in Figure 2 while the effect of VG on the drag area (CdA) of a female middle distance leg are shown in Figures 3.

Figure 2 shows that the bare cylinder and one covered in a smooth stretch fabric do not undergo a DC and reduction in C_d at any velocity reached by the thigh or chest segments of male and female sprinters (denoted as M S or W S) or middle distance runners (denoted as M MD W MD in the graph). In contrast, the thigh and chest segment of both middle distance and sprint athletes will undergo a DC and reduction in C_d if covered in the appropriate size of VG. This reduction in Cd occurs at the lowest V measured (3.5 m/sec), suggesting that the VG are effective as soon as movement is initiated. Figure 2 also demonstrates that while VG with heights of 2 to 3.5 mm will be effective in reducing cylinder F_d, the lower 2 mm height provides a slightly lower minimum Cd than the taller VG, which may be protruding beyond the boundary layer of the cylinder and creating parasitic drag. Alternatively, the 2 cm half step alternate row spacing of the VG may have caused interference between vortices created by a leading VG and the one 4 cm behind it [8]. In later tests, every second row of VG were removed with the cylinder C_d then reduced by an additional 12 to 24% at V above 8 m/sec. When this pattern change was applied to full-scale tests, there was also a positive reduction in F_d.

Figure 3 demonstrates that the VG are also effective in reducing the drag area (CdA) of the limb segments, with the VG tested on the female distance leg (FDL) providing a substantially lower CdA than the textured tights developed for the 2012 Olympics. In general, applying two 5 cm wide strips of VG to the thigh and calf areas of leg models reduced the drag by 7.3 to 15.0% for women's and men's distance leg models and by 7.3 to 11.9% for women's and men's sprint leg models. Figure 3 also shows that a combination of VG with different heights and spacings, tailored to the specific diameter and maximum V of the limb segments, maybe more effective than a single height and spacing of VG over the entire limb. Results of these combination VG tests were utilized to develop a body map of the appropriate size, shape and type of VG to be applied to garments covering the limb segments and torsos of male and female sprint and distance athletes. These body maps distilled complex aerodynamic data into four simple charts that could be utilized in the design and construction of final race garments.

3.3 Effect of VG on the F_d of full-scale mannequins

The application of VG panels to bare full-scale mannequins was found to provide substantial reductions in F_d of between 2.6% for the male middle distance mannequin to 10.5% for the male sprinter mannequin. If the VG were applied directly to a garment, then the magnitude of the reduction in F_d was between 4.6% and 6.8% for female middle distance and sprinter mannequins, and between 3.7 and 4.9% for male middle distance and sprinter mannequins compared to the most popular race apparel worn by middle distance and sprint athletes at the London 2012 Olympics. In some apparel configurations VG directly applied to a garment were less effective because the height of fabric wrinkles may have exceeded the height of the VG, which would render the VG inoperative. Thus, an athlete must wear form-fitting garments with limited wrinkling in order for the VG to reduce F_d.

While VG are generally applied ahead of the line of flow separation on a body, the non-linear path of the limb segments during the running motion will alter the position of the VG on a garment and this yawing could also reduce the effectiveness of the VG. To simulate this situation, 5 and 10 cm wide strips of VG were applied to the front flanks of male and female torso models and the F_d of these models was compared at yaw angles of 0 and 15 degrees. In general, both the overall F_d and the drag reducing properties of the VG were slightly decreased at a yaw angle of 15 degrees however the VG remained effective and provided less F_d than the bare mannequin torso or the torso covered in a 2012 Olympic long sleeve top. A comparison of the effectiveness of 5, 10 and 15 cm wide strips of VG applied to each flank of a sleeveless singlet revealed that the 5 cm wide strips provided between 3.1 and 7.1% less F_d than the 10 cm wide strips and between 1.9 and 4.3% less F_d than the 15 cm wide strips. The 5 cm wide strips probably provided a sufficient number of VG to cause a DC without providing excessive parasitic drag and without the following rows of VG causing interference with the vortices already formed by the leading row of VG. This result influenced the number of rows and location of VG on the final race garments.

3.4 Impact of Drafting on the effectiveness of VG

Sprint events are generally run in individual lanes where drag reduction through drafting is not possible. In the middle and distance running events, competitors often run in tight groups where drafting may reduce F_d. The authors attempted to determine the effect of drafting on the F_d of a middle distance runner by measuring the F_d on the male middle distance mannequin when it was partially shielded from the wind by a live runner statically positioned either 0.5, 1.0 or 1.5 m ahead of the mannequin. The drafting test was conducted initially with the mannequin clothed in a standard race kit (singlet and shorts) or an innovative tight fitting garment that was appropriately covered with VG. The results of the drafting test (Table 1) show that there is a substantial reduction in F_d of between 48 and 67% when running within 1.5 m of a lead runner. The reduction in F_d with drafting is maintained, regardless of whether the following runner is wearing standard apparel or streamlined apparel however the athlete wearing streamline apparel will benefit from having an initial, undrafted F_d that is approximately 4% lower than the athlete wearing standard apparel. These results, along with unpublished studies of turbulence measurements behind a live runner conducted by the authors, suggest that VG will be effective in reducing F_d even in the slightly turbulent flow conditions found behind a group of runners.

When the lead runner was replaced by a large sheet of plywood positioned 0.75 m ahead of the mannequin, the F_d of the mannequin was reduced by 97.8%. Historically, in European bicycle track racing, there have been specific motorcycle paced race events where the competitors race behind a motorcycle and the motorcyclist stands up to block airflow and allow the cyclists to race in a very low drag environment. This would also seem to be a viable strategy for over speed running training and for the setting of middle distance race records.

Table 1. Effect of drafting on the drag of standard and novel garment with VG at a V of 7.28 m/sec

Following distance (m)	% decrease in Fd with standard singlet and shorts	% decrease in Fd with novel garment with VG	Estimated time savings in 1500 m race with novel apparel and drafting (sec)
0.5	- 67.4	- 67.6	8.42
1.0	- 58.9	- 55.7	6.94
1.5	- 48.2	- 47.4	5.9
0.75 (with near total flow blockage)	n/a	- 97.8	12.18

3.5 Time Savings provided by race apparel with VG

As noted above, race garments that contain VG provide reductions in F_d of between 3.7 and 6.8% compared to equivalent advanced race apparel developed for the 2012 London Olympics which in turn provided substantially lower drag than conventional race apparel. A previously developed [1] mathematical model of time savings due to F_d reduction was utilized to predict the effect of a conservative 4% reduction in F_d on world record sprint and distance running performances (Table 2).

Table 2. Predicted effect of a 4% reduction in F_d on race times

Event	Time Savings Men's Event (sec)	Time Savings Women's Events (sec)
100 M	0.013	0.013
400 M	0.067	0.69
1500 M	0.5	0.46
Marathon	10.9	10.5

The magnitude of these time savings is sufficient to alter the finishing order of many world class races.

4.0 Summary

The application of VG to race garments have allowed the development of garments that are aerodynamically effective and stable at race velocities from the marathon to the 100 m sprint, with reduced body coverage, simplified construction and lower weight as additional benefits. The results of this study have demonstrated that race garments with VG can reduce the F_d of sprint and distance runners that should translate into significant race time savings. As these time savings require little from the athletes in terms of additional training or race preparation, race garments with VG provide a simple method for world-class athletes to reach their full athletic potential.

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