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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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Keywords: vortex generators; drag reduction; athletic apparel

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: