# Application of theoretical principles to swimsuit drag reduction

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## Abstract

This study investigated the basic fluid mechanics associated with the hydrodynamic drag of a human. The components of drag (friction $D_{SF}$, pressure $D_P$ and wave $D_W$) on a human swimmer were analysed by applying classical fluid dynamic fundamentals. General methods of reducing drag were considered and the most probable method identified, applied and tested on swimsuit hydrodynamic drag. This study employed turbulators, either one (upper back) or three (across the upper back, the chest and across the buttocks), that were compared to an identical full body suit with no turbulators. Male and female elite competitive swimmers ($n$ = 7 each) were towed in an annular pool to determine passive drag at speeds from 0.4 to 2.2 m s$^{-1}$. The total drag was reduced by 11–12% by one turbulator and 13–16% by three turbulators. The total drag was decomposed into $D_{SF}$, $D_P$ and $D_W$ to determine the mechanisms responsible for the reduced total drag by the turbulators. The presence of the turbulators did not significantly increase friction or wave drag; however, flow was attached to the body as there was a significant reduction in pressure drag (19–41%), with the greatest reduction being for three turbulators (chest, back, buttocks). This study demonstrated the importance of pressure drag in determining total drag at high human swimming speeds, and that drag reducing technology can significantly reduce it, in this case by appropriately sized and placed turbulators.

**Keywords:** competitive swimming, swimsuits, trip wires, drag, friction drag, pressure drag, wave drag

## Introduction

In recent years, competitive sports have begun to rely increasingly on technology. Because the margin of time difference between athletes in racing events is measured in hundredths of seconds, every possible method to reduce race times is being pursued. Since racing events are usually held in a fluid (air or water) fluid mechanical drag can be a major source of energy expenditure and thus a potential opportunity for improvement through drag reducing techniques. Swimming is an event in which drag plays a major role due to the viscosity of the fluid: thus a small reduction in drag can result in a major improvement in swimming time and placement in competitions.

With the availability of a new generation of suits that cover large parts of the body with special materials and devices, there is a potential for drag

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reduction. These new suits are reported to reduce skin friction of the material itself by 16% without a swimmer and by 10% when worn by a swimmer (Owen & Bearman, 2001). A Lycra suit with vortex generators and riblets covering the torso of male swimmers reduced the energy demand of swimming, compared with a standard racing suit, presumably due to the drag-reducing characteristic of the suit (Starling *et al*., 1995). The opinion that these new suits improve performance is, however, not universally accepted. It has been concluded that these types of suits do not reduce drag or improve performance (Sanders *et al*., 2001; Toussaint *et al*., 2002; Roberts *et al*., 2003).

Materials have been used that reduce friction by using a dense weave that reduces porosity and surface roughness (Warring, 1999). Other materials with polymer coatings have been used to decrease the shear stresses at the surface (Warring, 1999). Tight fitting suits have been used to smooth out body contours, reducing form drag (Warring, 1999). Longitudinal riblets have been used to reduce turbulent friction (Warring, 1999). Recently, vortex generators have been used to increase the momentum in the boundary layer on the back to delay flow separation and reduce pressure drag (Warring, 1999). The vortex generators proposed by Warring (1999) may have been larger than required: Lin demonstrated that low profile vortex generators (10 to 20% of the boundary layer height) might be more effective (Lin, 2002).

To develop methods to reduce drag on swimsuits, it is necessary to properly understand and model the physics involved in swimming. The focus of this study was to analyse the resistive or drag forces that impede the forward motion of a swimmer. Because of the complicated nature of the drag forces, a distinction between active drag (associated with swimming) and passive drag (associated with a body towed in a static position) has been made. In order to focus on the potential drag reduction of a swimming suit, and to eliminate the effects of swimming technique, this study focused on passive drag of elite human swimmers; as opposed to manikins or free-swimming subjects.

The drag associated with a body can be separated into components: friction ($D_{SF}$), pressure ($D_P$), and wave drag ($D_W$). It has been shown in a previous study that, as velocity increases, the friction drag contribution remains approximately constant and the pressure and wave drag increase significantly, where 21% is friction drag, 23% wave drag, and 52% pressure drag at 2.2 m s$^{-1}$ (Mollendorf *et al*., 2004). Pressure drag continues to dominate the overall drag, even at maximum swimming velocities.

Drag reducing technologies could be effective by reducing $D_{SF}$ or $D_W$; however, reducing $D_P$ may result in the greatest improvement. The effectiveness of using a trip wire (or turbulator) to reduce pressure drag on a sphere was shown by Prandtl in 1914 (in Schliching, 1960).

The previous study (Mollendorf *et al*., 2004) included only male swimmers; however, since the design of swimsuits for men and women is different, which could affect total drag as well as $D_{SK}$, $D_P$ and $D_W$, we studied both men and women. In addition, previous studies have shown that the energetics of swimming and body drag differ between men and women owing to body composition differences (di Prampero *et al*., 1972; Pendergast, *et al*., 1977; Zamparo *et al*., 1996a, 1996b.

The purpose of this study was to combine theoretical models with passive drag measurements to determine whether the use of circular wires wrapped around the circumference of the body (trip wires or turbulators) of precise size and location are drag reducing, and if so, what the physical mechanisms behind the reduction in drag are.

## Methods

Seven men (20.2 ± 0.5 years of age, 171 ± 12 cm in height, 71.80 ± 1.66 kg in weight, 51.3 ± 0.9 cm in chest width, 25.4 ± 0.4 cm in chest depth, and 8 ± 1% body fat) and 7 women (20.0 ± 0.5 years of age, 168 ± 7 cm in height, 67.27 ± 9.09 kg in weight, 49.4 ± 7.1 cm in chest width, 20.2 ± 2.3 cm in chest depth, and 14 ± 8% body fat) University Division I swimmers participated in this study. The study was approved by the University's Institutional Review Board; subjects completed a medical history, were given a physical examination, and completed an informed consent form.

The suits were made of microfibre polyester and Lycra material. All testing was done with the suits initially dry, and the order of the suits in testing was randomly assigned for each swimmer. All of the swimmers wore conventional swimming caps.

## Measured towing drag

Drag measurements were determined by passive towing at the surface in an annular pool 58.6 m in circumference, over the path of the swimmer, and 2.5 m wide and 2.5 m deep. The pool temperatures were maintained at 28°C ± 0.2°C, with the air temperature at 22°C ± 2.0°C. Each swimmer held onto a handle that was attached by a wire through pulleys to a vertically mounted dynamometer (Model TDC 4A, Schaevitiz Engineering, Pennsauken, NJ), fixed to a monitoring platform that towed the swimmer. The platform speed was set by a calibrated impeller flow meter which allowed the towing speed to be set and maintained (Model HP301A2M, Mead Instruments, Riverdale, NJ). The velocities started at 0.2 m $s^{-1}$ and were increased in 0.2 m $s^{-1}$ increments every three minutes up to 2.2 m $s^{-1}$. Swimmers breathed through a swimmer's snorkel (Finis Inc., Tracy, CA). Force (total drag; *D*) was measured using the vertically mounted dynamometer, the output of which was conditioned using a linear variable differential transformer (Model 300D, Daytronics, Dayton, OH). The output of the LVDT was processed using an A/D converter (Model PPIO-AI08, ComputerBoards, Mansfield, MA) via software developed 'in house' to average and store velocity and force every minute using a personal computer (Model 770, IBM Thinkpad, Armonk, NY). The data were then plotted as a function of velocity. All devices were calibrated before and after each experiment. The centrifugal force on the swimmer and swimming platform were borne by the centrifuge arm and did not influence the (tangential) drag measured by the force transducer mounted on the monitoring platform.

## Theoretical consideration

Pressure drag is caused by the resultant pressure force from the pressure distribution over the body. Usually, there is a higher resultant pressure force on the front of the body than on the back, because of the separation of the flow on the back of the body. Flow separation is caused by an adverse pressure gradient in conjunction with a reduced velocity zone, called the boundary layer, caused by viscosity and the no-slip condition of a solid surface (friction). The velocity in the outer flow around a body reaches its maximum near the thickest part of the body, owing to the reduced flow area. Bernoulli's relationship then dictates that the pressure will be lowest at the point of highest velocity. As the flow begins to expand again at the rear of the body, the flow decelerates and the pressure increases. This can create an adverse pressure gradient if the curvature is pronounced enough. In addition, the friction at the surface of the body continually decreases the velocity in the part of the boundary layer closest to the skin until it is zero at the surface. If the surface has sufficient curvature (adverse pressure gradient) then the flow will separate from the surface. A region of recirculation and vortex formation, called the wake, then appears behind the body. Consequently, the energy taken by the wake causes an increase in drag on the body. On blunt bodies, the wake is large at low Reynolds numbers and remains large until it reaches the critical Reynolds number. At the critical Reynolds number, the boundary layer will transition to turbulent flow before reaching the point of minimum pressure. Turbulence increases the momentum in the part of the boundary layer near the surface and helps prevent flow separation to a location further downstream on the body. As a result, there is a significant decrease in the size of the wake and the resulting drag. As the Reynolds number increases beyond the critical value, there is an increase in the vortex formation and subsequent increase in wake size and drag (Naumann *et al.*, 1966). Another phenomenon that affects the pressure distribution on a body near or penetrating the free surface of the water is ventilation. Ventilation is the process of air being sucked into a cavity behind the body from the free surface. Also, a complex vortex structure is created behind an object near or penetrating a free surface (Naumann *et al.*, 1966).

It is well known that surface characteristics have an effect on fluid mechanical drag. In general, the effect of uniformly distributed surface roughness is to decrease the transition-to-turbulence Reynolds number. This will increase skin friction drag because turbulent skin friction drag is higher than laminar skin friction drag. Single protuberances with height a fraction of the boundary layer thickness may also decrease the transition-to-turbulence Reynolds number. Appropriately engineered surface roughness or protuberances may attenuate overall drag of the swimmer, secondary to the decrease in transition-to-turbulence Reynolds number.

## Data analysis

A passively towed swimmer's surface can be approximated by an arrangement of a sphere and circular cylinders in axial flow. Because the boundary layers are typically thin compared with the radii, the frictional drag can be modeled to a good approximation as flows over flat plates (Cooper & Tulin, 1953; Eckert, 1958; Landweber, 1949). This amounts to ignoring the small contribution of secondary flows resulting from the rounded 'corners' and 'edges' of the body on frictional drag. Such 'bluff' geometry effects will, however, contribute to the pressure drag. This is accounted for in terms of the drag coefficient, which is included in the regression analysis. The Reynolds number, $\mathrm{Re}_L$, based on a characteristic length, $L$, is defined as

$$\mathrm{Re}_L = \frac{VL}{\nu}$$

where $V$ is the swimming speed and $\nu$ is the fluid kinematic viscosity. For high Reynolds numbers, as observed in competitive swimming, the flow experiences transition-to-turbulence, separate from the surface. For flow over a flat plate at zero angle of attack, transition-to-turbulence begins at about $\mathrm{Re}_L = 5 \times 10^5$ and ends at about $\mathrm{Re}_L = 10^7$ (Fox & McDonald, 1992). For a swimmer 170 cm tall, the Reynolds numbers based on swimmer length (height) corresponding to $V = 0.3$ m s$^{-1}$ and 2.2 m s$^{-1}$ are $5.10 \times 10^5$ and $3.74 \times 10^6$, respectively. Consequently, the flow in the boundary layer over the length of the swimmer's body is neither completely laminar nor completely turbulent; it is transitional and ill-defined, with the forward portion of the swimmer in laminar flow, and most of the aft portion in transitional flow (Mollendorf *et al.*, 2004). A previous study (Mollendorf *et al.*, 2004) showed that, for a speed of 2 m s$^{-1}$, the laminar flow ends at about 25 cm aft of the swimmer's head, and most of the body of the swimmer is in the near-laminar/transition-to-turbulence region. For the towing procedure used in the present study, the swimmer's arms were outstretched. It was assumed that the outstretched arms are quite streamlined and do not significantly disturb the flow or contribute to drag, which could lead to an unspecified error. The head, followed by the shoulders, represents the 'leading edge' of the main part of the body. The actual extent of the laminar flow region depends upon both swimming speed and the transition-to-turbulence Reynolds number. The latter is determined as one of the fit parameters in our regression of the data reported here. Typical Reynolds numbers are about $3 \times 10^3$, which corresponds to a distance of about one percent (1%) of the swimmer's height as measured from the head.

Total drag was decomposed into its components as previous described by Mollendorf *et al.* (2004). The skin friction drag of the swimmer, $D_{SF}$, was calculated as for a flat plate in the transition-to-turbulence region as:

$$D_{SF} = q\,A_S \left[ \frac{0.074}{\mathrm{Re}_L^{1/5}} - \frac{1740}{\mathrm{Re}_L} \right] \tag{1}$$

where $q$ is the dynamic pressure, $q = ½\rho V^2$, $\rho$ is the fluid density, and $A_S$ is the surface area. The corresponding pressure drag ($D_P$) was calculated using the results of Schmitt (1954). As a starting point in the data regression, the skin friction drag was calculated using one-half (½) of the body surface area, because it is assumed that the swimmer would be partially out of the water. The actual body surface area is not needed, however, because it is 'buried' in the regression coefficient. The pressure drag $D_P$ was formulated to be proportional to the second power of the velocity and directly proportional to the frontal surface area, which is a measured function of the body angle variation with speed (see eqn. 3). The wave drag $D_W$ was formulated to be proportional to the fourth power of the velocity. Thus the experimental data were used as the basis for the theoretical calculations. Drag decomposition consisted of summing the drag components and then determining the proportionality constants as well as the transition Reynolds number using a standard multiple, nonlinear regression package (NonlinearFit, Mathematica, Wolfram Research) with the expression:

$$D = K_1 D_{SF} + K_2 A_f(\theta) V^2 + K_3 V^4 \tag{2}$$

where $D_{SF}$ and $A_f(\theta)$ are given by eqns. 1 and 3, respectively; and $K_1$, $K_2$ and $K_3$ are regression coefficients.

*Body position*

In order to evaluate the hydrodynamic drag on swimmers, it is essential to know the position of the body in the water. This position was prostrate, facing downward with some degree of incline and with some portion of the head, arms, and shoulders out of the water during part of the cycle. During the passive towing experiments, the swimmers (and a calibration frame) were videotaped through an underwater window using a video camera (DCR TRV 840, Sony, Oradell, NJ). A simple vertical and horizontal linear scale was used as a camera calibration frame. After each swim, the video was replayed and the frontal area, $A_f(\theta)$, of the swimmer was calculated from the whole body angle, $\theta$, from the horizontal (averaged over the body length) using the following equation:

$$A_f(\theta) = A_{f0}\cos\theta + \frac{A_S}{2}\sin\theta \qquad (3)$$

where $A_{f0}$ is the frontal area when the swimmer is horizontal ($\theta = 0$) and $A_S$ is the body surface area.

*Flow description*

We used an estimate of the Reynolds number (Re), a non-dimensional parameter, to establish some major characteristics of the fluid flow around the body. The Reynolds number was used to estimate the flow characteristics within the boundary layer over a six-foot male swimmer's body. The equations used to calculate the boundary layer thickness were:

$$\delta_1 = \frac{5.2x}{\sqrt{\mathrm{Re}_x}} \quad \text{and} \quad \delta_1 = \frac{0.37x}{\mathrm{Re}_x^{1/5}} \qquad (3)$$

where $\delta_1$ is the laminar boundary layer thickness, $\mathrm{Re}_x$ is $Vx/\nu$ and $\delta_t$ is the turbulent boundary layer thickness (Kuethe & Chow, 1958). Additionally, the transition is estimated to occur at Re = $1.2 \times 10^6$.

The critical Reynolds number, at which transition of the boundary layer from laminar to turbulent occurs, depends on the shape, surface texture and velocity of an object and on the amount of free stream turbulence (Hoerner, 1958). Hoerner (1958) has estimated that the critical Reynolds number in water is of the order of half of that in air.

To calculate the Reynolds number, the length scale ($x$) in the Reynolds number equation was referenced from the top of the head (leading edge). The water temperature in competitive swimming pools (27ºC) was used to estimate the kinematic viscosity of water, which was approximately $8.57 \times 10^{-7}$ m$^2$ s$^{-1}$ (Owen & Bearman, 2001; Schilichting, 1968). Typical maximum competitive swimming velocities vary between 1.4 m s$^{-1}$ and 2.2 m s$^{-1}$.

To estimate the locations where separation is likely to occur, namely the upper back near the shoulders, chest and the buttocks, we used a convex surfaces model, as the stability limit is approximately the same as on plane walls (Cooper & Tulin, 1953; Eckert, 1958; Hoerner, 1958; Landweber, 1949). Since the upper part of the human back is essentially a convex surface, we will use a plane wall assumption for this surface. With the head as the leading edge of the body, the Reynolds number at the thickest part of the torso is between $6.2 \times 10^5$ and $1.2 \times 10^6$ $\mathrm{Re}_x$. Because the fluid is water, and because of the amount of turbulence in the water generated by the presence of the arms and hands in front of the body, in addition to the turbulence from the head, we could expect the critical Reynolds number to be close to the lower part of the range, near $5 \times 10^5$. It is possible that the flow around the middle of the back is laminar; however, based on our analysis, it is more likely that it is turbulent.

With the head as the leading edge of the body, the local Reynolds number at the middle of the buttocks is between $1.2 \times 10^6$ and $2.3 \times 10^6$. Again, this is above the expected critical Reynolds number: the flow at this point is likely to be turbulent.

Visual analysis of video data taken during passive towing suggests that separation of the boundary layer occurs near the middle of the back and chest. An area of recirculation and eddy formation then occurs in the lower back near the buttocks.

*Methods of reducing drag*

Reducing the total drag on a body involves having a net reduction in the combination of friction, pressure and wave drag. Our goal of reducing drag through swimsuit construction was limited to reducing friction and/or pressure drag, since wave drag can primarily be reduced through swimming technique.

**Reducing friction:** friction drag can be reduced by making the surface as smooth as possible. Smooth surfaces minimise the interaction of the surface with the fluid, as well as delaying the transition of the boundary layer from laminar to turbulent. Another method of delaying or suppressing the transition of the boundary layer is to provide a compliant surface to dampen the velocity fluctuations that lead to turbulence. An further method of reducing the friction of a turbulent boundary layer is to use riblets. The suits tested in this study used a smooth surface design between the turbulators.

**Reducing pressure drag:** One of the main causes of pressure drag is the lack of pressure recovery on the back of the body, due to separation of the flow around the body. In order to decrease flow separation and the resulting pressure drag, a combination of increased velocity of the boundary layer (with constant or decreased adverse pressure gradient), and/or a decreased adverse pressure gradient (with constant or increased velocity), must occur. Although there are many methods of maintaining the boundary layer velocity, only the addition of vortices into the flow above the body by moving high velocity fluid from the outer region toward the surface of the body is applicable to swimming suits (Warring, 1999). Another method of increasing the velocity in the boundary layer is to stimulate turbulence in a laminar layer before the point of separation. Excitation of turbulence can be accomplished by use of mechanical vibrations, sound waves, or protuberances such as surface roughness or transverse tripping wires (turbulators); the latter were used on the suits tested in this study.

Eddies formed in the wake behind a body are created from energy taken out of the flow. Suppression of the eddy formation and reduction of the size of the wake decreases the amount of energy taken out of the flow by the body, reducing the drag. Naumann *et al*. (1966) has shown that, on circular cylinders above and below the critical Reynolds number, broken and wavy separation wires can be effective in disrupting vortex shedding patterns and reducing the drag. Drag reductions of 64% on cylinders and 35% on airfoils with blunt trailing edges have been achieved (Owen & Bearman, 2001).

A novel method to reduce drag on swimsuits is to use broken or wavy separation lines. It has been demonstrated on blunt bodies and airfoils that broken or wavy separation surfaces can interrupt the vortex formation and reduce wake size and drag (Bearman & Owen, 1997; Darekar & Sherwin, 2001; Hover *et al*., 2001; Naumann, 1966; Owen & Bearman, 2001; Tanner, 1970). Owing to the curvatures and circumference changes at the head, back and buttocks, and the associated adverse pressure gradients, it is expected that large eddy regions might develop. These areas may therefore benefit from vortex suppression using trip wires (turbulators); thus, this technique was used on the suits tested in this study.

We propose that the most effective region for use of a two-dimensional roughness to transition of the boundary layer to turbulent is on the upper back. However it can also be proposed that the head, torso, and buttocks locations may be potentially beneficial. Although it has previously been shown (Mollendorf, 2004) that the transition to turbulence occurs at 0.25 m from the tip of the head in a towed swimmer, the boundary layer in this location is extremely thin, and thus we conclude that a turbulator in this location would not be effective. The effective range of Reynolds numbers at the torso is $5 \times 10^5$ to $2 \times 10^6$, 2.8 to $5.5 \times 10^5$ at the head and $5 \times 10^5$ to $2.5 \times 10^6$ at the buttocks . Based on these values, the point of separation on the back of a six-foot male swimmer occurs at approximately 0.46 m as measured from the top of the head. Although Mollendorf *et al*. (2004) previously showed separation at 0.25 m from the head due to the thin boundary layer, it is assumed in this study that the flow reattaches, and then separates again, in the region of the adverse pressure gradient of the shoulders. Dimensions for swimmers of other heights can be scaled accordingly. In order for the turbulation to be effective, it is necessary for the transition to occur upstream of the separation point. At a location of 0.42 m, the critical or minimum height required for the roughness to create transition is 0.31 mm (Huber & Mueller, 1987). To calculate the point of transition with respect to roughness height and position, we can use Dryden's empirical law (Shilichting, 1968). For the transition to occur directly behind the roughness, the height is 0.375 mm (Schilichting, 1968). For the transition to occur 2 cm behind the roughness, a height of 0.34 mm is required. With these calculations in mind, a suitable tripping wire height would be 0.34 mm, and would be a located at 0.40 m from the top of the head. These are the measurements used on the suits in this study.

**Separation lines:** as stated earlier, locations that could benefit from wavy separation surfaces are the upper back, chest and buttocks, where separation takes place. The separation lines should be located just before separation occurs on the upper back, approximately between 0.45 m and 0.5 m, and on the buttocks, between 0.8 m and 0.84 m, as measured from the top of the head. Experiments have shown that the ratio of the wavelength ($\lambda$) of the wavy line and the cross- sectional height ($D$) of the body should be between approximately 3 and 10 and that the ratio of the peak to peak width ($w$) of the wavy line to the wavelength ($\lambda$) should be between approximately 0.1 and 0.3. With a ratio of $\lambda/D = 3$ and a cross-sectional height of 0.24 m at the thickest part of the torso, the wavelength would be 0.72 m. Since this is much longer than the width of the torso, we used a curved separation face instead. This uses essentially half of a wave, with the lowest part of the curve in the middle of the back. Curved separation faces on the back of blunt based airfoils have been shown to reduce drag more than wavy separation faces when the ratio of $A/D$ is greater than 0.62, where $A$ is the depth of the curve. Drag reductions of 35% have been achieved using this method (Owen & Bearman, 2001). With a value for $A/D$ of 0.62, the value of $A$ is 0.15 m. The height of the separation line should be high enough to force the separation of the boundary layer from the body. Previous researchers have used ratios of separation wire diameters to body diameters of 0.02 and 0.013 (Igarashi, 1986; Naumann *et al*, 1966). Using these size ratios and a body width of 24 cm, the separation wire size should be between 3 mm and 5 mm. This was the location of the turbulator in the one-turbulator suit.

The recommended swimsuit drag reduction method used in this study for the three-turbulator suit had turbulators on the pectoral area and buttocks, as well as the one on the back described above. The additional turbulators were constructed out of a 3.4 mm diameter cylindrical material and attached to the suit in locations described above.

We hypothesised that the addition of one turbulator at the chest would reduce the total drag by 10%, assuming that the flow separates as described above and that the turbulator was successful in providing complete attachment of flow down the body. The addition of the two turbulators on the pectoral and buttocks areas was hypothesised to reduce drag by an additional 3–5%.

## Results

The data for the change in body angle as a function of towing velocity are shown in Fig. 1 for male and female swimmers. The values for women and men were not statistically different from each other, but specific values for each gender were used in the decomposition of drag. The angle from the horizontal, on average, was not significantly different for men and women at any speed and decreased from 21 ± 11° at 0.4 m s$^{-1}$ to 9 ± 5° at 2.2 m s$^{-1}$.

Although total and decomposed drags were calculated for all speeds, only the data for competitive speeds are shown in Table 1. Total drag was 30% greater in men than women at 1.4 m s$^{-1}$; the difference decreased to 21% at 2.0 m s$^{-1}$. Total drag ($D_T$) increased as a function of velocity ($V$) over this range of speeds with the expression

*for women:*

$D_T = 20.1 - 24.3V + 30.6V^2$ for no turbulator
$D_T = 3.8 - 7.3V + 23.8V^2$ for one turbulator
$D_T = 4.4 - 9.2V + 24.4V^2$ for three turbulators

*for men:*

$D_T = 19.8 - 14.3V + 30.6V^2$ for no turbulator
$D_T = 10.0 - 14.3V + 30.6V^2$ for one turbulator
$D_T = 5.0 - 3.5V + 25V^2$ for three turbulators

Using one turbulator significantly decreased total drag averaged across speeds in both women (11 ± 2%) and men (12 ± 3%), as did three (13 ± 2% and 16 ± 2%, respectively).

The decomposed drag data are also shown in Table 1 for competitive swimming speeds only. At 1.4 m s$^{-1}$ in women wearing the no turbulator suit, $D_{SF}$ accounted for 45%, $D_P$ 51% and $D_W$ 4%. At faster velocities the contribution of $D_{SF}$ decreased to 42%, and $D_W$ increased to 8%, with $D_P$ remaining the same. For men, at 1.4 m s$^{-1}$, $D_{SF}$ accounted for 47%, $D_P$ 50% and $D_W$ 3%. As speed was increased to 2.0 m s$^{-1}$ the relative percentage of $D_{SF}$, $D_P$ and $D_W$ for men did not change significantly.

The addition of one or three turbulators slightly reduced $D_{SF}$ in women (6 ± 1% to 7 ± 1%). However, for men it decreased 15 ± 2% with one, and increased 2 ± 1% with three turbulators. $D_w$ increased with one and three turbulators in women (to 13 ± 14% and 29 ± 14%, respectively). $D_w$ in men increased with one turbulator (100 ± 66%), but decreased 47 ± 12% with three turbulators. The changes in $D_{SF}$ for both men and women were small and, although the percentage changes in $D_w$ were large, due to the small contribution of $D_w$ over this ranges of competitive speeds, they were not major changes. The major reduction in total drag was caused by the reduced $D_P$, which, when averaged across speeds, decreased 17 ± 5% and 29 ± 2% with one turbulator, and 18 ± 4% and 41 ± 3% with three turbulators, for women and men, respectively.

**Table 1** Average values for total drag, decomposed into skin friction ($D_{SF}$), pressure ($D_P$), and wave ($D_W$) drag for men and women swimming at speeds ($V$, m s$^{-1}$) observed during competitive swimming, expressed in newtons (N)

| | | No turbulator | One turbulator | | | Three turbulators | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | N | N | %No T | Signif | N | %No T | %One T | Signif |
| **Women** | | | | | | | | | |
| $V$ = 1.4 | $D_T$ | 46.1 | 40.2 | 13 | * | 39.2 | 15 | 2 | * |
| | $D_{SF}$ | 20.6 | 19.6 | 5 | * | 19.6 | 5 | 0 | * |
| | $D_P$ | 23.5 | 18.6 | 21 | * | 16.7 | 29 | 10 | * † |
| | $D_W$ | 2.0 | 2.0 | 0 | | 2.9 | 45 | 45 | * † |
| $V$ = 1.6 | $D_T$ | 59.8 | 53.0 | 11 | * | 52 | 13 | 2 | * |
| | $D_{SF}$ | 26.5 | 24.5 | 8 | * | 24.5 | 8 | 0 | * |
| | $D_P$ | 30.4 | 24.5 | 19 | * | 22.6 | 26 | 8 | * † |
| | $D_W$ | 2.9 | 3.9 | 34 | | 4.9 | 69 | 26 | * † |
| $V$ = 1.8 | $D_T$ | 75.5 | 67.7 | 10 | * | 66.7 | 12 | 1 | * |
| | $D_{SF}$ | 32.4 | 30.4 | 6 | * | 31.4 | 3 | 3 | * |
| | $D_P$ | 38.2 | 31.4 | 18 | * | 28.4 | 26 | 10 | * † |
| | $D_W$ | 4.9 | 5.5 | 12 | * | 6.9 | 41 | 25 | * † |
| $V$ = 2.0 | $D_T$ | 94.1 | 84.3 | 10 | * | 83.4 | 11 | 1 | * |
| | $D_{SF}$ | 39.2 | 36.3 | 7 | * | 37.3 | 5 | 3 | * † |
| | $D_P$ | 47.1 | 38.2 | 19 | * | 35.3 | 25 | 8 | * † |
| | $D_W$ | 7.8 | 9.8 | 26 | * | 10.8 | 38 | 10 | * † |
| **Men** | | | | | | | | | |
| $V$ = 1.4 | $D_T$ | 59.8 | 50.0 | 16 | * | 49.0 | 18 | 2 | * |
| | $D_{SF}$ | 29.4 | 24.5 | 17 | * | 30.4 | 3 | 24 | * † |
| | $D_P$ | 31.4 | 21.6 | 31 | * | 17.7 | 44 | 18 | * † |
| | $D_W$ | 2.0 | 2.9 | 45 | * | 1.0 | 50 | 66 | * † |
| $V$ = 1.6 | $D_T$ | 75.5 | 65.7 | 13 | * | 63.7 | 16 | 3 | * † |
| | $D_{SF}$ | 39.2 | 33.3 | 15 | * | 39.2 | 0 | 18 | † |
| | $D_P$ | 38.2 | 27.5 | 28 | * | 23.5 | 38 | 15 | * † |
| | $D_W$ | 2.0 | 4.9 | 150 | * | 1.0 | 50 | 80 | * † |
| $V$ = 1.8 | $D_T$ | 93.2 | 83.4 | 11 | * | 79.4 | 15 | 5 | * † |
| | $D_{SF}$ | 47.1 | 41.2 | 13 | * | 48.1 | 2 | 17 | † |
| | $D_P$ | 50.0 | 35.3 | 29 | * | 29.4 | 38 | 17 | * † |
| | $D_W$ | 2.9 | 6.9 | 137 | * | 2.0 | 30 | 70 | † |
| $V$ = 2.0 | $D_T$ | 113.8 | 104.0 | 9 | * | 98.1 | 14 | 6 | * † |
| | $D_{SF}$ | 57.9 | 50.0 | 14 | * | 58.8 | 2 | 18 | † |
| | $D_P$ | 59.8 | 43.2 | 28 | * | 36.3 | 39 | 16 | * † |
| | $D_W$ | 4.9 | 10.8 | 120 | * | 2.9 | 41 | 73 | * † |

% No T: Percentage change from no turbulator
% One T: Percentage change from one turbulator
* significantly different from no turbulator
† significantly different from one turbulator

## Discussion

One of the major, and perhaps most important, determinants of aquatic performance is the swimmer's total body drag (Pendergast *et al.*, 2005). The total drag in turn comprises the drag from $D_{SF}$, $D_P$, and $D_W$, which are all speed-dependent. Methods of determining total drag have been described in previous studies (di Prampero *et al.*, 1972; Toussaint *et al.*, 1989). Although some authors argue that drag determined with the swimmer actually swimming (active drag) (Pendergast *et al.*, 1977 , 2005; Toussaint *et al.* 2002a, 2000b; Sanders *et al.*, 2001) should be measured, and that drag-reducing suits do not lower it (Sanders *et al.*, 2001), active drag is dominated by the technique of the swimmer and makes it difficult to expose the drag of the suit *per se*. Previous studies, but not all, have suggested that drag reducing suits reduce drag (Mollendorf *et al.*, 2004) and improve swimming performance (Starling *et al.*, 1995) of swimmers. Passive drag (swimmer towed inactive) is better suited to studing the basic physics and affects of drag reducing technology (Chatard *et al.*, 1990), since it eliminates the potential noise of swimming technique.

Both male and female top division swimmers were used in this study. Although passive drag was studied, male and female swimmers have different body geometries and densities, which could affect the effectiveness of the turbulators and their placement. Furthermore, swimmers used experiences to minimise the effects of changes in body position during towing, which could have influenced the reliability of the data.

A method of decomposing total drag into its component parts, $D_{SF}$, $D_P$ and $D_W$, has recently been developed (Mollendorf *et al.*, 2004). Based upon fluid physics, the drag of the swimmer at the surface can be reduced by decreasing surface area, promoting laminar flow over the surface, promoting attached flow and minimising the production of waves and spray.

Reducing the frontal surface area of the swimmer would require that the body assumes a more horizontal attitude in the water. At low speeds, swimmers' bodies are not horizontal in the water, and thus have a large frontal and surface area (Fig. 1). This body attitude is determined by the individual swimmer's body density and the torque around the centre of gravity that it produces (Chatard *et al.*, 1990; McLean & Hinrichs, 1998; Pendergast *et al.*, 1977; Zamparo *et al.*, 1996a, 1996b). Although the torque can be reduced by wearing a wet suit (Toussaint *et al.*, 1989), drag-reducing suits do not have this effect (Roberts *et al.*, 2003; Mollendorf *et al.*, 2004), and this would be illegal in competition. During competitive swimming the hydrodynamic lift offsets the body's torque, and the swimmer's body is more horizontal in the water; thus, little further benefit could be derived by changes in the body's attitude in the water.

It has previously been argued that frictional drag is low in swimming humans; thus, to reduce it would have little benefit (Sanders *et al.*, 2001; Walsh, 1998). However, more recent studies using correct physics have shown that $D_{SF}$, $D_P$ and $D_W$ all play a role in total drag, and therefore reducing them may reduce total drag. In fact, $D_{SF}$ has been shown to be reduced by shaving body hair (Sharpe & Costill, 1998) and by the use of vortex generators and riblets (Warring, 1999; Walsh, 1998) by as much as 7%.

Most studies on drag reducing suits have studied FastSkin swimsuits that use a system of microscopic vortex generators and riblets (Starling *et al.*, 1995; Toussaint *et al.*, 2002; Mollendorf *et al.*, 2002; Roberts *et al.*, 2003). Active drag (Toussaint *et al.*, 2002) and passive drag and performance (Roberts *et al.*, 2003) have been shown not to be improved by wearing the FastSkin suits; however, this is not universally accepted: Mollendorf *et al.* (2002) found reduced passive drag and Starling *et al.* (1995) reported improved performance. The differences among the results of these studies may be due to the level of swimmers used in studies that measured active drag, or the speed range studied, as speeds below the competitive range have different balances of drag components.

Vortex generators and riblets on swimsuits have been suggested to reduce drag (Warring, 1999). The vortex generators used by Warring (1999) may have been oversized, as the same size generators were used on the upper back as on the buttocks of the body. Since the boundary layer in a fluid flow is smaller towards the leading edge of an object, and greater at the trailing, the boundary layer will be thinner at the back than at the buttocks. Therefore, the vortex generators used on the upper back should be lower in height than the ones at the buttocks, which was not the case in the Warring work (1999). Lin has demonstrated that low-profile vortex generators with heights between 10% and 20% of the turbulent boundary layer thickness can be effective in producing the needed longitudinal vortices while producing less drag than larger generators. Warring used vortex generator heights of 25% of the boundary layer thickness, so may not have achieved optimal drag reduction. Warring's work used the fingertips of a swimmer's extended arms as the leading edge for the boundary layer thickness estimates. As stated earlier, using the head as the leading edge of the body may be more representative of actual swimming positions. In this case, the estimate of the boundary layer thickness would decrease 50% at the upper back and 35% at the buttocks. This would decrease the vortex generator heights by the same amount. Warring used a 3 mm vortex generator height on his model, which translates into a 6 mm vortex generator height on a six-foot male. Using 10% and 20% of the adjusted boundary layer thicknesses, the vortex generator height on the upper back is 0.9 mm and 1.9 mm, respectively. Using 10% and 20% of the adjusted boundary layer thickness, the vortex generator on the buttocks is 1.7 mm and 3.3 mm, respectively. Because vortex generators larger than required will increase drag, sizing and location of these generators is critical to reducing drag, which may explain why the reductions in drag in the current study exceeded those reported by Warring (1999) or currently used in some swimsuits.

An alternative technique to reduce drag is the application of turbulators on swimsuits, as was used in this study. To our knowledge, although this technology has been widely used in other situations, this was the first attempt to use it in swimming; however, it has previously successfully reduced drag in downhill skiing (Jacobs *et al*., 1998, 2000) and speed skating (Baum, 2004). As described in the theoretical method section, the principle is that turbulators disrupt flow separation, and attach the flow to the body, thus reducing pressure drag, at the expense of increased frictional drag. It should be noted that attached turbulent flow typically has higher skin friction drag but lower pressure drag than detached (separated) laminar flow. A previous study (Mollendorf *et al*., 2004) has shown that laminar flow is disrupted at the head, which suggests that tripping the boundary layer at the head may be beneficial, although, because of the thin boundary layer, it would have to be smaller in size than the turbulator on the chest, back and buttocks used on the suits in this study. As flow separation may occur at all parts of the body where there are marked changes in curvature (head, shoulders, buttocks), turbulators at multiple locations on the body may be required to give the greatest reduction in drag, as observed in this study.

The precise size of the turbulator in relation to the boundary layer, and the location of the turbulator relative to the changes in body shape, are critical. The major conclusion of this study was that using three turbulators on a total body swimsuit, with smooth surfaces between turbulators, significantly reduced passive drag in women and men. The reduction in total drag was due primarily to a significant reduction in pressure drag, as skin friction and wave drag changed very little. This observation fits the theoretical principles, as attached turbulent flow typically has higher skin friction drag but lower pressure drag than detached (separated) laminar flow. It has been reported that protuberances reduce drag, with 2.5 mm being recommended; however, higher protuberances have a negative effect (Mollendorf *et al*., 2004). The data from the present study would suggest that the turbulators were correctly sized and that the placement of three turbulators was appropriate (shoulder area, chest, and buttocks) in both men and women. These data support the conclusion that the turbulators tripped the boundary layer and that the flow remained attached to the body past the shoulders, chest and buttocks, in transitional phase, and thus lowered $D_P$. The absences of significant or important increase in $D_{SF}$, as expected, may be due to the smooth surface of the suit material used between the turbulators.

This study measured passive drag and focused on competitive swimming speeds. A previous study has reported that active drag at low speeds was not affected by FastSkin drag-reducing suits; however, at higher speeds (1.65 m s$^{-1}$), active drag was reduced (Toussaint *et al*., 2002), as was the case in this study for passive drag. There was significant drag reduction with the turbulator suit on all subjects, in spite of their gender, height and weight differences, suggesting that this was achieved because turbulator placement was scaled relative to the variable heights of the subjects with differently sized suits. Although adding a turbulator on the swim cap is suggested by this study, it needs verification; however, the three turbulator suit significantly reduced passive drag and would appear ready for commercialisation.

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