The Influence of Apparel on Aerodynamic Drag in Running

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The aerodynamic drag associated with three types of commercially available running apparel (SS: nylon singlet and shorts; L: nylon/spandex bodysuit and RS: nylon rainsuit) and two bodysuits of newly developed stretchable, water vapour permeable fabrics (T and K) was measured in a wind tunnel on a mannequin at four velocities (4.7, 7.1, 8.8 and 9.7 m·sec⁻¹). The effect of apparel on drafting efficiency was also examined by positioning a human subject on various grid coordinates around the mannequin and alternating the apparel worn by the subject and mannequin. Commercially available running apparel caused consistently higher drag than the T and K bodysuits. Under all conditions the high sheen and tight fit of the K fabric allowed drag reductions of between 17.5 and 7.4% at running speeds. A hood over the hair was responsible for 6 of the 7.4% reduction in drag noted with the K suit. It is estimated that reduction in drag of this degree provide real time savings of between 1.05% in the marathon to 2.75% in the 100m dash. A field trial of the K suit with 16 male subjects (mean age: 22 years) revealed a significant ($p \leq .025$) decrease in 100m running time amounting to a time saving of 1.17% at a velocity of 7.43 m·sec⁻¹. Results of the drafting investigations suggested that 1.0m is the optimal distance to draft behind a lead runner. At a forward velocity of 7.1 m·sec⁻¹ this practice provided a 62.7% reduction in drag. Further reductions in drag were possible if the following runner was clothed in the K apparel. Practical race strategies are suggested by these results and by the observation that running abreast a lead runner results in a larger shared drag than would be encountered by either runner alone.

Key words : Drag Forces, Running, Racing Apparel

INTRODUCTION

In a variety of sporting events such as cycling, speed skating and downhill skiing, strategies have been developed to alleviate the effects of opposing wind speed on the forward velocity of athletes. In bicycle racing, where wind drag comprises over 90% of the total mechanical resistance to motion, specialized wheels, contoured helmets, close fitting clothing, a streamlined posture and racing tactics have been developed to minimize wind resistance (Kyle, 1979; Anderson, 1984). In contrast, systematic measures to reduce wind resistance in running have yet to be developed.

This deficiency may have an important impact on

performance since the energy expenditure required to overcome wind resistance at sprint (10 m·sec⁻¹) and middle distance (6 m·sec⁻¹) speeds has been estimated to be 13.6% and 7.5%, respectively, of the total energy expenditure of the endeavour (Pugh, 1971). In middle distance competitions, Kyle (1979) has suggested that runners adopt a technique termed "drafting" in which a following runner is shielded from drag forces by a front runner. This technique may reduce the energy required to overcome air resistance by 40% (providing a theoretical saving of 1.42 sec/400m lap at a pace of 6.13 m·sec⁻¹) for all following runners. Unfortunately, this technique is untenable in the sprint races, which are run in

individual lanes and in many races where competitive tactics prevent consistent positioning behind the leader. The drag force on a runner may be expressed by :

$$D = 0.5\rho A_p C_d V^2 \quad \text{Eq. 1}$$

where D is the drag force (N) ; ρ is the air density ($\text{kg}\cdot\text{m}^{-3}$) ; A_p is the athlete's projected area normal to the wind (m^2) ; C_d is the drag coefficient and V is the wind velocity ($\text{m}\cdot\text{sec}^{-1}$) (Pugh, 1971 ; Davies, 1980 ; Ingen Schneau, 1982).

It follows from equation 1, that a reduction in air density, projected area or drag coefficient will decrease the drag force and allow maintenance of a higher forward velocity without additional energy expenditure. Ward-Smith (1984) noted that times in the sprint events (100, 200, 400m) at the 1968 Mexico City Olympics were approximately 1.7% lower than might have been expected if the races had taken place at sea level. Air density is reduced approximately 23.5% at the altitude of Mexico City (2,300m) which reduces drag and coincidentally, the oxygen tension of inspired air. In the Mexico City games, Pugh (1976) found a 6% decrement in performance in events longer than 800m. Unfortunately, in the middle and long distance events, performance enhancement, attributable to reduced drag, is probably obscured by a larger debilitating effect on performance caused by the low barometric pressure and lower alveolar oxygen tension at this altitude. At present, there is a paucity of information on the dependence of C_d or A_p with body build, posture or clothing. Hoerner (1965) noted that C_d was reduced by 5 to 10% in nude subjects. Pugh (1976) observed a 6% range in A_p through the various phases of running which suggests that A_p may not be reduced substantially through style or posture modification.

An athlete's A_p however might be significantly reduced by the use of a tight fitting, one piece body suit which would cover the body hair and eliminate the sharp edges of traditional racing apparel. In addition, a high fabric sheen may decrease surface friction, mimicking the minimal drag of a nude,

hairless body. While Shanebrook and Jaszczak (1976) suggested an experimental protocol involving cloth covered cylinders to determine the effect of clothing on aerodynamic drag, no published reports to date have explored this important area further. The purpose of the present investigation was to determine the aerodynamic drag associated with commercially available and newly developed running apparels. By altering the fabric composition of the new garments, it was anticipated that an apparel could be developed with optimal drag characteristics.

MATERIALS AND METHODS

All experiments were conducted in a $2.4\times 1.6\text{m}$ wind tunnel of the Mechanical Engineering Department, University of British Columbia. Proper fitting samples of three types of commercially available running apparel (SS : nylon singlets and shorts ; L : nylon/spandex body suit ; RS : nylon/polyester rain suit) and body suits manufactured from two new, stretchable, water vapour permeable fabrics (K : fabric from the Kuwata Rubber Co. and T : 'Polus' fabric from Teijin Limited) were tested on a 1.4m tall store display mannequin. Use of a mannequin eliminated measurement errors resulting from inconsistent body position. All body suits were sewn from an identical pattern to allow comparison of the effects of fabric type on drag. The mannequin was secured to a steel post which protruded through the wind tunnel floor on to the pan of a custom built, six component balance (Aerolab Supply Co., Philadelphia, U.S.A.). The drag cell of the balance was calibrated daily using known weights of 0.449 to 4.527 kilograms. During a three day period, drag cell calibration varied by $\pm 0.53\%$. Wind velocity was calculated from the dynamic pressure q , ($q = 0.5\rho V^2$) which was measured with a pitot-static tube placed 33cm above the floor of the tunnel, 58cm lateral and 1.1m anteriorly to the mannequin. Pressure readings were recorded with a Wilhlambrect Gottingen (type 655M16) manometer. Daily measurements of ambi-

ent temperature and pressure in the tunnel revealed slight variations in the air density, ρ , throughout the investigation period, from 1.186 to 1.191 kg·m⁻³. These variations were corrected in the final calculations.

Considerable care was exercised to ensure the accuracy of projected area (A_p) measurements. The effects of parallax were reduced by means of a small mirror placed on the chest of the mannequin which was used to align the reflection of a camera lens in the ground glass viewfinder of a 35mm single lens reflex camera such that the circumference of the lens was described within the concentric circle of the viewfinder. Photographs of each apparel were taken pre and post wind exposure with a reference card of known dimensions placed on the mannequin's chest. The projected area of the mannequin and apparel was determined by planimetry, using a Keuffel and Esser Compensating Polar Planimeter (model 620005).

For comparison purposes, the mannequin was tested in a "nude" (Nu) condition. All apparel, with the exception of the Nu and SS apparel, were tested (a) with a wig and (b) with a hood (+H), which covered the wig. In all trials the apparel was mounted on the mannequin and photographed. In each experiment air velocity was varied by means of a solenoid pneumatic control. Dynamic pressure inside the chamber (indicating wind speed) and drag forces on the mannequin were measured. Drag measurements were recorded at four predetermined pressures equal to air velocities of 4.3, 7.1, 8.8 and 9.7m·sec⁻¹ respectively. The selection of air velocities, commonly observed in competitive athletics, eliminated the confounding influence of a change in Reynold's number of C_D since the effects of Reynold's number on C_D are constant at velocities below 18.5m·sec⁻¹ (Pugh, 1976; Davies, 1980).

In a second series of experiments, a human subject, successively wearing different apparel, was positioned at various coordinates on a grid surrounding the mannequin. Drag measurements with

the 'competing' runner in these various positions indicated the effect of lateral and anterior/posterior spacing of an accompanying runner on drag forces experienced by the mannequin and permitted comparison of the effects of dissimilar apparel on the drag of leading and following runners. Finally, a 100m dash trial of the K suit was conducted on a regulation 400m synthetic surface running track. Visible light sensors and light sources (model 63501, Lafayette Instrument Co., Lafayette, IN) were established 100m apart at regulation start and finish lines while an electronic clock (model 54427-A, Lafayette Instrument Co., Lafayette, IN), accurate to .01 sec, was positioned near the start line. Nineteen male volunteers (mean age: 22 years) warmed up for ten minutes prior to running four maximal sprints of 100m. None of the subjects were in sprint training but all subjects were athletically active and all ran a minimum of 20km·week⁻¹. Nine subjects wore the K suit over shorts, socks and training shoes while ten subjects wore a t-shirt, nylon shorts, socks and training shoes for the first two trials, the apparel was then reversed for the last two further trials. Subjects were instructed to use a standing start, to run maximally for the entire distance and to run through trigger light beams located above the start/finish lines. Subjects were permitted to recover fully (3 to 5 minutes) prior to each trial. All trials were conducted over a 3 hour period, at an ambient temperature of 14°C against a variable headwind of .17 to 2.03m·sec⁻¹, measured by a fan type anemometer (model W131, Weather Measure Corp., Sacramento, CA). Three of the subjects failed to complete four trials, hence their data were excluded from analysis. All results were analysed by one way analysis of variance for repeated measures with significance accepted at the .05 level.

RESULTS

Analysis of pre and post wind exposure photographs showed that the projected areas of the mannequin were within $\pm 4.8\%$ in all conditions

except RS (rain suit), where projected areas decreased by as much as 8.3%. Since the actual A_p during the wind exposure were unknown, all calculations were based on an average of the pre and post wind exposure values. Results of the Nu and SS conditions are shown in Table 1.

Errors of measurement

Methodological error of the measurements should be noted before comparison of the results with other published reports are made. In some of the latter, common errors noted here were not considered. The test-retest reliability of the apparatus was determined to be within $\pm 1.5\%$ (at velocities of 8.8 and $9.7 \text{ m} \cdot \text{sec}^{-1}$). This value incorporates a $\pm .53\%$ diurnal drift of the drag cell. Three factors tended to modify absolute values of D and C_D : (a) the influence of a turbulent boundary layer at the base of the mannequin; (b) additional drag on the support post; and (c) alteration of laminar air flow in the tunnel by the projected area of the mannequin. The effect of the turbulent floor boundary layer, about 5cm thick, was considered to be minimal. Measurements on an exposed support post revealed that 4.4 to 5.0% (at velocities of 8.8 and $9.7 \text{ m} \cdot \text{sec}^{-1}$, respectively) of the A_p of the Nu with wig (Nu+W) condition could be attributed to the support post although these estimates may be somewhat overestimated, since the post was approximately 50% shielded by the mannequin in all conditions. A more serious error was the fact that the ratio of mannequin frontal area to tunnel cross-sectional area (0.

08) undoubtedly resulted in some blockage of the air flow through the tunnel. El-Sherbiny (1972) suggested an empirical formula for blockage correction of cylinders which provided a better fit to his data than the more commonly quoted formula of Maskell (in Ingen Schneau 1982). Using El Sherbiny's formula, C_D values were adjusted 12% downward to correct for this blockage effect. It is important to note that these errors do not limit conclusions inferred from the comparative results reported in the study since apparel was the only variable modified.

Aerodynamics

A comparison of the aerodynamic characteristics of various apparels at four air velocities is presented in Table 2. For comparative purposes, results

Table 2. Showing percentage change in A_D with various apparel clothing on a mannequin at various wind velocities

Apparel	Wind Velocity ($\text{m} \cdot \text{sec}^{-1}$)			
	4.7	7.1	8.8	9.7
Nu+W	0.0	0.0	0.0	0.0
SS	+ 1.4	+ 2.3	+ 5.3	+ 4.4
L	+ 4.2	+ 9.0	+11.1	+10.4
L+H	- 2.0	+ 5.8	+ 5.0	+ 4.4
T	- 2.5	+ 3.5	+ 3.2	+ 3.6
T+H	-16.3	- 4.3	- 1.5	- 0.6
K	- 6.5	+ 1.7	- 0.9	- 0.6
K+H	-17.5	-10.4	- 7.9	- 7.4
RS	+16.9	+38.2	+40.3	+43.5
RS+H	+14.1	+28.3	+36.2	+41.4

Table 1. Drag areas (A_D) at four wind velocities on a bare mannequin with and without a wig or clothed in running singlet and shorts

Apparel Conditions	A _p (m ²)	——— Wind Velocity ———				ρ (kg•m ⁻³)	C _o *
		(m•sec ⁻¹)					
		4.7	7.1	8.8	9.7		
Nu, bald	.289	.339	.324	.321	.313	1.1882	.99
Nu	.322	.355	.346	.340	.338	1.1882	.95
SS, blad	.313	.350	.336	.329	.332	1.1910	.95
SS	.323	.360	.354	.358	.353	1.1910	.97

*at a velocity of $7.1 \text{ m} \cdot \text{sec}^{-1}$

were first converted to drag areas, A_D where:

$$A_D = A_p \cdot C_D = D / 0.5 \rho V^2 \quad \text{Eq. 2.}$$

Results were then converted to "drag ratios:" a ratio of the drag area of the test apparel compared with the drag area of the Nu+W condition. These results reveal consistent intra-apparel trends, attributable to an increasing wind velocity and inter-apparel differences which reflected clothing design and fabric properties such as stretch and drapability. Current, commercially available running apparel (SS, L, RS) provide considerably higher drag than the T and K skin-tight bodysuits. The L suit, while form fitting, was observed to stretch and billow in the wind, thus increasing A_p and the drag on the mannequin.

The aerodynamic advantages of bodysuits composed of T and K fabrics appeared to result from a combination of their surface sheen, stretchability and the suit design. At high speed ($V = 9.7 \text{ m} \cdot \text{sec}^{-1}$), the difference in drag ratio between the L, T or K suits with hood and the same suits without hood was approximately 6%. Thus, at a velocity of $9.7 \text{ m} \cdot \text{sec}^{-1}$, 6% of the 7.4% reduction in drag experienced in the K+H condition is probably due to the effect of a hood which covers the hair and reduces the projected area of the mannequin. At low velocity ($4.7 \text{ m} \cdot \text{sec}^{-1}$), the advantage of wearing a hood over exposed hair remains constant at 6% for the L suit but is increased to 11 and 13.8%, respectively, for the K and T suits. The fact that the K suit retained near baseline or sub-baseline drag in all differing wind velocities may be linked to a subjective observation that the K suit had the best stretch fit and highest sheen of any suit tested. A high fabric sheen may reduce the thickness of the boundary layer of air next to the surface of the suit, thus reducing the minimal contribution of the frictional component of drag.

Energy Expenditure

While the K fabric appears to have impressive drag reduction characteristics, the importance of

this property for track running has not been demonstrated. Kyle (1979), using a nomogram from Margaria et al. (1963), developed an equation for the estimation of velocity increase resulting from drag reduction by drafting. The basic energy requirement (E) to run on a treadmill at zero gradient at velocity V ($\text{m} \cdot \text{sec}^{-1}$) with no relative wind speed with subjects wearing standard SS apparel was determined to be:

$$E = 0.00775 + 0.2485V \quad \text{Eq. 3.}$$

where E is the total rate of energy expenditure in $\text{KJ} \cdot \text{kgf}^{-1} \cdot \text{min}^{-1}$. Kyle also suggested that the energy consumption in combating drag, E_w , may be calculated from:

$$E_w = (C_D \cdot A_p \cdot \rho \cdot V^3) / (2F \cdot M \cdot e) \quad \text{Eq. 4.}$$

where A_p is in m^2 , M is the subject's mass in kg, ρ is in $\text{kg} \cdot \text{m}^{-3}$, V is the athlete's velocity in $\text{m} \cdot \text{sec}^{-1}$ and e is the mechanical efficiency of running. With this choice of units, F is a dimensionless conversion factor, equivalent to 16.66 in the present experiments. Although the mechanical efficiency of performing work against drag has not been conclusively determined, several workers (e.g. Margaria et al. 1963; Cavagna et al. 1964; Zacks 1973) have suggested a value of $e = .4$. In the present analysis, the weight of the mannequin with all its running apparel was converted to a human equivalent weight of 45.45 kg. If it is assumed that Margaria's subjects wore apparel similar to the SS apparel, the total energy consumption of running in SS apparel with no relative wind speed at velocity V may be calculated from Eq. 3. The reduction in energy required to run at equivalent velocity with the K+H suit is then given by addition of an E_w term to Eq. 3 calculated from the different E_w values between the SS apparel and the K+H suit at a specific running speed. For example, at a base velocity of $7.1 \text{ m} \cdot \text{sec}^{-1}$, $E = 1.7721 \cdot \text{KJ} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ and $E_{w_{SS}} = 0.0006099V^3$ while $E_{w_{K+H}} = 0.0005342V^3$. Thus the total energy expenditure of a subject wearing the K apparel will be less than while wearing SS apparel. If one assumes that in a foot race an athlete is

expending energy at a maximum rate (proportional to the race distance) regardless of apparel, then the lower drag of the K+H apparel should translate into an ability to maintain a higher velocity wearing K+H apparel than while wearing the SS apparel. Solution of the quadratic, Eq. 5 :

$$1.7721 = 0.00775 + 0.2485(V) - 0.0000757V^3$$

Eq. 5.

for V gives the new velocity resulting from reduction in drag energy expenditure due to the K+H apparel compared with SS. Thus $V_{K+H} = 7.215 \text{ m} \cdot \text{sec}^{-1}$ compared with $V_{SS} = 7.1 \text{ m} \cdot \text{sec}^{-1}$. Over 1500m, this 1.62% increase in velocity would translate into an impressive decrease of 3.37 sec for a 1500m race. Results of similar calculations comparing SS and K+H apparel over a range of velocities are provided in Table 3. These results should be considered cautiously however, since the effect of body hair on drag was not measured in the SS condition, and the energy required to stretch the fabric of a bodysuit has also not been determined although the latter would be minimal with the K material.

Effect of runner position

The effect of runner position and the spacing between runners on drag at a velocity of $7.1 \text{ m} \cdot \text{sec}^{-1}$ is presented in Table 4. Column headings are displacement distances leftwards from the mannequin of a static runner while row headings are anterior-posterior displacement distances measured from the mannequin (at 0,0). These distances were all measured from the centre of the mannequin support post

to the approximate center of gravity of the human subject. All results have been expressed as a percentage of the drag on the mannequin when the human subject was at a grid position, compared with the drag when a subject was not in the tunnel. Extending earlier comments on blockage, the presence of another object in the tunnel probably increased the measured drag by approximately 24% in the worst case in which mannequin and subjects were side by side, 0.5m apart. Blockage effects were

Table 4. Showing drag as a % of reference drag in drafting at a velocity of $7.1 \text{ m} \cdot \text{sec}^{-1}$ on a mannequin placed posteriorly/anteriorly and laterally to an accompanying runner, each wearing singlet & shorts

Relative Mannequin Displacement			
Anterior-Posterior Displacement Meters			
Lateral Displacement Meters	0.5	0.25	0.0
1.5	107.0	82.5	46.9
1.0	105.5	90.6	37.3
0.5	110.6	93.5	—
0.0	127.2	—	Mannequin
0.5	101.0	96.5	93.5
1.0	94.7	92.7	92.2

Table 3. Effect of singlet and shorts (SS) and a one piece suit (K) on predicted race times for various distances

	BASE VELOCITY ($\text{m} \cdot \text{sec}^{-1}$)	TIME TO COMPLETE IN APPAREL		TIME DIFFERENCE (min : sec)	PERCENT DIFFERENCE
		SS	K		
Marathon					
42.195km	4.7	2h29:37.66	2h28:03.16	1:34.50	—1.05
1500m	7.1	3:31.27	3:27.90	3.37	—1.62
400m	8.8	45.45	44.30	1.15	—2.53
100m	9.7	10.309	10.025	.284	—2.75

minimal when one object was directly ahead or behind the other. In addition, the inability of a human subject to maintain a constant position at various coordinates decreased the accuracy of these measurements. For maximum effect, the optimal distance to draft behind a lead runner was 1.0m. At a velocity of $7.1\text{m}\cdot\text{sec}^{-1}$, mean savings of 62.7 and 53.1% in drag could be attained by following 1.0 and 1.5m, respectively, behind a lead runner. By combining Kyle's formula for speed increase with drafting (Kyle (1979): equation 14) and these data on drag reduction on the mannequin at a velocity of $7.1\text{m}\cdot\text{sec}^{-1}$, the enhanced velocity due to drafting may be determined from:

$$1.7721 = 0.00775 + 0.2485V - 0.0006099V^3n \quad \text{Eq. 6.}$$

Tabel 5. Showing drag as a % of reference drag in drafting at a velocity of $7.1\text{m}\cdot\text{sec}^{-1}$ alternatively with mannequin dressed in K+H suit, subject in SS*; mannequin dressed in SS, subject in K+H suit**

Relative Mannequin Displacement			
Anterior-Posterior Displacement Meters			
Lateral Displacement Meters	0.5	0.25	0.0
1.5	106.2*	93.8	45.9
	103.2**	94.0	56.7
1.0	105.9	93.8	30.6
	102.7	88.4	39.6
0.5	105.9	87.8	—
	109.0	96.3	—
0	126.1	—	Mannequin
	122.2	104.6	
0.5	100.8	91.9	94.3
	104.4	102.3	97.9
1.0	92.8	92.4	92.1
	98.8	97.9	96.5
1.5	91.6	92.4	93.8
	98.6	98.4	98.1

where n is the fractional reduction in drag due to shielding. Solution of Eq. 6 with $n = .531$ (% reduction in drag at 1.5m posterior to the front runner in our experiments) gives a velocity of $7.69\text{m}\cdot\text{sec}^{-1}$ which would provide a time saving of 4.32sec saving per 400m lap.

Combined Effect of position and clothing on drag

The influence of clothing on drafting efficiency is presented in Table 5 in which the human subject and mannequin were alternatively dressed in the K+H and SS apparel. These results confirm the trends noted above and suggest that optimal drafting occurs when the following runner is dressed in the K apparel and the lead runner is dressed in the SS apparel. In this situation, with a 1.5m spacing between runners, the following runner could develop a velocity of $7.77\text{m}\cdot\text{sec}^{-1}$ while drafting at an energy expenditure equivalent to that at a velocity of $7.1\text{m}\cdot\text{sec}^{-1}$ when unprotected. (Note that for this analysis, the constants of Eq. 5 were changed from 0.2485 to 0.2445 and from 0.0006099 to 0.0005342, respectively). This enhanced velocity for equivalent energy expenditure would allow a 4.86 second time saving per 400m lap, which is superior to the time saving achieved wearing SS apparel.

Results of the K suit field trial

In the field trial the ANOVA analysis revealed a significant trials effect ($p \leq .01$), indicating a potential confounding influence of fatigue on the apparel results. Examination of the four trial means ($\bar{x}_1 = 13.27$; $\bar{x}_2 = 13.54$; $\bar{x}_3 = 13.54$; $\bar{x}_4 = 13.78$ seconds) revealed equivalence of the means of trials 2 and 3, thus fatigue effects were negligible in these two trials. Since subjects randomly and alternatively wore one apparel and then the other in trials 2 and 3, a paired t-test was conducted between trials 2 and 3 to determine apparel induced differences. The mean time with the K suit ($\bar{x} = 13.46 \pm .16$ seconds) was found to be significantly lower ($p \leq .025$) than with the SS apparel ($\bar{x} = 13.62 \pm .14$ seconds). This

Table 6. Drag indices derived in the present experiment and from previous investigations

SOURCE	CONDITION	A_p (m ²)	C_D	A_D (m ²)
present investigation	human model, SS apparel	.327	.96-.98	.317
Hill (1927)	model	—	.90	—
Davies (1980)	runner on treadmill	.454	.87	—
Pugh (1976)	runner on treadmill	.478	.70	.334
Shanebrook & Jaszczak (1976)	cylindrical model	—	1.2	—
Hoerner (1965)	clothed human, standing	.624	1.17	.730
Ingen Schenau (1982)	speed skater	.29	.87	.252
Penwarden <i>et al.</i> (1978)	clothed human, standing	.55	1.18	.649
Kyle (1979)	clothed human, standing	—	.95-1.14	—

advantage translated into a time saving for a 100m race of 1.17% at this speed of running.

DISCUSSION

The baseline aerodynamic drag data derived in this investigation are in agreement with other published measurements performed on humans and models (Table 6). Substantial errors in drag measurements may result from failure to compensate for blockage effects in small tunnels. However, with the exception of Ingen Schenau (1982), most investigators have ignored this effect. In the present investigation, failure to correct for tunnel blockage would have led to a 12% overestimation of C_D . The relatively narrow range of C_D (0.96 to 0.98) observed here for the SS apparel suggests that the range of velocities selected were below the threshold required to generate a critical Reynold's number which would have caused a sharp decline in C_D . Thus, comparisons between apparels among all velocities studied could be analysed.

Penwarden, Grigg and Rayment (1978) considered their frontal area measurements accurate within $\pm 2\%$ although no author has described methods to limit parallax errors in frontal area measurement

previous to the present investigation. Pugh (1971) observed a 5% reduction in the A_p of walkers pre and post wind exposure to an airstream due to residual flattening of apparel against the body. While the 4.8% range in A_p noted here is of similar magnitude, the occurrence of a larger A_p after wind exposure indicates that the airstream may catch loose flaps in the material and thus introduce unsuspected error in subsequent drag measurements. Given the problems encountered in photographing A_p during actual wind exposure and the inaccuracies common to A_p measurement, it is more meaningful to express drag as a non-dimensional ratio. While the present static results may not be directly applicable to the kinetic case, nonetheless they provide an appropriate starting point on which to base further investigations.

Practical aerodynamic advantage of new K and T apparels

Design of current running apparel which is based on conservative tradition rather than on efficient function is deficient aerodynamically. A significant aerodynamic advantage seems able to be realized by wrapping the runner in a shiny, skin-tight suit

which covers hair and sharp edges and thus reduces A_p . Inclusion of a hood covering the hair is responsible for the largest portion of drag reduction at sprinting speeds. Individuals with thick body hair and those racing longer distances appear to be able to benefit from the tight fit and high sheen of the K suit as well. Since the T and K suits were manufactured from the same pattern, fabric characteristics are the most likely source of variation in drag found between these apparels. Although low speed drag measurements are subject to greater inaccuracies, the consistency of measurements on the T and K suits at velocities of 4.7 and 7.1 m·sec⁻¹ indicate that these suits have significant potential for drag reduction in practical race situations.

The advantages of drag reduction are clearly shown in the predicted time required to complete various distances. The theoretical advantage of wearing the K suit to reduce drag increases from 1.05% of the normal race time in a marathon to 2.75% in a 100m sprint (Table 3). The increased effect in the 100m race time is because of the higher running speed since the effects of drag increase as the second power of velocity. The benefits calculated in this study correspond well to other theoretical values. In speed skating at a velocity of 10 m·sec⁻¹, Ingen-Schenau (1982) considered the advantage of wearing streamlined apparel to be a reduction in lap times of 2 to 3%. Davies (1980) suggested that the effect of drag in the 100m sprint is critical during the last 60m only, since an athlete is travelling at a relatively low velocity during the first 40m. Nonetheless, Davies estimated that the elimination of drag at a forward velocity of 10 m·sec⁻¹ would decrease the 100m time by .25 to .50sec. If the current estimation of a .284 sec decrease in 100m time with the K suit was reduced even by 40%, a reasonable benefit of .17 sec (1.65%) would still accrue to sprinters wearing streamlined apparel. In the 100m field trial, non-sprinters, without benefit of competition, starting blocks or spiked shoes, improved their 100m sprint time by 1.17% with the

K apparel. This improvement is close to the conservative value of 1.65% calculated for the higher sprint velocity of 9.7 m·sec⁻¹ (vs 7.43 m·sec⁻¹ in the field trial). The relative agreement between predicted and actual values for time saving in 100m run at a velocity of 7.43 m·sec⁻¹, supports the theoretical values estimated for longer races shown in Table 3. The margin of victory in World class competition is often much less than the apparel-induced time saving determined in this study.

Drafting strategies utilizing new apparels

Although several authors have estimated the effects of drafting by means of oxygen consumption measurements (Pugh, 1971; Davies, 1980), drag measurement on cylindrical models (Shanebrook & Jaszczak, 1976), air pressure changes behind a subject on a treadmill (Pugh, 1976) or so-called coastdown tests (Kyle, 1979), the present analysis represents the first attempt to measure drafting effects in a wind tunnel. The 62.7% reduction in drag with shielding, noted for a 1.0m spacing ($V = 7.1 \text{ m} \cdot \text{sec}^{-1}$) is similar to the value of 80.0% calculated by Pugh (1976) for a velocity of 6.0 m·sec⁻¹ but is excessive given actual observation of a 1.0 sec per lap advantage measured under race conditions (Pugh, 1971). Davies (1980) also reported that shielding reduced drag by 80 to 85%, potentially saving 1.0 sec per lap ($V = 6.0 \text{ m} \cdot \text{sec}^{-1}$) although he did not provide calculations to support this estimate. Kyle (1979) proposed that a 40% reduction in drag at a 2.0m spacing would provide a 1.66 sec per lap advantage ($V = 7.0 \text{ m} \cdot \text{sec}^{-1}$). The value of 53.1% noted here for a 1.5m spacing is similar to Kyle's estimate although the present calculation suggests a larger advantage of 4.32 sec per lap. The discrepancy between theory and Pugh's (1971) direct observation are probably due to: (a) a following runner being unable to follow consistently within 1 to 1.5m of a front runner and (b) variations in drafting efficiency as a front runner alters his/her posture, changing the A_p and converts potential drag to body lift (Davies, 1980). A third

possible effect may also be proposed from drag measurements taken with the human subject positioned 0.5m laterally abreast the mannequin. Although the true result of this effect was somewhat obscured by a substantial blockage effect, it was nonetheless evident that as a following runner shifted laterally closer and abreast the leader, the drag on the leader (and presumably, on the follower) exceeds the drag experienced by either alone. This effect occurs because the combined A_p of the two runners results in a larger shared drag.

Optimal Strategy for drafting

Kyle (1979) and Davies (1980) both proposed that an optimal strategy for middle distance racing is for a potential winner to be shielded by clubmates until the last straightaway. The current results suggest an extension of this plan in which several clubmates would alternate running beside a rival leader to cause him to expend additional energy.

Streamlined apparel worn by a following runner provides additional drafting benefit. Conversely, following a runner wearing streamlined apparel limits the effectiveness of drafting. Thus the introduction of streamlined apparel to competitive middle distance races would be uniformly disadvantageous to traditionally dressed competitors. The foregoing assumes that the thermal load of wearing a complete body suit and the energy demands of stretching the fabric would not detract substantially from performance. Preliminary experiments comparing the aerobic demands of wearing lycra tights and SS apparel at intensities of 72 and 83% of $\dot{V}O_{2max}$ have indicated no significant difference during a 6 minute test (Stipe, 1984). In races of short duration, fabric stretch and thermal characteristics do not appear intolerable. However, further research is required to develop an apparel which has both an aerodynamic and thermal advantage for longer distance events.

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