AERODYNAMIC AND THERMAL CHARACTERISTICS OF RUNNING APPAREL

by

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A ERODYNAMIC AND THERMAL CHARACTERISTICS

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Abstract

The aerodynamic drag associated with three types of commercially available

running apparel (SS: nylon singlet and shorts; L: lycra/nylon 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 human

mannequin at four velocities (4.7, 7.1, 8.8 and 9.7 $m \cdot sec^{-1}$).

Commercially available running apparel provided 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. At sprint 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

reductions in drag of this size 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 ($\bar{x}$ age: 22 yr) 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 $m \cdot sec^{-1}$. The thermal properties of the SS, L and K suits and a suit

of stretchable, membrane porous fabric (B) were investigated at

environmental temperatures of 0° and 25° C subsequent to the

aerodynamic study. Six male, middle distance runners performed 30 minute

runs on a treadmill at a pace requiring approximately 80% of maximum oxygen

uptake against a fan generated wind of 4.2 $m \cdot sec^{-1}$. Oxygen uptake

kinetics, heart rate, sweating rate, core and skin temperature and perceived

exertion were recorded. At 25 ^{o}C, the K suit retained 23.5 and the B

suit 9.1 times as much sweat as SS apparel ($p \leq$ .01). Both suits were

intolerable to run in beyond 22 and 25 minutes, respectively ($p \leq .01$) at the designated speed. At $0^{o}C$, subject tolerance for all apparels exceeded the criterion time. In the cool ($0^{o}C$) condition the comparatively high air permeability of the L suit resulted in a significantly lower core temperature increase ($p \leq .05$), compared with the other apparel.

Even in cool conditions, the K suit retained significantly more sweat than the other apparel ($p \leq .01$); however subjects favoured the K suit over the B suit due to its lighter weight and greater stretchability. This research suggests that aerodynamic clothing may have a significant influence upon running performance. In order to maintain efficient thermoregulation during extended wear in hotter environments, future running suits should be developed from stretchable materials which have better vapour permeability.

To the memory of Dr. Gordon L. Diewert,
respected friend and teacher

Rust never sleeps.

-Neil Young

Acknowledgements

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1.0. Introduction :

In a variety of sporting events such as cycling, speed skating and downhill skiing, strategies have been developed to alleviate the effects of aerodynamic drag on the forward velocity of athletes. In bicycle racing, where 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 drag (Kyle 1979, Anderson 1984). In contrast, systematic measures to reduce drag in running have not yet been developed. This deficiency may have an important impact on performance since the energy expenditure required to overcome drag at sprint (10 $m \cdot sec^{-1}$) and middle distance (6 $m \cdot sec^{-1}$) speeds is equivalent to 13.6% and 7.5%, respectively, of the total energy expenditure of the endeavor (Pugh 1976). In middle distance competitions, Kyle (1979) has suggested that runners should adopt a technique termed "drafting" in which a rear runner is shielded from drag by a front runner. This technique may reduce the energy required to overcome drag by 40% (amounting to a saving of 1.42 sec per 400 m lap at a pace of 6.13 $m \cdot sec^{-1}$) for all following runners. However, this technique is untenable in the sprint races, which are run in individual lanes and in many races where competitive tactics prevent lead taking until the final turn. Thus, the development of streamlined racing apparel would be an important contribution to optimum performance. Unfortunately, limited research interest has led to a paucity of technological innovation in the manufacture of running apparel. Beyond aerodynamic considerations, the color, weight, stretchability and heat dissipation qualities of running apparel have received limited systematic

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investigation. This thesis represents the first formal attempt to design

and test suits which effectively combine both streamlining and heat

dissipating qualities.

1.1. Aerodynamic factors contributing to efficient sports performance :

Air resistance (Fw) is the force exerted by the air on a solid object

moving through still air or on a static body in moving air (Pugh 1971).

Although wind resistance was the term originally used by Eiffel (in Pugh

1971), aerodynamicists prefer the term drag (D) which refers specifically to

the component of air resistance acting in the direction of undisturbed air

flow (Pugh 1976). The drag force acting on a person or any obstacle may be

expressed as:

$$D = 0.5 \cdot \rho \cdot V^2 \cdot Ap \cdot Cd \qquad \qquad \text{Eq. 1-1.}$$

where D = drag force in kgf, ρ = air density in kgf·sec^2·m^{-4}, V =

air velocity with respect to the subject in m·sec^{-1}, Ap = subject's

projected area in m^2 and Cd = drag coefficient, (dimensionless)

(Penwarden, Grigg and Rayment 1978).

The total drag on an object is the sum of a frictional component, D_f

(which is determined by frictional forces in the boundary layer) and a

pressure component, D_p. At running speeds (4 to 10 m·sec^{-1}) D_f

contributes minimally to the total drag on the athlete (Ingen Schneau 1982).

While the distribution of air pressure and velocity over the surface

of the human body in moving air is quite variable, the overall pressure

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approximates the dynamic air pressure, q (Pugh 1976). The dynamic pressure

is the pressure head between air in motion and static air, normally measured

with a Pitot-static tube. It is equivalent to the kinetic energy per unit

volume of a moving solid body and is defined:

$$q = 0.5 \cdot \rho \cdot V^2 \qquad \text{Eqn. 1-2.}$$

(Pugh 1971).

The drag force in kilograms of force (kgf) acting on the body at a given

dynamic air pressure depends on the body's projected area, Ap (the area

projected in a plane normal to the direction of motion) and on the drag

coefficient. The drag coefficient (Cd) is the ratio of drag to the dynamic

air pressure (q) of a moving airstream:

$$Cd = D \cdot q^{-1} \cdot Ap^{-1} \qquad \text{Eqn. 1-3.}$$

(Pugh 1971).

Thus, Cd represents the influence of body shape and surface characteristics

on drag (Ingen Schneau 1982). When the projected area is unknown, drag

characteristics are expressed in terms of drag area (Ad) which is the

observed drag at a given wind velocity divided by q at the same wind

velocity, thus:

$$Ad = Cd \cdot Ap = D \cdot q^{-1} \qquad \text{Eqn. 1-4.}$$

so that Ad represents the combined effect of Cd and Ap; and Ad multiplied by

q is the drag force in kgf at any given dynamic air pressure (Pugh 1976).

The coefficent of drag (Cd) is a function of another dimensionless

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quantity, the Reynold's number (R):

$$R = \ell \cdot V \cdot \gamma^{-1}$$
Eqn. 1-5.

where ℓ is a representative dimension of the body such as diameter or length and γ is the kinematic viscosity of the air at a given temperature and pressure. Kinematic viscosity is the ratio of air viscosity (u) to air density (ρ):

$$\gamma = u \cdot \rho^{-1}$$
Eqn. 1-6.

(Pugh 1971).

Hoerner (1965) and Shanebrook and Jaszczak (1976) considered the human body to resemble a circular cylinder with the magnitude of R related to cylinder diameter. With circular cylinders, Cd remains constant over a range of R values of $10^3 < R < 10^5$ because the boundary layer separates from the cylinder surface at approximately the same location.

Pugh (1971) suggested that with runners, R will approach a value of 1 x 10^5 at an air velocity of 18.5 m·sec^{-1}.

Above R = 1 x 10^5, Cd falls progressively, reaching a new low level at R = 5 x 10^5, a value known as the critical Reynold's number (R_{crit}). The fall in Cd as R_{crit} is approached is associated with a change in the characteristics of the air flow behind the cylinder such that the boundary layer clinging to the sides of the cylinder extends further round the circumference, causing the wake to narrow, thereby reducing drag. This condition is known as fully developed turbulence (Pugh 1971).

Surface characteristics may alter the relationship of R and Cd to air speed in circular cylinders. Compared with a smooth cylinder surface, a rough surface may trigger turbulence in the boundary layer, forcing R to

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reach R_{crit} and causing the wake to narrow at relatively low values of air velocity. Once R_{crit} is attained, a rough surface will offer no advantage while a smooth surface will reduce the frictional component of drag. In practical application, the motion of a runner's limbs probably triggers turbulence in the runner's boundary layer and negates the effectiveness of a rough surface. Thus, a smooth surface is probably advantageous for a runner at all running speeds.

Experimental determination of drag force is normally conducted on a force platform in a wind tunnel (Kyle 1979). Using a force platform and Eq. 1-1, all variables except Cd may be directly measured (Penwarden, Grigg and Rayment 1978). Table 1-1 shows aerodynamic indices of athletes in a variety of sporting activities. Careful interpretation of these data is required because the number of subjects and range of wind speeds used were too small to allow uniform comparison.

In wind tunnels, wind velocity is determined best from a pitot tube located 2 m in front of the subject (Ingen Schneau 1982). In order to make reliable determinations of drag, the subject stands on a pedestal mounted above the floor of the tunnel. This technique separates the subject from boundary layer conditions near the floor in which air velocity is not constant because of friction between air and ground (Watanabe and Ohtsuki 1977). Alternatively, wind velocity may be measured with cup or vane anemometers although Pugh (1971) noted that turbulence in a wind tunnel will result in a $1.0 \text{ m} \cdot \text{sec}^{-1}$ variation in cup anemometer readings at high wind velocities. Penwarden, Grigg and Rayment (1978) measured wind velocity with a linearized hot wire anemometer with digital readout which could be integrated into online data collection equipment.

TABLE 1-1: AERODYNAMIC INDICES

Position	Walking		Running	Cycling		Skating		Skiing	
Source*	1	2	1	1	3	4	5	6 French egg position	6 Arms extended
Condition									
weight (kgf)	80.4	67.0	67.8	75.9	69.5	81.6	73.3	–	–
height (cm)	181.4	170.0	179.7	185.8	175.3	179.0	180.0	–	–
subjects	3	331	2	4	15	1	6	1	1
Ap (m²)	0.63	0.55	0.47	0.42	0.50	0.34	0.29	0.23	0.32
velocity (m.sec⁻¹)	1.3	8.3	6–10.0	12.0	12.0	12.0	12.0	30.0	30.0
Cd	1.08	1.18	0.70	0.76	0.56	0.46	0.87	0.96	0.99
Drag Area (m²)	0.68	0.65	0.33	0.32	0.28	0.16	0.25	0.23	0.32
Drag (kgf)	0.07	2.56	0.8–2.36	3.00	2.45	1.36	4.50	11.80	16.90

1.* Hoerner (1965)

1. Pugh (1976)
2. Penwarden, Grigg and Rayment (1978)
3. Davies (1980^a)
4. Di Prampero et al. (1976)
5. Ingen Schenau (1982)
6. Watanube and Ohtsuki (1977)

A variety of techniques have been used to measure projected area (Ap). Pugh (1976) and Di Prampero et al. (1976) estimated Ap by photographing subjects beside a rectangular board of known dimensions. The relative areas of the subject compared with a standard were determined by the weight of cut portions of enlarged prints or by planimetry. Penwarden, Grigg and Rayment (1978) found a relationship between a subject's surface area (A_{Du}) (Dubois formula, Dubois and Dubois 1916) and projected area. These authors measured the projected area of 331 standing subjects by comparing paper tracings from a video screen to a known standard. This technique provided an acceptable estimated error of measurement of from 2 to 5%. The mean ratio Ap/A_{Du} gave a standard deviation equal to 6.7% of the mean value ($\bar{x}$ = .326; SD = $\pm$ .022) compared with a standard deviation of 12.5% for the measured Ap. This ratio approach appears valuable in reducing the scatter of Ap measurements determined by different methods.

Pugh (1971) measured D by equating it to the force needed to maintain a life-size piece of plywood in a vertical position against various wind velocities. Pugh (1971) found that a rectangle of the same area as the silhouette had the same Cd (1.04) and that both values were similar to published engineering data and to model values determined earlier by Hill (1927). However, compared with the present measurements of drag using a precision balance and a realistic three dimensional clothed model, Pugh's estimates must be considered relatively inaccurate.

Little experimental evidence has been published on the dependence of Cd or Ap with body build, posture or clothing. Pugh's (1976) observation of a 6% variation in Ap through the various phases of running suggests that unless skintight apparel is worn, relatively little reduction in Ap in

running is possible. Hoerner (1965) noted a 5 to 10% reduction in Cd in nude subjects. Thus, beyond the advantage contoured clothing may have in reducing Ap, a high fabric sheen may reduce the frictional component of drag although this component would have minimal impact on total drag at running speeds.

McMiken and Daniels (1976) attempted to measure differences in oxygen uptake ($\dot{V}O_2$) of six trained male athletes during track and treadmill exercise at speeds upto 260 m·min^{-1} (4.3 m·sec^{-1}). In this range of speeds, no significant differences were found in the oxygen cost of track and treadmill running, thus drag was not a factor. Under both conditions, the oxygen cost was a linear function of speed. The use of an automobile to collect expired gas may have confounded the true effects of drag in these track experiments by providing a windscreen.

Pugh (1971) compared the oxygen cost of treadmill running in the presence and absence of various–fan generated wind speeds. At a wind speed of 18.5 m·sec^{-1}, and running speed of 4.45 m·sec^{-1}, $\dot{V}O_2$ was 63 % higher than under calm conditions. From these results, the effect of drag on the oxygen cost of fast running was determined to be:

$$\dot{V}O_2 - \dot{V}O_2' = K \cdot s \cdot V^2 \qquad \text{Eq. 1-7.}$$

where $\dot{V}O_2$ is oxygen cost of running at a treadmill speed s, and wind velocity V; $\dot{V}O_2'$ is the oxygen cost of running at treadmill speed s, and zero wind velocity; and K is a constant incorporating factors for conversion of units, mechanical efficiency and an air resistance coefficient (Pugh 1970). On the track in calm conditions, the air velocity may be

assumed equal to the running speed:

$$\dot{V}O_2 - \dot{V}O_2' = K \cdot V^3 \qquad \text{Eq.1-8.}$$

Pugh suggested that drag accounted for 8% of the energy cost of track running at middle distance speeds (upto 7 $m \cdot sec^{-1}$).

Kyle (1979) considered the energy drain due to drag (Ew) to be:

$$Ew = (Cd \cdot Ap \cdot \rho \cdot V^3)/(2 \cdot F \cdot m \cdot e) \qquad \text{Eqn. 1-9.}$$

where e is the mechanical efficiency of doing work against drag and m is the mass of the subject. F is a conversion factor equivalent to 16.66 when Ap is expressed in m^2, m in kgf, ρ in $kgf \cdot m^{-3}$ and V, the air velocity, in $m \cdot sec^{-1}$. By substituting these experimentally determined drag measurements in Eq. 1-9, Kyle found the excess oxygen uptake due to drag at a running speed of 6 $m \cdot sec^{-1}$ to be 4.9 % of the total energy cost.

Preliminary comparisons of the aerobic demands of wearing nylon/spandex tights versus shorts at intensities of 72 and 83% $\dot{V}O_2$max have shown no significant difference during a six minute test (Stipe 1984). Body suits of nylon/spandex lack waterproofness and require further testing to deliniate their heat dissipating qualities.

Given the foregoing it appears possible that streamlined apparel may reduce drag on a running athlete and potentiate performance. From a thermoregulatory viewpoint, however covering the body with a complete suit may result in an intolerable thermal burden being placed on a subject. Indeed, metabolic and thermal factors may then limit maximal performance and

obscure any advantage of drag reduction.

1.2. Optimal thermal characteristics of athletic apparel :

Athletic racing apparel should be lightweight, comfortable and provide little resistance either to wind or heat dissipation throughout a wide range of environmental conditions. In a hot, humid environment even minimal clothing may inhibit evaporation and lead to discomfort. Apparel regulations of the International Amateur Athletic Federation (1981) (the world sport governing body of athletics) are stated:

'In all events competitors must wear clothing which is clean and so designed and worn as not to be objectionable. The clothing must be made of a material which is non transparent even if wet.'

These rules address appearance rather than function and provide little direction for the development of advanced running apparel. Traditional clothing includes a singlet and shorts made of cotton or nylon, socks and spiked shoes for track running or lightweight racing shoes for road racing. Such clothing has been found to be inadequate under cold conditions such as the 1982 Seattle marathon (temperature $2^{o}C$; moderate to heavy rain and high wind speeds) in which several competitors required hospitalization for treatment of hypothermia.

In warm conditions Astrand and Rodahl (1970) estimated that an

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endurance athlete running at a pace requiring 4 $l \cdot min^{-1}$ oxygen uptake could produce enough heat to raise the temperature of a 70 kg man from 37^oC to 60^oC if excess heat were not dissipated. Heat dissipation is an unlikely limiting factor in races of short duration ($\leq$ 3000m) however, a primary metabolic demand on the circulation during prolonged exhaustive exercise may lead to inadequate dissipation of metabolic heat at the periphery with a consequent increase in core temperature (Greenleaf 1979). Well trained individuals may sustain a metabolic heat production of 565 $kcal \cdot m^{-2}$ hr for 2.5 hours and more than 1000 $kcal \cdot m^{-2}$ hr for 0.5 hour (Adams et al. 1975, Stolwijk 1977). These heat loads are dissipated by cutaneous vasodilation and evaporation of sweat. In such cases core temperature reaches a steady state when evaporative, radiative and convective heat losses equal heat production (Nadel 1980). Each 1.7 ml of sweat evaporated from the skin surface relieves the body of 1 kcal of heat load (Knochel 1974). Kobyashi et al. (1980) found that unacclimated subjects reached a maximum sweat rate of 21 $g \cdot min^{-1}$ (1260 $ml \cdot hr^{-1}$) during prolonged exercise at 45% of $\dot{V}O_2max$. Pugh, Corbett and Johnson (1967) reported a higher (1800 $ml \cdot hr^{-1}$) sweating rate in a trained athlete during a marathon run in moderate conditions (temperature: 23^oC; relative humidity: 58%). A sustained high sweating rate depletes plasma volume and causes acute dehydration which may limit performance by increasing hematocrit (and blood viscosity) and reducing circulatory efficiency (Greenleaf 1979). Warm, humid environmental conditions may exacerbate the effect of fluid depletion and depress the effectiveness of heat loss by sweating. The debilitating effects of hyperthermia on metabolic and regulatory systems may then cause the cessation of exercise

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long before muscle glycogen stores are depleted. In cool conditions, $\dot{V}O_2$max and exercise heart rate decrease linearly at rates of 6%·$^\circ C^{-1}$ and 8 b·min^{-1}·$^\circ C^{-1}$, respectively, at esophageal temperatures below 37.5°C (Bergh and Ekblom 1979). This finding defines a narrow range of temperatures within which core temperature must be regulated for efficient performance. Since thermoregulation is the prime limiting factor in endurance exercise, efficiency of heat dissipation is an important consideration in the design of any aerodynamically styled running suit.

1.3. Potential Fabrics for athletic apparel :

A fabric for use in athletic apparel ideally would have a high sheen, follow the body contour closely, be stretchable, lightweight, permeable to water vapour and impermeable to rain. Additionally, the fabric should be available in a variety of colours for appropriate adsorption or reflection of radiant heat. In reality, no available fabric may satisfy all these criteria simultaneously so a composite suit of various materials or several suits for extreme environments may be required. Weaver and Sellers (1985) have identified three categories of fabrics currently in use in athletic apparel:

(a) Gore-tex, a microporous (9 billion micropores per 6.54 cm^2) film of polytetrafluoroethylene laminated between two layers of nylon is used extensively in applications requiring a material impermeable to liquid water and free air currents but highly permeable to water vapour. The Gore-tex

membrane has pores 700 times larger than water molecules, allowing these to dissipate from the skin surface to the environment while water droplets (20,000 times larger than the pores) are held on the outer membrane surface. Under warm (35°C, 30% relative humidity) conditions, heat loss through Gore-tex (250 $W \cdot m^{-2}$) was found to be superior to that of polyester (150 $W \cdot m^{-2}$) and wool (100 $W \cdot m^{-2}$) (Farnworth and Nordli 1982). Unfortunately, standard Gore-tex is not stretchable and will not conform to body contours, so that its aerodynamic characteristics are unsuitable. In November, 1985, a new formulation of Gore-tex, which has limited stretchability, was introduced. This fabric has not been subjected to formal testing.

(b) Polyurethane coatings, applied either externally to a fabric (eg. Kuwata Rubber Co. test material) or as a thin membrane within a composite of inner nylon interlock and nylon/lycra outer fabric (eg. Bion II, Entrant, Permia and HellyTech) provides another method of maintaining ventile properties in water resistant garments. Although the vapour permeability of these fabrics is quite low, the stretch characteristics of the polyurethane coating have allowed production of waterproof fabrics which are stretchable.

(c) The development of super high density woven materials by the Japanese represents a new approach to the manufacture of a water impermeable fabric. The yarn used is polyester 75 denier (a denier is a unit of rayon or silk yarn size; 1 denier = 5 cg weight$\cdot$450 m^{-1} length of yarn), 72 filament yarn for warp and super fine denier yarn for weft (Anonymous 1982). Fabrics such as Savina DP, VersaTech, Action-tek, and Gamex are wind and water

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resistant and very vapour permeable but have limited stretch characteristics. While Savina DP has only one half the permeability of a nylon/spandex blend, it is water resistant and is three times as permeable to water vapour as Gore-tex, the current industry standard. More importantly, Savina DP derives its water resistance/water vapour permeability characteristics from the alignment and spacing of individual fibers rather than from a polyurethane coating or teflon membrane so that its permeability is not subject to problems of coating delamination, membrane fouling or shatter in extreme cold (Gray 1984).

While techniques for the experimental determination of the aerodynamic and thermal characteristics of apparel are well developed, these techniques have not been applied to the design of running apparel. Systematic research on running apparel is urgently required to maximize athletic performance under a variety of environmental conditions.

1.4. Purpose of the study :

Limited research has been undertaken on the aerodynamic and thermal characteristics of athletic apparel. The primary question of interest is whether, a significant aerodynamic advantage may be derived from wearing correct apparel while running at speeds from 4 to 10.0 $m \cdot sec^{-1}$. On balance, one must decide whether such advantage outweighs any concomitant reduction in performance due to reduced thermoregulatory efficiency. Most studies purporting to measure the $\dot{V}O_2$ cost of running have used treadmill protocols which neglect the effect of drag. Results of these investigations lack generality due to this highly artificial protocol. With

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the exception of three qualitative notes (Ingen Schneau 1982, Anderson 1984, Kyle 1986), quantitative data on the aerodynamic properties of various athletic apparel have not been reported. Furthermore, any reduction in oxygen uptake (ie. increase in running efficiency) expected from wearing streamlined apparel is unknown. The reduction in thermoregulatory efficiency resulting from wearing streamlined apparel is similarly, unknown. Loss of thermoregulatory efficiency after prolonged exercise under warm environmental conditions may be a limiting factor in performance. Conversely, under cool environmental conditions, the insulative value of streamlined apparel may aid in maintenance of an optimal core temperature for high level performance.

The present investigation considers both the aerodynamic and heat dissipating qualities of four types of athletic racing apparel. The four apparels are (1) nylon singlet and shorts (SS); (2) nylon/spandex bodysuit (L); (3) two bodysuits sewn from water vapour permeable, waterproof fabrics. The hypotheses of the study are:

(i) that the new suits will provide less aerodynamic drag than the SS and L apparel.

(ii) that the metabolic cost of wearing the new suits during prolonged running will be the same or less than that in L or SS apparel.

(iii) that thermoregulatory efficiency during prolonged running with the new bodysuits will be the same or better than with L or SS apparel.

2.0. Pilot Studies :

2.1. General overview :

The aerodynamic and thermal properties investigations were delayed initially by an inability to secure samples of prototype or speciality fabrics from manufacturers and trading companies in Japan, the United States and Britain. This problem was alleviated through the efforts of Mr. Tom Kuwata of the Kuwata Rubber Co. who kindly donated fabric samples from a variety of Japanese manufacturers. Examination of the donated samples revealed that without comparative technical data, the ventile and stretch characteristics of each fabric were difficult to predict. In May, 1985, samples of all fabrics of interest were sent to Dr. B. Farnworth of the Defense Research Establishment, Ottawa, for vapour permeability assessment by the technique of Farnworth and Dohlan (1984). Concurrently, matched fabric samples were tested at Simon Fraser University for ventile characteristics by the oxygen diffusion technique of Mekjavic et al. (1986). Results of these investigations are presented in Table 2-1. Unfortunately, quantities of all fabrics of interest were not available until July, 1985. Consequently, the preliminary aerodynamic investigation (completed during May, 1985) was conducted exclusively with commercially available apparel.

Prior to investigation of the thermal characteristics of different materials, a pilot study was conducted on suits made from ventile fabrics of limited stretch, sewn from the identical suit pattern to be used in the main experiment, to determine heat dissipating efficiency and characteristics of

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TABLE 2-1: RELATIVE WATER VAPOUR RESISTANCE OF SELECTED FABRICS

Fabric	Water Vapour Resistance* ($m^2 \cdot Pa \cdot s \cdot kgf^{-1}$)	Ratio Relative to		K^{-1}**
		Gore-tex	Nylon Spandex	
Biotex Bion II	1.0×10^3	1/4.5	1/30	132
Kuwata	3.2×10^8	1/14.5	1/97	509
Tenijin Polas	2.3×10^8	1/10.5	1/70	425
Kanebo Savina DP	$.072 \times 10^8$	1/.33	1/2	1.3
Nylon spandex	$.033 \times 10^8$	1/.15	1	–
Gortex	0.22×10^8	1	1/6.7	100

* Farnworth and Dolhan (1984)
** K=rate constant for free diffusion of O_2 through fabric as determined by Mekjavic et al. (1986)

various materials' stretch, fit and comfort during running. This procedure

permitted rejection of several fabrics which displayed inadequate stretch or

ventile properties.

2.2. Methods :

2.2.1. Aerodynamic properties of racing apparel :

During May, 1985, aerodynamic tests of racing apparel were conducted in

the 2.4 x 1.6 meter wind tunnel of the Mechanical Engineering Department,

University of British Columbia. All methods were identical to those

described in Chapter 3 with the exception that only singlet and shorts (SS),

nylon/spandex bodysuit (L) and nylon rainsuit (RS) were compared. All

apparel were designed to fit a 1.8 m tall man and needed special adaption to

fit the 1.4 m store display mannequin used in the wind tunnel investigation.

The latter were necessarily somewhat imperfect representations of the

apparels' true aerodynamic characteristics.

2.2.2. Thermal properties of racing apparel :

During September, 1985 a pilot investigation was conducted to determine

basic thermal characteristics of several fabrics. A 30 year old female

distance runner (estimated $\dot{V}O_2$max: 2.5 l$\cdot$min^{-1}) who fitted the

custom mannequin suits served as the single subject in this investigation.

All tests were conducted in a 4 x 5 x 2.5 meter environmental chamber with

temperature maintained at 23 $\pm$ 2°C. A constant workload was delivered

by a motor-driven treadmill (Quinton, Seattle, WA) set at a velocity of 3.4

m·sec^{-1} at 1° incline. The subject ran for a maximum of 20 minutes,

until volitional fatigue supervened or until core (rectal (Tre)) temperature

exceeded 39.0°C. A Panasonic model F1608C desk fan (Estrin

Manufacturing, Vancouver, B.C.) provided an airflow which averaged 1.3 m·

sec^{-1} over the subject's frontal area. This airflow was measured by a

Weather Measure model 131 anemometer (Sacramento, CA).

The subject performed six trials in which nylon singlet and shorts

(SS), a suit of the Kuwata (Japan) polyurethane coated nylon/spandex test

fabric (K), a suit of nylon/spandex with polyurethane membrane (Biotex Ind.

'Bion II', United States; (B)), a suit of Kuwata polyurethane coated cotton

(W), a suit of polyurethane coated nylon (Barracuda Ltd., Britain;(Ba)) and

a suit of acrylic resin coated nylon (Teijin Ltd. 'Polous',Japan; (T)) were

each tested once. The subject's core (rectal) temperature, heart rate,

maximum running time, weight loss and subjective impressions of the

flexibility, fit and comfort of each apparel were recorded.

Prior to each trial, the subject inserted a rectal thermister (YSI

model 43TD, Yellow Springs Instrument Co., Inc.) approximately 15 cm past

the anal spincter. The subject was then weighed in the apparel on a beam

balance sensitive to 50 g. Heart rate was determined from an

electrocardiograph (model 1500A, Hewlett Packard, Richmond, B.C.) using

Medi-Trace F23T disposable foam backed electrodes (Graphics Controls,

Gananoque, Ont.) applied bilaterally at the mid axillary line at the level

of the nipples and on the right scapula. The rectal temperature and heart

rate response were manually recorded every minute of exercise. After each

trial, the subject and apparel were measured together to provide a measure

of evaporative water loss.

2.3. Results and Discussion :

2.3.1. Aerodynamic properties of racing apparel :

Nude mannequin drag measurements were quite consistent however the apparel measurements displayed large variations which appeared dependent upon the amount of wind-induced movement in the supposedly close fitting suits. As a result of this observation, all furthur trials were photographed pre and post wind exposure to quantify, by planimetry, the effect of wind on the projected (frontal) area of the mannequin. In addition, custom-fitted suits were sewn for the mannequin. The results of this investigation confirmed that measurement of aerodynamic drag on a human form clothed in various apparel could discriminate apparel-induced changes in drag force on the mannequin at various wind speeds. With the procedural modifications noted above, a study of the aerodynamic drag associated with several running apparels was conducted. This investigation is presented as Chapter 3 of this thesis.

2.3.2. Thermal properties of racing apparel :

The results of the pilot investigation on the thermal effects of the various suits on performance are presented in Table 2-2. The Ba and T suits were found to have extremely limited two-way stretchability and would not

TABLE 2-2: THERMOREGULATORY, CARDIAC AND SUBJECTIVE RESPONSES OF ONE SUBJECT TO SIX TYPES OF RUNNING APPAREL AT 23°C.

	SS	K	W	B	Ba	Apparel T
Total Running Time (min)	20	20	18	20	–	–
Mean Heart Rate (b·min⁻¹)	168	176	172	170	–	–
Final Rectal Temperature (°C)	38.0	38.1	39.0	38.3	–	–
Increase in Rectal Temperature (°C)	1.0	1.1	1.0	1.1	–	–
Body and Suit Weight Loss (kg)	.38	.25	.55	.24	–	–
Subjective Stretch & flexibility rating	excellent	very good	poor	good	intolerable	intolerable

permit normal running movements. The W suit was found to become intolerably hot after 18 minutes of running and was rated as 'poor' in flexibility and stretch. This was the only suit in which core temperature exceeded the criterion value of $39^{\circ}C$ within 20 minutes of exercise. The K and B suits appeared comparable to the SS assembly in terms of rate of core temperature increase and final attained rectal temperature. The K suit was associated with a higher heart rate (176 b·min^{-1}) than the SS apparel (168 b·min $^{-1}$) however the significance of this finding could not be determined from data on a single subject. The technique of measuring body weight loss while the subject was wearing the suit was found inappropriate because the weight of sweat retained in the apparel could not be determined. Overall, the results of this investigation suggested that the K and B suits were comfortable enough to wear for long periods and did not quickly overwhelm an individual's thermoregulatory ability during work. An extended investigation of the thermal properties of SS, K and B apparel and a commercial suit of nylon/spandex (L) was initiated. This investigation is described in Chapter 4 of this thesis.

3.0. The influence of apparel on aerodynamic drag in running :

3.1. Introduction :

Systematic measures to reduce aerodynamic drag in running have not yet
been developed. 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 the races had taken place at sea
level. Air density is reduced approximately 23.5% at the altitude of Mexico
City (2,300 m) which reduces the drag and coincidently, the oxygen tension
of inspired air. In the Mexico City games, Pugh (176) found a 6% reduction
in performance at distances beyond 800 m. In the middle and long distance
events, it is probable performance benefits, attributable to reduced drag,
were obscured by the more debilitating effect on performance of impaired
oxygen uptake at this altitude. Aside from a diminished air density,
reductions in projected area or drag coefficient will decrease drag force
and allow maintenance of a higher forward velocity without additional energy
expenditure. At present, there is little information on the dependence of
C_D or Ap on 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 Ap through the various phases of running which suggests that Ap may
not be reduced substantially through style or posture modification.

An athlete's Ap 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.

3.2. Materials and methods :

All experiments were conducted in a 2.4 x 1.6 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 1.4 m
tall store display mannequin. Use of the 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 kgf. During a
three day period, drag cell calibration varied by $\pm$ 0.53%. Wind velocity

was calculated from the dynamic pressure q ($q = 0.5 \cdot \rho \cdot V^2$) which was measured with a pitot-static tube placed 33 cm above the floor of the tunnel, 58 cm lateral and 1.1 m anteriorly to the mannequin. Pressure readings were recorded with a Wilh lambrect Gottingen (type 655M16) manometer. Daily measurements of ambient temperature and pressure in the tunnel revealed slight variations in the air density, ρ , throughout the investigative period, from 1.186 to 1.191 kgf·m^{-3}. These variations were corrected for in the final calculations.

Considerable care was exercised to ensure the accuracy of projected area (Ap) measurements. The effects of parallax were reduced by means of a small mirror placed on the chest of the mannequin which was used to allign the reflection of a camera lens in the ground glass viewfinder of a 35 mm 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 (1) with a wig and (2) 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

9.7 m·sec^{-1}, respectively. The selection of air velocities, commonly observed in competitive athletics, eliminated the confounding influence of a change in Reynold's number on C_D since the effects of Reynold's number on C_D are constant at velocities below 18.5 m·sec^{-1} (Pugh 1976, Davies 1980b).

In a second series of experiments, drag measurements were taken on the K suit after it was modified by the addition of a rounded foam block to the dorsal area of the suit to form a more aerodynamic shape. Thirdly, 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 100 m dash trial of the K suit was conducted on a regulation 400 m synthetic surface running track. Visible light sensors and light sources (model 63501, Lafayette Instrument Co., Lafayette, IN) were established 100 m apart at regulation start and finish lines while an electronic clock (model 54427-A, Lafayette Instrument Co., Lafayette, IN), calibrated to .01 sec, was positioned near the start line. Nineteen male volunteers ($\bar{x}$ age: 22 years) ran 1.6 km and stretched for ten minutes prior to running four maximal sprints of 100 m. None of the subjects were actively sprint training but all subjects were athletically active and all ran a minimum of 20 km·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

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then reversed for the last two 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 full subjective recovery (3 to 5 minutes) prior to each trial. All trials were conducted over a 3 hour period, at an ambient temperature of $14^{O}C$ against a variable headwind of .17 to 2.03 $m \cdot sec^{-1}$, 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.

3.3. Results :

Pre and post wind exposure photographs provided projected areas which were within $\pm$ 4.8% in all conditions except RS, where projected areas decreased by as much as 8.3%. Since the actual Ap during the wind exposure are unknown, all calculations have been based on an average of the pre and post wind exposure values. Results of the Nu and SS conditions are shown in Table 3-1.

3.3.1 Errors of measurement :

Methodological error of the measurements should be noted before comparison of the results with other published reports on which some of the common errors noted here were not considered. The test-retest reliability

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TABLE 3-1: 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 (m²)	Wind Velocity (m·sec⁻¹)				ρ (kgf·m⁻³)	C_D *
		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, bald	.313	.350	.336	.329	.332	1.1910	.95
SS	.323	.360	.354	.358	.353	1.1910	.97

* at a velocity of 7.1 m·sec⁻¹

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of the apparatus was determined to be within $\pm$ 1.5% (at velocities of 8.8 and 9.7 m·sec^{-1}). This value incorporates a $\pm$ 0.53% 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) the alteration of laminar air flow in the tunnel by the projected area of the mannequin. The effect of a turbulent floor boundary layer, about 5 cm 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 m·sec^{-1}, respectively) of the A_D 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 conditons. More seriously, the ratio of mannequin frontal area to tunnel cross-sectional area (0.80) 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.

3.3.2 <u>Aerodynamics</u> :

A comparison of the aerodynamic characteristics of various apparels at four air velocities is presented in Table 3-2. For comparative purposes,

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TABLE 3-2: SHOWING PERCENTAGE CHANGE IN (A_D) WITH VARIOUS APPAREL CLOTHING A MANNEQUIN AT VARIOUS WIND VELOCITIES

Apparel	Wind Velocity ($m \cdot sec^{-1}$)			
	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
K + H + foam	−	−	− 8.2	− 9.2

results were first converted to drag areas, A_D where:

$$A_D = Ap \cdot C_D = D/0.5 \cdot \rho \cdot V^2 \qquad\qquad Eq.\ 3-1.$$

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, reflecting clothing design and fabric properties of stretch and drapeability. Current, commercially available running apparel (SS, L, RS) provide considerably higher drag than the T and K skin-tight body suits. The L suit, while form fitting, was observed to stretch and billow in the wind, thus increasing Ap and drag on the mannequin.

The aerodynamic advantages of bodysuits composed of T and K fabrics result from a combination of their surface sheen, stretchability and the suit design. At high speed ($V = 9.7$ m·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 m·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 m·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.

An attempt to provide a more aerodynamic shape by the addition of foam to the back of the K + H suit resulted in a further slight reduction in drag, the magnitude of this effect however only bordered the $\pm$ 1.5% test-retest reliability of the apparatus.

3.3.3. Energy Expenditure :

While the K fabric appears to have impressive drag reduction characteristics, the importance of this property to 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 ($m \cdot sec^{-1}$) with no relative wind speed with subjects wearing standard SS apparel was determined to be:

$$E = 0.00775 + 0.2485V \qquad \text{Eq. 3-2.}$$

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

$$Ew = (C_D \cdot Ap \cdot \rho \cdot V^3)/(2 \cdot F \cdot M \cdot e) \qquad \text{Eq. 3-3.}$$

where Ap is in m^2, M is the subject's mass in kgf, ρ is in $kgf \cdot m^{-3}$, V is the athlete's velocity in $m \cdot sec^{-1}$ 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 (eg. Cavagna, Saibene and Margaria 1964, Kyle 1979, Zacks 1973) have suggested a value of e = .4. In the present analysis, the weight of the mannequin and all running apparel was converted to a human equivalent weight of 45.45 kgf. 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. 3-2. The reduction in energy required to run at equivalent velocity with the K + H suit is then given by addition of an Ew term to Eq. 3-2 calculated from the different Ew values between SS apparel and the K + H suit at a specific running velocity. For example, at a velocity of 7.1 $m \cdot sec^{-1}$, E = 1.7721 $KJ \cdot kg^{-1} \cdot min^{-1}$ and Ew_{SS} = $0.0006099V^3$ while Ew_{K+H} = $0.0005342V^3$. Thus the total energy expenditure of a subject wearing the K apparel will be less than while wearing the 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 SS apparel. Solution of the quadratic Eq. 3-4:

$$1.7721 = 0.00775 + 0.2485(V) - 0.0000757V^3 \quad \text{Eq. 3-4.}$$

gives the new velocity resulting from reduction in drag due to the K + H apparel compared with SS. Thus, V_{K+H} = 7.215 m·sec^{-1} compared with V_{SS} = 7.1 m·sec^{-1}. Over 1500 m, this 1.62% increase in velocity would translate into an impressive decrease of 3.37 sec for a 1500 m race. Results of similar calculations comparing SS and K + H apparel over a range of velocities are provided in Table 3-3. 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 body suit has not been determined although the latter would be minimal with the K material.

3.3.4. Effect of runner position :

The effect of runner position and spacing on drag at a velocity of 7.1 m·sec^{-1} is presented in Table 3-4. Distances indicated on the axes are 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 to the drag when the subject was not in the tunnel. Extending earlier comments on blockage, the presence of another object in the tunnel was considered to increase the measured drag by approximately 24% in the worst case in which mannequin and subject were side by side, 0.5 m apart. Blockage effects were minimal when one object was directly ahead or behind the other. In addition, the inability of the human subject to maintain a constant position at various grid coordinates would decrease the

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TABLE 3-3: EFFECT OF SINGLET AND SHORTS (SS) AND A ONE PIECE SUIT (K) ON PREDICTED RACE TIMES FOR VARIOUS DISTANCES

	BASE VELOCITY (m·sec⁻¹)	TIME TO COMPLETE IN APPAREL		TIME DIFFERENCE (min:sec)	PERCENT DIFFERENCE
	BASE VELOCITY $(m \cdot sec^{-1})$	SS	K	TIME DIFFERENCE (min:sec)	PERCENT DIFFERENCE
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

TABLE 3-4: SHOWING DRAG AS A % OF REFERENCE DRAG IN DRAFTING AT A VELOCITY OF 7.1 m·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

accuracy of these measurements. For maximum effect, the optimal distance to draft behind a lead runner was 1.0 m. At a velocity of 7.1 m·sec^{-1}, mean savings of 62.7 and 53.1% in drag could be attained by following 1.0 and 1.5 m, respectively, behind a lead runner. By combining Kyle's (1979) formula for speed increase with drafting (Kyle 1979: equation 14) and the data collected on the mannequin, the drag reduction at a velocity of 7.1 m·sec^{-1} may be determined to be:

$$1.7721 = 0.00775 + 0.2485V - 0.0006099V^3 n \qquad \text{Eq. 3-5.}$$

where n is the fractional reduction in drag due to shielding (equivalent to .531 at a spacing of 1.5 m). Solution of Eqn. 3.5 with n=.531 gives a velocity of 7.69 m·sec^{-1} which would provide a time saving of 4.32 sec per 400 m lap.

3.3.5. Combined effect of position and clothing on drag :

The influence of clothing on drafting efficiency is presented in Table 3-5 in which the human subject and mannequin were alternately 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 1.5 m spacing between runners, the following runner could develop a velocity of 7.77 m·sec^{-1} while drafting at an energy expenditure equivalent to a velocity of 7.1 m·sec^{-1} when unprotected. (Note that for this analysis, the constants of Eq. 3-5 were changed from

TABLE 3-5: SHOWING DRAG AS A % OF REFERENCE DRAG IN DRAFTING AT A VELOCITY OF 7.1 m·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* 103.2**	93.8 94.0	45.9 56.7
1.0	105.9 102.7	93.8 88.4	30.6 39.6
0.5	105.9 109.0	87.8 96.3	– –
0	126.1 122.2	– .104.6	Mannequin
0.5	100.8 104.4	91.9 102.3	94.3 97.9
1.0	92.8 98.8	92.4 97.9	92.1 96.5
1.5	91.6 98.6	92.4 98.4	93.8 98.1

0.2485 to 0.2445 and from 0.0006099 to 0.0005342, respectively). This velocity would allow a 4.86 second time saving per 400 m lap, which is superior to the time saving achieved wearing SS apparel.

3.3.6. Results of the K suit field trial :

ANOVA 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 wore one apparel and then the other in trials 2 and 3, a paired t-test was conducted to determine apparel induced differences between trials 2 and 3. The mean time with the K suit ($\bar{x}$ = 13.46 seconds) was found to be significantly lower ($p \leq .025$) than with the SS apparel ($\bar{x}$ = 13.62 seconds). This advantage translated into a time saving over 100 m of 1.17%.

3.4. Discussion :

The baseline aerodynamic drag data derived in this investigation are in agreement with other published measurements performed on humans and models (Table 3-6). Substantial errors in drag measurements may result from failure to compensate for blockage effects in small tunnels. With the exception of Ingen Schenau (1982), most researchers have ignored this

TABLE 3-6: DRAG INDICES DERIVED IN THE PRESENT EXPERIMENT AND FROM PREVIOUS INVESTIGATIONS

SOURCE	CONDITION	A_p (m²)	c_D	A_D (m²)
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 et al.(1978)	clothed human, standing	.55	1.18	.649
Kyle(1979)	clothed human, standing	–	.95–1.14	–

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 precipitated a sharp decline in C_D. Thus, logical comparisons between apparels over all velocities could be performed.

Penwarden, Grigg and Rayment (1978) considered their frontal area measurements accurate within ± 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 Ap of walkers pre and post exposure to an airstream due to flattening of apparel against the body. While the 4.8% range in Ap noted here is of similar magnitude, the occurence of a larger Ap post wind exposure indicates that the airstream may catch loose flaps in the material and thus introduce unsuspected error in susequent drag measurements. Given the problems encountered in photographing Ap during actual wind exposure and the inaccuracies common to Ap measurement, it would appear more meaningful to express drag results as non dimensional ratios. While the present static results may not be directly generalized to the kinetic case, nonetheless they provide an appropriate starting point on which to base further investigations.

3.4.1. Practical aerodynamic advantages of new K and T apparels :

Current running apparel, based on conservative tradition rather than efficient function was found to be deficient aerodynamically. By wrapping

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the runner in a shiny, skin-tight suit which covers hair and sharp edges and thus reduces Ap, significant aerodynamic advantages may be realized. At sprint speeds a hood over the hair is responsible for the largest portion of drag reduction. Individuals with thick body hair and those racing at longer distances appear to be able to benefit from the tight fit and high sheen of the K suit as well as the presence of a hood. In the present investigation, the T and K suits were manufactured from the same pattern so that fabric characteristics are the most likely source of variation in drag associated with these apparel. 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} indicates that these suits have significant potential for drag reduction in practical race situations. The lower drag of the K suit at all velocities indicates that it has a better contour fit and a higher sheen than the T fabric.

The advantages of drag reduction are clearly revealed when presented as the respective theoretical reductions in time required to complete standard race distances. The advantage of wearing the K suit increases from 1.05% in a marathon to 2.75% in a 100 m sprint (Table 3-3). This increased effect is a consequence of the higher velocity produced in short events 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 (1980b) suggested that the effect of drag in the 100 m sprint is critical during the last 60 m only since the athlete is travelling at a relatively low velocity during the first 40 m. Nonetheless,

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Davies estimated that the elimination of drag at a forward velocity of 10 m·sec^{-1} would decrease the 100 m time by .25 to .50 sec. If the current estimation of a .284 sec decrease in 100 m 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 100 m field trial, non-sprinters, without benefit of competition, starting blocks or spiked shoes, improved their 100 m sprint time by 1.17% with the K apparel. This improvement corresponds favourably with the conservative value of 1.65% calculated for a higher velocity (9.7 m·sec^{-1} vs 7.43 m·sec^{-1} in the field trial). The time saving in 100 m at a velocity of 7.43 m·sec^{-1} supports the theoretical time saving estimates for longer races (Table 3-3). Streamlined apparel would find greatest application in world class competition where the margin of victory is often much less than the apparel-induced time saving determined in this study. As discussed below, drafting strategies in middle distance races may also utilize streamlined apparel advantageously.

3.4.2 <u>Drafting strategies utilizing new apparels</u> :

Although several authors have estimated the effects of drafting by means of oxygen consumption measurements (Davies 1980b, Pugh 1971), drag measurements on cylindrical models (Shanebrook and Jaszczak 1976), air pressure changes behind a subject on a treadmill (Pugh 1979) or coastdown tests (Kyle 1979), the present analysis represents the first attempt to measure drafting effects on a human model in a wind tunnel. The 62.7% reduction in drag with shielding noted for a 1.0 m spacing (V = 7.1 m·

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 observations of a 1.0 sec per lap advantage under race conditions (Pugh 1971). Davies (1980b) reported that shielding will reduce drag by 80 to 85% with a potential saving of 1.0 sec per lap (V = 6.0 m·sec^{-1}) although he did not provide calculations to support this estimate. Kyle (1979) proposed that a 40% reduction in drag at a 2.0 m spacing would provide a 1.66 sec per lap advantage (V = 7.0 m·sec^{-1}). The value of 53.1% noted here for a 1.5 m spacing is similar to Kyle's estimate although the present calculations suggest a larger advantage of 4.32 sec per lap. The discrepancies between theory and Pugh's (1971) direct observation are probably due to (a) a following runner being unable to follow consistently within 1 to 1.5 m of a front runner and (b) variations in drafting efficiency as a front runner alters his/her posture, changing his Ap and converting potential drag to body lift (Davies 1980b). A third possible mechanism may be proposed from drag measurements taken with the human subject positioned 0.5 m lateral to the mannequin. Although the true result of this effect was somewhat obscured by a substantial blockage effect, it was nonetheless evident that as the following runner shifted laterally closer and abreast the leader, the drag on the leader (and presumably, on the follower) would exceed the drag experienced by the leader alone. This effect occurs because the combined Ap of the two runners will result in a larger shared drag than either runner would encounter alone.

3.4.3 Optimal strategy for drafting :

Kyle (1979) and Davies (1980b) have proposed that the optimal strategy for middle distance racing is for the eventual winner to be shielded by clubmates until the last straightaway. The current results suggest an extension to 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 additional thermal load on a runner 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 $\dot{V}o_2$max 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 aerodynamic and thermodynamic advantages for longer distance events.

4.0. Thermal characteristics of athletic racing apparel :

4.1. Introduction :

The foregoing wind tunnel investigation has revealed that current racing apparel is aerodynamicallly deficient. By wrapping the runner in a shiny, skin-tight suit which covers hair and sharp edges, a significant aerodynamic advantage was realized, amounting to 1.17% in the 100m dash at a velocity of 7.43 $m \cdot sec^{-1}$. Unfortunately, wearing a whole body suit may add a substantial thermal stress to endurance performance. Since thermoregulation is the prime limiting factor in exhaustive endurance exercise, efficiency of heat dissipation is an important consideration in the design of any aerodynamically styled running suit.

Using apparatus which measures resistance to water vapour flow, Farnworth and Dolhan (1984) and Mekjavic et al. (1986) measured the vapour permeability of several stretchable and nonstretchable fabrics (Table 2-1). From these results, subjective impressions of stretchability and the results of the previous aerodynamic study, two stretchable, water vapour permeable fabrics (K: Kuwata and B: Bion II) were manufactured into whole body suits for physiologic tests at ambient temperatures of 0° and 25°C. The purpose of the present investigation was to determine if thermoregulatory and cardiorespiratory responses to prolonged exercise were equivalent in commercially available and newly developed running apparels.

4.2. Methods :

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4.2.1 Subjects :

Six male subjects underwent a medical examination and gave their written informed consent to serve as subjects. All subjects were highly trained and competed at either a collegiate or national level in middle and long distance running events. Physical and physiological characteristics of the subjects are shown in Table 4-1. Body surface area was calculated from the Dubois nomogram (Dubois and Dubois 1916).

4.2.2. Apparel :

Two types of commercially available running apparel (SS: singlet and shorts; L: nylon/spandex bodysuit) were compared with whole body suits of special materials (K;B). The fabric composition of the four apparels were: SS: 100% nylon; L: 82% nylon, 18% spandex; K: 82% nylon, 18% spandex with a surface coating of 100% polyurethane; B: 82% nylon, 18% spandex exterior with an inner lining of microporous polyurethane protected by a 100% nylon interlock. All suits were secured in sizes to fit the subjects comfortably. Suit colours were chosen to minimize radiant heat adsorption. During tests under cold conditions, a long sleeve, 100% cotton t-shirt was added to the SS apparel to simulate cool weather racing apparel more accurately. The K and B suits were somewhat heavier (K: 0.397 kgf; B: 0.438 kgf) than the SS and L apparel (SS: 0.132 kgf; L: 0.256 kgf) although the addition of a t-shirt to the SS apparel reduced this weight differential somewhat (weight of SS for cold trials: 0.269 kgf). After each trial all suits were machine washed and dried. With the exception of the K suit

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TABLE 4-1: PHYSICAL AND PHYSIOLOGICAL CHARACTERISTICS OF THE SUBJECTS

Subject	Age years	Height cm	Weight kg	VO_2 max $ml \cdot kg^{-1} \cdot min^{-1}$	Surface Area m^2	Main Competitive Event	Best Time Performance minutes
BB	30.9	167	58.3	77	1.6	Marathon 42.195km	2hr:14min
BR	21.7	180	62.6	74	1.8	5,000 m	14:50
JG	21.6	173	58.8	68	1.7	1,500 m	3:55
GM	21.2	171	68.0	68	1.8	5,000 m	14:52
RC	24.2	173	63.5	80	1.8	10,000 m	30:05
TL	29.8	186	73.8	68	2.0	10,000 m*	33:10
Mean	24.9	175	64.1	73	1.8		
S.D.	±4.4	±6.8	±5.9	±5.3	±0.1		

* Subject is an "A" level squash player

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(which displayed some delamination of the polyurethane coating at seam edges) all apparels retained form and integrity during the course of the investigation. Although the suits were to be measured after the investigation to acertain changes in vapour permeability, this has not been performed to date to maintain the integrity of the suits for further physiological tests.

4.2.3 Design :

Subjects were at first scheduled to perform eight separate bouts of prolonged exercise (30 minute maximum) in a 2 x 4 repeated measures matrix of temperature ($0^{o}C$, $25^{o}C$) and apparel (SS,L,K,B). Due to a technical breakdown of the cooling function of the environmental chamber after the start of the experiments, all $25^{o}C$ tests were performed prior to the $0^{o}C$ tests. However, each subject did complete four trials at each temperature wearing apparel chosen in random order. Subjects were instructed not to eat or consume caffeinated beverages for 2 hours prior to a trial and subjects performed each trial at the same time of day, with a 1-3 day interval between consecutive trials to minimize circadian variations in core temperature and chronic fatigue (Aschoff 1968).

4.2.4 Protocol :

All tests were conducted in a 4 x 5 x 2.5 meter environmental chamber with temperature and humidity maintained at either $0^{o}C$ or $25^{o}C$ $\pm$ $1^{o}C$ DB and 50 $\pm$ 10% RH respectively. Each athlete maintained a

constant work rate approximating 80% of his $\dot{V}O_2$max by running on a motor

driven treadmill (Quinton, Seattle, WA) for a period of 30 minutes. The

treadmill speed was calibrated prior to the experiments and was checked

again at the end of the experiments. A two fan combination (Panasonic model

F1608C and Dayton model 3C 155, Estrin Manufacturing, Vancouver, B.C.)

provided an air flow which averaged 4.2 m·sec^{-1} over the subject's

frontal area. The wind velocity was measured by an anemometer (model W131,

Weather Measure Corp., Sacramento, CA). In all trials, each subject

provided his own cotton socks and racing shoes. Once a subject was weighed

and connected to thermal and cardiorespiratory analysis equipment (elapsed

time: approximately 30 minutes), he ran for 5 minutes at a pace of 3.1 m·

sec^{-1} on the treadmill. At the end of 5 minutes, the treadmill speed

was increased and the subject ran continuously for 30 minutes, until

volitional fatigue or until core temperature (rectal: Tre) exceeded

39.0^{o}C. This temperature was considered a safe standard which would not

normally be exceeded in 30 minutes of exercise at 80% of $\dot{V}O_2$max at an

ambient temperature of 25°C.

4.2.5. Thermal Data :

Prior to being weighed, subjects inserted a rectal thermister (YSI

model 43TD: Yellow Springs Instrument Co.,Inc.) approximately 15 cm past the

anal sphincter. Each subject was then weighed in shorts pre and post

exercise on a beam balance sensitive to $\pm$ 50 g with each item of clothing

weighed pre and post exercise on a Berkel balance (Berkel Products Ltd.,

Toronto, Ont.) accurate to one gram. Sweat production was calculated

from weight loss after correction for respiratory gas exchange (Snellen 1966). Skin temperatures were measured from four multistrand copper-constantan thermocouples (Omega Scientific, Stamford, CT) placed at the left lateral calf, left hand, forehead and lower back. Mean skin temperature (Tsk) was calculated from the regression equation of Nielsen and Nielsen (1984). To allow normal heat flux at the skin surface, the welded end of each thermocouple rested against the skin inside a 9mm hole in an adhesive backed corn plaster.

4.2.6. Heart rate :

Heart rate (HR) was determined from an electrocardiograph (Fukada Denshi model FD-13, Overseas Monitor Corp., Vancouver, B.C.) using Medi-Trace F23T disposable foam backed electrodes (Graphic Controls, Gananoque, Ont.) applied bilaterally at the mid-axillary line at the level of the nipples and the right scapula. The problem of mechanical interference caused by suit fabric rasping on the electrodes was prevented by taping small plastic cups over the electrodes. All leads from electrodes and thermocouples were gathered into a single umbilical suspended above the running subject which led to a HP3497A Data Logger coupled to a HP85 microprocessor (Hewlett Packard, Richmond, B.C.). The data logger provided a $0^{o}C$ reference voltage for the thermocouples. All thermal and cardiac variables were sampled every 10 seconds and displayed every minute by the data logger.

4.2.7. Respiratory gas exchange :

While running, each subject breathed through a low resistance two-way valve (Hans Rudolf Inc., Kansas City, MO). Inspired air was drawn through a pneumatic turbine (model VMM, Alpha Technologies, Laguna, CA) to measure ventilation. Expired air was directed through a 5 liter mixing chamber connected to S3A oxygen and CD3A carbon dioxide analysers (Applied Electrochemistry Inc., Sunnyvale, CA) which sampled at the rate of 300 ml·min^{-1}. The overall resistance to breathing measured 1 cm·H_2O·l^{-1} min^{-1} during inspiration and 2 cm H_2O·l^{-1}· min^{-1} during expiration. Analog signals from these instruments were sampled and digitized through an HP3497A data logger connected on line to the same HP85 microprocessor used for thermal measurements. A basic data acquisition program controlled the sampling rate of the HP 3497A and computed 10 second values of $\dot{V}O_2$, carbon dioxide production ($\dot{V}CO_2$), minute ventilation ($\dot{V}E$) and the respiratory exchange ratio (R). These values were averaged over one minute intervals and displayed. Nonsynchronization between turbine flow signals and gas analyser signals introduced by connective tubing delays, flow dependent characteristics of the mixing chamber and different rise times of the analysers were measured and compensated by appropriate algorithms in the microprocessor software. The turbine calibration was initially checked by drawing air through the turbine at known flow rates upto 140 l·min^{-1} by a motor-driven bellows and required no daily adjustment. Prior to each day's experiments, the gas analysers were calibrated from room air and precision gas samples which had been checked by chemical analysis. The validity of the system was determined during a series of maximum aerobic capacity tests for which respiratory variables

were compared with minute value measurements calculated from expired gas collection by the Douglas bag technique. The mean difference between the two techniques was $\pm$ 1.6%.

4.2.8. Maximum oxygen uptake :

Prior to participation in the main investigation, each of the six subjects completed a ramp treadmill test to exhaustion. Tests were performed in the environmental chamber, at room temperature ($20^{o}C$). Subjects wore normal nylon singlet and shorts, were weighed and ECG electrodes were attached as previously described. A subject warmed up by running on the treadmill at a 2% incline for 5 minutes at 9.7 $km \cdot hr^{-1}$ (2.68 $m \cdot sec^{-1}$). The subject rested briefly while a mouthpiece and nose clip were inserted and then began a ramp incremental speed run to volitional fatigue during an 8-10 minute period during which the opposing wind force was held constant at 4.2 $m \cdot sec^{-1}$ and treadmill speed was increased by .8 $km \cdot hr^{-1}$ every 30 seconds (Whipp et al. 1981). $\dot{V}O_2max$ was observed as the final oxygen uptake during the last 30 seconds of exercise.

4.2.9. Subject Questionaire :

Subjective impressions of the comfort of running in each apparel under environmental conditions were assessed by means of a simple questionaire presented to subjects after each trial. The questionaire queried subjects about: (1) their perceived exertion (Borg Scale; Borg 1982), (2) cold, hot, or uncomfortable areas of each suit and (3) the suitability of each apparel

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for 1,500 and 10,000 meter races and for high intensity training.

4.2.10. Data Analysis :

One of the six subjects was found to have a compromised

thermoregulatory ability due to a history of several hyperthermal episodes.

At $25^{\circ}C$, this subject was able to tolerate the K suit for only 10

minutes and the data from this subject for all warm temperature trials was

subsequently deleted. The non-random sequence of hot and cold trials

imposed by the technical failure of the environmental facility produced a

serious limitation on the validity of warm and cold test comparisons

originally made by the conceived analysis. Subsequently, therefore, all

analyses for warm and cold tests were conducted separately. Due to the

limited tolerance of subjects in the B and K suits at $25^{\circ}C$, only the

first 17 minutes of cardiorespiratory and thermoregulatory responses of the

subjects while wearing different suits were compared under the warm

conditions. Results for all dependent measures (with the exception of $\dot{V}E$,

$\dot{V}O_2$, HR and Tsk) were subjected to a one way analysis of variance

(ANOVA) for repeated measures with no grouping factor. Cardiorespiratory

and skin temperature measures were analysed by a two way ANOVA for repeated

measures with no grouping factor (Dixon 1983). Repeated measures ANOVA

require the assumptions of normality and homogeneity of variance required by

any ANOVA together with the assumption that the correlation among pairs of

the repeated variable are constant (Howell 1985). This assumption is

routinely violated in many experiments and has been modified in the current

analysis by narrowing the acceptance region of each hypothesis through a

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conservative technique termed the Huynh-Feldt correction (Dixon 1983). In any analysis, a large number of analytical comparisons will lead to more Type I errors when the null hypothesis is true and there are thus more significant differences reported than have actually occurred. This phenomenon, termed familywise error rate (FW) was controlled in the current analyses by use of the Tukey analysis of critical differences to locate significant differences between group means. The Tukey test maintains the FW rate at a constant level (in this case α = .05) for the entire set of pairwise comparisons (Keppel 1982).

4.3. Results :

4.3.1. Warm conditions (25°C):

In each trial five subjects ran at a constant velocity of from 4.25 to 4.92 m·sec^{-1} which required 79% (S.D. = $\pm$ 7%) of the group mean $\dot{V}O_2$max at a group mean HR of 154 (S.D. = $\pm$ 11) b·min^{-1}. Ignoring differences between apparels, the mean sweat rate was 1.6 l·hr^{-1}. During each subject's first 17 minutes of exertion, Tsk, HR, $\dot{V}O_2$ and $\dot{V}E$ all displayed significant increases (p $\leq$ .001) with time however there were no significant apparel effects or apparel by time interactions. These equivocal results suggest that within the accuracy of laboratory measurements, no significantly different cardiovascular demand is made on an individual running in a suit made of any of the materials at 25°C, 50% RH during a period of 17 minutes. Group mean HR data for the first 17 minutes of exercise is shown in Figure 4-1. The relationship of the HR

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Figure 4-1 : Mean heart rate response of five subjects to four types of running apparel at 25 oC
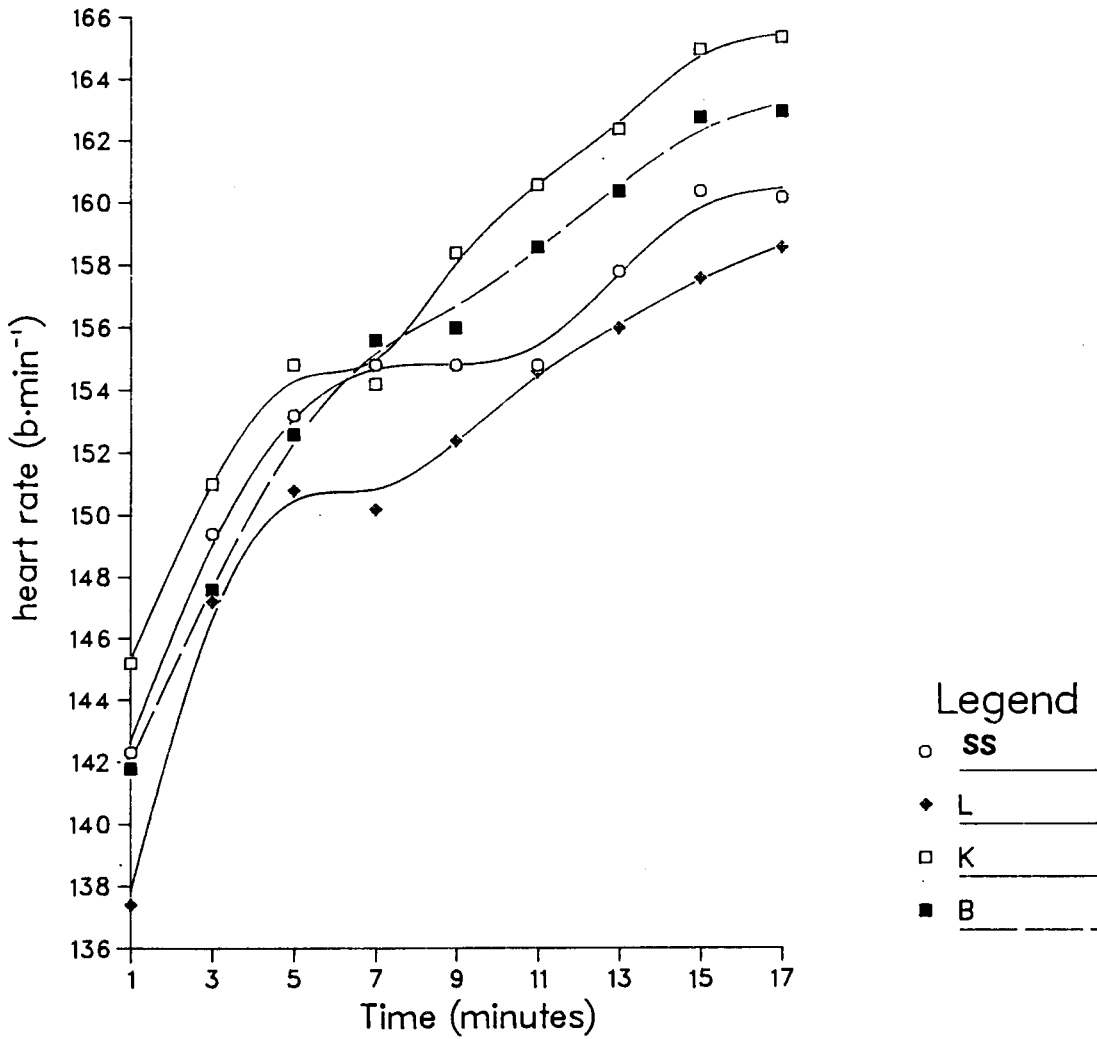
TABLE 4-2: Thermoregulatory, cardiorespiratory and subjective responses of five subjects to four types of running apparel at 25°C. Mean values (±1 S.D.) with different subscripted letters are significantly (p<0.05) different.

	SS	L	K	B
Total running time (min)	29.6a (0.9)	30.0a (0.0)	21.4b (3.5)	24.2b (4.7)
Oxygen uptake ($l \cdot min^{-1}$)	3.5 (0.2)	3.6 (0.4)	3.5 (0.3)	3.4 (0.3)
Minute Ventilation ($l \cdot min^{-1}$)	76 (10.6)	77 (12.0)	75 (11.4)	78 (10.2)
Heart Rate ($b \cdot min^{-1}$)	154 (9.4)	152 (10.1)	158 (13.2)	156 (10.0)
Mean Skin Temperature (°C)	30.9 (1.1)	31.5 (1.2)	33.0 (0.7)	32.3 (0.7)
Final Rectal Temperature (°C)	38.9 (0.1)	38.8 (0.2)	38.7 (0.5)	38.9 (0.1)
Increase in Rectal Temperature (°C)	1.8 (0.1)	2.0 (0.3)	2.0 (0.3)	2.1 (0.2)
Body Weight Loss (kg)	1.0 (0.3)	0.9 (0.2)	0.8 (0.1)	0.7 (0.1)
Body weight loss (% of initial weight)	1.4 (0.4)	1.4 (0.3)	1.3 (0.2)	1.0 (0.3)
Weight of Sweat in Clothing (g)	13.6a (9.2)	23.0a (12.4)	320.0c (50.5)	123.2b (37.9)
Sweatrate ($l \cdot hr^{-1}$)	1.8 (0.6)	1.7 (0.4)	1.5 (0.2)	1.3 (0.3)
Borg perceived exertion	1.8bd (1.6)	2.2cd (2.0)	4.2ac (3.7)	3.2cd (2.5)

results to a phenomenon termed 'cardiovascular drift' is discussed below.

At an ambient temperature of 25°C, 50% RH, the thermal stress of wearing the K and B suits exceeded the runner's volitional tolerance or critical core temperature elevation (set at 39.0^{o}C) after 21-24 minutes (Table 4-2). These limits of tolerance are significantly (p $\leq$ .01) less than the times noted for the SS and L apparel. Indeed, the thermal stress produced by the L apparel appeared extremely similar to that of the SS apparel however its form-fitting property was lost even under low wind conditions and the suit was observed to billow and flutter in the wind, resulting in a higher drag coefficient than with either tight fitting suit.

At 25°C the ability of subjects to evaporate sweat in the K and B suits was severely limited since the K suit retained 23 times and the B suit retained 9.1 times as much sweat as the SS apparel (p $\leq$ .01). Further considerations of the pre-post thermoregulatory results must be made cautiously since the K and B data were affected by the shorter endurance ability of the runners while wearing these suits. For example, the group mean final core temperature value (38.7^{o}C) was lowest with the K suit but this probably reflected the abbreviated running time of subjects in this suit rather than its superior heat dissipation qualities. In support of this view, the group mean perceived severity of exertion was significantly (p $\leq$ .05) higher wearing the K suit than while wearing the SS apparel. A questionaire distributed to subjects after each trial showed that 40% of subjects would consider wearing the L suit in a 1500 m race, but only 20% would consider wearing either the B or K suit in a 1500 m race and no subject would wear either B or K suit at race distances beyond 1500 m under similar ambient conditions as were presented to them in this section of the

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study.

4.3.2. Cool conditions (0°C):

In a cool environment the six subjects ran at a constant velocity of 4.25 to 4.92 m·sec^{-1}. This level of exertion required 80% (S.D. = ± 6%) of the group mean $\dot{V}O_2$max at a group mean HR of 152 (S.D. = ± 10) b·min^{-1}. At 0°C, all subjects easily tolerated 30 minutes of running in each of the four apparels. During 30 minutes of exercise, group mean $\dot{V}O_2$, $\dot{V}E$ and HR displayed significant increases (p ≤ .001). In contrast to the 25°C environment, the mean HR of the group of runners in the cool environment stabilized quickly and increased at a slow rate throughout the duration of each test (Figure 4-2). A qualitative difference in the rate of rise of HR between the 0°C and 25°C environmental conditions suggests that there was a reduced thermal stress imposed by the cool environment and a less severe cardiovascular adjustment was required than during the same exercise task in the hot environment. The high air permeability of the L suit resulted in excessive body cooling and limited the rise in rectal temperature to 1.4°C, significantly lower than the 1.7°C increase noted in the K and B suits (p ≤ .05) (Table 4-3). The simularity of core temperature increase during work in the cool environment between the SS apparel and any of the other ensembles (L, B, or K) is probably due to a limited sample size preventing clear definition of the relationship between suits on this variable. The weight of sweat retained in the K suit was significantly higher (p ≤ .01) than in the other apparels (11.1 times the weight of sweat retained in the SS apparel). No

Figure 4−2: Mean heart rate response of six subjects to four types of running apparel at 0 oC
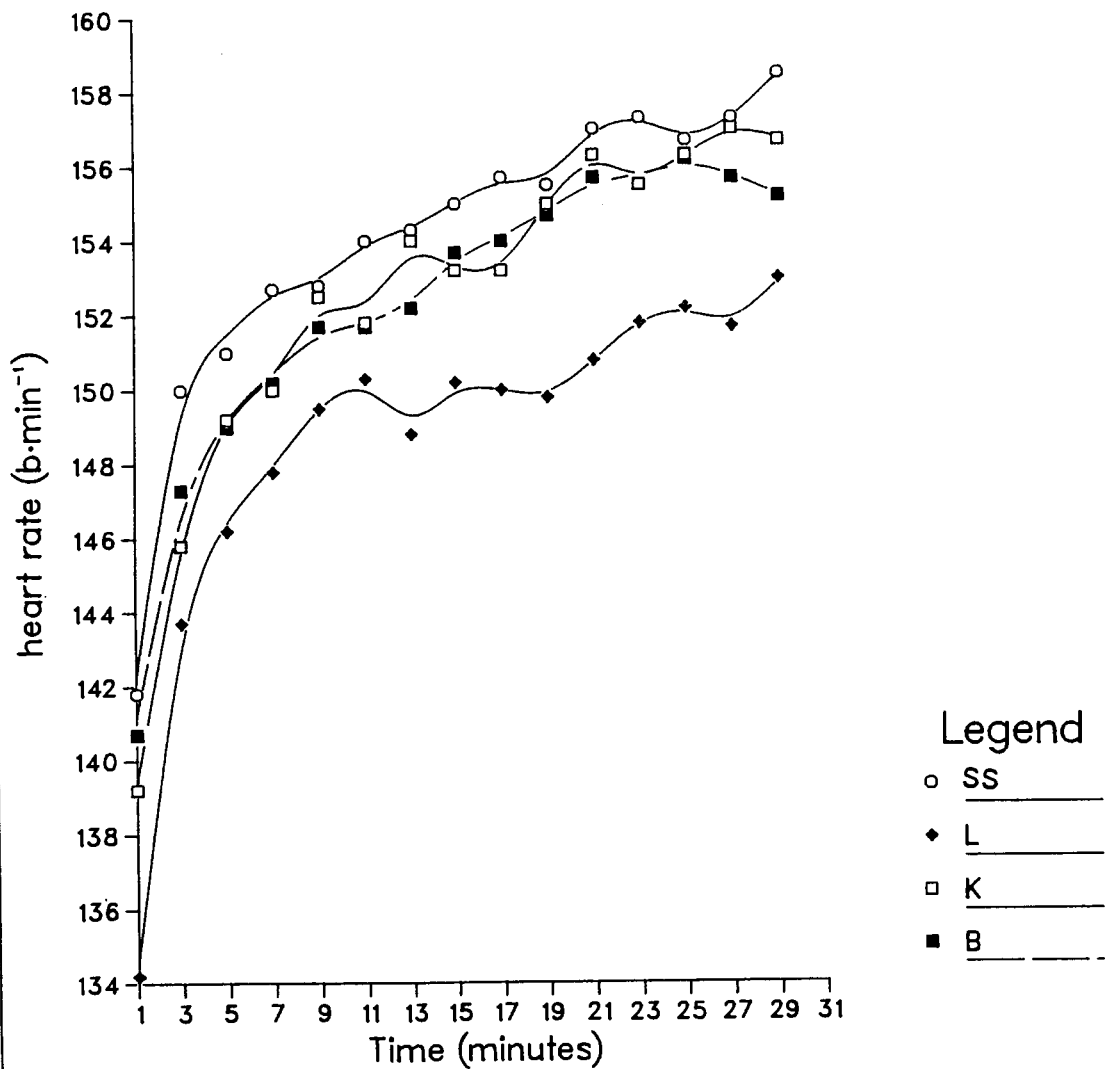
TABLE 4-3: Thermoregulatory, cardiorespiratory and subjective responses of six subjects to four types of running apparel at 0°C. Mean values (± 1 S.D.) with different subscripted letters are significantly (p < 0.05) different.

	SS	L	K	B
Total Running Time (min)	30.0 (0.0)	30.0 (0.0)	30.0 (0.0)	30.0 (0.0)
Oxygen Uptake ($l \cdot min^{-1}$)	3.8 (0.3)	3.7 (0.3)	3.7 (0.3)	3.7 (0.2)
Minute Ventilation ($l \cdot min^{-1}$)	82 (7.8)	80 (8.3)	81 (8.0)	82 (7.1)
Heart Rate ($b \cdot min^{-1}$)	154 (9.5)	149 (9.4)	153 (10.8)	152 (10.5)
Mean Skin Temperature (°C)	25.7 (1.4)	26.8 (1.1)	26.8 (0.8)	27.3 (0.9)
Final Rectal Temperature (°C)	38.4 (0.3)	38.2 (0.2)	38.4 (0.2)	38.4 (0.3)
Increase in Rectal Temperature (°C)	1.5ca (0.3)	1.4bc (0.3)	1.7a (0.2)	1.7a (0.2)
Body Weight Loss (kg)	0.4 (0.1)	0.4 (0.2)	0.6 (0.2)	0.4 (0.1)
Body Weight Loss (% of initial weight)	0.5 (0.1)	0.6 (0.4)	0.9 (0.3)	0.6 (0.1)
Weight of Sweat in Clothing (g)	13.3a (8.8)	6.3a (4.8)	147.5b (41.0)	30.3a (14.8)
Sweat Rate ($l \cdot hr^{-1}$)	0.6 (0.2)	0.7 (0.4)	1.0 (0.4)	0.7 (0.2)
Borg Perceived Exertion	2.2 (2.5)	2.3 (2.0)	3.3 (2.0)	3.0 (1.8)

other dependent measure differed significantly between tasks because of suit type suggesting that cardiovascular and thermoregulatory adjustments needed to wear the K and B suits continuously while running in a cool environment were minimal. Subjectively, subjects found the B suit thicker and more restrictive to movement and only 50% reported that they would consider wearing the B suit in competition. At least 67% of the subjects considered the SS, L, and K apparels suitable for 1500 and 10,000 m races at 0^OC.

4.4. Discussion :

The mean group sweat rate in runners performing work in a hot (25^OC) environment found in this investigation (1.6 l·hr^{-1}) is slightly lower than that found by Costill, Kammer and Fisher (1970) (1.93 l·hr^{-1}) for subjects running at 70% $\dot{V}O_2$max on the treadmill and by Pugh, Corbett and Johnson (1967) for a subject running a marathon at 23^OC (1.8 l· hr^{-1}). Nonetheless, the limited vapour permeability of the K and B suits caused excessive sweat retention in less than 30 minutes of exercise at 79% $\dot{V}O_2$max in the present experiment. Sawaka, Knowlton and Critz (1979) reported an average core temperature rise to 39.7^OC following 80 minutes of running at 70% of $\dot{V}O_2$max in seven subjects during treadmill running at an environmental temperature of $22-25^O$C. Since subjects in the current investigation either stopped running or reached the critical maximum core temperature designated for termination of the test (39.0^OC) in much less than 80 minutes, these suits must have negatively affected thermoregulatory efficiency and/or the subject's perception of thermal comfort. In running trials at 25^OC, the lack of significant differences

between dependent measures may be related to:

(1)the insensitive dependent measures;

(2) the confounding effect of limiting running time to the attainment of a designated critical rectal temperature for termination of the test;

(3) fatigue caused by the subjects' personal training programs;

(4) individual tolerances for thermal discomfort.

Stipe (1984) used $\dot{V}O_2$max as the criterion for determining differences in performance between nylon/spandex tights (pants) and nylon SS apparel during 6 minute trials at work rates requiring approximately 72 and 83% of a subject's $\dot{V}O_2$max. As in the current investigation no significant differences were found in the dependent measure attributable to the apparel. Katch, Sady and Freedson (1982) have reported that in repeated $\dot{V}O_2$max tests performed during a 2-4 week period, simple biological variability accounted for a range in $\dot{V}O_2$max values of some $\pm$ 5.6%. The magnitude of this variation probably exceeds any determinable apparel-induced difference in oxygen uptake while running under the different conditions. Thus, measurements of a subject's exercise $\dot{V}O_2$ is probably only sufficient to discriminate between relative work rates but does not have sufficient resolution to discriminate between different racing apparel worn by a subject under similar conditions of work rate and ambient environment.

Elite athletes were used as subjects in order to provide the most critical and realistic feedback on the potential mass use of these suits. Unfortunately, these athletes were involved in individual training regimes which demanded 110 to 150 $km \cdot wk^{-1}$ of running. Although testing was conducted during a non-competitive time of year, the results were

undoubtedly somewhat affected by each subject's chronic training fatigue.

The group mean core temperature noted in subjects wearing both the SS and L apparels at the termination of 30 minutes of exercise at 25°C (38.9^{o}C $\pm$ 0.1^{o}C and 38.8^{o}C $\pm$ 0.2^{o}C) suggests that the practice of stopping a trial upon attainment of a core temperature of 39.0^{o}C provided a safe and realistic end point for exertion.

The magnitude and rate of HR increase during the 25°C tests (Figure 4-1) indicates that subjects did not reach a steady HR at a constant work rate during exercise in the heat. This lack of a steady state attainment in cardiovascular indices during work under thermal stress has been previously termed 'cardiovascular drift' (Nadel 1979, Nadel 1980, Rowell 1983, Shaffrath and Adams 1984). The high circulatory and metabolic demands for blood during exercise in the heat are met sucessively by means of cardioacceleration, vasoconstriction of splanchnic and renal vasculature, attenuation of the skin blood flow response despite a rising core temperature (in the face of the metabolic demands of working muscles) and finally, cessation of exercise. Measurements of blood flow were not conducted in the present experiment however group mean HR data suggest that 'cardiovascular drift' was initiated in every subject and undoubtedly influenced subject's tolerance to the B and K suits.

Significant differences between apparels were noted during exercise in the heat on the subjects' total running time and perceived exertion responses. These results indicated that the tolerance of well trained subjects for the B and K suits was limited. Birnbaum and Crockford (1978) identified thermal comfort as the most important quality of any clothing assembly. In the present study (under the ambient temperature 25°C), it

is apparent that a real or perceived aerodynamic advantage would not be sufficient to convince subjects to wear the suits for even a short race of 1500 meters. In a race which requires less than four minutes of effort however, thermoregulatory efficiency should not be a problem and the subjects' tolerance is difficult to rationalize. Objectively, a certain negativism must be attached to the opinions of mature runners confronted with a new piece of equipment which requires a period of adjustment to its use. The use of streamlined apparel by even one or two successful competitors would undoubtedly influence opinion enormously. The inescapable conclusion however, is that acceptance of one piece suits for any race under warm ambient conditions will be severely limited unless the present problems of limited vapour permeability and sweat retention have been solved. In short distance races held in dry weather, a limbless suit with hood would reduce a large portion of drag. If this suit were manufactured from a highly permeable, stretch fabric with good form fitting characteristics, it might provide an acceptable compromise between thermoregulatory necessity and aerodynamic efficiency.

Under cold conditions ($0^{o}C$ and below) or in wet, windy conditions, the B and K suits should find immediate application. National cross-country championships are often run in freezing temperatures with associated precipitation and wind. The current practice of wearing SS apparel regardless of environmental conditions is archaic and inefficient. Given the known decrement in performance caused by a low core temperature (Bergh and Ekblom 1979), maintenance of an optimal core temperature is critical for the attainment of maximum performance. In cold, wet conditions, nylon/spandex bodysuits are highly air permeable, absorb water and have

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been shown to be aerodynamically inefficient in the preceding wind tunnel investigation. In the current investigation at an ambient temperature of $0^{\circ}C$, core temperature was significantly lower in the L suit. Under these conditions, the use of the B or K suit appears a viable alternative albeit the B suit was not preferred by 50% of the subjects due to excessive restriction of movement. Nonetheless, the B suit might offer a considerable advantage in winter sports where aerodynamic drag has a significant influence on performance and where waterproofness and contour fit are important. Although 67% of subjects considered the K suit viable for competition at $0^{\circ}C$, the significantly higher rate of sweat retention in this suit (p $\leq$ .01) would add weight and detract from thermal comfort. While the ultimate goal would be to improve the vapour permeability of the K fabric, a practical immediate solution might be effected by the partial substitution of a non-stretch fabric with excellent ventile and waterproof characteristics (eg Savina DP) into areas of the suit where stretchability is not a prime requirement (eg chest, back, head). Whatever the fabric composition of a composite suit, fabric colour should optimize control of radiant heat adsorption since dark colours increase Tsk upto $1^{\circ}C$ on a sunny day (Dawson 1976).

Clarke et al. (1974) found that the convective heat loss of a swinging limb (as in running) is approximately double that of a limb moving in a straight line with the same mean velocity. This result suggests that the heat loss, vapour permeability and thermal comfort of a complete racing ensemble can not be determined from static tests and emphasizes the requirement for physiological tests of all new designs of racing apparel. In future, however, a new method of determining the oxygen permeability of

fabrics and complete ensembles may allow more complete evaluation of potentially useful material for apparel prior to physiologic testing (Mekjavic et al. 1986).

In conclusion, only the limited vapour permeability of contemporary stretch fabrics or future competitive regulations appear to be obstacles to an expanded use of one piece suits in athletics. Limbless, hooded suits or composite suits of Savina DP and Bion II or Savina DP and Kuwata fabric may maintain the aerodynamic advantages of a one piece suit without impeding the important thermoregulatory processes allowing enduring exhaustive exercise. The performance characteristics of these composite suits await investigation.

5.0. Conclusions and future directions :

5.1. Aerodynamic properties of racing apparel :

The aerodynamic investigations suggest that a significant performance benefit may accrue to competitors wearing streamlined racing apparel. The development of aerodynamic apparel for runners may enhance elite athletic performace in many sports where drag and inclement weather impede performance. The development of one piece suits for endurance activities will require significant integration of optimal aerodynamic and thermal characteristics of clothing materials. As the next stage in the development of an efficient suit, the aerodynamic properties of several prototype materials should be investigated using the techniques developed in this thesis. Materials with enhanced aerodynamic capabilities may then be fabricated for determination of thermal characteristics. Suits which meet the dual thermal criteria of allowing endurance performance with little thermoregulatory impairment should be practically tested with elite athletes using carefully controlled time trial evaluations.

5.2. Thermal properties of racing apparel :

With the exception of the first hypothesis (enhanced aerodynamic efficiency of one piece suits) the hypotheses listed in Chapter 2 were not positively established in the thermal investigation. Wearing the new suits in warm conditions did not impede oxygen uptake. Metabolic measurements ($\dot{V}O_2$) were somewhat equivocal due to the inherent biological variability

of this parameter and this prevented observation of small differences in $\dot{V}O_2$ between apparels. In future apparel research, $\dot{V}O_2$ and $\dot{V}E$ may be important only in establishing gross differences between apparels and in the attainment of stable work rates. The marked differences in heat dissipating efficiency (including weight of sweat retained in each suit) suggest that no single fabric meets the ideal specifications of stretchability, water vapour permeability, rain and wind impermeability. The development of ventile properties in waterproof, stretchable fabrics must be considered critical to the development of a running suit with efficient heat dissipating properties.

5.3. Ventile fabrics :

The results of aerodynamic and physiologic tests, vapour permeability measurements and subjective evaluations strongly suggest that stretch fabrics with optimal waterproof and ventile properties are not currently available. Weaver and Sellers (1985) note that there is an inverse relationship between the water resistance and vapour permeability of current fabrics. The present investigation did not include tests of water resistance, however the B and K suits with internal membranes or external coatings of polyurethane were much less permeable to air and more water resistant than the L apparel. While the ultimate goal of ventile fabric research is to improve the permeability of waterproof stretch fabrics, there are three immediate solutions to the problem of maintaining the thermoregulatory efficiency of a performer in an aerodynamic, whole body
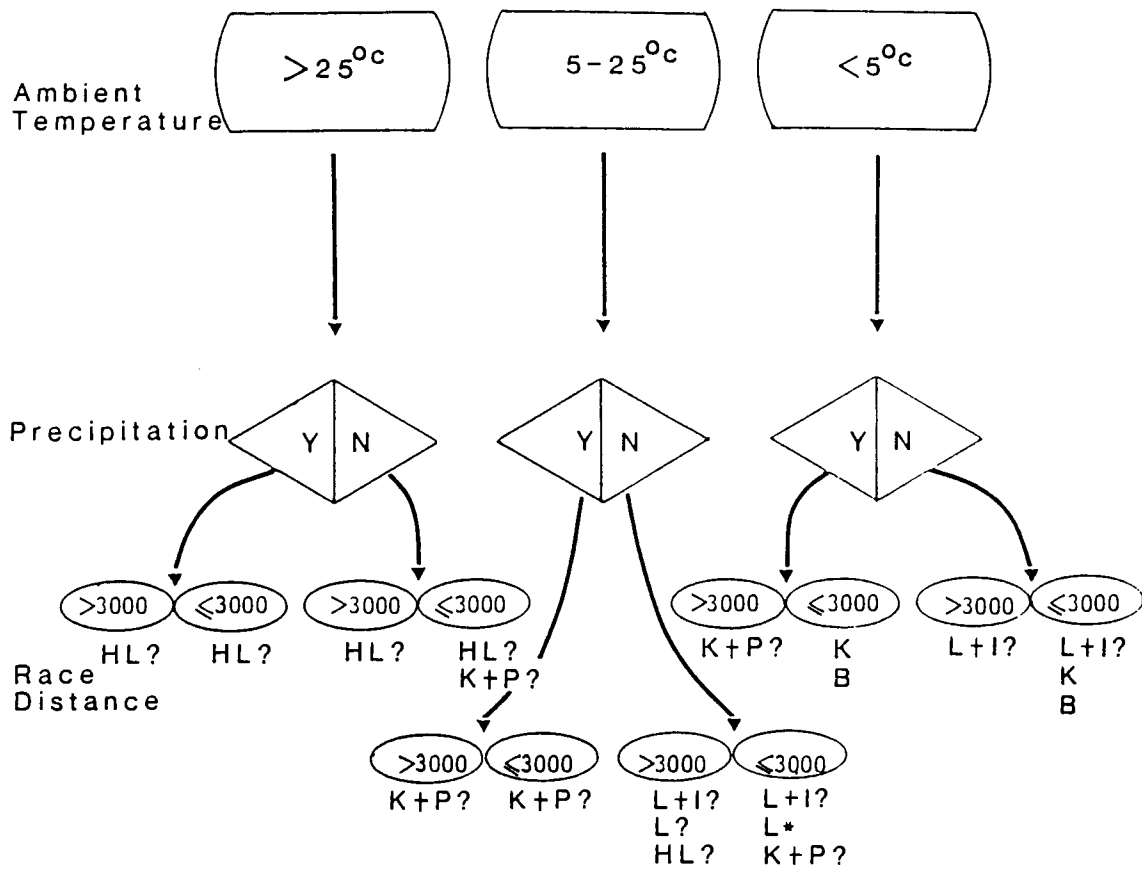
suit. They are:

(a) Develop a hooded, limbless suit for warm weather races. The rationale for this development is that the most significant aerodynamic advantage possessed by a suit for short distance races is provided by the hood. The choice of materials for this suit would depend primarily on aerodynamic and stretch considerations since thermoregulation would not present a problem if the limbs were exposed.

(b) Panels of a nonstretch fabric with excellent ventile properties (eg Savina DP) might be profitably incorporated into static areas of a full body suit where stretchability is not a prime requirement (eg chest, back). A composite suit of K fabric and Savina may be viable for a wide range of environmental conditions and race distances.

(c) Bond an interlock or liner onto a nylon/spandex fabric to increase the contour fit of the fabric and decrease the amount of wind billowing and stretching encountered when wearing suits made of nylon/spandex. The choice of backing material could be adjusted to modify the air permeability of the suit, thus broadening its environmental range. Once prototypes of these suits are constructed, their permeability should be evaluated by the oxygen diffusion technique of Mekjavic et al. (1986). This testing should be followed by aerodynamic tests, evaluation of thermal efficiency and practical field trials to establish optimum uses for each suit.

Figure 5-1 provides a hypothetical model for uses of the suits. The question marks (?) next to some apparel indicate that experimental evidence has not established the appropriateness of these suits either to race distance or designated environmental condition. Figure 5-1 illustrates the considerable degree of research remaining before firm guidelines maybe

FIGURE 5-1: RUNNING SUIT SELECTION

Ambient Temperature

>25°c   5-25°c   <5°c

Precipitation   Y | N   Y | N   Y | N

>3000 ≤3000   >3000 ≤3000   >3000 ≤3000   >3000 ≤3000

HL?   HL?   HL?   HL?   K+P?   K   L+I?   L+I?
                          K+P?   B   K
                                                         B

Race Distance

>3000 ≤3000   >3000 ≤3000

K+P?   K+P?   L+I?   L+I?
               L?   L*
               HL?   K+P?

Legend: Fabric composition of suits

    B: Bion II
    K: Kuwata
    L: Nylon/Spandex
  L+I: Nylon/Spandex & liner
K+P: Kuwata & Savina panels
  HL: Hooded,limbless suit of Kuwata

*use dependent on windspeed and temperature

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established on the optimum running apparel for any set of environmental
conditions.

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