Thermoregulation in Athletic Racing Apparel

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The thermal properties of two types of commercially available running apparel (SS : nylon singlet and shorts ; L : spandex/nylon bodysuit) and two bodysuits of newly developed stretchable, water vapour permeable fabrics (B and K) were investigated under ambient conditions of 0° and 25°C, 50% RH. 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 $4.2\text{m}\cdot\text{sec}^{-1}$. Oxygen uptake kinetics, heart rate, sweating rate, core and skin temperature and perceived exertion were recorded. At 25°C, the K suit retained 23.5 and the B suit retained 9.1 times as much sweat as SS apparel ($p \leq .01$). Both suits became intolerable for running in beyond 22 and 25 minutes, respectively ($p \leq .01$) at the designated speed. However, at 0°C, subject tolerance for all apparels exceeded the criterion running time. In the cool condition the comparatively high air permeability of the L suit resulted in a significantly lower core temperature increase ($p \leq .035$), compared with the other apparels. Even in cool conditions, the K suit retained significantly more sweat than the other apparels ($p \leq .01$). However, subjects favoured the K suit over the B suit due to its lighter weight and greater stretchability. In order to maintain efficient thermoregulation during extended wear in the hotter environment, future running suits should be developed from stretchable materials which have better vapour permeability.

Key words : Running, Racing Apparel, Thermoregulation

INTRODUCTION

Recent wind tunnel investigations have revealed that current racing apparel is aerodynamically deficient (Kyle, 1986 ; Brownlie et al., 1987). Wrapping the runner in a skin tight suit which covers hair and sharp edges provides a significant aerodynamic advantage for sprinters. However wearing a body suit, while offering some solution to the problem of reducing drag force may, at the same time, pose a thermoregulation problem for the endurance athlete. Whether or not the latter effect may be tolerated and, on balance, aerodynamic benefits prevail, remains to be investigated. It is well known that acclimation to heat stress is possible (Wyndham, 1968), and that well trained individuals already have a better developed thermoregulatory system, more responsive to and tolerant of heat stress, than un-

trained individuals (Piwonka et al., 1967). Nevertheless the inevitable consequence of any exercise, such as running, is an associated rise in body temperature. The critical core temperature above which integrated functional responses are lost is considered to be about 42°C (Knochel, 1974 ; Greenleaf, 1979 ; Hanson, 1979). Core temperature is usually regulated well below this level however, even during prolonged exercise in the heat. Steady state levels of core temperature commonly average 38°C to 40°C for workrates of 70% $\dot{V}O_2$ max (Sawaka et al., 1979). National class male marathon runners produce a metabolic heat load of $565\text{ kcal}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$ ($657\text{ w}\cdot\text{m}^{-2}$) for up to 2.5 hours while running at $5.5\text{ m}\cdot\text{sec}^{-1}$. Faster runners over much shorter distances of 1500m to 5000m may have to dissipate heat loads up to 1.5 times as great. The normal thermoregulatory

response to exercise involves increased circulatory and sudomotor (sweat gland) activity and the predominant mechanism of heat dissipation is by evaporative sweat loss, eliminating 0.58kcal per gm of water evaporated. Sweat rates of 1 or 2 l·hr⁻¹ have been reported during moderately heavy exercise even in relatively temperate conditions (Myhre et al., 1982). Prolonged activity therefore, may create a problem of water balance. Although performance may be continued in spite of heavy water loss, it is demonstrably impaired when as little as 2% of the body weight is lost as fluid (Wyndham, 1969). Efficient use of sweat in the sense of evaporating all sweat as it is formed to regulate body temperature, allowing none to drip or accumulate in clothing, is of prime importance. Convective heat loss also becomes important in dissipating the metabolic heat load at the high air velocity encountered in running at 25km·hr⁻¹ (7m·sec⁻¹). It accounts for heat loss up to 1/3 that of evaporative heat loss. It would seem from this that the faster the speed, the better the thermoregulatory aid induced, indeed, in work recently completed in our laboratory (Brown and Banister, 1984) on racing cyclists riding at 75% of $\dot{V}O_2$ max for 90 minutes (speed of riding: 37km·hr⁻¹; 10.7m·sec⁻¹). The cyclists showed very little thermoregulatory distress while riding at 30°C ambient with simulated sun (movie lights) and fan-generated drag, wearing close-fitting cyclist clothing (wool or nylon/spandex). In

high intensity movement, however, interspersed with relatively less active periods, a real danger of hypothermia may develop from sweat saturated clothing surrounded by cold ambient conditions.

Clothing made from materials allowing vapour from the micro environment of the skin surface to escape to the material surface might allow more efficient heat dissipation of a fully clothed subject than heretofore both by evaporative heat loss and by direct conductive and convective heat loss. In the present investigation, two stretchable, water vapour permeable prototype fabrics (K: Kuwata and B: Bion II) were manufactured into whole body suits for physiological 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 both in commercially available and the newly developed running apparel.

MATERIALS AND METHODS

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 1. Body surface area was calculated from the Dubois nomogram (Dubois and Dubois,

Table 1. Physical and physiological characteristics of the subjects

Subject	Age years	Height cm	Weight kg	$\dot{V}O_2$ max ml·kg ⁻¹ ·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	5,000m	14 : 50
JG	21.6	173	58.8	68	1.7	1,500m	3 : 55
GM	21.2	171	68.0	68	1.8	5,000m	14 : 52
RC	24.2	173	63.5	80	1.8	10,000m	30 : 05
TL	29.8	186	73.8	68	2.0	10,000m*	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

1916).

Apparel

Two types of commercially available running apparel (SS: nylon 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 manufactured in sizes to fit the subjects comfortably. Light colours were chosen to minimize radiant heat absorption. 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: 397gm; B: 438gm) than the SS and L apparel (SS: 132gm; L: 256gm) although the addition of a t-shirt to the SS apparel reduced this weight differential somewhat (weight of SS for cold trials: 269gm). After each trial all suits were machine washed and dried. With the exception of the K suit (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 ascertain changes in vapour permeability, this has not been performed to date to maintain the integrity of the suits for further physiological tests.

Design

Subjects were at first scheduled to perform eight separate bouts of prolonged exercise (30 minute maximum) in a 2×4 repeated measures matrix of temperature (0°C, 25°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°C tests were performed prior

to the 0°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).

Protocol

All tests were conducted in a 4×5×2.5meter environmental chamber with temperature and humidity maintained at either 0°C or 25°C±1°C DB and 50±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 4.2m·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 3.1m·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: T_{re}) exceeded 39.0°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.

Thermal Data

Prior to being weighed, subjects inserted a rectal thermister (YSI model 43TD: Yellow Springs Instrument Co., Inc.) approximately 15cm past the anal sphincter. Each subject was then weighed in shorts pre and post exercise on a beam balance sensitive to ± 50 g. Each item of clothing was 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 (T_{sk}) 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 was rested against the skin inside a 9mm hole in an adhesive backed corn plaster.

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 acapula. 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°C reference voltage for the thermocouples. All thermal and cardiac variables were sampled every 10 seconds and displayed every minute by the data logger.

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 $300\text{ml}\cdot\text{min}^{-1}$. The overall resistance to breathing measured $1\text{cm H}_2\text{O}\cdot\text{l}^{-1}\cdot\text{min}^{-1}$ during inspiration and $2\text{cm H}_2\text{O}\cdot\text{l}^{-1}\cdot\text{min}^{-1}$ 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 HP3497A and computed 10 second values of $\dot{V}\text{O}_2$, carbon dioxide production ($\dot{V}\text{CO}_2$), minute ventilation ($\dot{V}\text{E}$) and the respiratory exchange ratio (R). These values were averaged during one minute intervals and displayed. Flow dependent characteristics of the mixing chamber and different rise times of the analysers were measured and compensated by appropriate software algorithms. The turbine was initially calibrated and periodically checked by drawing air through the turbine at known flow rates up to $140\text{l}\cdot\text{min}^{-1}$ by motor-driven precision bellows. 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 $\pm 1.6\%$.

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°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 $9.7\text{km}\cdot\text{hr}^{-1}$ ($2.68\text{m}\cdot\text{sec}^{-1}$). 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 $4.2\text{m}\cdot\text{sec}^{-1}$ and treadmill speed was increased by $.8\text{km}\cdot\text{hr}^{-1}$ every 30 seconds (Whipp et al., 1981). $\dot{V}\text{O}_2\text{max}$ was observed as the final oxygen uptake during the last 30 seconds of exercise.

Subject Questionnaire

Subjective impressions of the comfort of running in each apparel under environmental conditions were assessed by means of a simple questionnaire presented to subjects after each trial. The questionnaire 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 for 1,500 and 10,000 meter races and for high intensity training.

Data Analysis

One of the six subjects was discovered to suffer from a thermoregulatory instability due to a history of several hyperthermal episodes. At 25°C, this subject was able to tolerate the K suit for only 10 minutes and data from this subject for all warm temperature trials were subsequently deleted. The non-random sequence of hot and cold trials imposed by technical failure of the environmental facility limited the validity of the warm and cold test comparisons in a 2×4 repeated measures design originally planned. 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°C, only the first 17 minutes of cardio-

spiratory 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 $\dot{V}\text{E}$, $\dot{V}\text{O}_2$, 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). A repeated measures ANOVA requires the assumption of normality and homogeneity of variance and an 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 conservative technique termed the Huynh-Feldt correction (Dixon, 1983). The occurrence of Type 1 errors resulting from a number of comparisons, a phenomenon termed family wise error rate (FW), was controlled in the current analyses by 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 $\alpha = .05$) for the entire set of pairwise comparisons (Keppel, 1982).

RESULTS

Warm conditions (25°C)

In each trial five subjects ran at a constant velocity of from 4.25 to $4.92\text{m}\cdot\text{sec}^{-1}$ which required 79% (S.D. = $\pm 7\%$) of group mean $\dot{V}\text{O}_2\text{max}$ at a group mean HR of $154\text{b}\cdot\text{min}^{-1}$ (S.D. = ± 11). Ignoring differences between apparels, the mean sweat rate was $1.6\text{ l}\cdot\text{hr}^{-1}$. During each subject's first 17 minutes of exertion, Tsk, HR, $\dot{V}\text{O}_2$ and $\dot{V}\text{E}$ all increased significantly ($p \leq .001$). However there were no significant inter-apparel differences or apparel by time interactions. Group mean HR data for the first 17 minutes of exercise are shown in Figure 1.

At an ambient temperature of 25°C, 50% RH, the

thermal stress of wearing the K and B suits exceeded a runner's volitional tolerance or the established critical core temperature elevation for termination of the experiment (39.0°C), after 21-24 minutes (Table 2). These limits of tolerance are significantly ($p \leq .01$) less than the times noted for the SS and L apparel. The thermal stress produced by the L apparel was similar to that of the SS apparel. However its form-fitting property was lost even under low wind conditions as 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 limited: the K suit retained 23 and the B suit retained 9 times as much sweat as the SS apparel ($p \leq .01$) under the same conditions. Further interpretation of the pre and 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 tempera-

ture value (38.7°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 dissipating 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 questionnaire distributed to subjects after each trial showed that 40% of subjects would consider wearing the L suit in a 1500m race, but only 20% would consider wearing either the B or K suit in a 1500m race and no subject would wear either B or K suit at race distances beyond 1500m under similar ambient conditions as were presented to them in this section of the study.

Cool conditions (0°C)

In a cool environment the six subjects ran at a constant velocity of 4.25 to 4.92m·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 152b·min⁻¹ (S.D.=±10). At 0°C, all subjects easily tolerated 30 minutes of running in each of the four apparels.

Table 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·min ⁻¹)	3.5 (0.2)	3.6 (0.4)	3.5 (0.3)	3.4 (0.3)
Minute Ventilation (l·min ⁻¹)	76 (10.6)	77 (12.0)	75 (11.4)	78 (10.2)
Heart Rate (b·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)
Sweat Rate (l·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)

Table 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·min ⁻¹)	3.8 (0.3)	3.7 (0.3)	3.7 (0.3)	3.7 (0.2)
Minute Ventilation (l·min ⁻¹)	82 (7.8)	80 (8.3)	81 (8.0)	82 (7.1)
Heart Rate (l·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·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)

Figure 1. Mean heart rate response of five subjects to four types of running apparel at 25°C

During 30 minutes of exercise, group mean $\dot{V}O_2$, $\dot{V}E$ and HR all increased significantly ($p \leq .001$). In contrast to the 25°C environment, the group mean HR of the runners in the cool environment stabilized quickly and increased at a slow rate throughout the duration of each test (Figure 2). A qualitative difference in the rate of rise of HR between the 0°C and 25°C environmental conditions reflects the reduced thermal stress imposed by the cool 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 ($p \leq .05$) (Table 3).

The similarity of core temperature increase during work in the cool environment between the SS apparel and any of the other ensembles (L, B, or K)

may be due to a limited sample size preventing clear definition of the relationship between apparel on this variable. The weight of sweat retained in the K suit was significantly higher ($p \leq .01$) than in the other apparels (11.1 times the weight of sweat retained in the SS apparel). No other dependent measure differed significantly between tasks because of suit type suggesting that any 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 10,000m races in cool weather.

Figure 2. Mean heart rate response of six subjects to four types of running apparel at 0°C

DISCUSSION

The mean group sweat rate in runners performing work in a hot (25°C) environment found in this investigation ($1.6 \text{ l} \cdot \text{hr}^{-1}$) is slightly lower than that found by Costill et al. (1970) ($1.93 \text{ l} \cdot \text{hr}^{-1}$) for subjects running at 70% $\dot{V}\text{O}_2\text{max}$ on the treadmill and by Pugh et al. (1967) for a subject running a marathon at 23°C ($1.8 \text{ l} \cdot \text{hr}^{-1}$). Nonetheless, the limited vapour permeability of the K and B suits caused excessive sweat retention in less than 30 minutes of exercise at 79% $\dot{V}\text{O}_2\text{max}$ in the present experiment. Sawaka et al. (1979) reported an average core temperature rise to 39.7°C following 80 minutes of running at 70% of $\dot{V}\text{O}_2\text{max}$ in seven subjects during treadmill running at an environmental temperature of 22–25°C. Since subjects in the current investigation either stopped running or reached the critical maxi-

mum core temperature designated for termination of the test (39.0°C) in much less than 80 minutes, these suits must negatively affect thermoregulatory efficiency and/or the subject's perception of thermal comfort. In running trials at 25°C, lack of significant differences between dependent measures may be related to:

- (1) the insensitiveness of the dependent measures;
 - (2) the confounding effect of limiting running time for termination of the test to the attainment of a designated critical rectal temperature;
 - (3) fatigue caused by the subjects' personal training programs;
 - (4) individual tolerances for thermal discomfort.
- Stipe (1984) used $\dot{V}\text{O}_2\text{max}$ 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 this measure attributable to the apparel. Katch et al. (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 sufficient only 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 new material suits. Unfortunately, the athletes were also 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 training regimen.

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°C $\pm$ 0.1°C and 38.8°C $\pm$ 0.2°C) suggests that the practice of stopping a trial upon attainment of a core temperature of 39.0°C provided a safe and realistic end point for exertion.

The magnitude and rate of HR increase during the 25°C tests (Figure 1) indicate 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 demand for blood during exercise in the heat are met successively by cardioacceleration, vasoconstriction of the 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 apparent in every subject and undoubtedly influenced a 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. It is apparent that a real aerodynamic advantage would not be sufficient to convince subjects to wear the suits for even a short race of 1500 meters under ambient temperatures of 25°C.

Under cold conditions (0°C $\pm$ 5°C) or in wet, windy conditions, the B and K suits could find immediate acceptance from competitors. National cross-country championships are often run in freezing temperatures and/or associated precipitation and wind. Under such conditions the current practice of wearing SS apparel is indefensible. Given the known decrement in performance caused by a low core temperature (Bergh and Ekblom, 1979), alleviation of any such decrement is critical for the attainment of maximum performance. Nylon/spandex bodysuits provide demonstrably inadequate protection against cold wet conditions and have also been shown to be aerodynamically inefficient (Brownlie et al., 1987). In the current investigation at an ambient temperature of 0°C, core temperature was significantly lower in the L suit compared with the B and K suits. 67% of subjects considered the K suit viable

for competition at 0°C, but 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 is to improve the vapour permeability of the K fabric, a practical immediate solution might be effected by partial substitution of parts of the current garment with non-stretch but excellent ventile and water-resistant material (e.g. Savina DP).

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 vapour permeable, non stretchable and stretchable fabrics 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.

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