PHYSIOLOGICAL AND PERCEPTUAL RESPONSES TO EXERCISE AND COLD STRESS WITH SPECIAL REFERENCE TO CLIMATIC AND TEXTILE FACTORS

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Declaration

I hereby declare that this thesis has been composed by myself, that the work of which it is a record has been done by myself except where assistance has been acknowledged, that it has not been submitted in any previous application for a higher degree and that all sources of information have been specifically acknowledged by means of references.

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Evelina Georgiades

TABLE OF CONTENTS

Chapter 2: The influence of garment air permeability on physiological and perceptual responses to cold stress during rest and exercise.

Chapter 3: The influence of garment wicking capacity on physiological and perceptual responses to cold stress during rest following physical activity.

Chapter 4: The effects of cooling on cardiorespiratory and metabolic parameters during incremental and constant-load exercise

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Summary

The primary objective of the first three studies was to provide an indirect assessment of the properties of garments designed for wear in cold environments using human trials. The study design incorporated a specific protocol that allowed for evaluation of specific garment properties, based on physiological and subjective responses. Based on some interesting trends in VO_2 response that were noted in the earlier studies, the fourth study aimed to determine the effects of cooling on the VO_2 response to exercise in moderate and heavy intensity domains.

The first two studies compared the performance of three garments that differed in the degree to which they were air-permeable: high (HP), medium (MP) and low (LP) permeability. The studies were conducted in two sub-zero environmental temperatures, against a constant wind speed. The protocol consisted of a 30 min rest period followed by 30 min of brisk walking on an inclined treadmill. The results suggest that HP was the least favourable garment in the imposed conditions, based on higher values for rating of cold perception (RPC) and elevated VO_2 (indicating a more marked shivering response). Furthermore, it appeared that MP was the most effective of the suits, despite having a greater air permeability than LP. This indicates that factors other than wind resistance properties may have a significant effect on garment performance in this particular environment, taking into consideration duration of exposure, ambient temperature, wind-speed and physical activity status.

The third study compared the wicking capacity of four garments (polyamide/nylon, capilene polyester, polyester and cotton), designed for wear as a base-layer, that varied in their physical properties and physical characteristics. It is recognised that

evaporation of sweat taking place after cessation of exercise in the cold will cool the body, during a period where heat preservation is especially important. The design of the present study incorporated a 20 min exercise period, followed by a subsequent 45 min rest period in cool environment (1° C), during which the garments were evaluated. Lower RPC values and a tendency for a lower VO_2 during rest, indicated that the polyester garment, which combined good wicking qualities with a high thermal resistance, was superior to the other garments in its capacity at offsetting heat loss. The results do not imply that heat transfer was prevented by the favourable garment, but rather that it was diminished in magnitude.

The principal aim of the final study was to investigate the influence of body cooling on the VO_2 response to exercise above and below the lactate threshold, employing square-wave cycle-ergometer exercise transitions for the two intensity domains. The design also allowed for determination of the influence of sub-normal temperatures on incremental cycling performance. The results showed that the induced cooling had detrimental effects on maximal aerobic performance. VO_2 during moderate constant-load exercise was significantly elevated following cooling; a similar effect, however, was observed only during the initial stages of heavy intensity constant-load exercise. Furthermore, the characteristic VO_2 slow-component observed during constant-load exercise above the lactate threshold remained unaltered by sub-normal temperatures. The results suggest that a graded suppression of shivering occurs with increasing exercise intensity. Furthermore, the findings indicate that temperature is likely to contribute to the slow-component of VO_2 by only a trivial amount.

Table of abbreviations

ATP	Adenosine triphosphate
C	Cotton
° C	Celsius
CO	Cardiac output
CO_2	Carbon dioxide
CP	Capilene polyester
CvO_2	Mixed venous oxygen content
$Cv(m)O_2$	Muscle venous oxygen content
ECG	Electrocardiogram
EMG	Electromyography
FFA	Free fatty acids
HC	Hypothermic conditions
HP	High permeability
HR	Heart rate
iEMG	Integrated electromyography
LP	Low permeability
MP	Medium permeability
NC	Normothermic conditions
NMR	Nuclear magnetic resonance
O_2	Oxygen
P	Polyester
PCr	Phosphocreatine
$P\text{-}O_2$	Phosphate oxygen
PN	Polyamide/nylon
PTFE	Polytetrafluoroethylene
QO_2	Muscle oxygen consumption
RER	Respiratory exchange ratio
RPC	Rating of perceived cooling

Table of abbreviations (cont.)

RPE	Rating of perceived exertion
rpm	Rotations per minute
RPS	Rating of perceived shivering
s.d.	Standard deviation
ss	Steady state
STPD	Standard temperature and pressure (dry)
T_R	Rectal temperature
T_{sk}	Weighted mean skin temperature
V_E	Ventilation
VCO_2	Carbon dioxide output
VO_2	Oxygen uptake
VO_{2max}	Maximum oxygen uptake
W	Watt
W_a	Work - time asymptote
WR	Work rate
δ	Kinetic delay
θ_L	Lactate threshold
τ	Time constant

List of Figures

List of Figures (cont.)

List of Tables

Chapter One

General Introduction

General Introduction

Extremes of ambient temperature present a serious challenge to humans. Body temperature homeostasis has been shown to be maintained better in temperate rather than cold environments. That is, while and although humans can live and function in cold environments, their limited physiological adaptive capacity places them at a distinct disadvantage. The biologist P.F. Scholander was the first to refer to humans as "tropical animals" (Edholm 1978), basing his classification on the fact that their critical temperature (defined as the environmental temperature below which metabolic rate starts to increase in order to maintain body temperature) is that of a tropical animal (Keatinge 1969). It is important, therefore, that humans are able to protect themselves during exposure, especially when the thermal gradient that exists between the body and the environment favours the loss of heat from the body. A number of physiological thermoregulatory mechanisms help in maintaining a tightly regulated core temperature. In reality, however, the ability to withstand the cold for anything other than very short periods is far more reliant on technological and behavioural, rather than on physiological, strategies.

The physiological response to cold stress and the influence of garments

Two principal physiological responses aim to prevent, or at least reduce, the rate of heat loss during exposure to a cold environment. With the exception of the head, constriction of superficial blood vessels increases tissue insulation, by redirecting blood flow into deeper blood vessels (Burton and Edholm 1955; Haymes and Wells 1986). This adjustment (controlled by the sympathetic nervous system) creates a cold "shell" that surrounds a warmer core within the body, and effectively minimises heat loss by reducing the temperature gradient (and hence, heat flux) between the body and the surrounding environment. Although important as a line of defence against heat loss, circulatory responses to cold can increase overall body insulation only by approximately the equivalent of 1 clo unit (defined as the thermal insulation necessary to maintain comfort in a resting human at an ambient temperature of 21° C and a humidity of less that 50 %) (Burton and Edholm 1955). At maximal degrees of vasoconstriction, when the body can no longer prevent a decrease in core temperature by minimising heat loss, an increase in metabolism occurs. Shivering, characteristic for its intermittent nature, raises metabolic heat production. At rest, shivering can increase metabolism to at least 2-3 times the resting value (Ward 1975; Haymes and Wells 1986; Lloyd 1986; Shepard 1993). In severe temperatures, resting metabolism may increase as much as 5-fold, especially in thin individuals (Tikusis et al. 1988, Tikusis et al. 1991). Unfortunately, some of the heat gain due to shivering is lost consequent to the muscular contractions, as there is no way of preventing a partial reversal of cold-induced vasoconstriction.

Clothing assists in the prevention of heat loss by increasing the total insulation of the body. Garments constitute part of the environmental barrier, and create a microenvironment between the body and the surrounding environment. Furthermore, clothing considerably influences the energy exchange between the body and the ambient environment, thus modifying thermoregulatory adjustments for maintenance of homeothermia (Gonzalez 1988). Unlike skin, which is considered to be the integral connection in the interaction between body and environment, clothing is largely a passive medium in the regulation of thermal energy processes between the two (Gonzalez 1988). The correct selection and use of garments are extremely important for effective thermoregulation and control of the microclimate, and a number of factors must therefore be considered when making a selection of garments. Apart from prevailing ambient temperature, variables such as physical activity (including its duration and intensity), wind and precipitation should all be taken into account when choosing clothing for the cold.

Metabolic heat generated through physical activity appears desirable in the cold, as it may offset heat loss. It may, however, have potentially deleterious consequences in a period of subsequent rest, when exercise thermogenesis no longer contributes to thermal balance. A thermal imbalance favouring heat production against its dissipation during activity (caused many times as a result of overdressing for exercise in the cold) will increase core temperature and initiate sweating. Typical outdoor winter activities, such as hiking at a moderate pace with a daypack or cross-country skiing, could raise the core temperature by as much as 4° C·hour^{-1}, were the heat not be dissipated (Dickinson 1995). Folk (1974) has reported the case of a soldier who participated in the 1965 Operation "Polar Siege". The average ambient temperature encountered was -40° C and yet the soldier was admitted to hospital with heat exhaustion. It is therefore remarkably easy and common to overdress for activity in cold weather and thus to sweat needlessly.

Sweating can be dangerous when combined with inactivity in a cold environment that is subsequent to physical activity. Moisture accumulation in a garment will cause it to feel cold and uncomfortable since heat is lost at rates 25 times greater through water than air (Keatinge 1969; Haymes and Wells 1986). Increased contact of a wet garment with the skin also increases chilling and clamminess (Gonzalez 1988). Furthermore, the clothing loses some of its insulative value and, hence, its ability to impede heat dissipation (Pascoe et al. 1994a). Holmer and Gavhead (1991) have reported losses in insulation of up to 50 % during treadmill exercise in sub-zero environments, attributable largely to the amount of sweat secreted. The intrinsic insulation of the garment is modified by contact with wet skin and/or condensation of sweat on the inner surface due to microclimate saturation (Candas and Hoeft 1995).

Furthermore, when the moisture generated by sweating remains in contact with the surface of the body, evaporation takes place. This is generally acknowledged to be the most important mode of heat loss in the cold, during inactivity that follows exercise of sufficient vigour to produce sweating. Cooling occurs at the site of evaporation (i.e. the skin) when heat is lost in the process of evaporating the moisture accumulated ("latent" heat) (Burton and Edholm 1955). Consequently, garments that can transfer or "wick" away moisture from the skin (to be evaporated on outer layers of clothing, thus conserving body heat) are of great importance in preserving body heat. The moisture that is evaporated at the skin condenses in the clothing, wicks to the surface of the clothing, and is re-evaporated there. Hence, only a fraction of the heat required for evaporation has actually come from the body (Burton and Edholm 1955). The potential danger, however, is the possibility of condensation occurring in outermost clothing layers. If this moisture is not evaporated, the clothing becomes very wet, and ice or frost may form. Subsequently, the garment becomes heavy and stiff and its insulation may deteriorate (Lotens 1987). Dickinson (1995) has identified four qualities that are important when considering the reaction of a fibre to moisture (Table 1.1).

Table 1.1: Garment qualities important for fibre reaction to moisture.

Garment Property
1. Ease of wicking action – i.e. the transfer of moisture from the body surface to the material (hydrophilic) or the transfer of moisture from the surface of the body across itself (hydrophobic) to the outer layers of clothing.
2. Evaporative ability or rate of drying.
3. Moisture regain – the amount of moisture a material can absorb before it feels cold.
4. The degree of insulation a material loses when it becomes wet.

As well as the wicking ability, insulation is also one of the principal requisites for the clothing layer next to the skin. Polyesters possess all the necessary requirements and best satisfy the needs of this layer. They are poor conductors (thereby good insulators), and are designed for moisture transfer and softness of feel (Dickinson 1995).

An important consideration for the protective layer is its resistance to wind. In the presence of moving air, heat is lost by convection. A large part of the insulation that a clothing ensemble provides is due to entrapped air layers and the clothing outer surface layer (Burton and Edholm 1955; Havenith et al. 1990). Any disturbance of entrapped air and outer surface layers will have considerable effects on garment insulation. Surface air insulation is first reduced with the introduction of wind, and thereafter the insulation due to the trapped air is diminished - either by reducing the amount of air present or causing convection within (Nielsen et al. 1985). A 4 km·hour^{-1} wind can almost double the rate of heat loss from a resting subject and reduce the clothing insulation to approximately 55 % of its initial value. When combined with exercise, the detrimental effects caused by wind are exacerbated (Belding et al. 1947; Burton and Edholm 1955; Pugh 1966; Olesen and Madsen 1983; Nielsen et al. 1985; Havenith et al. 1990). In a cold environment (-20° C), exercising in a 15 km·hour^{-1} wind can increase heat-loss rate by up to four times, compared to rest. Pugh (1967) reported that a combination of exercise, wind and wetting reduced the effective insulation of a typical clothing assembly to one tenth of the value determined in dry, still conditions. Wind can penetrate the outer garments and disturb trapped air layers, thus augmenting convective heat loss. Loose-fitting clothing will also increase convective heat loss, since air can be "pumped" through the clothing with a bellows-like action through openings at the neck, waistband, sleeves, ankles and pockets (Dickinson 1995). An “internal wind” - caused by movement of the body - can also greatly reduce the insulation of the clothing (Burton and Edholm 1955; Holmer and Gavhed 1991). As will become evident, ventilation within a clothing system can actually be beneficial in certain situations where additional ventilation is required to enhance heat loss from the microclimate. For instance, during moderate or high intensity physical activity, sweating must be reduced to a minimum to prevent wetting of garments. It is prudent therefore to increase ventilation of the microclimate (by adjusting fastenings, zips etc.), rather than to rely solely on the breathability of clothing material. The key is to be able to selectively control the amount of heat loss by both evaporation and convection.

Any multi-layer clothing ensemble (Fig. 1.1) consists of an underlayer, designed to be worn next to the skin and maintain a comfortable microclimate, and a protective outerlayer, whose main function is to prevent rain and wind from penetrating it. A further (intermediate) layer is required, whose principal role is to control heat escape through convection and conduction and provide further insulation (Dickinson 1995).

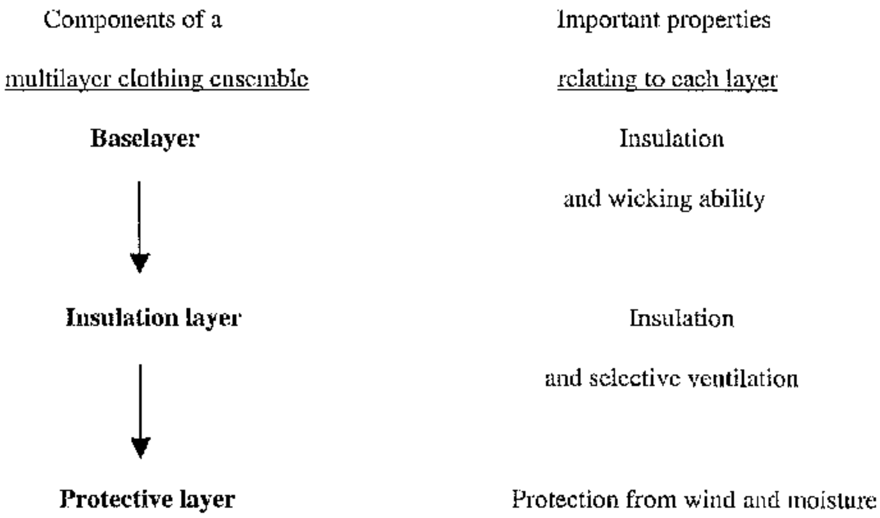


Figure 1.1: The main components and properties of a multi-layer clothing ensemble.

The total insulation of any ensemble is equal to the sum of the insulative properties of the trapped air layers and the fabric itself. When protection from wind and rain is not required, the insulation layer may also be the outermost layer. Contemporary materials eliminate the need for bulky and cumbersome clothing, which otherwise add extra weight and thus increase the effort required for a given task. Arctic clothing, for instance, can add up to 10 % to the metabolic cost of walking or running (Pascoe et al. 1994b). Furthermore, it has been shown by Lotens (1987) that each kg of clothing donned will increase the energy cost of walking by approximately 1.3 %. Consequently, exhaustion is reached faster and peak performance is lowered.

New advances in the design and technological performance of fabrics and garments are now being considered in the context of the physiological responses of the human body, in order to provide optimal protection during situations of cold stress. Pascoe et al. (1994a) have argued that "although manikins approximate human thermoregulatory responses, the ultimate validation of any clothing ensemble relies on testing with humans under actual conditions of intended use". That is, many evaluation techniques are only meaningful with human trials, especially those concerned with body movement and thermal sensation (like cold perception/comfort and shivering). Ultimately it is the wearer who decides whether a garment - or a system of garments - is effective or not in the imposed conditions.

The purpose of the first three studies in this dissertation was therefore to evaluate and compare certain properties of a series of garments with reference to the influence they exerted on the thermophysiological responses of humans during cold exposure. In particular, Studies I and II aimed to assess three different clothing ensembles in terms of how permeable they were to wind. The design of the studies incorporated a period of rest followed by exercise and garments were evaluated according to physiological and perceptual responses of participating subjects. Study III, on the other hand, indirectly compared the wicking capacity of four base layer garments. The garments were evaluated during a period of rest that was subsequent to exercise, introduced to generate sweating in subjects and, hence, moisture accumulation on the skin and in the garments.

Oxygen uptake kinetics in exercising humans

A parallel concern in the context of performance in the cold is the extent to which metabolism responds to, and can compensate for, challenges to body temperature. For sustained physical activity in the cold, the body's ability to transport O_2 from the atmosphere to be used as a terminal oxidant in the mitochondrial electron-transport chain is crucial in establishing the tolerable duration of a particular task. An invaluable frame of reference for evaluating O_2 transport and utilisation in the cold is provided by the response characteristics of pulmonary O_2 uptake ($\dot{V}O_2$) (and related cardiorespiratory responses) under normothermic conditions. In order to draw inferences about the physiological control of $\dot{V}O_2$, the response is best characterised in terms of its kinetics and amplitude at different exercise intensities.

Moderate-intensity exercise

In this context, it is now widely acknowledged that three intensity domains are usefully recognised, demarcated by the lactate threshold (θ_L) and the asymptote of the power-duration relationship (W_a). The domain of moderate exercise encompasses all work rates below the lactate threshold i.e. without the induction of sustained metabolic (lactic) acidaemia (e.g. Whipp and Ward 1990). For constant-load exercise within this region, the increase in $\dot{V}O_2$ is best described as being monoexponential (e.g. Whipp et al. 1982; Hughson et al. 1983; Cerretelli and DiPrampero 1987) (Fig.1.2 bottom panel).

Hill and Lupton (1923) were the first to recognise that $\dot{V}O_2$ increases rapidly with first order kinetics and in healthy individuals achieves a steady state within 3 min (i.e., the time-constant τ, is approximately 45 sec). In this intensity domain, τ does not vary appreciably between work rates (e.g. Whipp 1987). The off-transient $\dot{V}O_2$ time constant is also remarkably similar to the on-transient (Paterson and Whipp 1991). The traditional view of Hill and Lupton (1923) of a mono-exponential rise beginning without delay at the onset of exercise was challenged by Whipp et al. (1982) who, using breath-by-breath measurements of $\dot{V}O_2$, identified that the mono-exponential

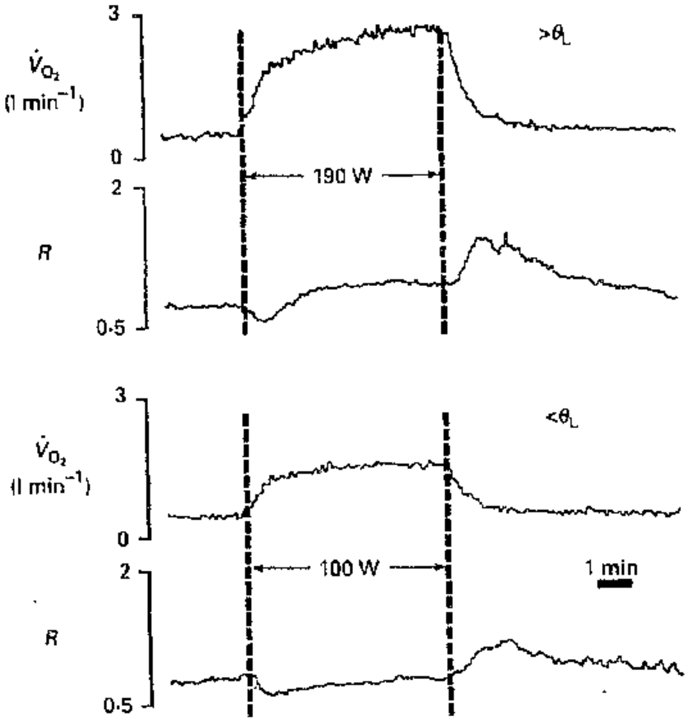


Figure 1.2: The responses of $\dot{V}O_2$ to square wave changes in WR above and below the lactate threshold. The sub-threshold response is well characterised by a mono-exponential function (bottom panel). The supra-threshold response becomes more complex with at least two exponentials needed for adequate characterisation (top panel). (Paterson and Whipp 1991).

process does not begin until a short period of time (i.e. 15-20 sec) has elapsed (phase I). Altogether, three separate temporal phases have been shown to characterise the $\dot{V}O_2$ response to constant-load moderate exercise (Fig. 1.3).

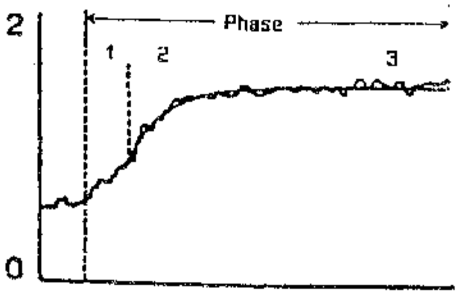


Figure 1.3: The temporal components of the $\dot{V}O_2$ on-response ($< \theta_L$) (Barstow et al. 1990).

The distinct temporal phases of the $\dot{V}O_2$ on-response reflect the underlying physiology of the transient phase. *Phase I* is the early, usually rapid response and its duration represents the circulatory transit delay between the exercising leg muscles and the lungs. Increases in $\dot{V}O_2$ in this delay-like component have been principally attributed to augmented cardiac output and hence pulmonary blood flow, with possible minor contributions from changes in lung stores and mixed venous O_2 content (Krogh and Lindhard 1913). *Phase II* is initiated by the arrival of venous blood from the exercising muscle at the lung, and gas exchange is supplemented by the influence of the altered $Cv(m)O_2$ on CvO_2. This event is of course delayed. It has been argued that pulmonary $\dot{V}O_2$ in phase II closely reflects muscle $\dot{V}O_2$. This is supported by modelling studies and also by the good temporal correlation between phase II pulmonary $\dot{V}O_2$ changes (Barstow et al. 1990) and changes in PCr concentration within the exercising muscle (Barstow et al. 1994; Rossiter et al. 1999). For constant-load (i.e. square-wave) exercise below the lactate threshold, the muscle QO_2 response is mono-exponential, like the pulmonary $\dot{V}O_2$ response (Grassi et al. 1996). Barstow et al (1990) modelled the relationship between the QO_2 time-constant and the phase II $\dot{V}O_2$ time-constant, and concluded that the difference between the two was likely to be less than 10 % for a wide range of cardiac output changes. Finally *phase III* represents a steady-state in terms of the $\dot{V}O_2$ response, whereby in the domain of moderate intensity, the $\dot{V}O_2 \cdot WR^{-1}$ gain is normally within the region of 9-11 ml $O_2 \cdot W^{-1} \cdot min^{-1}$ (Whipp and Wasserman 1972; Whipp 1987).

Heavy-intensity exercise

The lowest WR at which there is sustained lactate elevation in the blood (where blood lactate production exceeds its rate of removal) represents the initiation of the heavy exercise domain. The $\dot{V}O_2$ response within the heavy exercise domain becomes appreciably more complex, displaying time- as well as amplitude-based non-linearities (Paterson and Whipp 1991). Above θ_L the response is no longer well described as a mono-exponential function. An additional component of $\dot{V}O_2$ is superimposed upon the underlying kinetics (and, hence, the mono-exponential rise) (Fig. 1.2) and this represents an excess $\dot{V}O_2$ above that predicted from sub-threshold work rate considerations (Whipp and Wasserman 1972; Linnarsson 1974). Because this superimposed component is of delayed onset (initiated some minutes into the test), it has been termed the "slow component". The slow component is manifested above θ_L, irrespective of the absolute metabolic rate at which this occurs. Time to steady-state is delayed and when $\dot{V}O_2$ does eventually stabilise, the $\Delta\dot{V}O_{2\ (ss)}\cdot\Delta WR^{-1}$ is increased markedly compared to the moderate intensity work domain. Values of approximately 13 $ml\cdot min^{-1}\cdot W^{-1}$ are not uncommon during tests of 10-15 min duration (Roston et al. 1987; Whipp 1987). Findings regarding the characteristics of the early component at these heavy work rates indicate that its kinetics remain exponential and that it projects to a steady-state level that gives the same $\dot{V}O_2\cdot WR^{-1}$ gain as for sub-threshold exercise. There is disagreement, however, between investigators on the value of the phase II time-constant (τ). Paterson and Whipp (1991) concluded that above θ_L the time-constant is slow when compared to that of moderate intensity work, whereas Barstow and Mole (1991) found τ to be unchanged.

The mechanisms controlling the kinetics of the slow $\dot{V}O_2$ component (that can cause $\dot{V}O_2$ to climb inexorably to its maximum) are still poorly understood. Hypotheses compete as to whether its origin is in the exercising limbs or the rest of the body. A number of factors have been postulated to contribute to it. Various indirect approaches have highlighted lactate, epinephrine, cardiac and ventilatory work, temperature, a reduction in chemical-mechanical coupling efficiency, less efficient mitochondrial P-O_2 coupling and the recruitment of the lower-efficiency type II muscle fibres as possible contributors.

Exercising limbs, lactate, epinephrine and pulmonary ventilation. Poole et al. (1991) measured leg and pulmonary $\dot{V}O_2$ simultaneously during cycle ergometry, and demonstrated that beyond the third minute of exercise approximately 86 % of the increment in pulmonary $\dot{V}O_2$ could be accounted for by the increase in leg $\dot{V}O_2$. This observation indicated that the majority of the slow-component may be accounted for by the increasing oxygen consumption within the working musculature. It has also been shown that the magnitude of the slow component is highly correlated and related quantitatively to the rise in blood lactate during exercise (Roston et al. 1987; Poole et al. 1988). Wasserman et al. (1991), however, contended that it was not the lactate *per se,* but rather the accompanying acidosis that caused the $\dot{V}O_2$ to increase above its predicted value during heavy exercise. Pasma epinephrine concentration has been shown to increase considerably during heavy and severe exercise (coinciding with the appearance of the $\dot{V}O_2$ slow component) (Poole et al. 1988; Gaesser et al. 1994) and, thus, has also been considered as a possible mediator for the slow component. Finally, although the O_2 cost of respiratory work required to increase pulmonary ventilation has been proposed as a possible contributing factor to the progressive rise in $\dot{V}O_2$ at work rates above θ_L, investigation has shown that the contribution can only be trivial (Gaesser and Poole 1996).

Temperature. Core and muscle temperatures increase during exercise. It is possible that via the Q_{10} effect, the increase may contribute to the progressive rise in $\dot{V}O_2$ during exercise above θ_L (Gaesser and Poole 1996). The Q_{10} effect is a temperature coefficient that expresses the thermal dependence of investigated variables, and is described by the following equation:

$$Q_{10} = (R_2/R_1)^{10/(T_2-T_1)} \qquad \text{(Equation. 1.1)}$$

R_2 and R_1 are the rates of any given mechanical or chemical process, which can be measured at temperatures T_2 and T_1 respectively (T_2 being higher than T_1) (Ferretti et al. 1992). The equation simply describes the relative change in the rate at which a process takes place following a 10° C increase in local temperature. It is based on the law of Arrhenius which states that the rate of various enzymic reactions and the level of resting metabolism is decreased 2- to 3-fold for every 10° C decrease in local tissue temperature. The Q_{10} is a descriptive tool and does not imply any biochemical and/or mechanical process and/or limitation.

The Q_{10} effect in the working musculature has the potential to increase the $\dot{V}O_2$ by 5-10 times, if we take into account the fact that the Q_{10} increases $\dot{V}O_2$ proportionally to the attendant metabolic rate. By further deduction, increased temperature may be associated with the $\dot{V}O_2$ slow component, since the majority of the slow component is understood to arise within the working muscles, and any effect of temperature will certainly predominate in these. Poole et al. (1991) have estimated that a 1° C rise in temperature may cause approximately a 10 % rise in $\dot{V}O_2$ if a Q_{10} of 2.5 is assumed. Results revealed that this could amount to a sizeable figure for exercising muscles (in the order of 270 $ml \cdot min^{-1}$) - assuming that the observed 0.8° C rise of leg vein temperature accurately reflected muscle temperature.

The increased muscle temperature may also compromise P-O_2 coupling efficiency (Willis and Jackman 1994), thereby decreasing overall muscle efficiency and increasing O_2-cost of work. A 3° C rise in temperature within the muscles could result in a 10 % reduction in the efficiency of coupling of $\dot{V}O_2$ to ATP production (ADP/O ratio) and thus contribute to the slow component. Several contra-indications exist, however, that weaken the efficacy of the hypothesis. Poole et al. (1991) have reported of "many observations of stable pulmonary $\dot{V}O_2$ in the face of rising body (and presumably muscle) temperature". Findings by Koga et al (1997) were also inconsistent with the hypothesis that an exercise-induced increase in muscle temperature may be an underlying mechanism contributing to the slow component of $\dot{V}O_2$ during heavy exercise. Elevated muscle temperatures (which would have been expected to increase O_2 delivery and off-loading to the muscle via a rightward shift of the oxyhemoglobin dissociation curve) had no appreciable effect on the time-constant of the $\dot{V}O_2$ kinetics. Furthermore the increment in $\dot{V}O_2$ between 3 and 6 min ($\Delta\dot{V}O_{2\ (6-3)}$) during heavy exercise, was slightly but significantly smaller when elevated muscle temperatures were induced.

Motor unit recruitment. The likeliest explanation for the underlying mechanism(s) of $\dot{V}O_2$ slow component – as well as the most plausible – appears to lie in the study of muscle fibre (motor unit) recruitment pattern during exercise. Shinohara and Moritani (1992) have demonstrated a positive correlation between the integrated electromyogram (iEMG) and the rise in pulmonary $\dot{V}O_2$ (between 4 and 7 min) during high-intensity cycle ergometry. Since the iEMG largely reflects the changes occurring in motor unit firing frequency and/or recruitment patterns, it can be deduced that the slow component may be due to recruitment of further motor units - particularly fast-twitch ones. The energetic differences between slow- and fast-twitch fibres have been well documented, with Type II fibres having a higher energy cost of contraction and a slower time-constant (Gaesser and Poole 1996). Coyle et al. (1992) demonstrated a strong correlation between constant-power exercise $\dot{V}O_2$ and percentage of fast-twitch fibres in participating athletes, and concluded that a lower cycling efficiency (reflected by high $\dot{V}O_2$ cost) could be linked to a larger proportion of fast-twitch fibres.

Influence of reduced muscle temperature on O_2 uptake kinetics

To date, a limited number of studies have specifically looked at the influence of a reduction in muscle temperature on the oxygen kinetics during exercise (Beelen and Sargeant 1991; Ishii et al. 1992; Shiojiri et al. 1997). Confounding results have been reported.

Ishii et al. (1992) showed that the temporal kinetics of the $\dot{V}O_2$ on-response were not significantly affected by cooling their subjects. Although muscle blood flow was greatly reduced and its kinetics slowed, the $\dot{V}O_2$ kinetics were not affected. With regards to a possible mechanism behind the unaltered temporal $\dot{V}O_2$ kinetics, the investigators proposed that the recruitment of a greater muscle mass might counterbalance the expected slowing of the kinetics. Beelen and Sargeant (1991) also demonstrated unchanged temporal kinetics; $\dot{V}O_2$, however, during constant-load exercise that followed the pre-cooling period was slightly, but significantly, higher than the control situation after 3 min. The absence of a shivering response led the investigators to conclude that the increase in steady-state $\dot{V}O_2$ was associated with the additional energy cost of metabolising the larger amount of lactate, observed in the blood during cold conditions and is concomitant with the link between lactate and the slow component. It cannot, however, explain the unaltered kinetics at the onset of exercise (where a slowing would have been expected had there been a greater reliance on anaerobic energy).

Shiojiri et al (1997) performed similar experiments by cooling their subjects and found a slowing of the $\dot{V}O_2$ temporal kinetics, evidenced by a longer time constant for cold conditions compared to normothermia. In examining phase I, the investigators reported a significantly greater duration, as well as lower amplitudes for $\dot{V}O_2$ and $\dot{V}O_2$/HR in cooled conditions. A concomitant slowing of oxidative reactions due to the temperature-dependent reduction in enzyme activity and/or poor oxygen supply because of reduced diffusion rate were proposed as possible causes of the slowed $\dot{V}O_2$ on-response (Shiojiri et al. 1997). None of the investigations referred to above addressed the impact of cooling on the $\dot{V}O_2$ slow component.

It is evident that findings on the temporal aspect and magnitude of the $\dot{V}O_2$ response to constant-load exercise at sub-normal temperatures are equivocal. The final aim of this research, therefore, was to investigate the influence of cooling on aerobic performance during constant-load exercise in humans. Study IV incorporated progressive exercise tests to exhaustion, in addition to constant-load exercise tests of moderate and heavy intensity.

Chapter Two

(Study I and Study II)

The influence of garment air permeability on physiological and perceptual responses to cold stress during rest and exercise.

Introduction

Clothing constitutes one of the most important forms of protection man has against a cold environment, in view of the limited capacity humans have in adapting significantly in their physiological response to the cold (Dickinson 1995). Variables such as ambient temperature, the presence of wind and activity status should be taken into consideration in the correct choice of garments. The introduction of wind to a specific environment, for example, has been shown to reduce total insulation by decreasing surface air layer insulation (Haymes et al. 1982; Nielsen et al. 1985; Havenith et al. 1990), thereby increasing the clothing insulation requirement. Exercise may further facilitate this effect, and indeed it has been shown that wind, combined with body movement amongst other factors, significantly lowers garment insulation (Belding et al. 1947; Burton and Edholm 1955; Pugh 1966; Olesen and Madsen 1983; Nielsen et al. 1985; Havenith et al. 1990). The following two studies (Study I and Study II) aimed to compare the performance of three different outdoor clothing ensembles which varied in their degree of wind permeability, in cold and windy environmental conditions. The ensembles were of high (HP), medium (MP) and low permeability (LP). The design of the study incorporated a period of rest followed by exercise, in order to provide a realistic evaluation of the garments (using physiological and subjective responses of participating subjects) under conditions of intended use. Furthermore, by utilising this protocol, the influence of the rest period on the performance of the garments during exercise was assessed.

Methods

Subjects

Eight and ten male subjects participated in studies I and II respectively, both of which were approved by the University Ethics Committee. The subjects were all involved in regular physical activity at time of participation in the study and gave their informed consent. Their characteristics are as follows (mean ± s.d.): age 21.5 ± 1.6 years, body mass 68.9 ± 7.3 kg, height 1.77 ± 0.04 m and percentage body fat 11 ± 3 (Study I); age 22.2 ± 1.6 years, body mass 79.5 ± 9.8 kg, height 1.81 ± 0.07 m and percentage body fat 12 ± 3 (Study II).

Design

The two studies differed only in the environmental temperature at which they were conducted. For each study, subjects participated in three identical tests conducted at least one week apart - one test for each suit. Tests were carried out in an order based on a latin rectangular design to try and minimise any "learning"/acclimation effects that could arise from always beginning with the same suit. Testing took place in an environmental chamber at –6.0° C (Study I) and –10.0° C (Study II). Three fans generated a 4.5 $m \cdot sec^{-1}$ wind, which was standard in both studies.

Each test consisted of two discrete periods, rest followed immediately by exercise, during which subjects walked on a treadmill (Powerjog GX100, Sport Engineering Ltd, Birmingham, UK) set at 6 km·hr^{-1} on a 10 % incline. Each period lasted 30 min. All three tests for each subject were carried out at the same time of day, to minimise any differences that could occur in core temperature and other physiological responses due to diurnal variation (Lloyd 1986; Haymes and Wells 1986). Subjects were instructed to refrain from eating for at least three hours prior to each test as it has been documented that the ingestion of food is associated with changes in the diurnal pattern of rectal temperature (Iampietro et al. 1957).

Suits

Experimenters and subjects were blinded as far as possible as to the suit characteristics until completion of the whole study. Suits were labelled as HP, LP and MP. Suit characteristics are presented in Table 2.1.

The suits were provided in different sizes to ensure a good fit for each subject and were similar in their cut and design. Subjects were provided with a set of standard undergarments, as well as a hat and gloves. The hat minimised heat loss from the head - which can amount to 50 % of resting values (Froese and Burton 1957) - and gloves protected the hands, since their large surface area to mass ratio favours cooling (Spealman 1949).

Table 2.1: Physical properties and characteristics of suits.

Suit	Thickness (mm)	Thermal Resistance ($K{\cdot}m^2{\cdot}W^{-1}$)	Air Permeability ($cc.sec^{-1}$)	Label Specifications
HP	0.49	15.8×10^{-3}	31.0	75% cotton, 25% polyester; non-waterproof, water-repellent finish
LP	0.43	14.3×10^{-3}	0.6	synthetic woven outer, knitted liner (PTFE), waterproof, windproof, breathable
MP	0.49	14.4×10^{-3}	11.8	100% cotton, synthetic filaments, ripstop, non-waterproof, windproof water-repellent finish

Procedures

Upon arrival, each subject's body mass and height were recorded. Percentage body fat was estimated using the skinfold method outlined by Durnin and Womersley (1974). A thermistor was inserted 10 cm beyond the anal sphincter for measurement of rectal temperature as being representative of core temperature (T_R). Subjects were then seated in a comfortable environment (approximately 21° C) while thermistors were attached to the skin of the chest, triceps, thigh and calf on the right-hand side of the body for recording of skin temperature (T_{sk}). All thermistors were connected to a portable temperature logger (KM 1242, Comark Ltd, Hertfordshire, UK). Following this, a HR monitor (Polar Sport Tester, Polar Electro Oy, Kempele, Finland) was positioned on the chest of the subject. Once all test garments, including the hat and gloves (which concealed the HR receiver from the subject's view) had been donned, and the head-set, noseclip and mouthpiece positioned, the subject entered the climatic chamber.

Each test began with subjects sitting quietly on a chair positioned on the treadmill (so they would be exposed to exactly the same conditions - i.e. the impact of wind generated by the fans facing them). They were instructed to keep their feet flat on the ground and their hands on the sides of the treadmill. Subjects were required to sit in this position with no movement throughout the 30 min period. While the subjects were quietly seated, various physiological parameters were measured.

Following baseline temperature recordings at time zero (taken within approximately 1 min of entering the chamber), T_R, T_{sk}, HR and cold perception ratings (RPC) (using a scale modified from Gagge et al. 1969) were recorded every 5 min. Expired gas was collected in Douglas bags (150 l, polyurethane, Harvard Apparatus Ltd, Kent, UK) for 5 min at 5, 15 and 25 min during the rest period. The Douglas bags were connected to the mouthpiece using a 2700 valve, tubing and 2100 3-way stop cock valves, and were analysed (within 1 hour of completing each test) for oxygen uptake determination. O_2 content was measured with a Servomex 570A Oxygen Analyser (Crowborough, UK) and a PK Morgan 801A Carbon Dioxide Analyser (Morgan, Rainham, UK) determined CO_2 content. Gas volumes were measured by a Parkinson Cowan dry-gas meter (Cranlea, Birmingham, UK) and corrected to standard temperature and pressure, dry (STPD).

Subsequent to the 30 min rest period, the chair was removed and the subjects began exercise on the treadmill, the intensity of which was designed to represent a brisk hill-walk. Recordings for T_R, T_{sk}, HR and RPC were obtained every 5 min. Expired air was collected for 1 min at 5, 15, and 29 min during exercise. Following each test, weighted mean skin temperature (T_{sk}) was calculated using the equation of Ramanathan (1964).

Statistical Analysis

Data are expressed as the mean ± s.d. following a test for the normality of distribution. The group s.d. is used in graphical representation of results to aid clarity. The group s.d. is the pooled estimate of the common s.d. and represents the square root of the mean square error. The data were analysed using Repeated Measures Analysis of Variance. Subsequent follow-up Bonferroni-based Multiple Comparisons were carried out as appropriate depending on whether only the Suit main effect was significant or whether the Suit-Time interaction was significant. Paired t-tests determined when, and in which direction, a particular variable changed across time for each suit. Statistical significance was declared when $P < 0.05$.

Results

Study I

During the rest period, $\dot{V}O_2$ values for HP were significantly higher than those for LP and MP (Fig. 2.1). $\dot{V}O_2$ increased progressively across the rest period for HP and LP, but only displayed a significant increase at 25 min for MP (compared to the first value at 5 min). Furthermore during rest, the environment exerted a greater influence on HP in terms of RPC (Fig. 2.2), since values for HP were significantly higher than LP and MP. Values for all 3 suits showed a progressive rise during the course of the rest period.

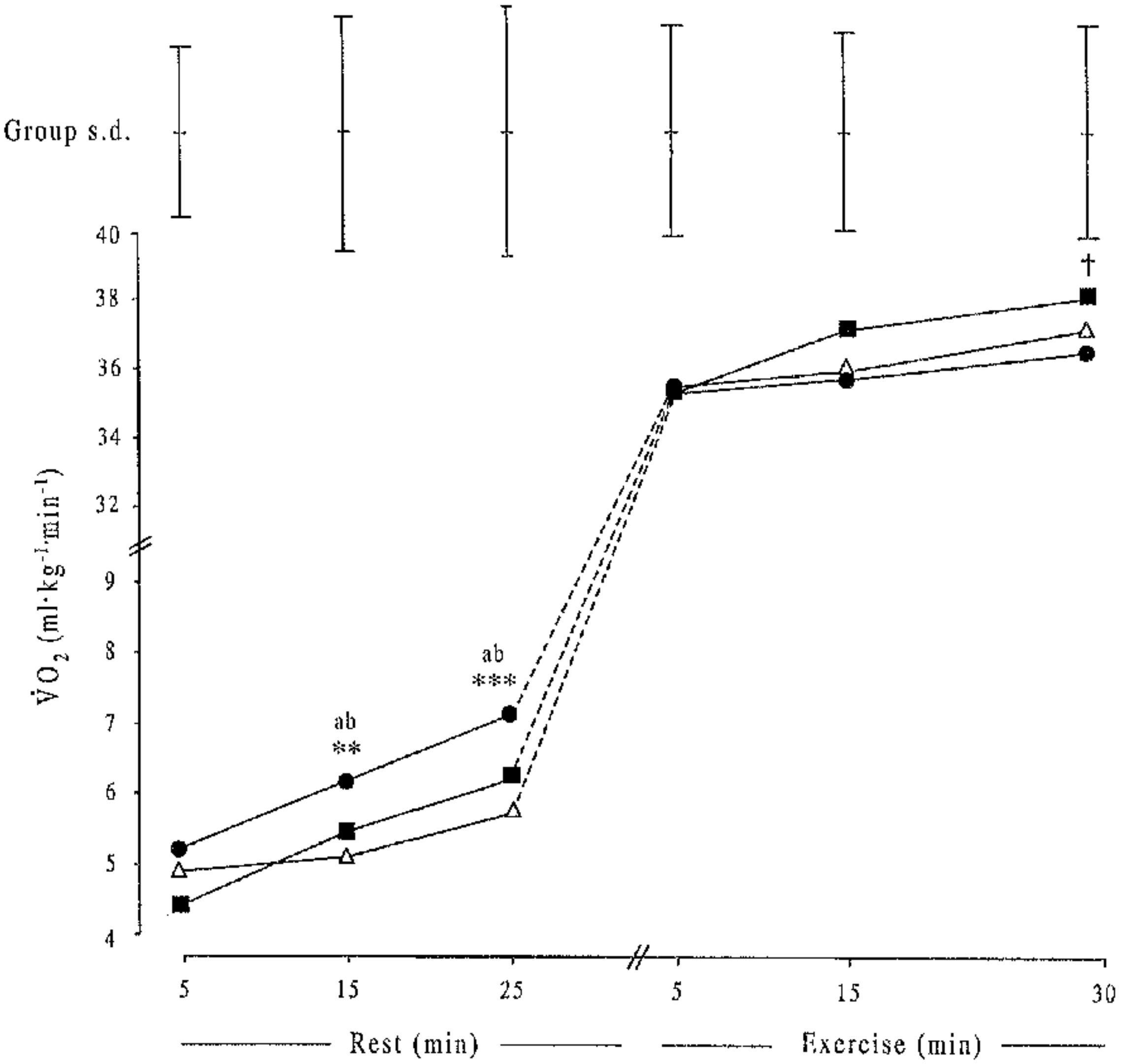
Exercise did not reveal any significant findings for the two variables discussed above. $\dot{V}O_2$ did not show any change across time during exercise for any of the suits - apart from LP where $\dot{V}O_2$ increased at the end of exercise compared the value obtained at 5 min into exercise (Fig. 2.1). RPC values on the other hand, decreased progressively from end-rest values for all suits upon initiation of exercise (Fig. 2.2).

Suits were not significantly different in terms of the T_R response during both rest and exercise (Fig. 2.3). During the rest period, the decrease in T_R for MP was delayed when compared to respective declines of HP and LP. Suits exhibited increases in T_R values (compared to values at the end of rest) during the second half of exercise and at the end of exercise they were no different to baseline values (i.e. time zero). No discernible differences were observed for suits in terms of T_{sk}, either during rest or exercise (Fig. 2.4). Like T_R, suits showed a progressive decline for T_{sk} across time during the rest period, values decreasing from baseline within the first 5 min. No change from values at the end of rest was observed for T_{sk} during exercise, and end-exercise values were significantly lower than baseline.

No differences were found among suits for HR during rest and exercise (Fig. 2.5). The rest period induced no change in HR in any of the suits, since values remained at stable levels throughout the 30 min. During exercise, HR progressively increased in all 3 suits.

Figure 2.1: $\dot{V}O_2$ (mean (s.d.)) during rest and exercise for HP (●), MP (△) and LP (■) (Study I). a: indicates a significant difference between HP and MP, b: indicates a significant difference between HP and LP. *: indicates a significant change from 5 min (rest), †: indicates a significant change from 5 min (exercise). The discontinuity in the time-axis (in all figures) represents the time elapsed (approximately 30 sec) for the rest-to-exercise transition.

Figure 2.2: RPC (mean (s.d.)) during rest and exercise for HP (●), MP (△) and LP (■) (Study I). a: indicates a significant difference between HP and MP, b: indicates a significant difference between HP and LP. *: indicates a significant change from 5 min (rest), †: indicates a significant change from 5 min (exercise).


Group s.d.
40
38
36
34
32
9
8
7
6
5
4
V̇O₂ (ml·kg⁻¹·min⁻¹)
ab
**
ab
***
†
5
15
25
5
15
30
Rest (min)
Exercise (min)

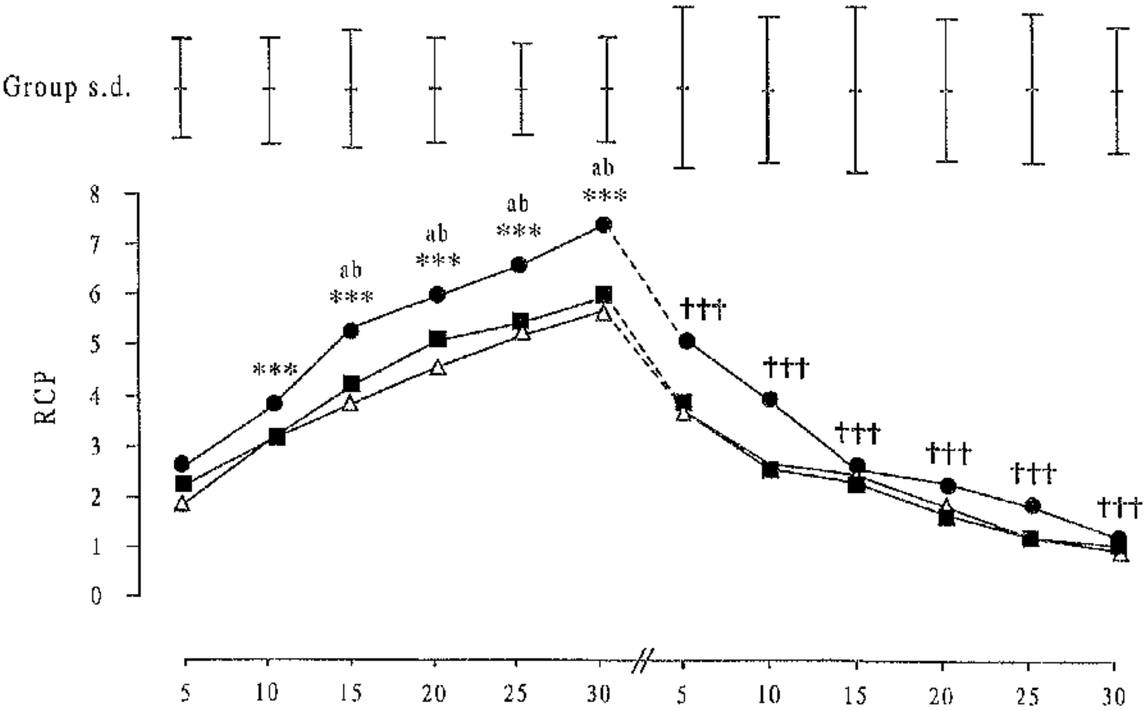

Group s.d.
8
7
6
5
4
3
2
1
0
RCP
***
ab
***
ab
***
ab
***
ab
***
†††
†††
†††
†††
†††
†††
5
10
15
20
25
30
5
10
15
20
25
30
Rest (min)
Exercise (min)

Figure 2.3: T_R (mean (s.d.)) during rest and exercise for HP (●), MP (△) and LP (■) (Study I). *: indicates a significant change from baseline (rest), †: indicates a significant change from 5 min (exercise).

Figure 2.4: T_{sk} (mean (s.d.)) during rest and exercise for HP (●), MP (△) and LP (■) (Study I). *: indicates a significant change from baseline (rest), †: indicates a significant change from 5 min (exercise).

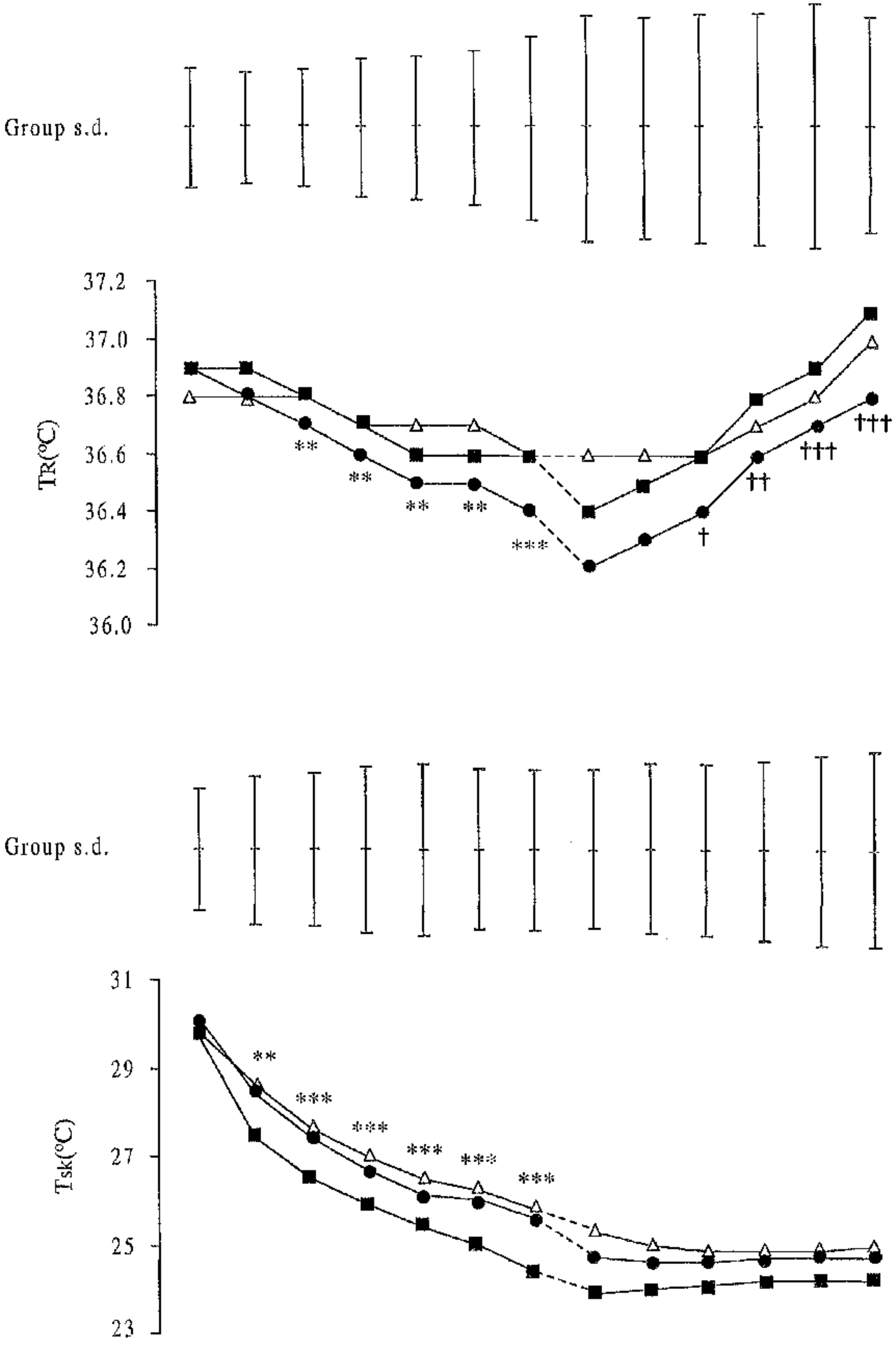
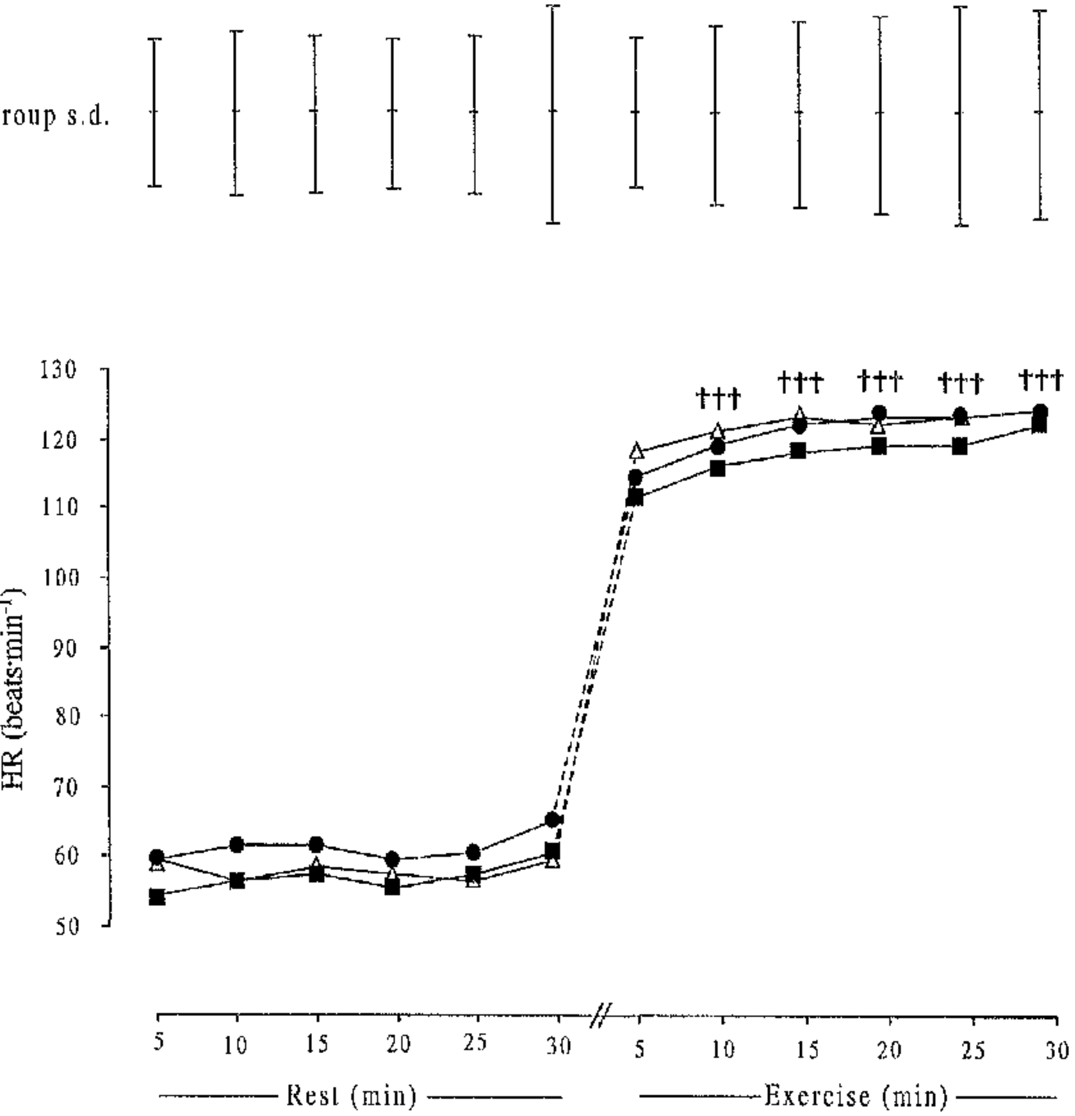

Group s.d.
37.2
37.0
36.8
36.6
36.4
36.2
36.0
TR(°C)
**
**
**
**
***
†
††
†††
†††
Group s.d.
31
29
27
25
23
Tsk(°C)
**
***
***
***
***
***
0
10
20
30
10
20
30
Rest (min)
Exercise (min)

Figure 2.5: HR (mean (s.d.)) during rest and exercise for HP (●), MP (△) and LP (■) (Study I). †: indicates a significant change from 5 min (exercise).


Group s.d.
130
120
110
100
90
80
70
60
50
HR (beats·min^{-1})
†††
†††
†††
†††
†††
5
10
15
20
25
30
5
10
15
20
25
30
Rest (min)
Exercise (min)

Study II

Suits were significantly different for $\dot{V}O_2$ at 25 min during the rest period (Fig. 2.6). $\dot{V}O_2$ for HP was significantly higher than LP and MP at this time-point. During rest, $\dot{V}O_2$ for HP rose progressively across time, but only increased at 25 min for MP compared to value measured at 5 min. The response for LP differed, in that $\dot{V}O_2$ increased significantly at 15 min compared to 5 min, but the value at 25 min was no different to that at 5 min. No significant differences were found among suits for the period of exercise, during which the only suit to show a progressive increase in $\dot{V}O_2$ across time was HP. $\dot{V}O_2$ values for LP and MP remained unchanged from those measured at 5 min into exercise, throughout the exercise period.

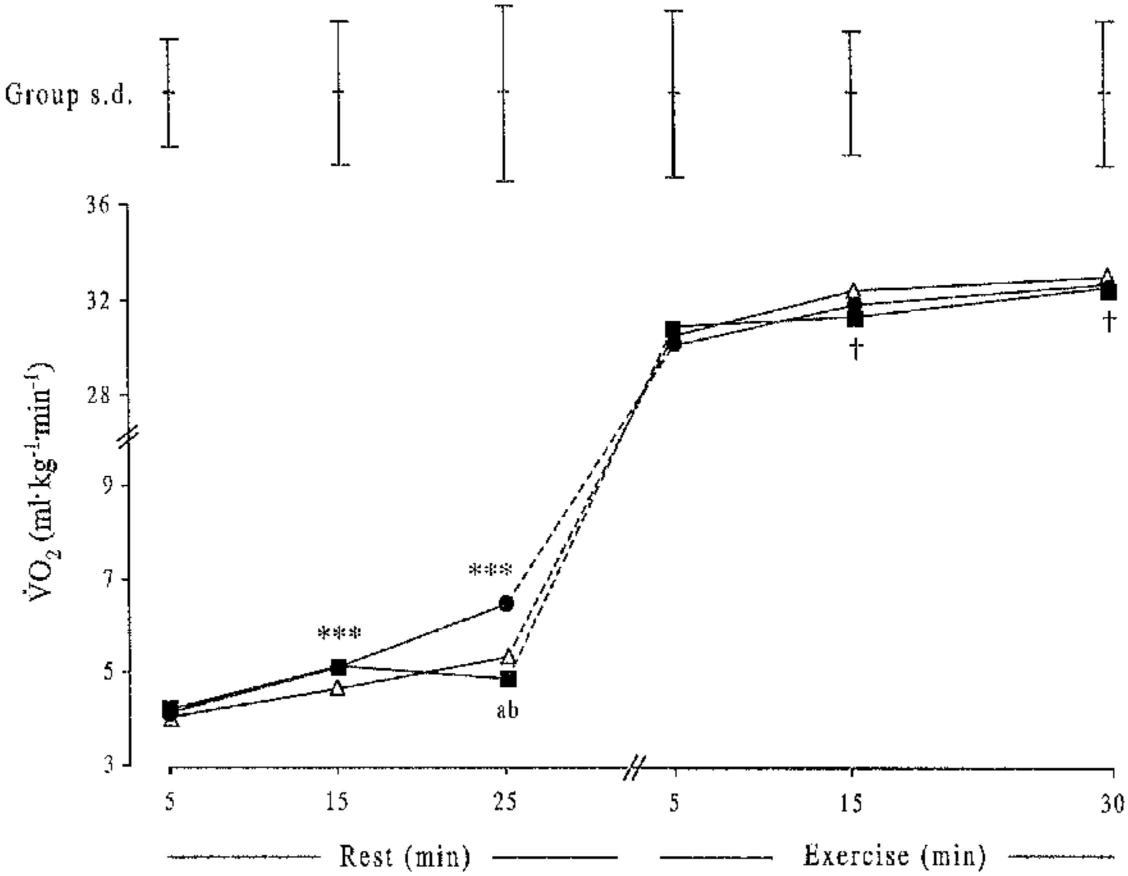
In terms of RPC results, HP produced the highest RPC values during rest, with MP displaying significantly lower values than the other 2 suits (Fig. 2.7). During the rest period, there was a significant increase in RPC values from 10 min onwards for all 3 suits, compared to values observed at 5 min. During exercise, RPC values for HP continued to remain significantly higher than those for LP and MP. All suits displayed a significant decrease from end-rest values within the first 5 min of exercise, and values at the end of exercise (30 min) were significantly lower than the first ratings given at rest (5 min) for all 3 suits.

T_R was not discernibly different among suits during rest and exercise. Fig. 2.8 illustrates the progressive decrease in T_R during rest and the concomitant increase during exercise that elevated T_R to baseline levels. During the rest period, T_{sk} values for MP were significantly higher than those for HP and LP (Fig. 2.9). There was a progressive decrease in T_{sk} during rest for the suits, with all 3 suits displaying a significant decline from baseline values, from 5 min onwards into the rest period. Significant differences among suits were also found during the exercise period that followed from rest, with significantly higher T_{sk} values for MP than corresponding values for HP and LP. There was no significant increase in T_{sk} from end-rest values for any of the suits during exercise, and therefore values at the end of the exercise period were significantly lower than baseline for all suits.

As for Study I, there were no differences among suits for HR, during both rest and exercise (Fig. 2.10). HR values remained unchanged during rest for LP, and only increased significantly at 30 min for HP and MP, when compared to values at 5 min. During exercise, HR rose progressively from values observed in the initial 5 min for all suits.

Figure 2.6: $\dot{V}O_2$ (mean (s.d.)) during rest and exercise for HP (●), MP (△) and LP (■) (Study II). a: indicates a significant difference between HP and MP, b: indicates a significant difference between HP and LP. *: indicates a significant change from 5 min (rest), †: indicates a significant change from 5 min (exercise).

Figure 2.7: RPC (mean (s.d.)) during rest and exercise for HP (●), MP (△) and LP (■) (Study II). a: indicates a significant difference between HP and MP, b: indicates a significant difference between HP and LP, c: indicates a significant differences between LP and MP. *: indicates a significant change from 5 min (rest), †: indicates a significant change from 5 min (exercise).


Group s.d.
36
32
28
9
7
5
3
$\dot{V}O_2$ (ml·kg⁻¹·min⁻¹)
***
***
ab
†
†
5
15
25
5
15
30
Rest (min)
Exercise (min)

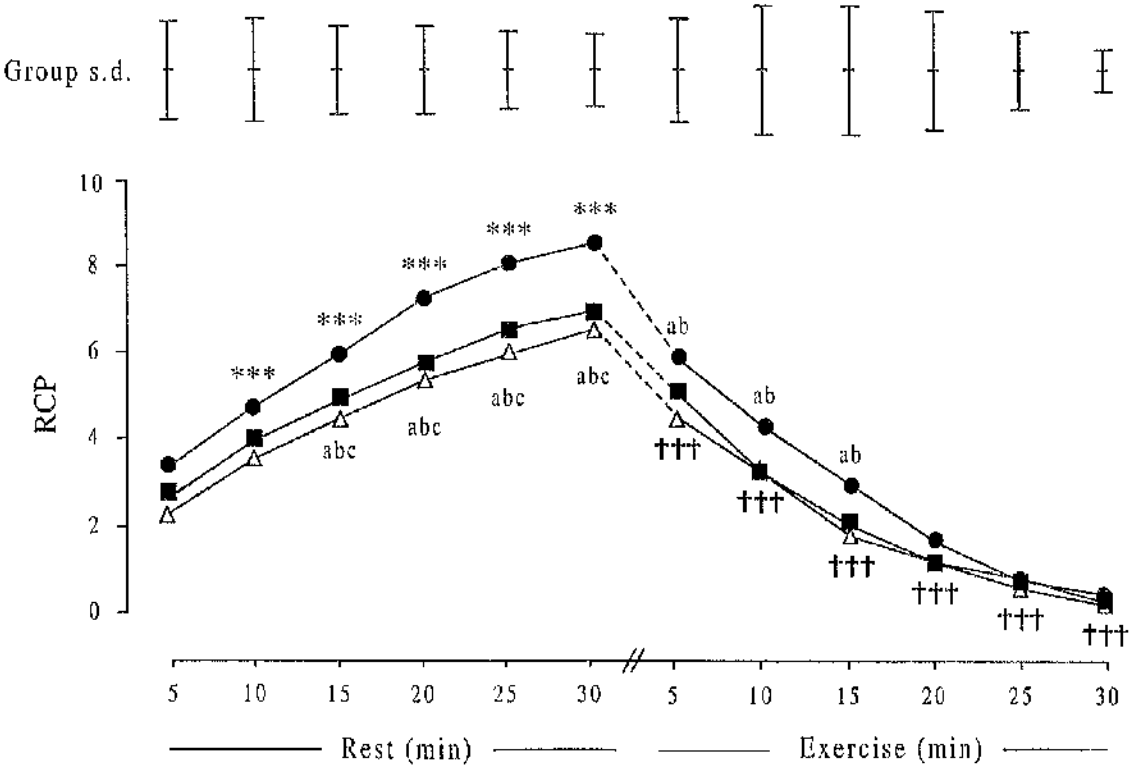

Group s.d.
10
8
6
4
2
0
RCP
***
***
***
***
***
***
abc
abc
abc
abc
ab
ab
ab
†††
†††
†††
†††
†††
†††
5
10
15
20
25
30
5
10
15
20
25
30
Rest (min)
Exercise (min)

Figure 2.8: T_R (mean (s.d.)) during rest and exercise for HP (●), MP (△) and LP (■) (Study II). *: indicates a significant change from baseline (rest), †: indicates a significant change from 5 min (exercise).

Figure 2.9: T_{sk} (mean (s.d.)) during rest and exercise for HP (●), MP (△) and LP (■) (Study II). a: indicates a significant difference between HP and MP, c: indicates a significant differences between LP and MP. *: indicates a significant change from baseline (rest), †: indicates a significant change from 5 min (exercise).

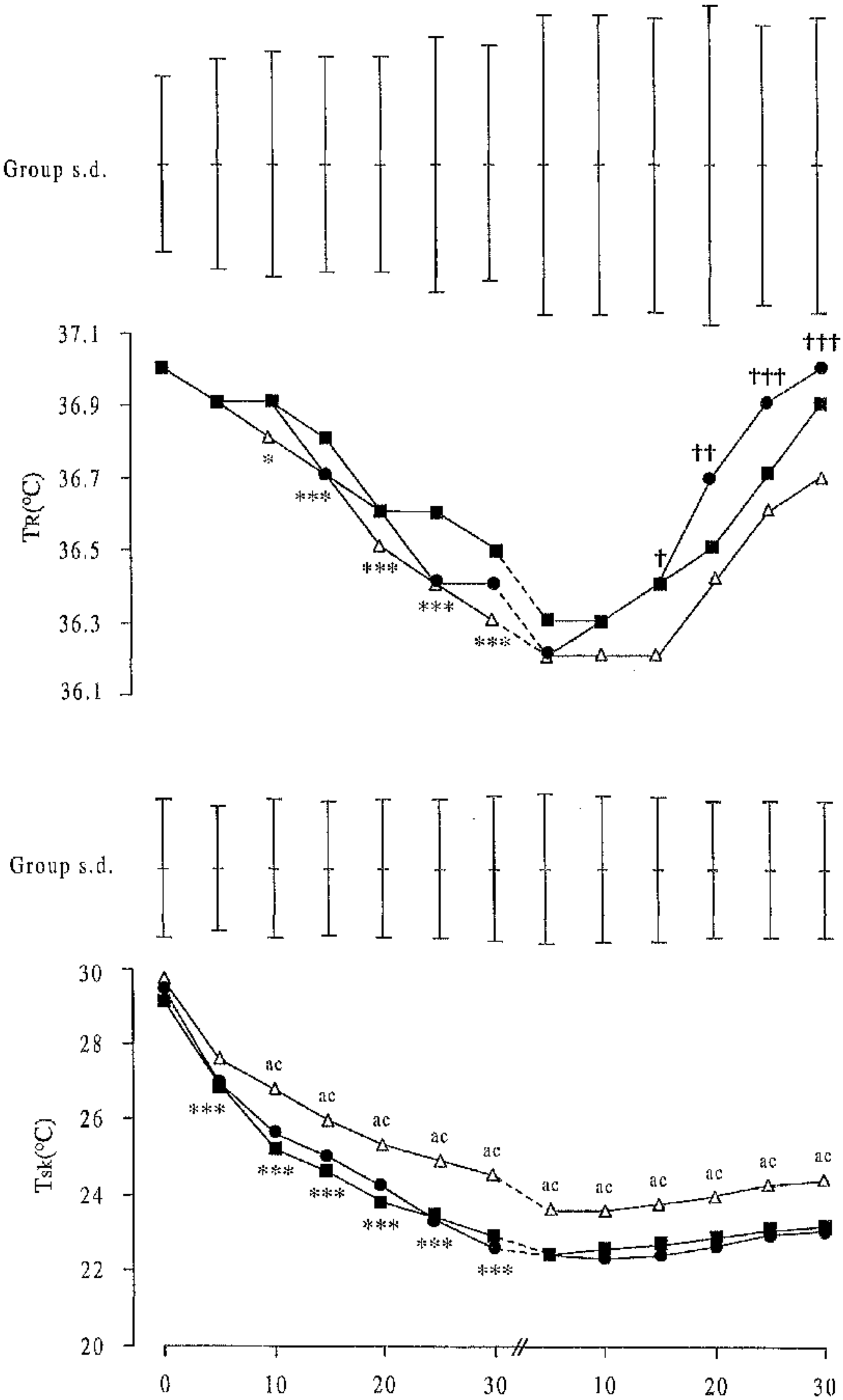
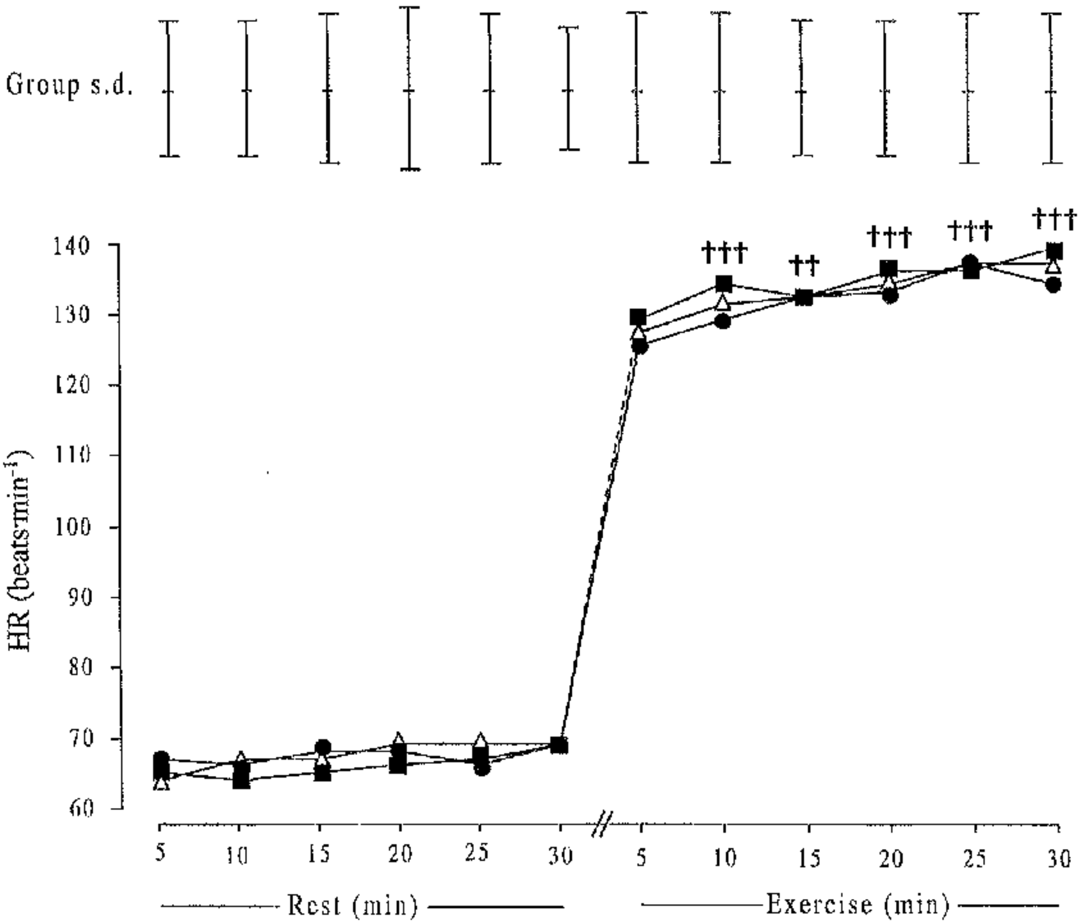

Group s.d.
37.1
36.9
36.7
36.5
36.3
36.1
TR(°C)
*
***
***
***
***
†
††
†††
†††
Group s.d.
30
28
26
24
22
20
Tsk(°C)
***
***
***
***
***
***
ac
0
10
20
30
10
20
30
Rest (min)
Exercise (min)

Figure 2.10: HR (mean (s.d.)) during rest and exercise for HP (●), MP (△) and LP (■) (Study II). †: indicates a significant change from 5 min (exercise).


Group s.d.
HR (beats·min⁻¹)
140
130
120
110
100
90
80
70
60
†††
††
†††
†††
†††
5
10
15
20
25
30
5
10
15
20
25
30
Rest (min)
Exercise (min)

Discussion

The results of the two studies indicate that HP is the least effective of the 3 suits in offering protection against the imposed environment, taking into consideration the duration of exposure and alternating activity status of subjects. Furthermore, the findings appear to suggest the preferential use of MP in the specified environmental conditions. The physiological adjustments evoked in response to the combined effects of cold and wind, alongside the subjective perceptions for each of the suits, allow certain conclusions to be drawn regarding suit performance.

Higher $\dot{V}O_2$ values were found for HP during the rest period compared to LP and MP for Study I, although all suits displayed a progressive rise in $\dot{V}O_2$ across rest (Fig. 2.1). HP was the only suit to exhibit a progressive increase in $\dot{V}O_2$ for Study II, and was significantly higher than LP and MP in terms of $\dot{V}O_2$ at 25 min (Fig. 2.6). The increase in $\dot{V}O_2$ is likely attributable to an increase in muscle tone (or "preshivering") and/or shivering, called upon by the body when vasoconstriction is maximal and it can no longer protect against a decrease in core temperature. Although shivering was not quantified directly in these studies, overt shivering was visible in some subjects, especially in the torso and upper body. Shivering is the only means by which the body can increase heat production in attempt to preserve T_R once vasoconstriction reaches upper limits. Limb blood flow has been shown to approach zero at a core temperature of 36° C (Pendergast

1988). Within Study II, at least 6 subjects displayed T_R values of 36° C towards the end stages of rest.

Under conditions of rest, thermogenic shivering and involuntary increases in muscle tone that may precede and accompany shivering are liable to cause a 2- to 3-fold rise in metabolism (Haymes and Wells 1986; Shephard 1993). Most the energy during shivering contractions is converted to heat as no external work is performed. Shivering translates to an added oxygen requirement since oxygen must be supplied to contracting muscles. $\dot{V}O_2$ therefore increases, and previous investigators have shown that this could amount to as much as 1.5 $l \cdot min^{-1}$ (Paton and Vogel 1984; Pendergast 1988). Resting $\dot{V}O_2$ levels did not rise to that extent in the present studies, most probably due to the stress of the environment not being severe enough and the relatively short duration of exposure. The cold and windy conditions did allow for differentiation between suits in terms of $\dot{V}O_2$, and the fact that HP displayed significantly higher values than LP and MP suggests that subjects were shivering to a greater degree when wearing HP. This finding further implies that subjects were colder when wearing HP compared to the other 2 suits, and the stimuli required to initiate thermogenic shivering, greater.

Results for RPC offer further support to the view that has HP emerging as the poorest of the suits in terms of protecting wearers in the specified environmental conditions. HP displayed significantly higher RPC values compared to the other suits during rest in both of the studies, thus indicating that subjects perceived themselves to be the coldest when wearing the particular suit. Furthermore, in Study II, subjects indicated that they perceived themselves to be warmer when wearing MP, since corresponding RPC values were significantly lower than the other suits.

Significantly higher T_{sk} values were found for MP compared to HP and LP during rest in Study II (Fig. 2.9), thus supporting findings for subjective perception of cold. The rest period that preceded exercise induced cooling in the subjects, and this was reflected by a progressive decline in both T_R and T_{sk} for all suits (Fig. 2.8 & 2.9, respectively). The progressive decrease from baseline for the two temperature variables during rest was present in both studies. When a subject is exposed to cold stress, the initial adjustment of the body is normally that of peripheral vasoconstriction (Spealman 1949; Burton and Edholm 1955; Lloyd 1986; Haymes and Wells 1986). The results of this study are consistent with this view, since subjects exhibited a decline in T_{sk}, before T_R had decreased to a significant extent from baseline values.

With the exception of the head, vasoconstriction of superficial blood vessels occurs in most areas of the body when it is cooled and skin temperature decreases (Haymes and Wells 1986). The response is mediated mainly via the sympathetic nervous system, although cold can sometimes have a direct effect on the vessels causing them to constrict (Lloyd 1986; Haymes and Wells 1986). It appears likely for Study II (remembering that T_{sk} for MP was significantly higher than values for the other two suits), that the requirement to decrease T_{sk} and thus effectively minimise the temperature gradient between the skin and the environment, was reduced in subjects wearing MP. Findings for

RPC confirm that subjects indeed perceived themselves to be warmer when wearing this suit.

Despite rating HP as the coldest of the suits, Study I revealed no measurable differences for T_R or T_{sk} during the rest period. This is especially surprising if the results for $\dot{V}O_2$ are taken into account. It would seem reasonable to assume that the necessary stimuli required to induce a greater degree of shivering and increases in muscle tone in subjects when wearing HP were more powerful in terms of magnitude. Although investigators are not in complete agreement as to the signals that initiate shivering, most of the available evidence concludes that shivering metabolism is best described by a multiplication of temperature signals from the core and skin (Hong and Nadel 1979; Pendergast 1988).

It does appear reasonable to assume that the initiating signals for shivering thermogenesis originate in the periphery since it is usually the first to respond to cold. Hong and Nadel (1979) observed shivering in one of their subjects almost immediately upon cold exposure (alongside a rapid fall in T_{sk}), and Jacobs et al. (1994) described how shivering occurred after less than 5 min of cold exposure in lean subjects. The present studies showed both T_R and T_{sk} declining from baseline level in a progressive manner during rest. The response for T_{sk} however was quicker in Study II, since subjects exhibited a decline in T_{sk} before T_R decreased from baseline to a significant extent. Although baseline values for $\dot{V}O_2$ were not measured in these studies (making it impossible to detect a change within the first 5 min), T_{sk} decreased significantly from baseline at 5 min and, as previously mentioned, this decline preceded a decrease in T_R. The differences between the two variables in terms of when a significant decline from baseline was observed, varied from 5 to 20 min.

Findings from Study I on the other hand, tend to oppose the idea that shivering is determined by transient changes in T_{sk}. Although HP and LP showed a progressive increase in $\dot{V}O_2$ during rest, measurable increases in $\dot{V}O_2$ for MP (from the value at 5 min) were not observed until 25 min, suggesting a delayed shivering response and indicating that perhaps subjects were less cold when wearing MP. For this suit, T_{sk} decreased significantly from baseline 10 min into the rest period but only showed a significant fall in T_R at the very end of rest. This conforms to the view that cold perception within the body core is the most important determinant of the shivering response following experiments that manipulated average skin and body core temperatures (Nadel et al. 1973; Hayward 1977).

No significant differences in either of the studies were found among suits for HR, which remained stable throughout the rest period. As a result of peripheral vasoconstriction during exposure to cold, venous return is enhanced and stroke volume is increased (Haymes and Wells 1986; Pendergast 1988). If CO is to remain constant, HR must decrease. Davies et al. (1975) have postulated that a fall in core temperature may directly affect cardiac function and result in decreased HR. However when shivering is initiated CO increases, the increase mediated both by an elevation in stroke volume and an increase in HR (Haymes and Wells 1986). It seems plausible that the two opposing responses (i.e., the decrease due to the effects of the cold and the increase resulting from shivering activity) could counteract each other, thus maintaining HR near normal resting levels.

The thermogenic capacity of exercise minimised the ability to distinguish between suits in terms of any of the variables measured in Study I. Significant differences were found only in the colder environment of Study II, for T_{sk} and RPC. During exercise, T_{sk} values for MP were significantly higher than HP and LP. T_{sk} (which, as previously discussed, exerts considerable influence the body's thermoregulatory responses) is affected by the microenvironment that exists between clothing and skin (Pascoe et al.1994a). Havenith et al. (1990) have shown that most of the insulation in a clothing ensemble is provided by the entrapped air layers and the clothing outer surface air layer. Any disturbance of these air layers will have measurable effects on the insulation value. When movement and wind are combined they interact, and both intrinsic clothing and surface air insulation are diminished (Havenith et al. 1990). The effects of movement were standardised as far as possible in the present study, and suits were closed very effectively around wrists and ankles preventing cold air being pumped underneath the clothing by a bellows-like action. Interestingly, baseline values for T_{sk} had not recovered in any of the suits at the end of exercise, in either of the two studies. This may reside in the fact that body movement during exercise increases convective and evaporative heat transfer coefficients, thereby increasing the rate of heat loss from skin to the environment (Hong and Nadel 1979).

RPC for HP was significantly higher than respective values for LP and MP during exercise in Study II. All suits showed a rapid decrease from end-rest figures for RPC without a corresponding change in T_{sk} and T_R. It is within reason to assume that during this time, the impact of the cooling that occurred during the rest period, continued to exert considerable effect. During the latter stages, where the heat-generating capacity of exercise had begun to take effect, the differences were less obvious between suits. No discernible differences were found for RPC in Study I. Values began to decrease from end-rest levels within the first 10 min of exercise initiation, indicating that heat production of exercise was having a measurable effect on cold perception.

The exercise period did not induce any measurable differences among suits for T_R in either study. Initiation of exercise produced no change in T_R for suits compared to values at the end of rest. A further decline in T_R from the value observed at the end of rest was found after 10 min of exercise in LP (Study II) (Fig. 2.8). This presumably reflects a redistribution of body heat content, since cold blood from cooled limbs is flushed through the warmer viscera in the body core, and is consistent with previous findings (Hong and Nadel 1979; Kruk et al. 1990). A time lag of approximately 20-25 min was observed for all suits before T_R began climbing significantly from end-rest values. Chappuis et al. (1976) explain this delay as corresponding to time elapsing before the heat produced by exercising muscles induces any measurable variation in internal temperature. On completion of exercise however, T_R for all suits was not significantly different from baseline values, indicating that the heat-generating capacity of exercise was adequate to compensate for the decline at rest (Studies I and II).

No overall differences were found among suits for $\dot{V}O_2$ during exercise in the two studies. During Study I, $\dot{V}O_2$ for the three suits remained essentially unchanged throughout the duration of exercise. For Study II, $\dot{V}O_2$ increased progressively over time for HP in contrast to the response for LP and MP (which showed no change in $\dot{V}O_2$ during exercise). The same suit also displayed a significantly higher $\dot{V}O_2$ at the end of rest, a finding most likely attributable to increased shivering and/or greater increases in muscle tone in subjects wearing HP. Although heat production of voluntary exercise can replace that of involuntary shivering contractions during cold exposure, shivering has been shown to co-exist with exercise (Nadel et al. 1973; Hong and Nadel 1979; Patton and Vogel 1984). It is possible that some subjects may have been shivering during the period of brisk walking - more so when wearing HP. A graded inhibition of shivering has been found during exercise in the cold, as the thermogenic capacity of exercise replaces shivering (Hong and Nadel 1979). Shivering contractions are weakened, and hence the additional oxygen requirement is reduced. Consequently (as evidenced by the absence of significant findings), the likelihood of discriminating among the 3 suits during exercise with respect to the magnitude of the $\dot{V}O_2$ response is diminished.

Increases in HR (from values recorded at 5 min into exercise) were found for all suits, although there were no measurable differences among the suits for this variable in either study. Differences may have been expected had subjects cooled to a greater extent during rest, since lowered T_R has been shown to slow HR by a direct effect on cardiac muscle function (Davies et al. 1975). Subjects exhibiting reduced sub-maximal and maximal HR, had been pre-cooled to T_R of approximately 35° C (Davies et al. 1975); in the present studies however the environment was not so severe to induce cooling of comparable magnitude.

On the basis of the findings from both studies, HP emerges as the suit offering the least protection in the imposed conditions, considering the wind speed, duration of exposure and activity status of subjects. Results also indicate that MP is the most effective of the suits, as evidenced by the higher T_{sk} values and lower RPC scores. HP is a predominantly cotton garment (75 %), incorporating a higher air permeability and higher thermal resistance than the other two suits. The latter characteristics are likely due to the more open-weave structure of the specific garment. The construction of a fabric has potential to influence the manner with which a garment conducts heat and moisture, along with fibre characteristics (Gonzalez 1988). The intrinsic thermal insulation of any garment is determined by the amount of still air that is trapped within the weave of the fabric. Suit characteristics (i.e., the highest thermal resistance) indicate that HP has the greatest capacity among the suits to trap air within its structure; the still air however can also easily be disturbed through forced convection. Evidently the microporous film coating HP (i.e. the fabric finish), does not provide adequate protection against wind (at least in the specified environment of this study), despite the fact that most films are designed to provide protection against both wind and water (Pascoe et al. 1994a). It was difficult to discriminate between the remaining two suits, both of which have a lower air permeability than HP, but also lower thermal resistance. It is likely that yarns in these suits are tightly interlaced, minimising the amount of stagnant air trapped, and thus decreasing thermal insulation. Furthermore, LP contains a PTFE membrane - very similar to Gore-Tex laminate, which combines breathability with a high resistance to both wind and water (Pascoe et al 1994; Dickinson 1995).

The findings indicate that MP was the most favourable of the suits in the imposed conditions, appearing to outperform even LP, which has a very low air permeability coefficient. MP is also a windproof garment (with a higher air permeability coefficient than LP), and has almost identical thermal resistance as LP. The discriminating factor between LP and MP therefore must lie in the difference in garment thickness. Although care was taken to ensure that suits fitted subjects equally and that this was standardised throughout tests, the thinner material of LP may have caused a looser fit. Gavhed et al. (1991) postulated that a comparatively looser fit of a garment could result in proportionately higher ventilation through any small openings of the clothing ensemble. If T_{sk} results are taken into consideration (remembering that T_{sk} for MP was consistently higher than LP, as well as HP), it appears plausible that a higher ventilation within the microclimate could account for the differences in T_{sk}. Nielsen et al (1989) also observed higher local skin temperatures with a tight fit, compared to a looser fit clothing layer (at equal values of clothing insulation).

Conclusion

The studies have shown that the degree to which an outer garment is permeable to wind, has the ability to significantly influence the thermoregulatory response to cold stress (- 6.0 and -10.0° C with 4.5 $m \cdot sec^{-1}$ wind-speed) during 30 min of rest, followed immediately by an equal period of exercise. Furthermore, the results indicate that there are other factors, for instance garment thickness and fit (even though the latter was not quantified), which may have a significant effect on performance in a specified environment.

Chapter Three

(Study III)

The influence of garment wicking capacity on physiological and perceptual responses to cold stress during rest following physical activity.

Introduction

During physical activity in the cold, significant quantities of sweat can be produced (Dickinson 1995) - a phenomenon common to skiers and mountain hikers who usually alternate between periods of high and low physical activity. Sweat will largely accumulate on the surface of the skin and in clothing, and can cause problems when physical activity ceases. The possibility of subsequent cooling is increased since metabolic heat from exercise no longer contributes to thermal balance. Furthermore, the concomitant heat loss incurred is enhanced due to the presence of moisture as heat is lost at rates approximately 25 times greater through water compared to air (Keatinge 1969; Haymes and Wells 1986; Lloyd 1986). It seems reasonable to assume that a garment, which actively removes moisture from the skin, should in theory, reduce cooling in cold conditions by effectively "sparing" heat lost through evaporation from the skin. Furthermore, the removal of fluid away from the skin avoids deterioration of the microclimate, which may become unpleasant to the wearer if wet clothing clings to the skin (Bakkevig and Nielsen 1994). The present study aimed to compare the performance of four different base-layer garments, which differed in their wicking capacity. The design of the study allowed for an indirect assessment of the wicking properties of the garments by inducing sweat production in exercising subjects, then allowing them to recover for 45 min in a cold environment. The garments were assessed during recovery, based on physiological and subjective responses from participating subjects. Differences in liquid absorbing and transporting abilities between the garments could be expected to affect evaporation from the body to the environment, thus contributing to variations in the development of post-exercise chill.

Methods

Subjects

Eight male subjects participated in the study, which was approved by the Ethical Committee at Glasgow University. The subjects were all involved in regular physical activity at the time of participation and gave their written informed consent agreeing to their participation. Subject characteristics (means ± s.d.) are as follows: age 22.3 ± 2.1 years, body mass 67.5 ± 6.1 kg, height 174 ± 5 cm and body fat 14 ± 2 %.

Design

Tests were conducted in an environmental chamber, the temperature of which was set at 1.2° C. Every subject participated in four identical tests at least a week apart - one test for each garment. The order of tests was based on a latin rectangular design in an attempt to minimise any 'learning'/acclimation effects that could possibly arise from always beginning with the same garment. Subjects undertook all tests at the same time of day to minimise any differences that could occur in core temperature and other physiological responses due to diurnal variation (Burton and Edholm 1955; Lloyd 1986; Haymes and Wells 1986) and fasted for at least 3 hours prior to each experiment.

The design of the study was similar to those of Ha et al. (1996, 1998), whereby severe exercise was followed by a longer period of recovery in a cold environment, in their attempts to discriminate between two kinds of underwear. Each 65 min test in the present study, incorporated a 20 min exercise period, followed by 45 min of rest. No measurements were made during exercise - its sole purpose was to induce sweating in the subjects. A number of physiological and subjective variables were recorded during the subsequent 45 min rest period however, providing feedback on garment performance.

Garments

All the garments tested (long-sleeved, zip-neck t-shirts) were designed for use as a baselayer in a wide range of outdoor activities and varied in their wicking capacity. CP and P had good wicking properties, PN medium, and C had poor wicking capacity. Garment characteristics are given in Table 3.1. Different sizes were provided to ensure a good fit for subjects. Experimenters and subjects blinded as far as possible to the make of each garment to avoid any possible bias. A number of tests were conducted on the four garments, confirming manufacturers' claims regarding characteristics and performance.

Material thickness and thermal resistance were measured using a Zweigle T675 Alambeta testing unit (Zweigle Textilprufmaschinen GmbH, Germany), which consists of two measuring heads between which the testing material is placed. The measuring principle is based on measuring and processing the time variation in heat flows, generated by creating a temperature gradient between sensors on the upper and lower measuring heads. Vapour permeability was assessed over a period of 24 hrs, by placing a sample of fabric from each of the garments over a beaker with a known quantity of water, sealing the edges and then obtaining another measurement 24 hrs later. The difference in weight for each garment corresponded to the amount of water

Table 3.1: Garment specifications and physical properties

Garment	Specifications	Thickness (mm)	Thermal Resistance $(K\cdot m^2\cdot W^{-1})$	Vapour Permeability $(gm\cdot m^{-2}\cdot hr^{-1})$	Wicking (cm)		Weight (g)
					2min	10min	
PN	Wicking garment designed for wear next to the body. Conducts moisture away from the body. 100% polyamide /nylon.	0.8	$24.9\text{x}10^{-3}$	58	3.0	5.0	159
CP	Midweight, capilene underwear. Made from fast-drying, wicking capilene polyester, with unique fibres and knit structure that mechanically transport moisture. Stripes of spun yarn and microfibre filaments, as well as air pockets on the inner surface, trap warm air and increase vapor transfer.	0.8	$21.9\text{x}10^{-3}$	55	5.5	9.0	222
P	Dryflo zipneck. Active thermal underwear made from 100% hydrophobic polyester fibres. A unique yarn denier gradient system transports moisture away from the body mechanically.	1.1	$40.3\text{x}10^{-3}$	60	6.5	9.0	196
C	100% cotton	2.0	$41.3\text{x}10^{-3}$	54	0.5	3.0	456

evaporated through the fabric. Finally, garments were directly evaluated for their wicking capability, by suspending strips of fabric (approximately 20 cm long by 5 cm wide) with the bottom edge dipped in coloured dye. The distance by which the dye had spread up each strip was measured at specified time-points.

Subjects wore long-johns (100 % hydrophobic polyester) and a lightweight jacket (made from polyester material backed with special polyurethane-based coating) throughout all four experiments. Furthermore, during exercise, subjects wore a hat and gloves. This was an attempt to facilitate sweat production, by minimising heat loss from the head and extremities (both of which constitute valuable heat exchange avenues) (Burton and Edholm 1955; Froese and Burton 1957). The hat and gloves were removed as soon as the rest period commenced.

Experimental Procedures

Subjects reported to the laboratory and preparations for tests took place in an antechamber at normal ambient temperature (approximately 20° C). Body mass and height were recorded, and percentage body fat was estimated using the skinfold method outlined by Durnin and Womersley (1974). Subjects were then instrumented for core (measured rectally) (T_R) and T_{sk} measurement. A thermistor inserted 10 cm beyond the anal sphincter was used to measure T_R; T_{sk} was recorded from four sites on the right-hand side of the body and a weighted average from these was taken as being representative of mean T_{sk} (Ramanathan 1964). A heart rate (HR) monitor (Polar Sport Tester, Polar Electro Oy, Kempele, Finland) was positioned on the subject's chest.

Each 65 min experiment began with a 20 min exercise period in the form of walking on an inclined treadmill (Powerjog GX 100, Sport Engineering Ltd, Birmingham, UK). The velocity was kept constant at 6 $km \cdot h^{-1}$, whereas the gradient on the treadmill was increased by 5 % every 2 min until 15 % was reached. Following exercise, the subjects were seated on a chair positioned in the middle of the treadmill for the remaining 45 min of the experiment. They were fitted with a headset, mouthpiece and noseclip, and instructed to keep their feet flat on the ground and their hands on the sides of the treadmill. A 4.5 $m \cdot sec^{-1}$ (10 $m \cdot h^{-1}$) wind was introduced as soon as subjects were seated, via three fans positioned opposite the treadmill.

During the period of inactivity physiological and perceptual measurements were obtained. Following baseline temperature recordings at time zero (taken within approximately 1 min of cessation of exercise), T_R, T_{sk}, HR and RPC (using a scale modified from Gagge et al. 1969) were recorded every 5 min. Expired gas was collected in Douglas Bags (150 l, polyurethane, Harvard Apparatus Ltd, Kent, UK) for 5 min at 5, 15, 25, 35 and 40 min. The Douglas bags were connected to the mouthpiece using a 2700 valve, tubing and 2100 3-way stop cock valves, and were analysed within 1 hr of completion of each test for oxygen uptake determination. O_2 content was measured with a Servomex 570A Oxygen Analyser (Crowborough, UK) and a PK Morgan 801A Carbon Dioxide Analyser (Morgan, Rainham, UK) determined carbon dioxide content. Gas volumes were measured by a Parkinson Cowan dry-gas meter (Cranlea, Birmingham, UK) and corrected to standard temperature and pressure, dry (STPD).

Statistical Analysis

Data are expressed as the mean ± s.d. following a test for the normality of distribution. The group s.d. is used in graphical representation of results to aid clarity. The group s.d. is the pooled estimate of the common s.d. and represents the square root of the mean square error. The data were analysed using Repeated Measures Analysis of Variance. Subsequent One-Way Analysis of Variance was performed where appropriate and, depending on results, was followed by Fishers LSD tests. Paired t-tests were carried out when appropriate to determine in which direction a particular variable changed across time for each garment. Statistical significance was declared when $P < 0.05$.

Results

Significant differences between garments were found for RCP at 25, 30, 35 and 40 min (Fig. 3.1). Results revealed that values for P were significantly lower than corresponding RCP values for PN and CP at these time-points. All garments displayed a progressive increase in RCP across time from 10 min onwards, compared to values at 5 min.

Analysis of $\dot{V}O_2$ data revealed a tendency for differences between garments only at 25 min (Fig. 3.2), with P and C producing lower $\dot{V}O_2$ values at this time-point compared to PN and CP. There was a significant increase in $\dot{V}O_2$ at 40 min from the value at 5 min in PN and CP. For P, $\dot{V}O_2$ showed a decrease at 15 min compared to the value at 5 min, then increased significantly at 40 min compared to the 15 min value. The response for C was similar to that of P - $\dot{V}O_2$ decreased from the initial value obtained at 5 min, at 15 min, then increased from this at 35 min onwards.

There were no significant differences among garments for T_R or T_{sk} over the 45 min period of rest (Fig. 3.3 and Fig.3. 4, respectively). Baseline values (i.e., time zero) were analysed and were found not to differ between suits. Values for T_R displayed a progressive decline from baseline, significant decreases observed within the first 5 min (apart from CP, where T_R showed a significant decline from baseline at 10 min). The response among garments for T_{sk} was similar, values progressively declining from baseline from 10 min onwards, with the exception of CP which decreased from baseline at 5 min.

Garments were not significantly different in terms of HR response (Fig. 3.5). HR fell progressively from values at 5 min within 15 min for P and C, and at 20 min for CP. PN displayed an initial decrease in HR at 15 min (compared to 5 min), followed by intermittent fluctuations between 20 and 30 min.

Finally, it must be noted that three of the subjects were unable to complete the full duration of the 45 min rest period when wearing either PN or CP. Two subjects terminated tests for PN and CP, and another subject was unable to complete the test for only CP because of unbearable cold perception.

Figure 3.1: RPC (mean (s.d.)) for PN (○), CP (■), P (□) and C (●). a: indicates a significant difference between PN and P, b: indicates a significant difference between CP and P. *: indicates a significant change from 5 min.

Figure 3.2: $\dot{V}O_2$ (mean (s.d.)) for PN (○), CP (■), P (□) and C (●). *: indicates a significant change from 5 min.

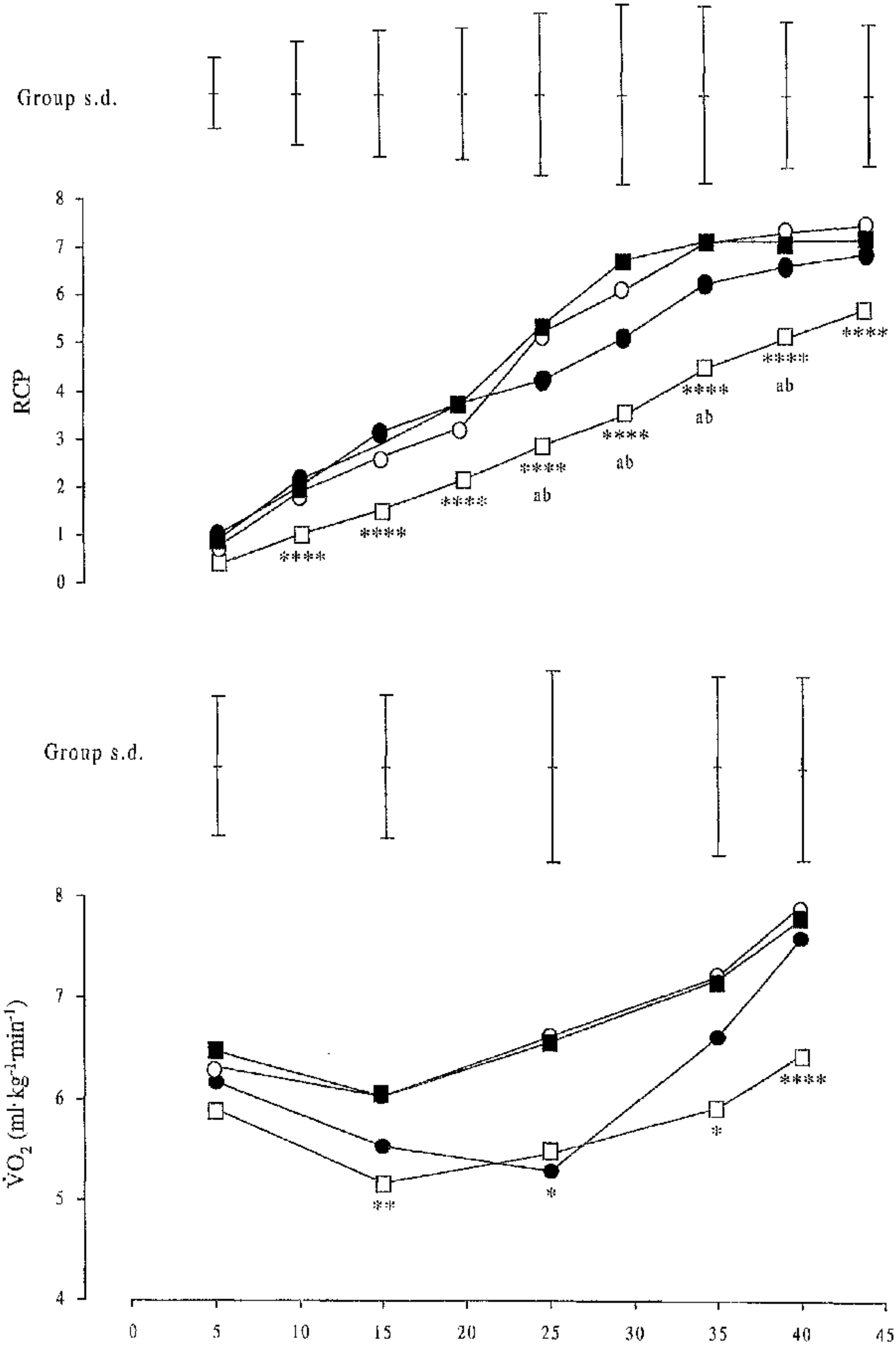

Group s.d.
RCP
8
7
6
5
4
3
2
1
0
****
****
****
****
ab
****
ab
****
ab
****
ab
****
Group s.d.
VO2 (ml·kg-1·min-1)
8
7
6
5
4
**
*
*
****
0
5
10
15
20
25
30
35
40
45
Time (min)

Figure 3.3: T_R (mean (s.d.)) for PN (○), CP (■), P (□) and C (●). *: indicates a significant change from baseline.

Figure 3.4: T_{sk} (mean (s.d.)) for PN (○), CP (■), P (□) and C (●). *: indicates a significant change from baseline.

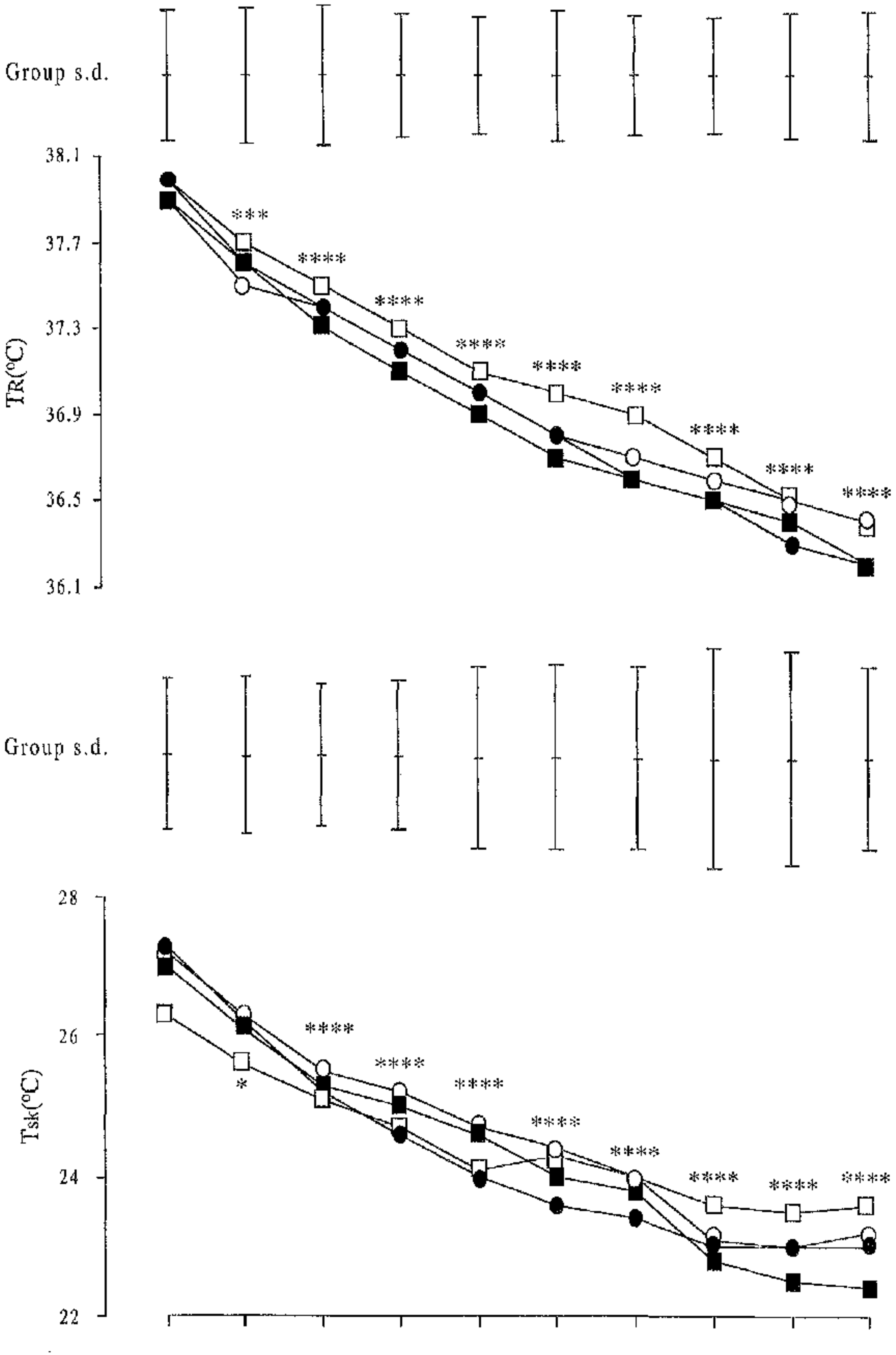
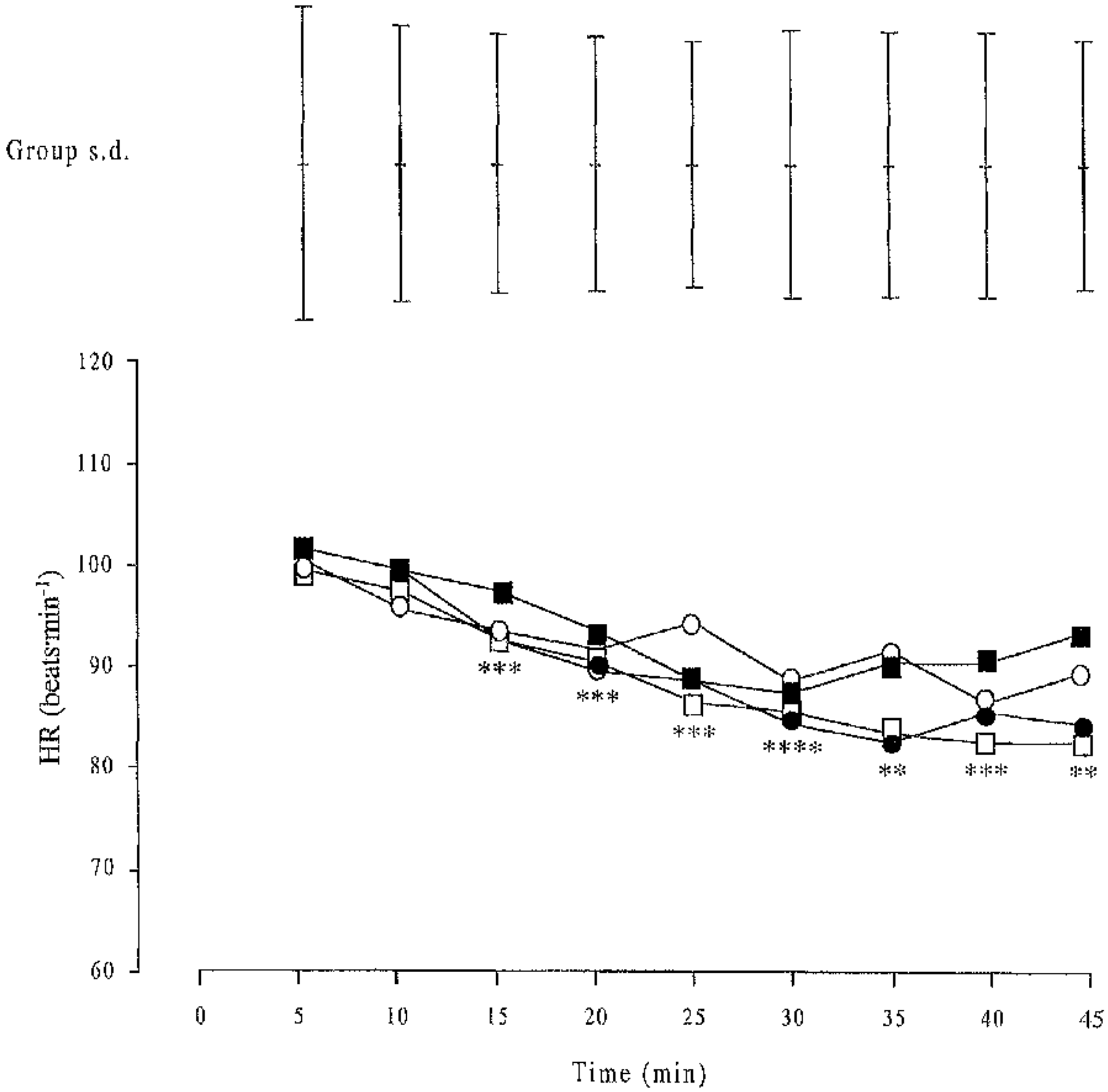

Group s.d.
38.1
37.7
37.3
36.9
36.5
36.1
TR(°C)
***
****
****
****
****
****
****
****
****
Group s.d.
28
26
24
22
Tsk(°C)
*
****
****
****
****
****
****
****
****
0
5
10
15
20
25
30
35
40
45
Time (min)

Figure 3.5: HR (mean (s.d.)) for PN (○), CP (■), P (□) and C (●). *: indicates a significant change from baseline.


Group s.d.
120
110
100
90
80
70
60
HR (beats·min-1)
***
***
***
****
**
***
**
0
5
10
15
20
25
30
35
40
45
Time (min)

Discussion

The findings from this study suggest that one of the two high wicking capacity garments, is the most effective out of the four garments in offering protection against the imposed environmental conditions. Following the completion of exercise, subjects were all visibly sweating and reported sensations of moisture accumulation in their clothing (although this was not quantified) and of "feeling very warm", despite the low environmental temperature. It appears that the exercise achieved its purpose of generating not only metabolic heat, but also sweat, and thus the garments could indirectly be evaluated for their wicking properties during the cooling period, as well as their insulating capacity.

Results for RPC indicate that P is the preferred garment in the imposed conditions, as values were significantly lower than PN and CP, from 25 to 40 min inclusive (Fig. 3.1). The high values for RPC corresponding to garments PN and CP show that subjects were coldest when wearing these garments, since higher RPC values denote colder sensations. Furthermore, termination of tests before the full duration of the cooling period had elapsed, provided further evidence in support of the poor performance of garments PN and CP. Subjects terminated tests only when wearing these two garments, reporting unbearable cold sensation on all occasions.

As previously discussed, a tendency for differences was noted between garments for the $\dot{V}O_2$ response. Results suggest that $\dot{V}O_2$ was lower at 25 min for P and C, when compared to PN and CP (Fig. 3.2), implying perhaps that subjects wearing garments P and C, exhibited less shivering and/or smaller increases in muscle tone (also termed "preshivering") around the specified time-point, compared to the other two garments.

Interestingly, the responses for RPC and $\dot{V}O_2$ appear to follow a similar trend. No significant findings were present during the initial stages of the cooling period and any differences found thereafter became indiscernible at the end of rest period. Evidently, any discrepancies existing between garments for the variables of interest were masked initially by the exercise-induced metabolic heat. Differences manifested themselves from 25 min onwards, once cooling had begun to take effect and the thermogenic effects of exercise had worn off; these differences are likely due to variations in garment properties. Disparities between garments ceased to exist at the end of the rest period when the cooling power of the environment surpassed the protective capacity of the garments, making indistinguishable in terms of the variables discussed.

The $\dot{V}O_2$ response for PN and CP did not change over time; the two garments only displayed a rise in $\dot{V}O_2$ (from the values at 5 min) near the end of the cooling period (at 40 min). They differed from P and C, in that the latter two garments showed decreases in $\dot{V}O_2$, before levels began increasing towards the end of the cooling period. Initially, $\dot{V}O_2$ for all garments was elevated as a result of the preceding exercise. An earlier onset of shivering in subjects wearing PN and CP, compared to P and C, as well as shivering contractions and/or increases in muscle tone of greater magnitude, would explain the absence of a decline in $\dot{V}O_2$ from elevated levels consequent to the preceding exercise. A progressive increase however in $\dot{V}O_2$ after 15 min for P and C (indicating shivering in subjects), resulted in similar levels to PN and CP by the end of rest period.

Results for RPC support the tendencies observed for $\dot{V}O_2$, since they indicate that subjects perceived themselves to be coldest during tests for PN and CP - from 25 to 40 min. At the end of exercise subjects could not distinguish between the garments. Despite the above findings, the present study revealed no measurable differences for T_R or T_{sk}. This is somewhat surprising, especially if the results for $\dot{V}O_2$, and thus shivering, are taken into consideration. It could however be argued that T_R may not represent core temperature accurately during thermal transients. For example, it has been shown that T_R is slow in responding to changes in blood and core temperature (Melette 1950); the slow response is probably due to a low rate of blood flow to the rectum (Aulick et al. 1981).

Shivering appears to be initiated by a multiplication of signals from the skin and the core of the body (Nadel at al. 1974; Hong and Nadel 1979; Haymes and Wells 1986). It seems reasonable to assume that either one, or both of these variables could exhibit a diminished response for P (and/or a heightened response for PN and CP). No discernible differences however were found between suits for either T_R or T_{sk}. There are those investigators who support the contention that shivering is primarily due to decrease in mean skin temperature (Tanaka 1978; Patton and Vogel 1984). This normally occurs before any measurable change in core temperature (Vanggaard 1975). The present study did not demonstrate any appreciable differences in time in terms of when significant declines from baseline were observed for T_R and T_{sk}. Furthermore (apart from the response for CP), significant decreases from baseline for garments for T_R were observed 5 min before any significant decline in T_{sk} from baseline values occurred. Justification, therefore, for the differences in RCP and the tendency for the $\dot{V}O_2$ response is not provided by temperature response profiles.

Garments did not differ significantly in their responses for HR. Values decreased from elevated levels (measured at 5 min) due to exercise, within the first 15-20 min of the subsequent rest period as expected. PN however showed fluctuations in HR thereafter. It is plausible that the fluctuations observed in HR correspond and coincide with oscillations in shivering intensity in subjects wearing PN (remembering also that this garment, alongside CP, displayed a tendency for highest $\dot{V}O_2$ values).

Based on the findings from this study, P emerges as the most effective garment in terms of offering protection in the imposed environment. The favoured garment, P, is made from polyester, one of the most widely employed materials in outdoor clothing (Dickinson 1995). It incorporates a graded yarn system designed to transport moisture away from the body surface. Polyester is a good insulator (and therefore a poor conductor), but Gonzalez (1988) claims that, generally by itself, the material has poor wicking properties. Additives to the fibre assist in the wicking action, by providing hydrophobic properties to the inner fibre but making the outer surface hydrophilic (Gonzalez 1988). Moisture is dispelled by a spreading action from the inner fibre to the exterior surface or by capillary transfer of moisture from one fibre to another adjacent to it (i.e., hydrophobic transfer) (Gonzalez 1988). Furthermore, materials consisting of two closely connecting layers - an inner layer with good mechanical properties which then wicks the moisture to an outer layer - prevent undesirable wet cling (thus making them unpleasant and uncomfortable to the wearer) (Lotens 1987; Umbach 1993). The preferred garment P demonstrated superior wicking capacity (similar though to CP), in combination with a higher thermal resistance than PN and CP. It is also greater in terms of thickness than the latter two garments, a likely explanation for the higher thermal resistance, since the effectiveness of thermal insulation is a property of the air trapped within the fabric. The thicker fabric allows for more air-pockets within its structure.

Results indicate that PN and CP are comparatively inferior to P and the least effective at protecting wearers in the specific conditions - duration, time of exposure and activity status all taken into consideration. The ineffectiveness of PN compared to P, could be the result of poorer wicking qualities and concomitant loss of insulation and/or poor evaporative ability (Dickinson 1995). Holmer and Gavhead (1991) reported up to 60 % loss of insulation in garments saturated with sweat (as a result of vigorous physical activity). Surprisingly, CP appears to have a similar wicking capacity as P (Table 3.1). Both PN and CP are thinner garments than P, and consequently have a lower thermal resistance.

Interestingly P, is not the heaviest of the garments in terms of absolute weight (Table 3.1). The heaviest (more than double the weight of P) and notably the thickest of the garments is C. Normally, thicker material provides greater insulation (although this is only true for garments that remain dry) (Dickinson 1995). Despite this, the thermal resistance of C is not too dissimilar to that of P. Although not specified, this discrepancy (i.e. the fact that thermal resistance was similar despite a different thickness) may reside in variation of fabric construction (i.e. knitted versus woven). The construction of any fabric invariably influences the ability of a garment to conduct heat and moisture (Cain and Farnworth 1986). Furthermore, it must be stressed that although cotton has the ability to wick moisture, it principally absorbs it (Umbach 1993) and has low resiliency (i.e., if fibres are distorted because of wetting or compression they do not readily spring back to their original position) (Woodcock

1962). Cross-linking the fibres reduces the hydroscopic properties of cotton, allowing for substantial wicking and less post-exercise evaporation (Meechels et al. 1966), although no information was provided on fabric construction or fibre weave characteristics for any of the garments tested in the present study.

Conclusion

In conclusion, the findings from the present study indicate that the polyester garment with high thermal resistance, was superior to the other garments in its capacity at offsetting heat loss to the environment in the imposed conditions. The results by no means imply that the specific garment actually prevented heat loss, but simply that a smaller loss of heat may have been incurred, evidenced by smaller RPC values (which incidentally are indicative of warmer subjects) and the tendency for a diminished $\dot{V}O_2$ midway through the cooling phase. It is important to be aware of the detrimental consequences of moisture accumulation as a result of sweating, once exercise (and its heat-generating capacity) in a cold environment has ceased. Although the correct choice of garments, beginning from the base-layer designed for wear next to the skin, is important, the primary aim should be prevention of moisture accumulation within clothing layers in the first place. Removal of outer layers during physical activity, and adequate ventilation through openings at the neck, wrists and ankles are methods by which heat loss may be regulated precisely, without the undesirable effects of sweat accumulation (Lotens 1987; Dickinson 1995).

Chapter Four

(Study IV)

The effects of cooling on cardiorespiratory and metabolic parameters during incremental and constant-load exercise.

Introduction

The final component of this collected research is based around observations made during the first two studies. In each of the conditions studied, the $\dot{V}O_2$ response for particular suits exhibited a progressive increase during the phase of constant-load exercise (it approximated 5-10 $mlO_2 \cdot min^{-1}$ exercise). On physiological grounds, it was reminiscent of the slowly-developing component of $\dot{V}O_2$ that several investigators have reported by constant-load normothermic exercise performed above (but typically not below) the "anaerobic" or "lactate" threshold (θ_L) (see Chapter 1). This raised an interesting auxiliary issue of exercise bioenergetics in the cold: what would the effect of hypothermia be on the temporal characteristics of the $\dot{V}O_2$ response to constant - load exercise at standardised intensities described to be a) moderate, lying below θ_L and b) heavy, lying above θ_L.

It is widely recognised that hypothermia affects physical performance, and adverse effects have been documented for sub-normal core and muscle temperatures of approximately 35° C (Davies et al. 1975; Bergh and Ekblom 1979). Decreases in $\dot{V}O_{2\,peak}$ have been reported (Davies et al. 1975; Bergh and Ekblom, 1979), as well as increased sub-maximal $\dot{V}O_2$ levels (Davies et al. 1975; Ishii et al. 1992). The present study was therefore conducted to further investigate the influence of whole-body cooling on the $\dot{V}O_2$ response to exercise of moderate and heavy intensity, conducted in a low environmental temperature (-10° C). This was achieved by adopting a 20 min square-wave exercise transition thus enabling investigation of the temporal and quantitative $\dot{V}O_2$ response (i.e. its kinetics). Furthermore, by specifying intensity domain, the effects of sub-normal temperatures on the $\dot{V}O_2$ slow component, characteristic of the heavy-intensity exercise domain, could be discerned. The results from the present study may provide important information for the as yet unresolved elucidation of the potential mediators of the slow component.

Methods

Subjects

Six healthy, physically active males volunteered to participate in this study. Having been informed of the procedures, subjects gave their informed consent and their health was screened with medical questionnaires as approved by the University Ethics Committee (Appendix A). Subjects were advised that they were free to withdraw from the study at any time. Subject characteristics are as follows: age 23.2 ± 4.5 years, body mass 76.5 ± 12.7 kg and height 1.80 ± 0.05 m.

Design

Following as least two familiarisation sessions, subjects participated in 3 different exercise tests (performed on a cycle-ergometer) at two ambient temperatures, totalling 6 experiments, and therefore 6 separate visits, per subject. Experiments were conducted in an environmental chamber at 20° C (normothermic conditions, NC) and -10° C (hypothermic conditions, HC). Experiments in HC included an initial cooling period, during which subjects remained quietly seated until their core temperature had reached a predetermined level of 36.3° C. Exercise tests consisted of an incremental work test to exhaustion, from which $\dot{V}O_{2\,max}$ was measured and the lactate threshold (θ_L) was determined indirectly using gas-exchange criteria (Whipp et al. 1986). Having completed both incremental work tests, subjects carried out two 20 min (or limit of tolerance if less) constant-load exercise tests - one within the moderate intensity domain and the second in the heavy intensity domain (i.e. below and above θ_L respectively). Subjects were assigned to NC and HC in a randomised order to minimise learning effects; the order of the exercise tests was also randomised (the only consideration being subjects completed both incremental tests before performing a constant-load test).

All experiments were conducted at the same time of day (approximately 14.00 hours) to minimise daily variations in core temperature as far as possible. This is particularly important for experiments in HC, where the starting point of each experiment was determined by the attainment of the preselected T_R level. Core temperature has been shown to exhibit a gradual rise from the early hours of the morning, with highest values observed during the late afternoon (Edholm 1978; Lloyd 1986). Subjects were requested to refrain from exercise on the day that preceded each experiment, as well as alcohol consumption for 48 hours before experiments. On the day of each experiment they were allowed a light meal, ingested at least three hours prior to the start of each experiment. It has been documented that the ingestion of food is associated with changes in the diurnal pattern of rectal temperature by its specific dynamic action on basal metabolic rate (Iampietro et al. 1957; Folk 1966; Shephard 1993).

Experiments in HC were conducted at least one week apart, thus effectively minimising the possibility of acclimation. Furthermore, experiments that succeeded incremental work-tests or constant-load test in the heavy-intensity domain were separated by a minimum of 48 hours.

Experimental procedures

Subjects reported to an ante-chamber (with an ambient temperature of approximately 20° C) approximately 15-30 min before each experiment was due to commence. Body mass and height were recorded and subjects were instrumented for T_R and T_{sk} measurement. A thermistor inserted 10 cm beyond the anal sphincter was used to measure T_R. T_{sk} was calculated as a weighted average taken from four sites on the right-hand side of the body (Ramanathan 1964). HR was recorded with a HR monitor programmed to record every minute (Polar Vantage NV, Polar Electro Oy, Finland). Electrodes were positioned on the chest of subjects for a 3-lead ECG.

Subjects wore shorts, a T-shirt and trainers for experiments in NC. Experiments in HC aimed to pre-cool subjects prior to their participation in each exercise test, as well as provide a cold ambient temperature during the tests. For experiments in HC, subjects wore thermal long-sleeved zip-necks and long-johns, as well as a hat and gloves. During the cooling period in HC experiments, subjects remained quietly seated inside the environmental chamber and were requested to keep movement to a minimum. Automatic recording of T_R and T_{sk} began immediately, with T_R being monitored continuously. During the cooling period, subjects were asked to provide individual perceptions relating to their perception of cold (RPC) (scale modified from Gagge et al. 1969) and the degree of shivering they were experiencing (RPS). Values for RPC and RPS were obtained in succession to each other throughout experiments in the study. The corresponding scales were shown to subjects prior to experiments and specific instructions were given on how to rate them. Ratings were obtained every 5 min throughout the cooling period. Subjects remained seated until their core temperature had reached 36.3° C (i.e., the predetermined value), and thereafter procedures were identical for tests in both NC and HC. Subjects were then seated on the cycle-ergometer, with the headset, mouthpiece and noseclip positioned and ECG leads connected.

Incremental work tests

Subjects performed an incremental test to exhaustion in each environmental condition (NC and HC). $\dot{V}O_{2\,max}$ was measured and the lactate threshold (0_L) was estimated indirectly using gas exchange criteria (Beaver et al. 1986). Whilst subjects were seated on the cycle-ergometer, a 3 min resting phase was initiated, during which expired-gas was collected. Automatic recording of T_R, T_{sk} and HR began on initiation of rest. Following rest, subjects were then instructed (by verbal signal) to begin cycling, increasing and maintaining the revolutions at 60 rpm. Subjects cycled for 5 min at 15 W (effectively unloaded "0"W) and thereafter the WR was increased manually by 15 W every min, until the subject reached exhaustion (defined as the workload at which 60 rpm could no longer be maintained). The load was then removed from the cycle-ergometer and subjects began a recovery period, pedalling with no load, until HR was below 120 beats·min^{-1}.

A 1 min expired-gas sample was collected at 3 min during unloaded cycling, followed by 1 min samples every second min on initiation of the incremental exercise test. After 4-5 samples, expired-gas was collected continuously every minute, to allow for greater density of data and hence more accurate estimation of θ_L. Ratings of perceived exertion (RPE) were recorded at 1.5 min during unloaded cycling, and every 3 min during the incremental, beginning at 0.5 min after its initiation. For experiments in

HC, RPS and RPC values were also recorded - on two separate occasions during Rest and once during the unloaded phase. Thereafter subjects provided values for RPS and RPC, 2 min after RPE was obtained. The test protocol is illustrated in Fig. 4.1.

Constant-load tests

Sub-threshold (90% θ_L). The work rate corresponding to 90 % of $\dot{V}O_2$ at θ_L was estimated for both environmental conditions (corrected for the kinetic delay from the steady-state requirement, Whipp and Ozyener 1998). If estimated sub-threshold work rates differed between NC and HC, the lower of the two was adopted for both tests in each environmental condition, so subjects were exercising at the same absolute work intensity.

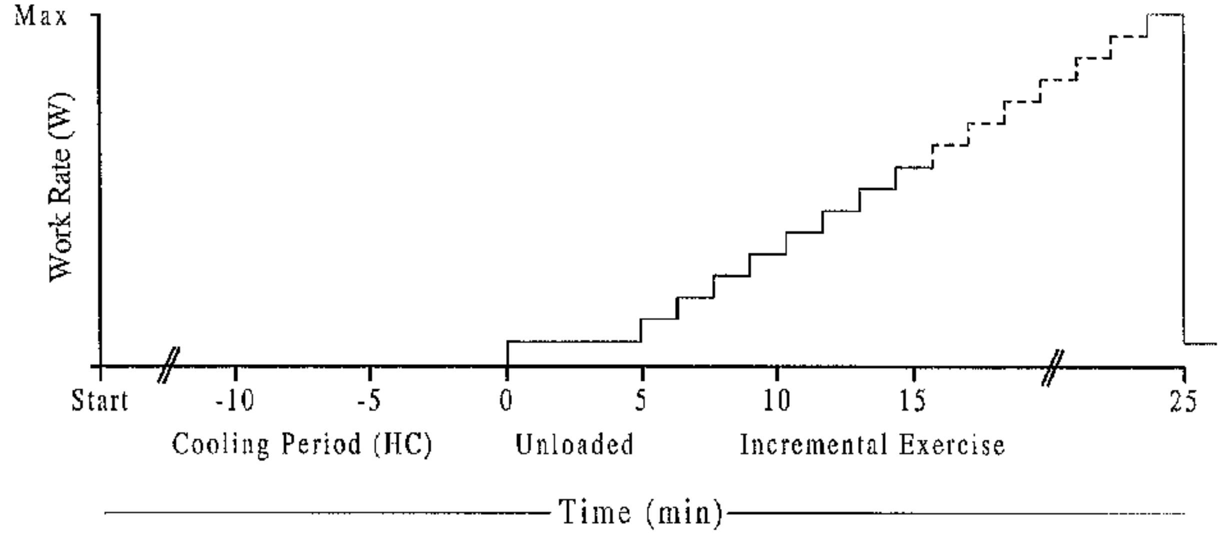
Subjects underwent pre-experiment procedures as previously described for incremental tests. Having obtained a resting blood sample, they entered the environmental chamber and were instructed to sit quietly on the cycle-ergometer. A 3 min resting period ensued, during which expired-gas was collected. Automatic recording of T_R, T_{sk} and HR began on initiation of rest. Subjects were then instructed by verbal signal to begin cycling, increasing the revolutions to 60 rpm and maintaining them at that level. Subjects cycling at 15 W (effectively unloaded) for 5 min. Following this was a stepwise increase in the WR to the predetermined value corresponding to 90 % θ_L (exercise); subjects were required to cycle at this work rate for 20 min. At the end of 20 min, the load was removed from the cycle-ergometer and subjects began a recovery period, pedalling with no load, until HR was below 120 beats·min^{-1}. The test protocol is illustrated in Fig. 4.2.

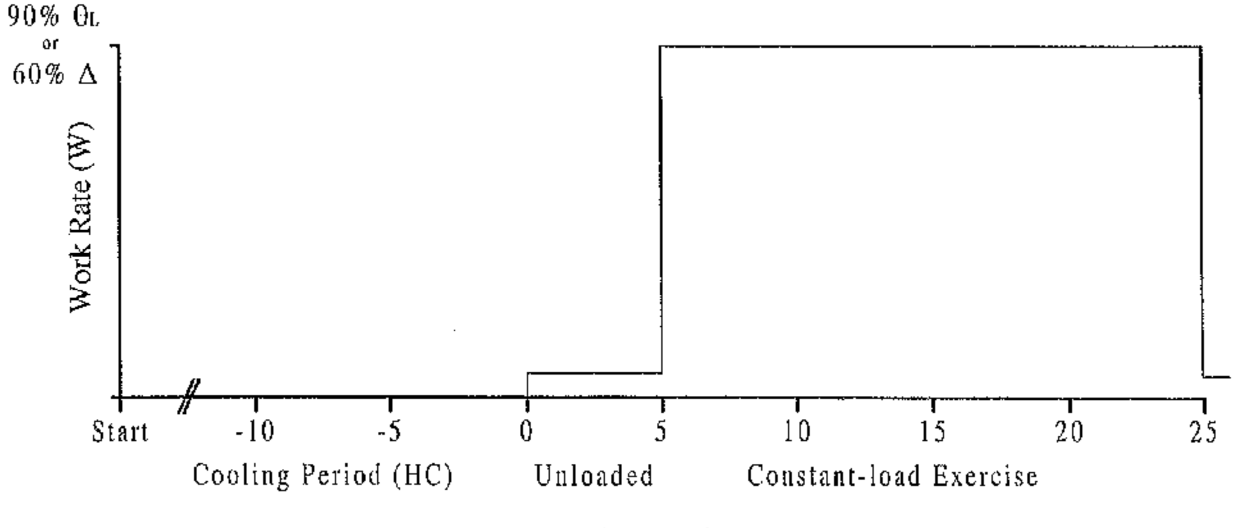
A 1 min expired gas sample was collected during the final min of unloaded cycling. Consecutive 40 sec samples were obtained during the initial 4 min of exercise, excluding the first 20 sec that correspond to the cardiodynamic phase. Thereafter, 1 min of expired-gas was collected every second minute until the end of exercise. Subjects were asked to rate RPE, as well as RPS and RPC during HC experiments at standardised time-points during the unloaded cycling and exercise. Blood samples were taken 15 sec after each rating was obtained. No subjective ratings or blood samples were taken during the first 3.5 min of exercise to minimise "noise" in the response during the initial stages of the square-wave transition.

Supra-threshold 60 % Δ. 60 % of Δ, defined as the difference between $\dot{V}O_{2\,max}$ and θ_L, was used to characterise constant-load exercise in the heavy intensity domain (i.e. above θ_L), and was estimated for NC and HC from incremental test results. Subjects were required to exercise at this intensity for 20 min or to the limit of tolerance if less. Like for sub-threshold tests, if there was a disparity between work rates estimated for each environmental condition, the lower of the two was adopted for both constant-load tests, so subjects were exercising at the same absolute intensity. The same square-wave protocol as for sub-threshold tests was employed and identical measurements were obtained.

Figure 4.1: The experimental design for incremental exercise tests.

Figure 4.2: The experimental design for constant-load exercise tests.


Max
Work Rate (W)
Start
-10
-5
0
5
10
15
25
Cooling Period (HC)
Unloaded
Incremental Exercise
Time (min)


90% θL
or
60% Δ
Work Rate (W)
Start
-10
-5
0
5
10
15
20
25
Cooling Period (HC)
Unloaded
Constant-load Exercise
Time (min)

Analyses

The Douglas Bags were analysed for their contents within 1 hour of completion of each test. $\dot{V}O_{2\,max}$ was determined and θ_L estimated using gas-exchange criteria. $\dot{V}O_{2\,max}$ was defined as the highest oxygen uptake measured which normally corresponded to the highest work rate reached. θ_L was estimated using the V-slope and Ventilatory-Equivalent methods, as well as by visual examination of graphs where mixed-expired gas concentrations (%[CO_2]e and %[O_2]e) and RER values were plotted against $\dot{V}O_2$ (Beaver et al 1986) (Fig. 4.3).

The $\dot{V}O_2$ response obtained from square-wave exercise during normothermic conditions was fitted, using commercially available software (Microcal Origin, Microcal Software, Inc., Northampton, MA, USA), with a first-order ("mono") exponential function (Whipp 1994):

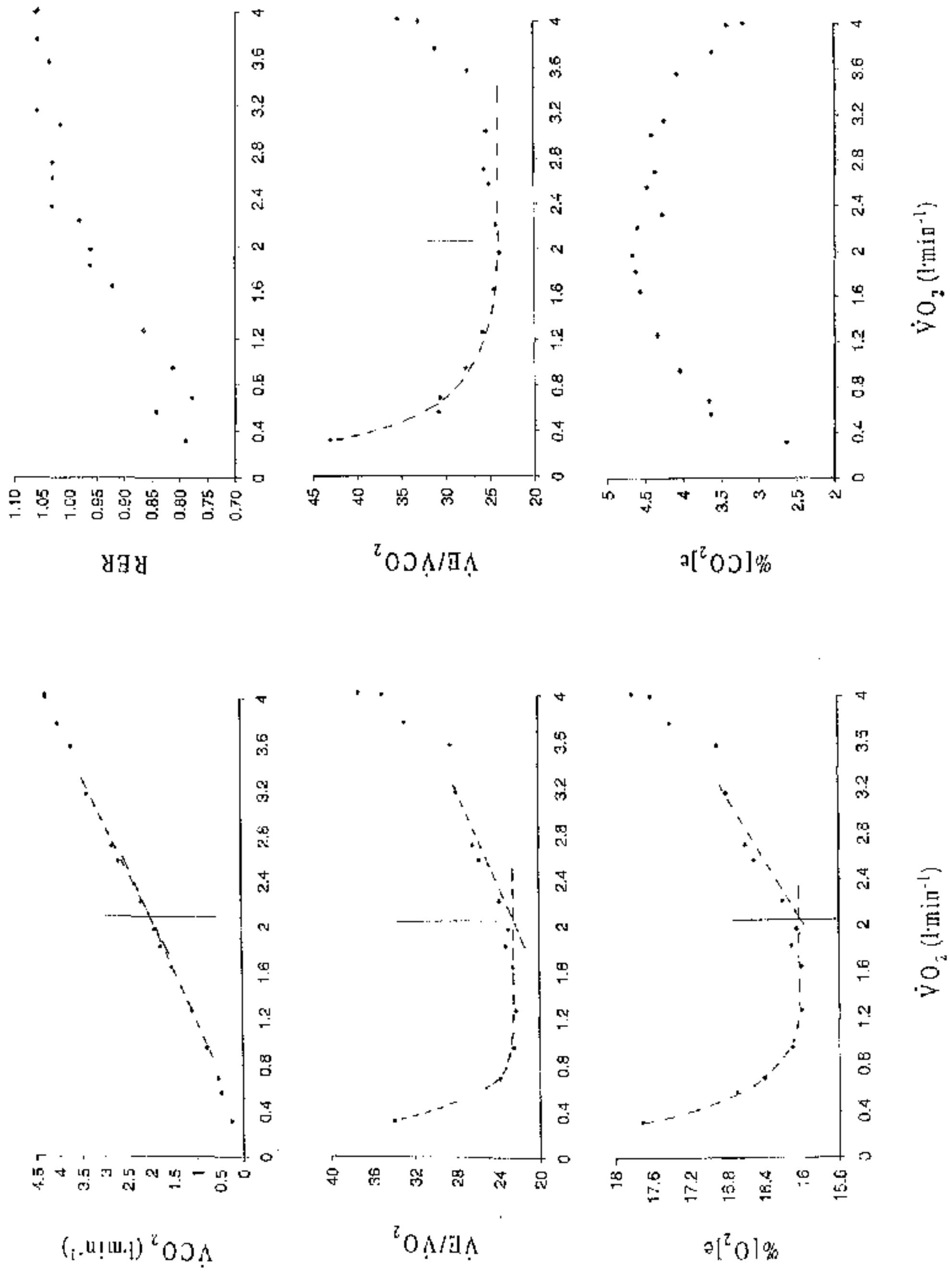
$$\Delta \dot{V}O_2\ (t) = \Delta \dot{V}O_2\ (ss)\ (1 - e^{-(t-\delta)/\tau}) \qquad \text{(Equation 4.1)}$$

Blood samples obtained during square-wave tests were analysed within 1 hour of completion of each test. The samples were analysed for blood lactate using an Analox GM7 analyser (Analox Instruments Ltd, London, UK). The analyser was calibrated prior to blood lactate analysis using an aqueous 8.0 $\text{mmol}\cdot\text{l}^{-1}$ lactate standard, and then cross-checked with a 5.0 $\text{mmol}\cdot\text{l}^{-1}$ standard. For analysis, two 7 μl samples were injected into the analyser. Two separate analyses were carried out for purposes of validity and the mean of the two values ($\text{mmol}\cdot\text{l}^{-1}$) was taken as being representative of the true blood lactate concentration. A third analysis was carried out (volume permitting) if a discrepancy of over 0.1 mmol·l^{-1} was observed between the two initial values.

Statistical Analysis

Data are expressed as the mean ± s.d. following test for the normality of distribution. The group s.d. is used in graphical representation of results to aid clarity. The group s.d. is the pooled estimate of the common s.d. and represents the square root of the mean square error. In some cases individual response profiles are used in graphical representation of results. Statistical analysis of the data was carried out using two factor ANOVA for repeated measures and followed by Paired t-test where appropriate. Statistical significance was declared when $P < 0.05$.

Figure 4.3: Respiratory markers of the lactate threshold.


V̇CO₂ (l·min⁻¹)
V̇E/V̇O₂
%[O₂]e
RER
V̇E/V̇CO₂
%[CO₂]e
V̇O₂ (l·min⁻¹)
V̇O₂ (l·min⁻¹)
0
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2
3.6
4
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
40
36
32
28
24
20
18
17.6
17.2
16.8
16.4
16
15.6
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
45
40
35
30
25
20
5
4.5
4
3.5
3
2.5
2

RESULTS

Incremental tests

Work rate and time to exhaustion. The WR attained at exhaustion (WR_{max}) tended to be lower for incremental exercise in HC when compared to NC ($P = 0.11$) (Table 4.1). Similarly, the time to exhaustion in HC (18.0 ± 2.7 min) was shorter than in NC (19.5 ± 3.6 min); this effect was significant ($P = 0.043$).

Pulmonary gas exchange and cardiorespiratory variables. The $\dot{V}O_2$ response to incremental exercise is shown in Fig. 4.4 (left panel, individual - Subject 2 - and right panel, group mean response). $\dot{V}O_{2\,max}$ tended to be lower in HC when compared to NC ($P = 0.078$) (Table 4.1). $\dot{V}O_2$ values at rest and during the "unloaded phase" were significantly higher for HC (Table 4.1); these differences persisted for approximately 11 min of incremental exercise (Fig. 4.4). $\dot{V}O_2$ at the estimated lactate threshold (θ_L) was not significantly different between HC and NC (Table 4.1).

VE was systematically higher for the first 11 min of incremental exercise during HC, compared to NC (Fig. 4.4). At exhaustion, however, there was a tendency for a higher VE in NC ($P = 0.074$). RER rose with increasing work rate with no significant differences, however, between the HC and NC response (Fig. 4.4).

HR_{max} was significantly lower in HC, compared to NC (Table 4.1) (Fig. 4.4). Significantly higher HR values were found during HC for rest and unloaded cycling, but HR at θ_L was significantly higher in NC (Table 4.1).

Table 4.1. Cardiopulmonary parameters during incremental exercise. * indicates a significant difference between conditions.

Subject No.	$\dot{V}O_2$ (Rest) (l.min^{-1})		HR (Rest) (beats.min^{-1})		$\dot{V}O_2$ (Unl) (l.min^{-1})		HR (Unl) (beats.min^{-1})		$\dot{V}O_2$ (θ_L) (l.min^{-1})		HR (θ_L) (l.min^{-1})		$\dot{V}O_2$max (l.min^{-1})		HRmax (l.min^{-1})		WRmax (watts)	
	HC	NC	HC	NC	HC	NC	HC	NC	HC	NC	HC	NC	HC	NC	HC	NC	HC	NC
1	1.1	0.3	91	77	1.2	0.5	96	86	1.9	1.7	113	160	2.7	2.6	177	191	240	225
2	1.5	0.3	80	71	1.3	0.6	83	79	2.7	2.6	132	151	4.3	4.6	172	186	345	375
3	0.8	0.3	79	58	1.0	0.6	85	77	1.6	2.0	103	152	3.6	4.0	193	202	285	315
4	1.1	0.5	82	73	1.5	0.7	82	75	2.1	2.2	101	125	4.4	4.3	182	197	345	360
5	1.0	0.3	86	66	1.3	0.7	90	72	1.7	1.6	103	106	3.5	3.9	178	186	270	270
6	0.8	0.3	74	79	0.9	0.6	82	79	2.0	2.0	109	148	3.5	4.1	172	188	270	315
Mean	1.1*	0.3*	82*	71*	1.2*	0.6*	86*	78*	2.0	2.0	110*	140*	3.7	3.9	179*	192*	293	310
S.D.	0.3	0.1	6	8	0.2	0.1	6	5	0.4	0.4	12	21	0.6	0.7	8	7	43	56

Ratings of perceived exertion. RPE progressively increased with work rate. However, no discernible differences were found for RPE values between the two conditions (Fig. 4.4).

Rectal and skin temperatures. No differences were found for either baseline T_R or baseline T_{sk} in each condition. There were significant reductions, however, in both variables at the end of the cooling phase. T_R subsequently remained essentially stable at the cooled value for the entire remainder of the protocol; i.e. T_R at $\dot{V}O_{2\,max}$ averaged 36.2 ± 0.4° C, compared to 36.3° C at the end of the cooling phase. In NC, T_R increased progressively from the initiation of unloaded cycling until exhaustion. Consequently, T_R was significantly lower in HC than NC throughout exercise (Fig. 4.5). As for T_R, T_{sk} in HC was lower than in NC throughout exercise. T_{sk} rose progressively during the protocol in HC, but did not reach baseline by end-exercise (Fig. 4.5). In NC, there was no discernible increase in Tsk across time during the incremental exercise.

Constant-load tests

(a) Sub-threshold ($< \theta_L$)

Pulmonary gas exchange and cardiorespiratory variables. Mean $\dot{V}O_2$ for HC was significantly higher than NC for rest, unloaded exercise and during the initial 160 sec of the sub-threshold exercise (Fig. 4.6). For the remainder of the exercise, $\dot{V}O_2$ in HC continued to be high, but the HC - NC differences were not statistically significant. A representative example of the NC $\dot{V}O_2$ response (subject 3) is presented in Fig.4.6 (top panel). This was well described by a first-order exponential, as described previously in Chapter 1. This provided estimates of the relevant phase II system descriptors: the time-constant (τ), and $\Delta\dot{V}O_2$ (A1). Individual results are given in Table 4.2. In one instance (subject 5), a good model fit was not obtained as the kinetic phase of the $\dot{V}O_2$ response was complete prior to the first expired gas sample been taken.

Table 4.2. Phase II system descriptors (< θ_L exercise)

Subject	τ (sec)	$\Delta\dot{V}O_2$ (A1) (l)
1	39	0.9
2	22	1.5
3	36	0.6
4	34	0.9
5	< 20	0.5
6	26	0.8
Mean ± s.d.	31 ± 7	0.9 ± 0.4

*Note: Parameters could not be accurately estimated for Subject 5

Unlike the NC condition, there was substantial variability in the form of the HC $\dot{V}O_2$ response across the different subjects; i.e. while there was often evidence of overshooting behaviour, its magnitude and time course varied widely. For example, the corresponding $\dot{V}O_2$ response in HC for subject 3 was strikingly different (Fig. 4.6). There was clear evidence of $\dot{V}O_2$ overshooting, with the maximum of the overshoot impacting on the $\dot{V}O_2$ equivalent of θ_L. $\dot{V}O_2$ declined subsequently to a new lower and stable value for the final 10 min of the exercise. It was evidently not appropriate to fit these data to the mono-exponential model used for NC. When the overshoot (expressed at the maximum $\dot{V}O_2$ difference between HC and NC) was expressed as a function of RPS, no correlation was found between the two variables.

The disproportionate increase in $\dot{V}O_2$ during the initial stages of the square-wave protocol was therefore quantified, for each subject, as the area under the $\dot{V}O_2$-time profile; i.e. yielding a total "volume" of O_2 utilised over the entire period of the $< \theta_L$ exercise. In all but one subject, the HC volume of O_2 utilised was greater than for NC (Table 4.3); this difference amounted to (3.1, -2.0 - 6.9) (median, range), but did not reach the level of statistical significance ($P = 0.071$). Finally, no differences were found between conditions in $\dot{V}O_2$ for the rest to "unloaded" exercise transition ($\Delta \dot{V}O_{2\,(unl-rest)}$).

Table 4.3. Volume of O_2 consumed during exercise for HC and NC ($< \theta_L$).

Subject	1	2	3	4	5	6	Mean ± S.D.
HC (l)	27.9	35.6	21.9	29.2	22.1	26.0	27.1 ± 5.1
NC (l)	23.0	37.6	15.0	25.2	20.7	23.9	24.2 ± 7.5

Significant differences were found between conditions for V_E during exercise, with systematically higher values for HC during the first 12 min of the square-wave protocol (Fig. 4.7). The V_E response for HC and NC, expressed as a function of VCO_2, was well described by a linear function (Fig. 4.14). For the mean data, the corresponding correlation coefficient (*r*) was equal to 0.95. No discernible differences were found for HR between HC and NC, which remained essentially stable from 3 min onwards in each condition (Fig. 4.7).

Blood-lactate concentration. No measurable differences existed between conditions for blood [Lac], either at rest or during the square-wave exercise protocol, although there was a tendency for higher values in HC. Mean blood-lactate levels in HC and NC remained essentially stable from approximately 3.5 min onwards (Fig. 4.7). Fig. 4.8 shows individual profiles for $\dot{V}O_2$ and blood [Lac] in HC.

Ratings of perceived exertion. RPE during the square-wave protocol for each environmental condition were similar: representative individual and the mean responses are illustrated in Fig. 4.7, confirming the absence of significant findings.

Rectal and skin temperatures. Significant differences were found for ΔT_R between NC and HC throughout the entire duration of the square-wave exercise (Fig. 4.9). There was a significant difference between ΔT_R obtained following cooling and ΔT_R (end exercise) in HC; i.e., with T_R decreasing progressively from the cooled value during rest and the unloaded phase. Subsequently, T_R remained at a stable level throughout the square-wave; i.e., as there was no change in ΔT_R. The increase in ΔT_R, however, indicated a progressive rise in T_R throughout the square-wave protocol in NC. T_{sk} was systematically higher in NC compared to HC throughout sub-threshold tests (Fig. 4.9). During NC, T_{sk} did not show any measurable changes from baseline values and remained at a stable level. In HC, however, there was a progressive increase in T_{sk} from baseline once the square-wave increase in work rate was initiated.

(b) Supra-threshold ($> \theta_L$)

Pulmonary gas exchange and cardiorespiratory variables. $\dot{V}O_2$ for HC was significantly higher than corresponding values for NC during rest, the unloaded phase and the first 160 seconds of exercise. Fig. 4.10 illustrates the mean profiles of the $\dot{V}O_2$ response in each environmental condition. Fig. 4.11 shows the $\dot{V}O_2$ responses of a single representative subject for square-wave exercise above θ_L, for the two environmental conditions. The system descriptors (τ and A1) for phase II were estimated by fitting the data for the first 3 min of the $\dot{V}O_2$ response; i.e., prior to induction of the "slow" component (Table 4.4). The $\dot{V}O_2$ slow component (Area 2 in Fig. 4.10) was also compared for each condition, in two ways: First, the area under the whole curve (Area 1 + Area 2) was estimated; then Area 1, the area equivalent to "steady-state extrapolation" of the phase II component, was subtracted from this. Secondly, the difference in $\dot{V}O_2$ between min 3 and 6 of the exercise ($\Delta \dot{V}O_{2(6-3)}$) was assessed (Table 4.4). No measurable differences were found between conditions for either index. The V_E response to heavy intensity square-wave exercise revealed significant differences between NC and HC during the initial 120 seconds of exercise, although V_E in HC tended to be higher than for NC between 120 - 260 seconds ($P < 0.1$). Individual and mean responses are illustrated in Figs. 4.12. The relationship between V_E and VCO_2 was also well described by a linear function over most, if not all, of the exercise (Fig. 4.14); the correlation coefficient (r) for the mean data was 0.95. No measurable differences were found for HR response between conditions; individual and mean responses are shown in Fig. 4.12.

Blood-lactate concentration. No significant differences were found for blood [Lac] between HC and NC for resting samples and throughout square-wave exercise. For both environmental conditions, blood [Lac] increased progressively from the unloaded values until approximately 8 min into the exercise (Fig. 4.12). Thereafter, blood [Lac] remained at steady-state until completion of exercise.

Ratings of perceived exertion. No differences were found for RPE between NC and HC (Fig. 4.12).

Rectal and skin temperatures. Significant differences were found between NC and HC for ΔT_R from the initiation of the unloaded phase onwards, until completion of exercise. There was no discernible change for ΔT_R from the start of rest during HC, although the profile illustrated in Fig. 4.13 indicates that T_R may have increased towards the end of the square-wave phase ($P < 0.1$). In NC, there was a progressive increase in ΔT_R throughout exercise.

Mean skin temperatures (T_{sk}) were also significantly different over time between NC and HC, with systematically lower values for HC. The individual and mean profiles show the progressive increase for T_{sk} from baseline during the square-wave protocol.

Table 4.4: System descriptors and slow component estimation for supra-threshold square waves.

Subject	τ (sec)		$\Delta \dot{V}O_2$ (A1) (l)		Area 2 (l)		$\Delta \dot{V}O_{2\ (6\text{-}3)}$ (l·min-1)	
	HC	NC	HC	NC	HC	NC	HC	NC
1	60	60	1.7	1.8	3.8	4.0	0.2	0.2
2	44	44	2.4	2.6	5.7	7.9	0.5	0.4
3	88	63	2.0	2.1	6.0	2.2	0.3	0.1
4	65	73	2.1	2.3	5.9	7.3	0.2	0.2
5	47	32	1.7	1.8	1.1	2.9	0.2	0.5
6	32	41	2.0	2.1	4.3	4.1	0.4	0.6
Mean ± S.D.	56 ± 19	52 ± 16	2.0 ± 0.3	2.1 ± 0.3	4.5 ± 1.9	4.7 ± 2.3	0.3 ± 0.1	0.3 ± 0.2

Figure 4.4: Individual (Subject 2) (left panels) and group mean (right panels) cardiopulmonary and perceptual responses for incremental tests (HC (■), NC (□)).

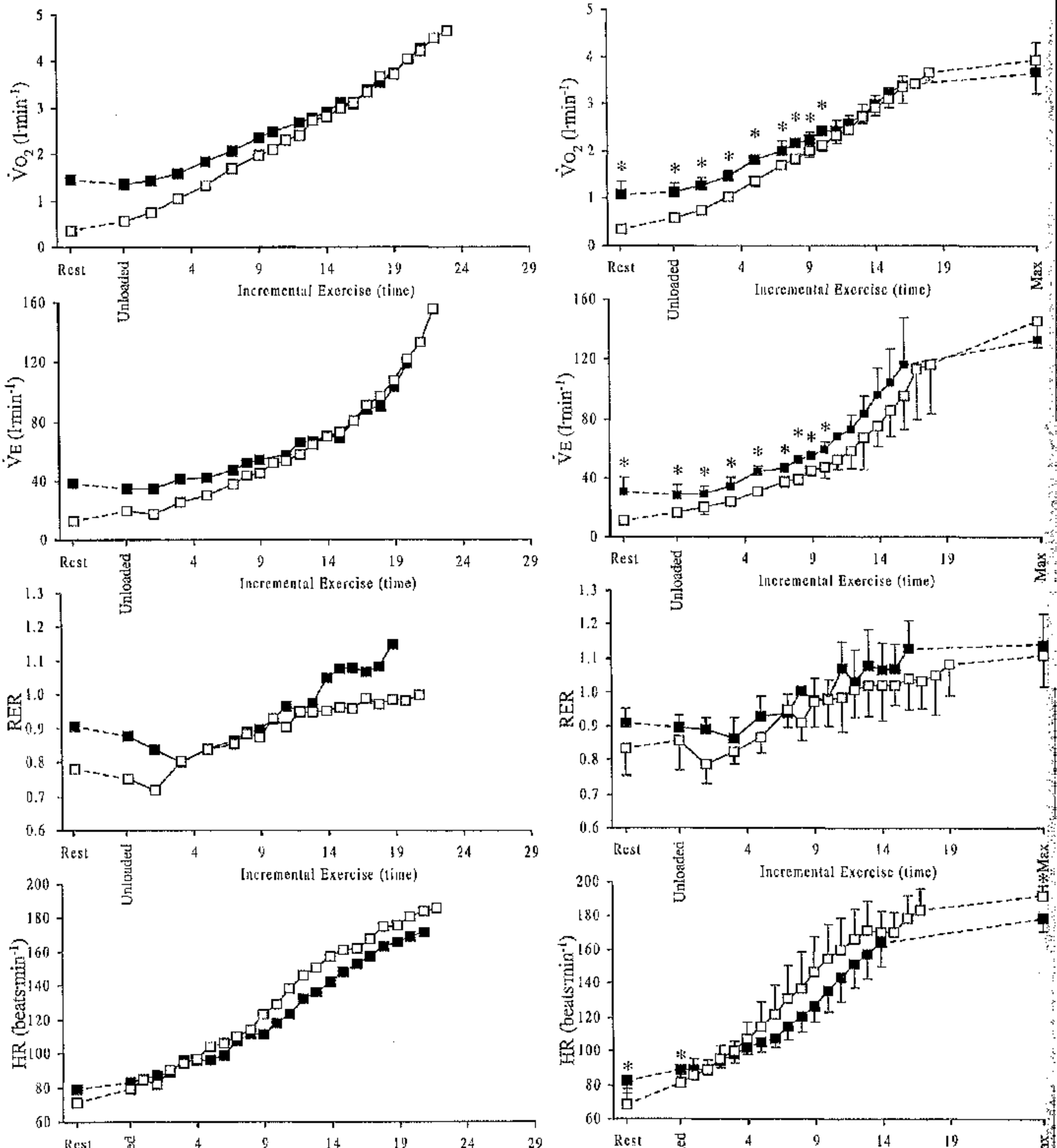
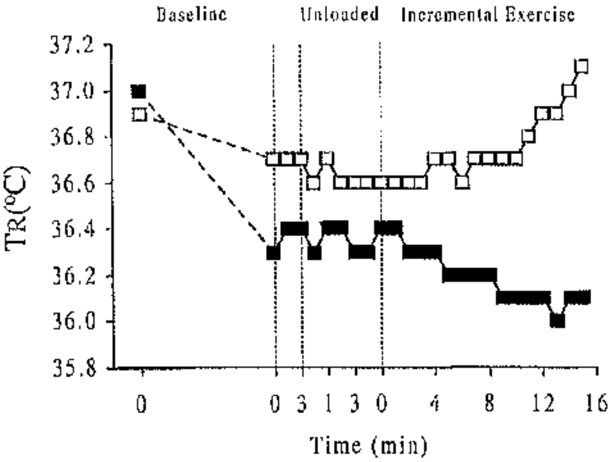
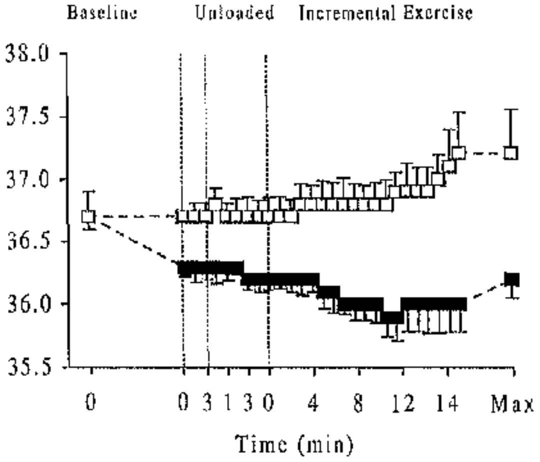
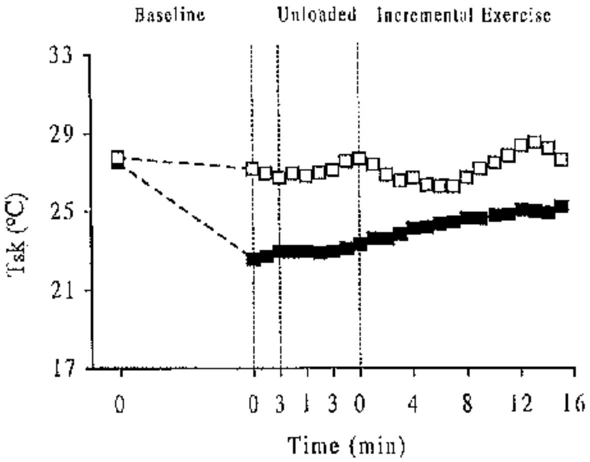

V̇O2 (l·min-1)
0
1
2
3
4
5
V̇E (l·min-1)
0
40
80
120
160
RER
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
HR (beats·min-1)
60
80
100
120
140
160
180
200
RPE
4
8
12
16
20
Rest
Unloaded
4
9
14
19
24
29
Max
Incremental Exercise (time)
*

Figure 4.5: Individual (Subject 1) (left panels) and group mean (right panels) T_R and T_{sk} profiles for incremental tests (HC (■), NC (□)). The responses were significantly different between conditions throughout the test protocol.


Baseline
Unloaded
Incremental Exercise
37.2
37.0
36.8
36.6
36.4
36.2
36.0
35.8
TR(°C)
0
0 3 1 3 0
4
8
12
16
Time (min)


Baseline
Unloaded
Incremental Exercise
38.0
37.5
37.0
36.5
36.0
35.5
0
0 3 1 3 0
4
8
12
14
Max
Time (min)


Baseline
Unloaded
Incremental Exercise
33
29
25
21
17
Tsk (°C)
0
0 3 1 3 0
4
8
12
16
Time (min)

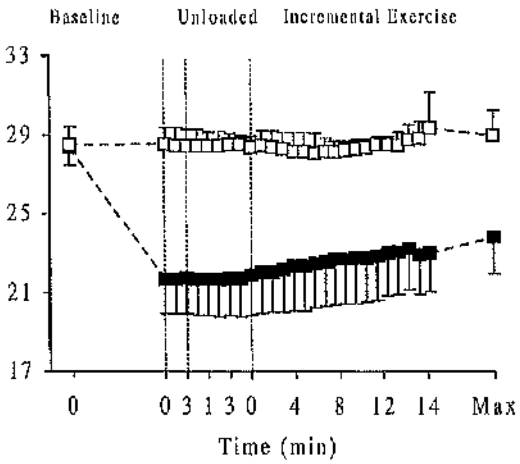
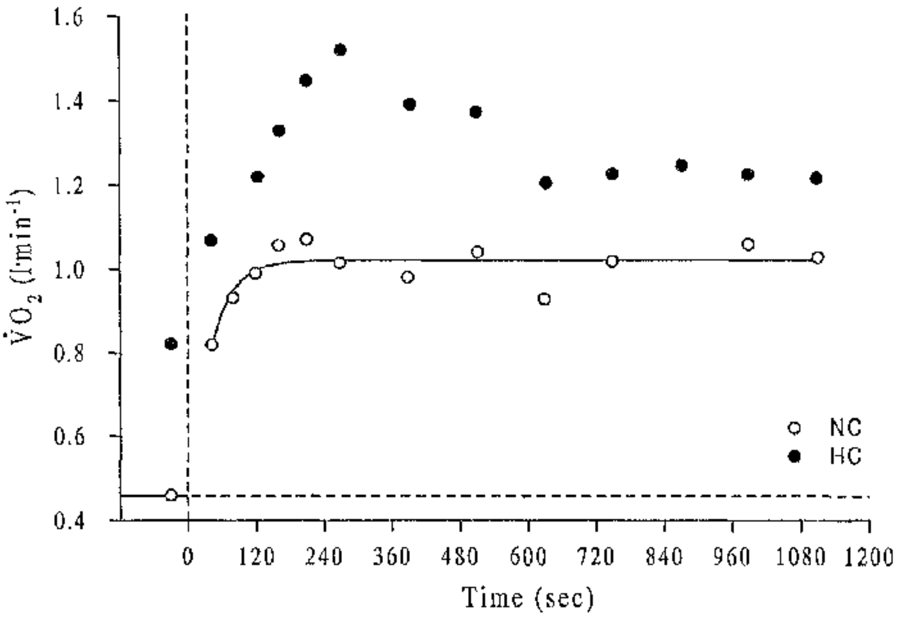

Baseline
Unloaded
Incremental Exercise
33
29
25
21
17
0
0 3 1 3 0
4
8
12
14
Max
Time (min)

Figure 4.6: Individual (Subject 3) (top panel) and group mean (bottom panel) $\dot{V}O_2$ response profiles for square wave exercise transitions ($< \theta_L$) (HC (■), NC (□)). *: indicates a significant difference between conditions.


1.6
1.4
1.2
1.0
0.8
0.6
0.4
$\dot{V}O_2$ (l·min^{-1})
0
120
240
360
480
600
720
840
960
1080
1200
Time (sec)
○ NC
● HC

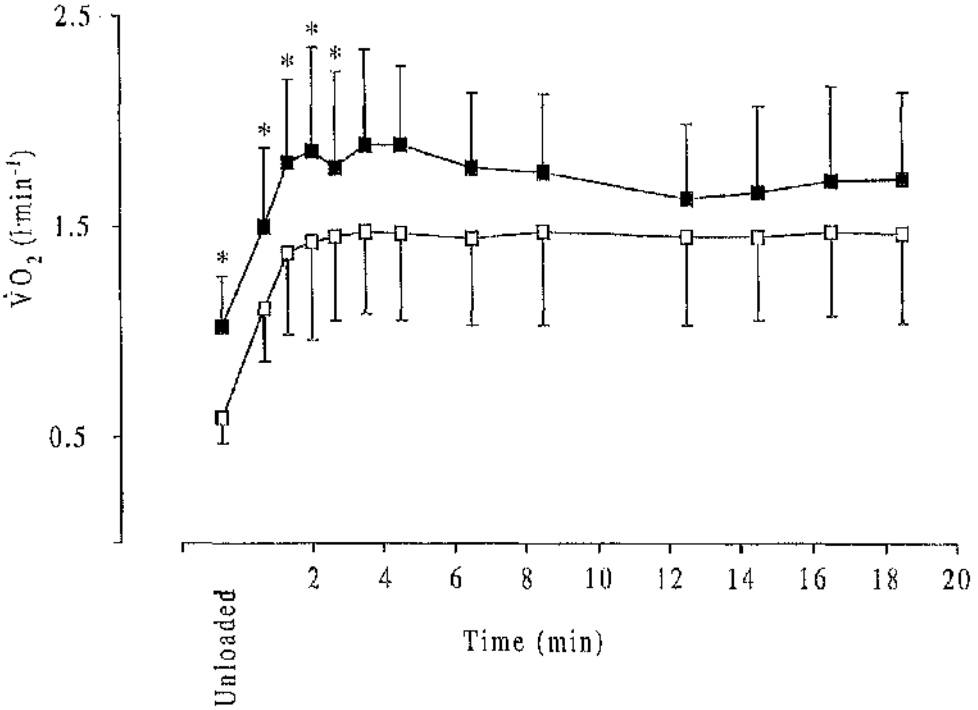
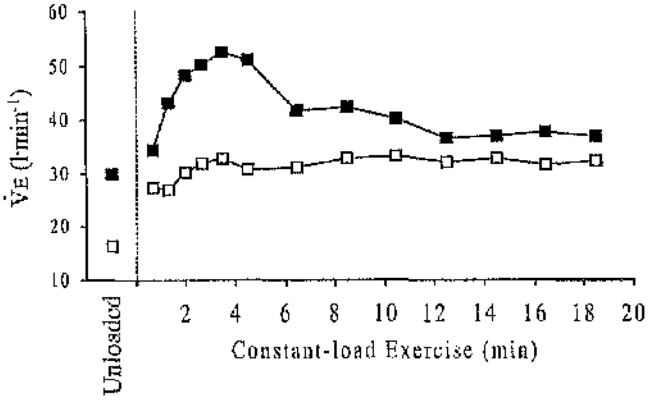
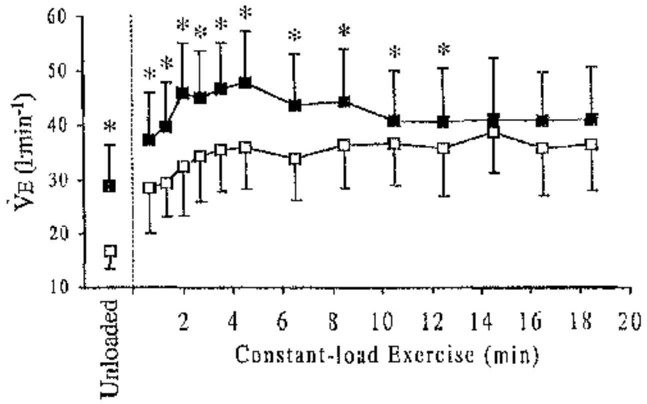
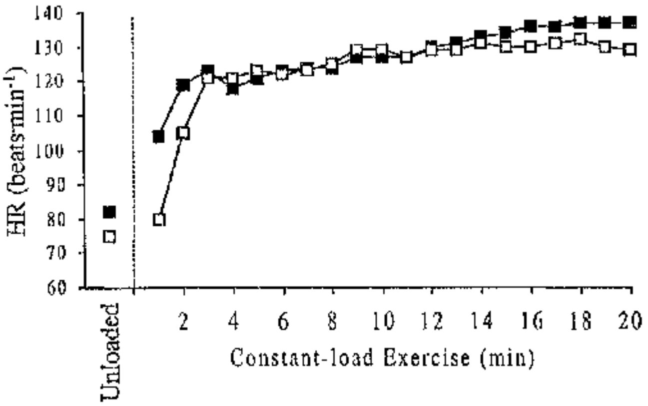
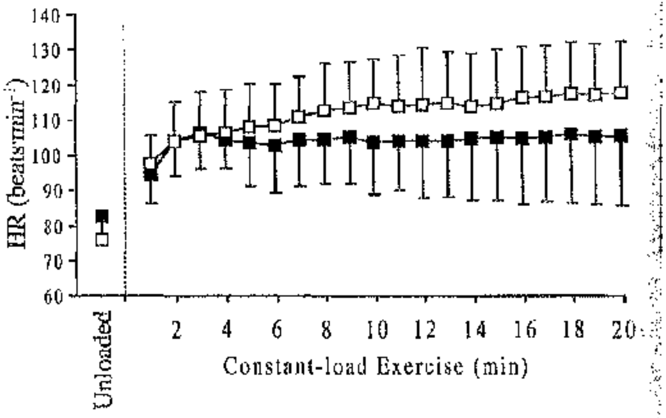

2.5
1.5
0.5
$\dot{V}O_2$ (l·min^{-1})
*
*
*
*
*
Unloaded
2
4
6
8
10
12
14
16
18
20
Time (min)

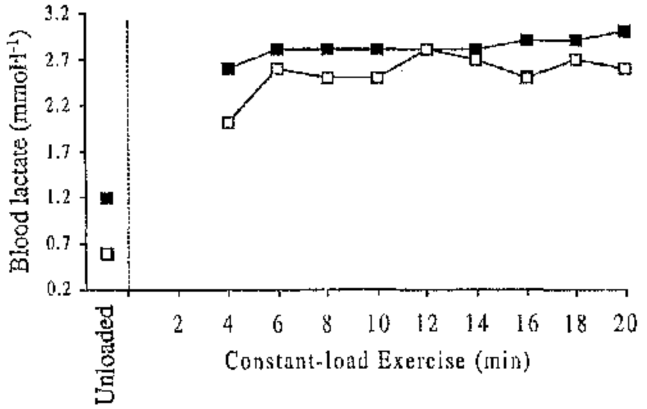
Figure 4.7: Individual (Subject 1) (left panels) and group mean (right panels) cardiopulmonary, metabolic and perceptual responses for constant load tests ($< 0_L$) (HC (■), NC (□)). *: indicates a significant difference between conditions.

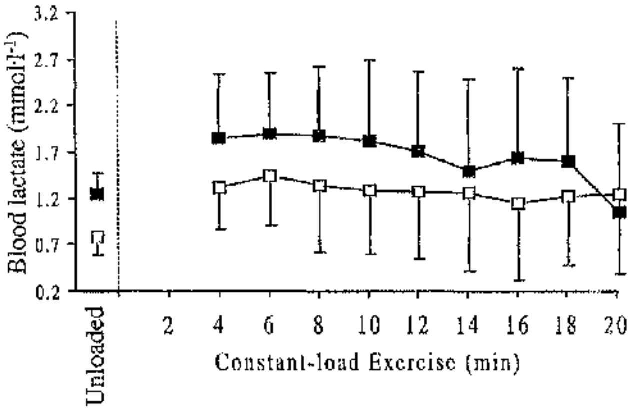

V̇E (l·min-1)
60
50
40
30
20
10
Unloaded
2 4 6 8 10 12 14 16 18 20
Constant-load Exercise (min)

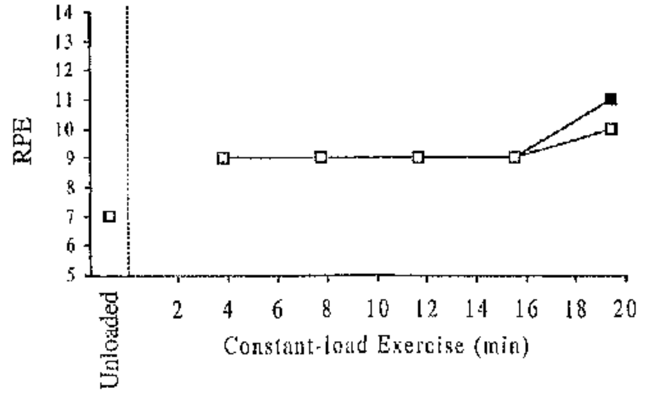

V̇E (l·min-1)
60
50
40
30
20
10
*
Unloaded
2 4 6 8 10 12 14 16 18 20
Constant-load Exercise (min)


HR (beats·min-1)
140
130
120
110
100
90
80
70
60
Unloaded
2 4 6 8 10 12 14 16 18 20
Constant-load Exercise (min)


HR (beats·min-1)
140
130
120
110
100
90
80
70
60
Unloaded
2 4 6 8 10 12 14 16 18 20
Constant-load Exercise (min)


Blood lactate (mmol·l-1)
3.2
2.7
2.2
1.7
1.2
0.7
0.2
Unloaded
2 4 6 8 10 12 14 16 18 20
Constant-load Exercise (min)


Blood lactate (mmol·l-1)
3.2
2.7
2.2
1.7
1.2
0.7
0.2
Unloaded
2 4 6 8 10 12 14 16 18 20
Constant-load Exercise (min)


RPE
14
13
12
11
10
9
8
7
6
5
Unloaded
2 4 6 8 10 12 14 16 18 20
Constant-load Exercise (min)

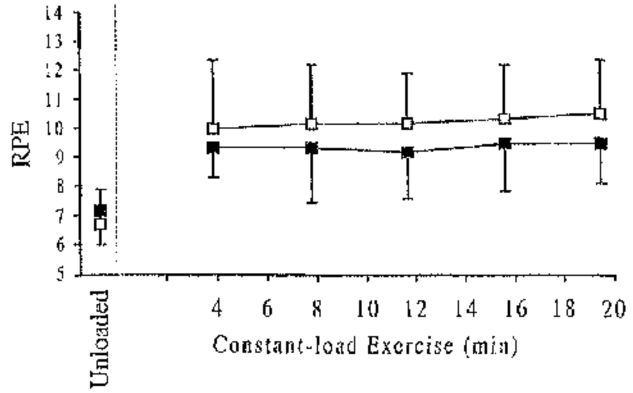
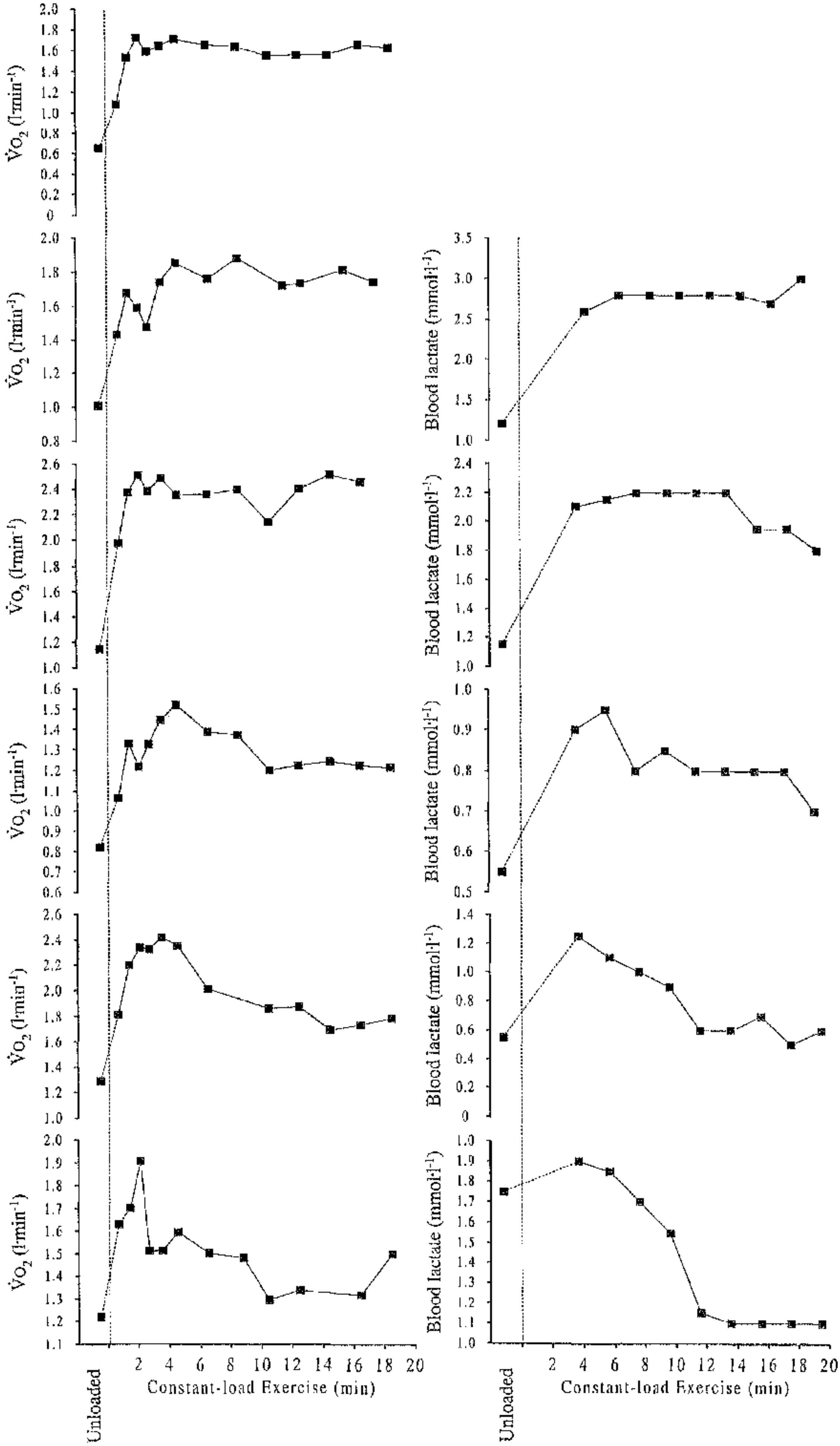

RPE
14
13
12
11
10
9
8
7
6
5
Unloaded
4 6 8 10 12 14 16 18 20
Constant-load Exercise (min)

Figure 4.8: Individual $\dot{V}O_2$ and blood [lac] responses for HC constant-load exercise ($< \theta_L$).



V̇O2 (l·min-1)
V̇O2 (l·min-1)
V̇O2 (l·min-1)
V̇O2 (l·min-1)
V̇O2 (l·min-1)
V̇O2 (l·min-1)
Blood lactate (mmol·l-1)
Blood lactate (mmol·l-1)
Blood lactate (mmol·l-1)
Blood lactate (mmol·l-1)
Blood lactate (mmol·l-1)
Unloaded
2 4 6 8 10 12 14 16 18 20
Constant-load Exercise (min)
Unloaded
2 4 6 8 10 12 14 16 18 20
Constant-load Exercise (min)

Figure 4.9: Individual (Subject 1) (left panels) and group mean (right panels) T_R and T_{sk} responses for constant load tests ($< \theta_L$) (HC (■), NC (□)). The responses were significantly different between conditions throughout the test protocol.

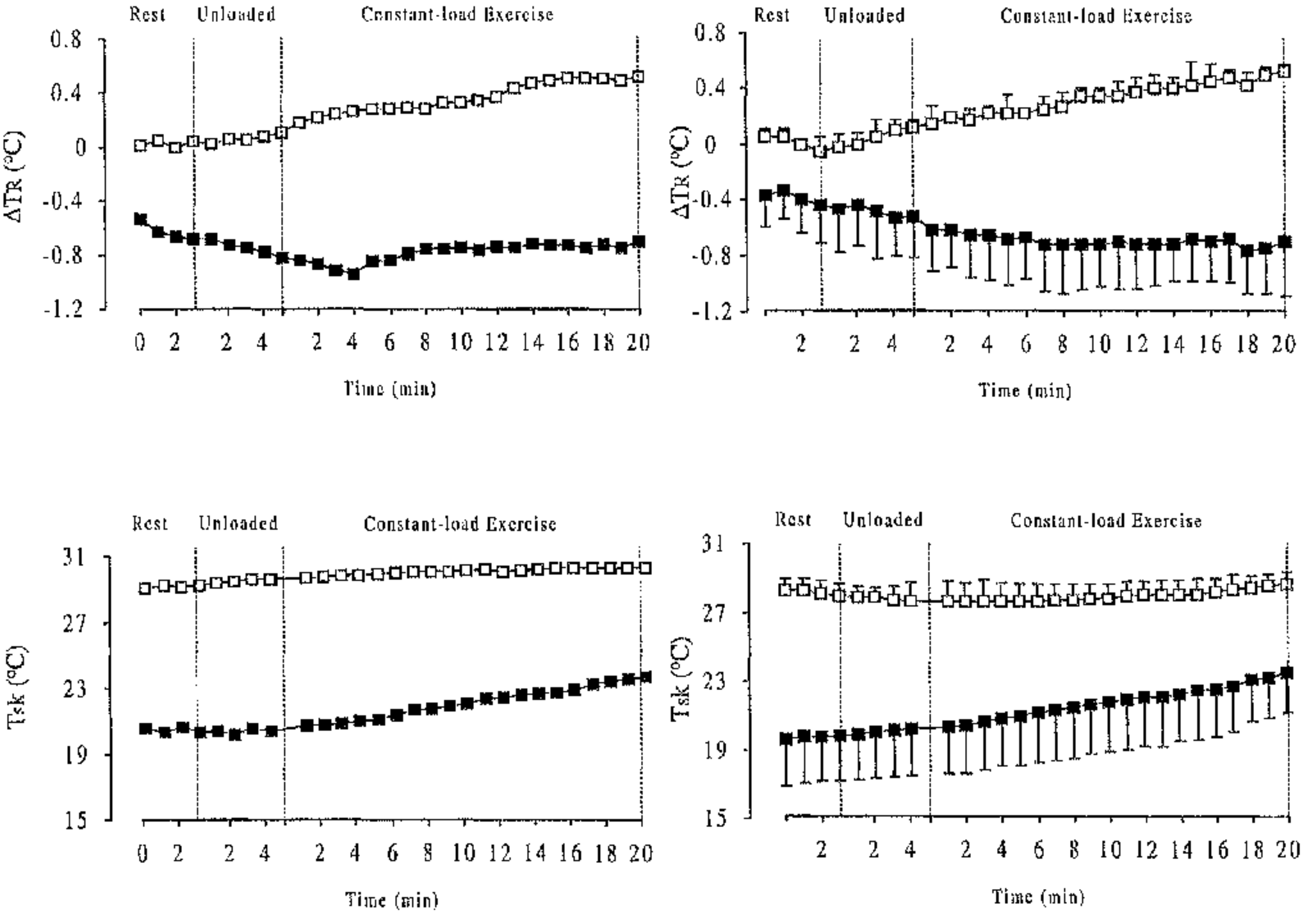
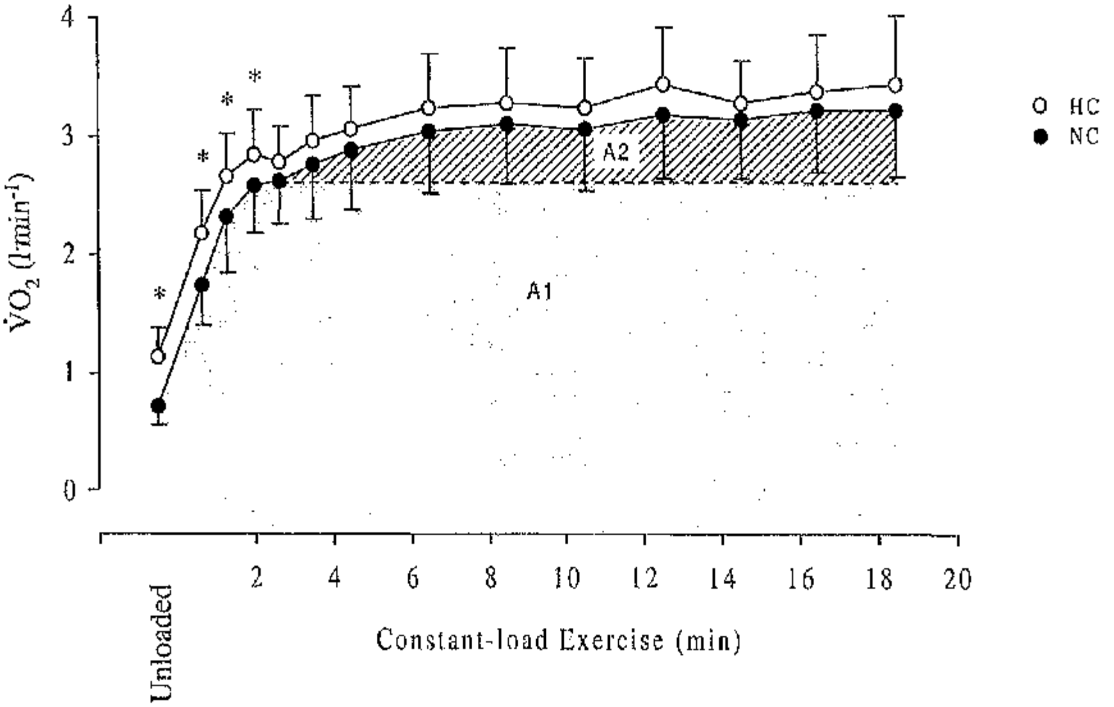

Rest
Unloaded
Constant-load Exercise
0.8
0.4
0
-0.4
-0.8
-1.2
ΔTR (°C)
0 2 2 4 2 4 6 8 10 12 14 16 18 20
Time (min)
Rest
Unloaded
Constant-load Exercise
0.8
0.4
0
-0.4
-0.8
-1.2
ΔTR (°C)
2 2 4 2 4 6 8 10 12 14 16 18 20
Time (min)
Rest
Unloaded
Constant-load Exercise
31
27
23
19
15
Tsk (°C)
0 2 2 4 2 4 6 8 10 12 14 16 18 20
Time (min)
Rest
Unloaded
Constant-load Exercise
31
27
23
19
15
Tsk (°C)
2 2 4 2 4 6 8 10 12 14 16 18 20
Time (min)

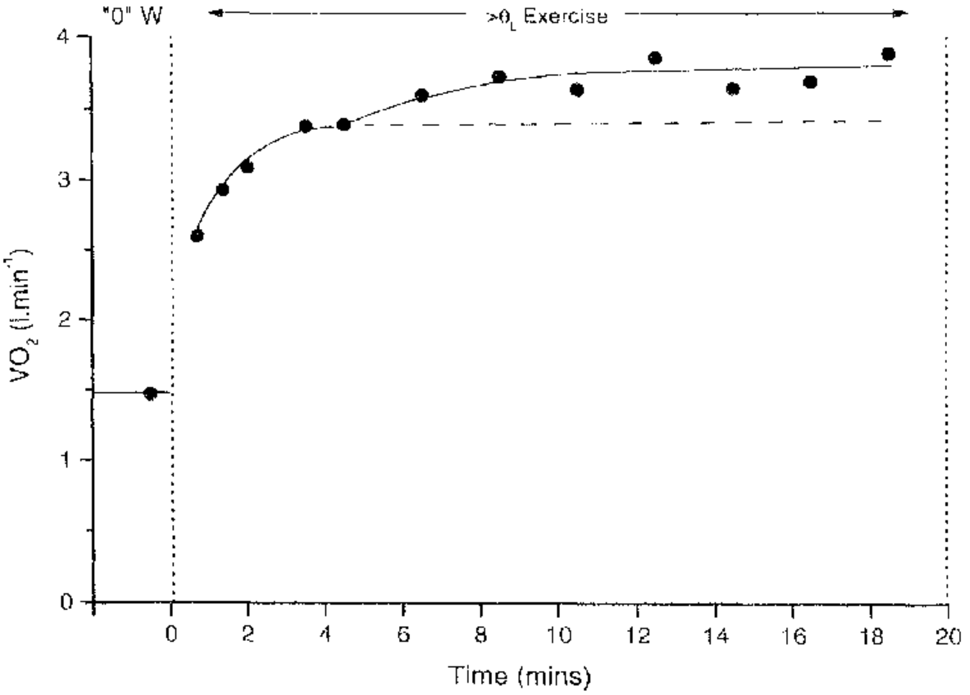
Figure 4.10: Group mean (s.d.) $\dot{V}O_2$ response profiles for constant load tests ($>\theta_L$). *: indicates significant differences between conditions. See text for further details.



$\dot{V}O_2$ (l·min^{-1})
4
3
2
1
0
Unloaded
2
4
6
8
10
12
14
16
18
20
Constant-load Exercise (min)
*
*
*
*
*
A2
A1
○ HC
● NC

Figure 4.11: Individual VO_2 response profiles for constant-load exercise ($> \theta_L$) in HC and NC (Subject 3).

HC


"0" W
>θL Exercise
VO2 (l.min-1)
4
3
2
1
0
0
2
4
6
8
10
12
14
16
18
20
Time (mins)

NC

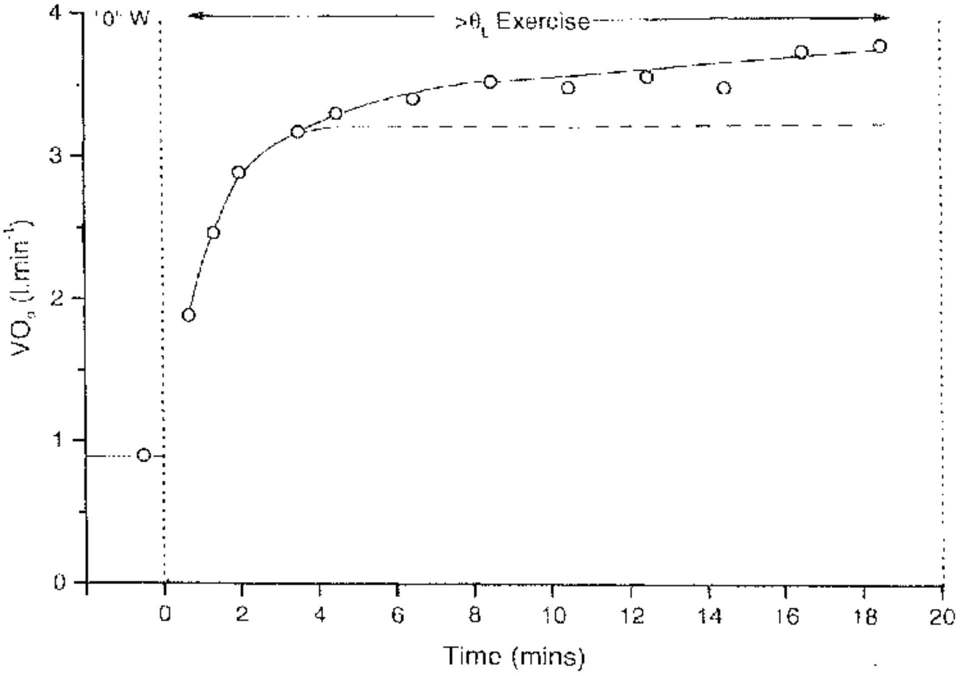
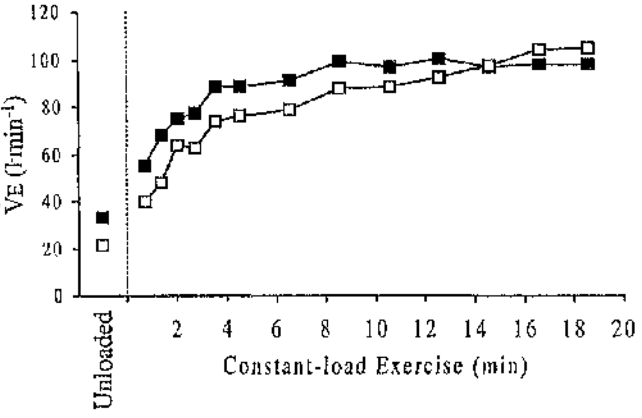
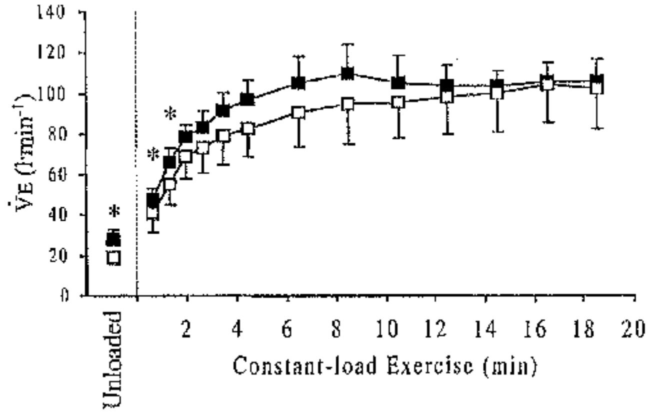

"0" W
>θL Exercise
VO2 (l.min-1)
4
3
2
1
0
0
2
4
6
8
10
12
14
16
18
20
Time (mins)

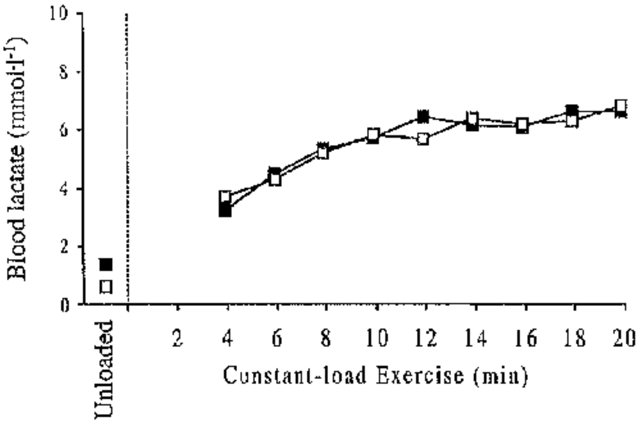
Figure 4.12: Individual (Subject 3) (left panels) and group mean (right panels) cardiopulmonary, metabolic and perceptual responses for constant load tests (> θ_L) (HC (■), NC (□)). *: indicates a significant difference between conditions.



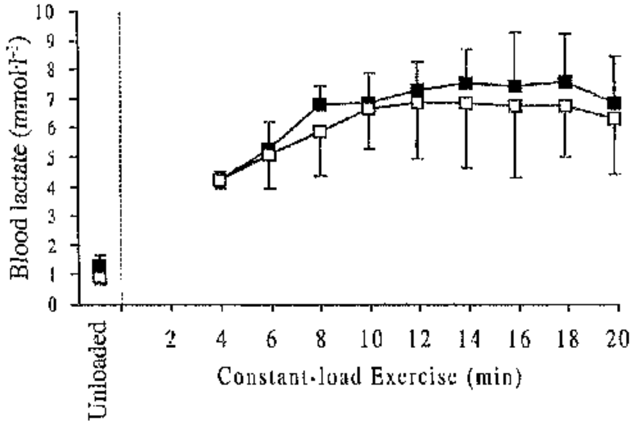
$\dot{V}_E$ (l·min^{-1})
0
20
40
60
80
100
120
Unloaded
2
4
6
8
10
12
14
16
18
20
Constant-load Exercise (min)



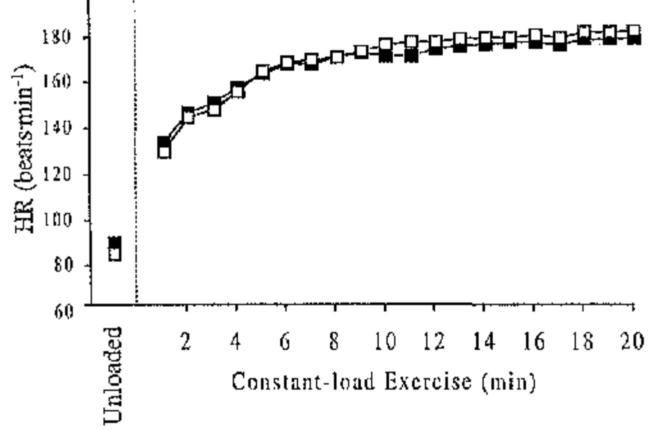
$\dot{V}_E$ (l·min^{-1})
0
20
40
60
80
100
120
140
*
*
*
Unloaded
2
4
6
8
10
12
14
16
18
20
Constant-load Exercise (min)



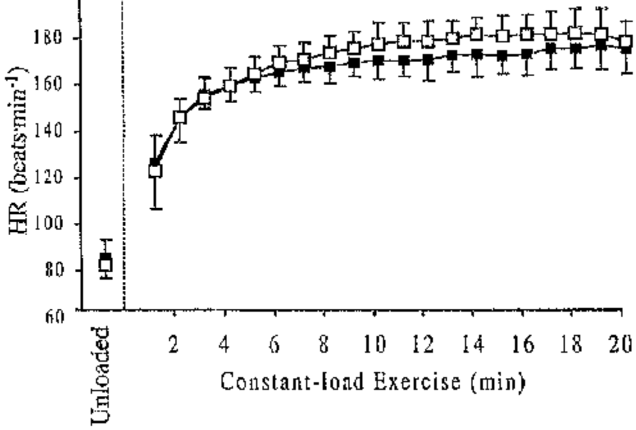
Blood lactate (mmol·l^{-1})
0
2
4
6
8
10
Unloaded
2
4
6
8
10
12
14
16
18
20
Constant-load Exercise (min)



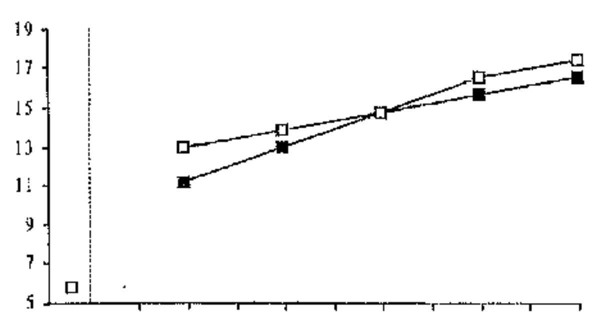
Blood lactate (mmol·l^{-1})
0
1
2
3
4
5
6
7
8
9
10
Unloaded
2
4
6
8
10
12
14
16
18
20
Constant-load Exercise (min)



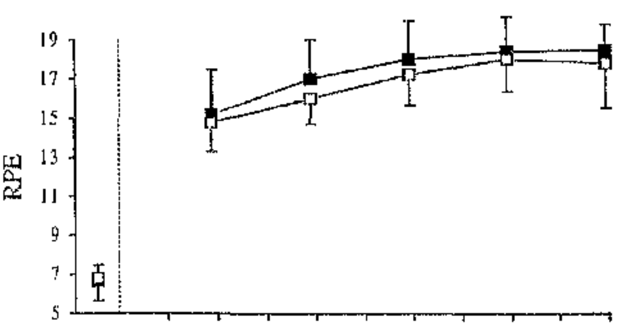
HR (beats·min^{-1})
60
80
100
120
140
160
180
200
Unloaded
2
4
6
8
10
12
14
16
18
20
Constant-load Exercise (min)



HR (beats·min^{-1})
60
80
100
120
140
160
180
200
Unloaded
2
4
6
8
10
12
14
16
18
20
Constant-load Exercise (min)

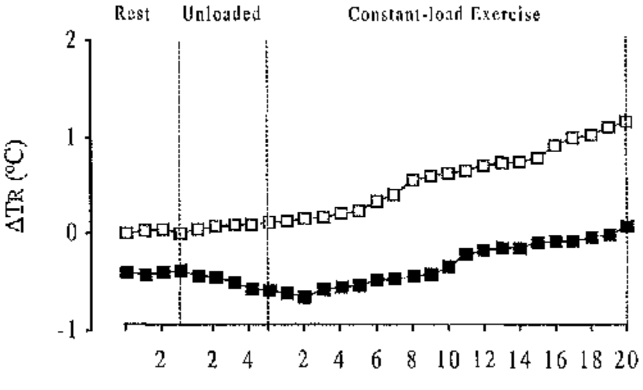


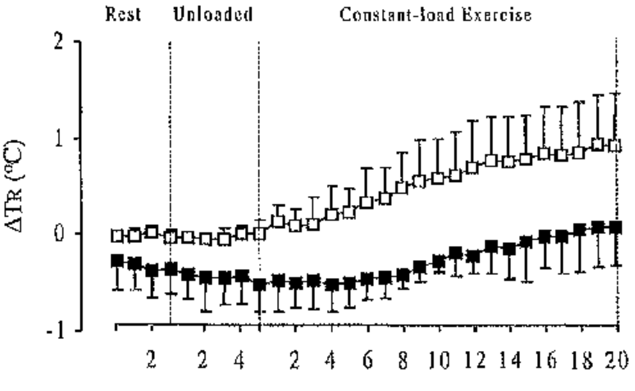
RPE
5
7
9
11
13
15
17
19
Unloaded
4
6
8
10
12
14
16
18
20
Constant-load Exercise (min)

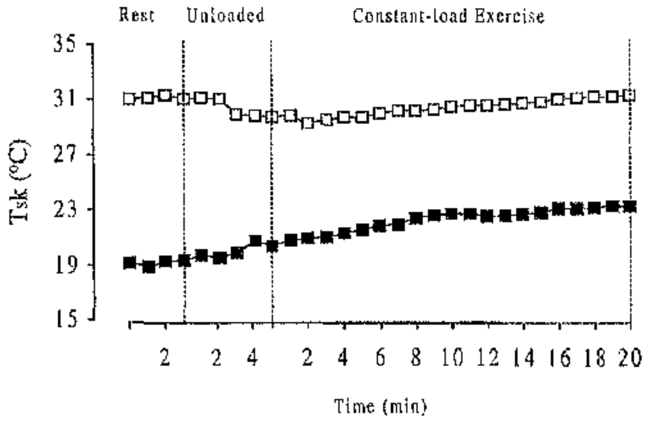


RPE
5
7
9
11
13
15
17
19
Unloaded
4
6
8
10
12
14
16
18
20
Constant-load Exercise (min)

Figure 4.13: Individual (Subject 3) (left panels) and group mean (right panels) T_R and T_{sk} responses for constant load tests ($> \theta_L$) (HC (■), NC (□)). The responses were significantly different between conditions throughout the test protocol.


Rest
Unloaded
Constant-load Exercise
ΔTR (ºC)
2
1
0
-1
2
2
4
2
4
6
8
10
12
14
16
18
20
Time (min)


Rest
Unloaded
Constant-load Exercise
ΔTR (ºC)
2
1
0
-1
2
2
4
2
4
6
8
10
12
14
16
18
20
Time (min)


Rest
Unloaded
Constant-load Exercise
Tsk (ºC)
35
31
27
23
19
15
2
2
4
2
4
6
8
10
12
14
16
18
20
Time (min)

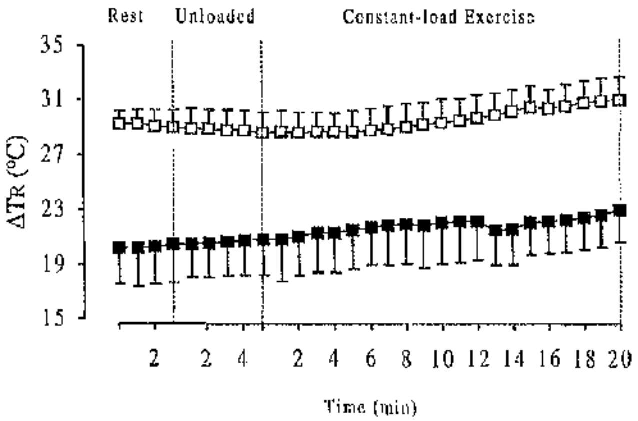
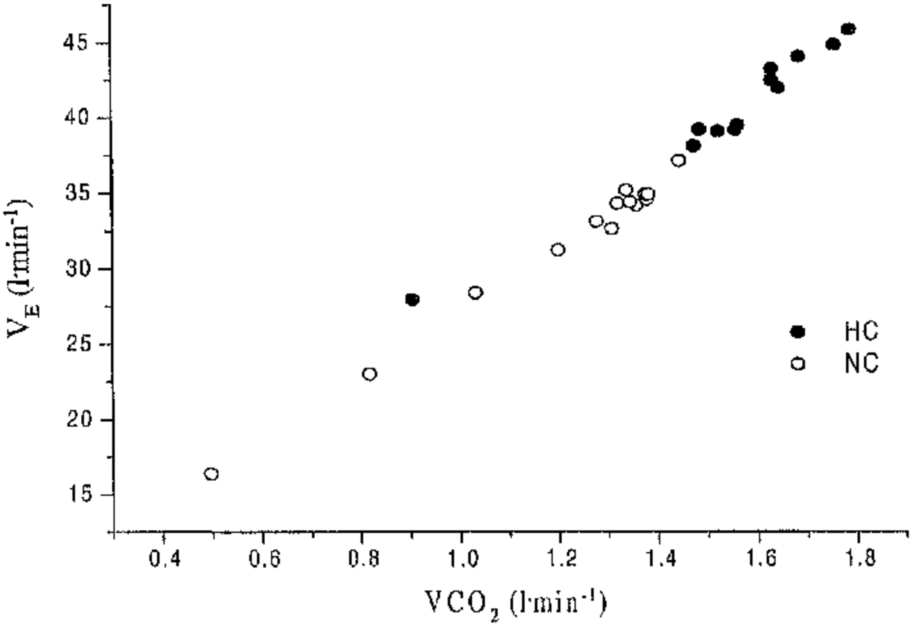
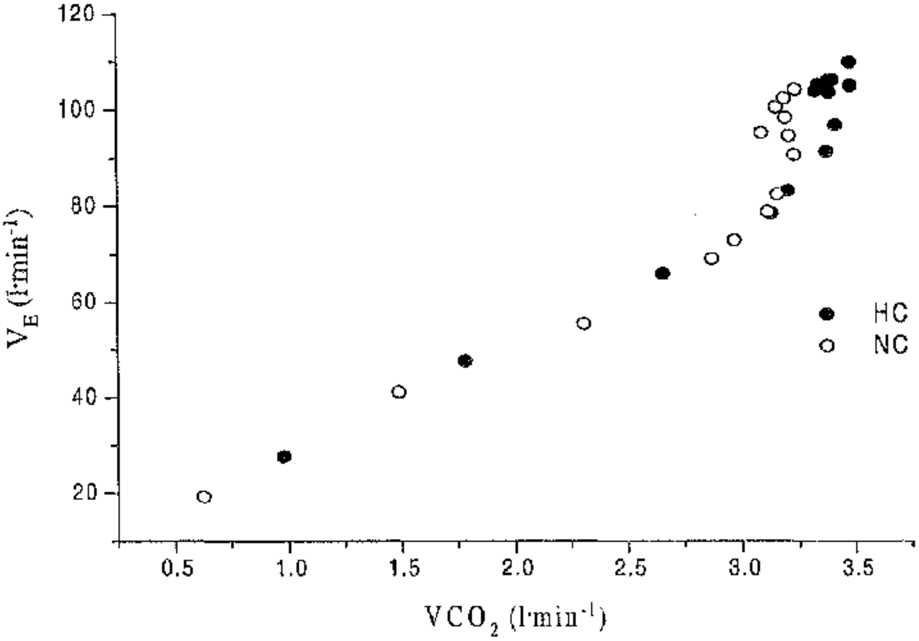

Rest
Unloaded
Constant-load Exercise
ΔTR (ºC)
35
31
27
23
19
15
2
2
4
2
4
6
8
10
12
14
16
18
20
Time (min)

Figure 4.14: Mean data for V_E expressed as a function of VCO_2 ($<\theta_L$, $>\theta_L$).



45
40
35
30
25
20
15
V_E (l·min^{-1})
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
VCO_2 (l·min^{-1})
● HC
○ NC



120
100
80
60
40
20
V_E (l·min^{-1})
0.5
1.0
1.5
2.0
2.5
3.0
3.5
VCO_2 (l·min^{-1})
● HC
○ NC

Discussion

Incremental Tests

The findings from incremental work tests demonstrated that sub-normal core and skin temperatures have an adverse effect on maximal aerobic performance. Subjects performed the incremental tests having exhibited significant decreases in both T_R (0.8 ± 0.4° C) and T_{sk} (7 ± 2° C) (induced by the cooling period); these lowered temperatures persisted throughout exercise. Significant reductions in the duration of incremental tests to exhaustion were found in HC. Furthermore, at maximal effort, hypothermia significantly reduced HR_{max} and tended to lower $\dot{V}O_{2\,max}$ and WR_{max}.

Several investigators have reported decrements in $\dot{V}O_{2\,max}$ at lowered core and muscle temperatures (Nadel et al. 1974; Davies et al. 1975; Bergh and Ekblom 1979; Quirion et al. 1989). Bergh and Ekblom (1979) demonstrated a linear fall in peak $\dot{V}O_2$ during maximal exercise, when muscle and core temperatures were lowered. Average lowered values reached during experimental procedures ranged from 35.1-36.5° C (muscle) and 34.9-35.8° C (oesophageal). The observed change in peak $\dot{V}O_2$ amounted to approx. 5-6 $\%\cdot°\ C^{-1}$. Davies et al. (1975) induced hypothermia in their subjects (core temperatures reaching approximately 35° C) by allowing them to swim at low speeds in a swimming flume containing water at 18° C. During the maximal exercise that followed, $\dot{V}O_{2\,max}$ was significantly reduced by 0.42 $l\cdot min^{-1}$.

Based on the criteria of Taylor et al. (1955), it appears likely that four out of the six subjects in the present study did not attain at "true" maximum in HC but simply reached a peak level in $\dot{V}O_2$. The differences in $\dot{V}O_{2\,max}$ between HC and NC amounted to more than the accepted/specified 150 ml·min^{-1}. The tendency for $\dot{V}O_2$ to be reduced at maximum in HC (if, indeed, it was attained) could be the direct consequence of a mechanical inefficiency, or changes in one or several physiological variables within the oxygen transport system.

The shorter duration of total work time, in conjunction with the tendency for a diminished $\dot{V}O_{2\,max}$ (seen in four subjects), suggests that subjects were stopping incremental exercise prior to having attained a true maximum. Evidently the sub-normal T_R and T_{sk}, which persisted throughout the incremental exercise, were imposing limitations to the work capacity of subjects. It has previously been shown that an increase in core temperature is necessary to reach maximal oxygen uptake (Bergh 1980). Although T_{sk} increased significantly from values obtained at the end of the cooling phase in the present study (Fig. 4.5), T_R remained unchanged during the incremental exercise (Fig. 4.5); neither variable attained baseline levels.

The low temperatures present during exercise may have affected chemical and physical processes at the cellular level in the skeletal muscle and, furthermore, resulted in a decreased net efficiency of exercise. Surprisingly, despite appearing to perform marginally better in NC, subjects did not perceive the incremental exercise in HC as being harder, based on the RPE results. This observation, however, confounds subjective reports following the incremental work tests: the majority of the subjects indicated a preference for exercising in NC rather than HC. For example, they complained of cold extremities and, particularly, stiffness in the legs during incremental tests in HC, and cited these as primary causes for termination of exercise rather than cardiorespiratory distress. These observations from the present study are consonant with previous findings by Quirion et al. (1989) who compared progressive maximal exercise performance at 20° C, 0° C and -20° C. They proposed that a direct effect of the cold on the muscles could be the reason why subjects found exercise intensities more tiring in the cold. Beelen and Sargeant (1991) have postulated that internal resistance within the muscle, related to tissue viscosity, may increase under cooled conditions. Consequently, a greater fraction of the power generated may be dissipated in moving the limbs; i.e., overcoming an increased internal resistance related to tissue viscosity.

Vangaard (1975) has suggested that impairment at the level of the neuromuscular junction may contribute significantly to the early onset of fatigue frequently observed during cold stress. Measurements of ulnar nerve latency have shown this to be highly temperature dependent; a 2° C decrease in nerve temperature doubling the latency. It has been proposed that a decreased conduction velocity will impair neuromuscular transmission under the influence of cooling, lengthening the duration of action potentials and, hence, prolonging the refractory period (Vangaard 1975). Consequently, the number of efferent stimuli reaching the muscle is attenuated and muscular contractions are impaired.

Consideration must be given to the possible influence of the reduction in HC incremental test duration. The diminished total work time may be a consequence of the increased sub-maximal $\dot{V}O_2$ levels that have frequently been seen during exercise in conjunction with lowered core temperatures (Nadel et al. 1974; Holmer and Bergh 1974; Davies et al. 1975). It appears logical to assume that more rapid onset of fatigue is likely to develop if a given WR represents a higher percentage of $\dot{V}O_{2\,max}$ in HC; in other words subjects reach $\dot{V}O_{2\,max}$ sooner than for normothermia. Fig. 4.4, which shows a representative of the typical pattern observed in subjects for $\dot{V}O_2$ as a function of WR, illustrates the higher oxygen uptake at lower WR in HC. $\dot{V}O_2$ for unloaded cycling was significantly higher in HC compared to NC; at θ_L discernible differences in $\dot{V}O_2$ ceased to exist between the two conditions. Evidently, the processes contributing the increased oxygen cost at low intensity exercise were offset to some extent by the heat-generating capacity of exercise as the WR progressively increased. Interestingly, the present study demonstrated a close coupling between the time profiles of elevated $\dot{V}O_2$ and V_E in HC for incremental exercise. Both variables were significantly higher in HC compared to NC for approximately the same duration during the initial stages of incremental exercise; the increases probably correspond to a marked shivering response.

A reduction in maximal aerobic capacity is, more often than not, accompanied by a reduction in HR_{max} (Nadel et al. 1973; Holmer and Bergh 1974; Bergh and Ekblom 1979). For example, Davies et al. (1975) demonstrated a reduction of 26 $beats{\cdot}min^{-1}$ at maximal effort under hypothermic conditions (which corresponds to a fall of approximately 14 %), whereas Bergh and Ekblom (1979) found a linear relationship between HR and decreasing body temperature during maximal exercise, the rate of reduction equaling 8 $beats{\cdot}min^{-1}{\cdot}°C^{-1}$. Results from the present study are consistent with previous findings and showed that HR_{max} was reduced by approximately 7 %. It has been suggested that the mechanical properties of the heart muscle are impaired by hypothermia; the rate of tension development per unit time is decreased, and times to peak tension and relaxation are prolonged (Bergh and Ekblom 1979). Bergh and Ekblom (1979) have postulated that the reduction in HR_{max} is likely to reduce cardiac output (CO) at peak levels. Maximum stroke volume (SV) probably remains unaltered (McArdle et al. 1976, Pendergast 1988) and, thus, the amount of oxygen made readily available to the exercising muscles is diminished.

In theory, circulatory impairment of O_2 delivery could be a further possible mediator for the observed effects on maximal aerobic performance. Cold-induced vasoconstriction, which may persist during exercise (especially at low intensities), could counteract the vasodilation induced by exercise (Holmer and Bergh 1974; Beelen and Sargeant 1991), further contributing to the diminished levels of circulating O_2 (see above). Ishii et al. (1992) found that muscle blood flow and its rate of adjustment tends to decrease under reduced muscle temperature conditions. A leftward temperature- dependent shift in the O_2-dissociation curve for haemoglobin is also likely. Impairment of O_2 delivery to the exercising muscles could, conceivably, result in local hypoxia and increased reliance on anaerobic metabolism. Similar levels for blood lactate concentration in HC and NC do not, however, support this hypothesis. It must be recognised, however, that blood lactate represents a balance between production and utilisation of lactate and few conclusions can be drawn about metabolic process by simply measuring the concentration in plasma. Therminarias et al. (1988) found lower plasma lactate concentrations during progressive exercise in the cold; these investigators have suggested that the findings may be due to increased lactate utilisation by shivering muscles, since lactate appears to be an important metabolic fuel for these (Minaire et al. 1971). The expected increase in blood lactate concentration may therefore have been counterbalanced by an increased uptake by the shivering musculature.

Sub-threshold constant-load tests

Individual profiles for the $\dot{V}O_2$ response in HC (< θ_L) showed a departure from the profile normally obtained in normothermia. The lack of consistency in the "temporal" shape of HC $\dot{V}O_2$ responses in the present study (Fig. 4.6) obviated similar kinetic analysis as for NC. The early $\dot{V}O_2$ "overshoot" observed for at least three subjects in HC (Fig. 4.8) distorted the characteristic mono-exponential profile normally obtained for sub-threshold square-wave exercise and formal first-order model-fitting was deemed inappropriate. Furthermore, because of the relatively low data density and the noise associated with the data (Lamarra et al. 1987), it is difficult *a priori* to select a model structure that is physiologically meaningful and significantly robust.

The effects of cooling induced in subjects became apparent when the $\dot{V}O_2$ response was compared between conditions, in terms of absolute magnitude. Higher $\dot{V}O_2$ values were found for HC throughout the square-wave protocol; the differences, however, between conditions were more pronounced during the initial stages of exercise. The apparent increase in O_2-cost for a given exercise intensity in HC could be the result of a number of factors, directly and indirectly attributable to cooling. A mechanical inefficiency, associated with an increase in the amount of energy expended to maintain a given work rate at a fixed cadence (Whipp and Wassermann 1969), was considered. It is plausible that the low environmental temperature may have augmented the resistance on the cycle-ergometer by increasing friction between the belt and the flywheel. This was ruled out, however, after no difference was found between conditions for the rest-to-unloaded cycling transition O_2-cost ($\Delta\dot{V}O_{2\ (unl\text{-}rest)}$). These findings provide strong evidence against a theoretical mechanical increment in O_2 uptake. This argument, however, does not rule out the possibility that inefficiencies at much higher work rates (i.e. $> \theta_L$) may have been introduced by the low temperature.

It is likely that shivering was the primary contributor to the observed disparity between $\dot{V}O_2$ in HC and NC. Shivering thermogenesis is responsible for increases in $\dot{V}O_2$ and heat production observed when humans are exposed to a cold environment, during both rest and exercise (Burton and Edholm 1955). Subjects in the present study exhibited significant elevations in resting $\dot{V}O_2$ for HC experiments; this thermogenic adjustment was apparent during rest, and exerted a considerable influence on the $\dot{V}O_2$ response during sub-threshold exercise, tending to persist for the entire duration of the exercise. During exercise at low WR, where the intensity of exercise in itself is insufficient to sustain body temperature, shivering is perceived to contribute significantly to increased (cold-induced) heat production, seen as an elevation in metabolism (Pugh 1967; Nadel et al. 1974; Hong & Nadel 1979; Shepard 1985). Integrated electromyographic data (iEMG) demonstrated that shivering and associated elevations in heat production were superimposed upon the rhythmic muscle contractions and heat production of cycle-ergometer exercise (Hong and Nadel 1979). It has been acknowledged that shivering can co-exist with exercise and is normally called upon by the body during low intensity exercise in the cold (Nadel et al. 1973; Hong & Nadel, 1979; Shepard, 1985; Weller et al. 1997).

The overall findings from the present study on $\dot{V}O_2$ kinetics in the cold offer support for the contention that the effect of moderate-to-heavy exercise is manifest as a graded inhibition of the shivering response (Hong and Nadel 1979). The effects of hypothermia on metabolic rate were evident at low WRs and were consistent regardless of the form of exercise. The thermogenic effect and associated heat flux during supra-threshold exercise was clearly higher than for sub-threshold exercise and hence concomitant respiratory and metabolic adjustments were attenuated for the higher intensity. This is reflected in the response for T_R. Although ΔT_R did not change appreciably from values obtained at the end of the cooling period, the profile for supra-threshold square-wave exercise (Fig. 4.13) indicates that T_R may have increased towards the latter stages of exercise. This is in contrast to the response for sub-threshold exercise, where T_R remained essentially unchanged during exercise, having exhibited a decrease during the unloaded phase (reflecting a redistribution of body heat content –Hong and Nadel 1979; Kruk et al. 1990).

As previously mentioned, the $\dot{V}O_2$ response profile in HC displayed an "overshoot" (seen clearly for three of the subjects) that was superimposed on the already elevated $\dot{V}O_2$ during sub-threshold exercise. No correlation was found between the magnitude of the overshoot and RPS. This may be, in part, due to the intermittent nature of shivering contractions or that subjects were being "stoic" and inaccurately reporting perceptions. Interestingly, analogous to the findings by Roston et al. (1987), the lactate-time profiles of subjects 4 and 5 in the present study (in whom blood [Lac] rose to an early peak and then decreased progressively during the remainder of exercise) closely resembled corresponding $\dot{V}O_2$ profiles for HC (Fig. 4.8). Both these subjects exhibited an early "overshoot" in $\dot{V}O_2$. Roston and his colleagues (1987) have demonstrated a significant correlation between the increase in blood lactate and the magnitude of the $\dot{V}O_2$ slow component; i.e. showing an association between increased lactate and the disproportionate increase in $\dot{V}O_2$. One might speculate, therefore, of a similar association for sub-threshold exercise under the influence of cold stress, taking into account, however, that it may not be lactate *per se*, but rather the accompanying acidosis that causes the observed effects on $\dot{V}O_2$ (Wasserman et al. 1991).

The oxidative reactions providing energy for exercise in cooled subjects may be slowed by the temperature-dependent reduction in enzyme activity mediated via the Q_{10} effect (Shiojiri et al. 1997). A slowing of chemical and physical processes within the cooled muscle is likely to generate a reduction in the velocity constant of ATP splitting, causing diminished breakdown and resynthesis of ATP (Ishii et al. 1992; Shiojiri et al. 1997). Ishii et al. (1992) postulated that the decrease in steady-state oxygen uptake ($\dot{V}O_{2\ (ss)}$) when expressed as its molar equivalent, was proportional to the reduction in the velocity constant of ATP splitting. The present study, however, revealed higher rather than lower absolute values for $\dot{V}O_2$ throughout exercise in HC, suggesting that if indeed ATP breakdown and resynthesis is slowed, it has been (over) compensated for by recruitment of a greater fraction of available active muscle mass to meet with the O_2-demand of shivering contractions and exercise.

Lower-efficiency, fast-twitch type II fibres, recruited as part of the increased fraction of muscle mass, active at any given time, may contribute to elevated sub-threshold exercise $\dot{V}O_2$ levels in HC. These fibres have a high O_2 cost (reflecting a low oxidative capacity) and longer time-constants (Barstow et al. 1996; Gaesser and Poole 1996). The proposed change in muscle recruitment pattern (including type II glycolytic fibres), as well as the additional muscle mass of the shivering musculature, may also have contributed to the tendency for higher blood lactate levels for sub-threshold exercise in HC.

Beelen and Sargeant (1991) have suggested that following cooling, more of the power generated may be dissipated in moving the limbs; i.e., overcoming internal resistances related to tissue viscosity which may increase under cooled conditions. Although difficult to estimate the magnitude of such a component, observations by the investigators led to the conclusion that overcoming internal resistance would require an equivalent $\dot{V}O_2$ in excess of approximately 0.2 $l.min^{-1}$. As previously stated, a number of subjects complained of stiffness in the legs, associated with difficulty in maintaining the selected cadence, alongside cold extremities during exercise in HC.

The O_2 cost of respiratory work necessary to increase pulmonary ventilation is unlikely to have contributed significantly to the elevated $\dot{V}O_2$ in HC. V_E was systematically higher for the first 12 min of sub-threshold exercise during HC; the elevation in V_E is consistent with previous findings by other investigators (Davies et al. 1975; Therminarias 1992; Ishii et al. 1992). The hyperpnoea associated with HC exercise did not, however, induce frank hyperventilation but was in its normal proportionality to CO_2 output; i.e. the slope of the V_E-VCO_2 relationship was within normal (NC) limits (Wasserman et al. 1987).

The sub-threshold $\dot{V}O_2$ findings for HC can only be compared in part to previous results of similar investigations that investigated the influence of cooling on O_2 kinetics during exercise. Three studies, investigating the effects of reduced muscle temperatures (by approximately 6-7° C) on the $\dot{V}O_2$ response at the start of exercise (Beelen and Sargeant 1991; Ishii et al. 1992; Shiojiri et al. 1997), induced cooling in subjects by immersing their legs in a cold water bath. This method of cooling effectively minimised the shivering response; Ishii et al (1992) were the only authors not to clothe the upper body during subject immersion which may explain why a shivering response was present in their subjects (evidenced by an elevation in resting $\dot{V}O_2$). In contrast to the present study, where no conclusions could be drawn on the temporal component of the HC $\dot{V}O_2$ response, Shiojiri et al. (1997) demonstrated slowed kinetics at the onset of exercise following cooling (τ was prolonged by approximately 8 sec). Ishii et al. (1992) and Beelen and Sargeant (1991) reported unchanged kinetics. Shiojiri et al. (1997), however, were the only investigators to demonstrate a mono-exponential $\dot{V}O_2$ response to the exercise transition. Ishii et al. (1992) quantified the O_2 kinetics using the half-time of the response (as opposed to τ); no examples of the data were shown and thus representation of mono-exponential kinetic analysis, using the half-time, should be treated cautiously. Analogous to the present study, Beelen and Sargeant (1991) determined $\dot{V}O_2$ from sequential Douglas bag collections. Although reporting unaltered kinetics, no information was provided on how data were fitted and, furthermore, on how the investigators reached their conclusion.

Finally, although the three studies referred to above, quantified the WR adopted for the rest-to-exercise transitions in terms of absolute magnitude (Ishii et al. 1992; Shiojiri et al. 1997) and expressed as a percentage of $\dot{V}O_{2\,max}$ (Beelen and Sargeant 1991), the intensity domain was not specified (see Chapter 1). The WR employed by Ishii et al. (1992) (i.e., 75W and 125W) and Shiojiri et al. (1997) (i.e., 50W) for the square-wave exercise transitions were low and it may be assumed that they were in the moderate intensity domain. This was not quantitatively assessed, however, and inferences made on the putative mechanisms contributing to altered $\dot{V}O_2$ profiles under the influence of cooling should be treated with caution.

Supra-threshold constant-load tests

The HC $\dot{V}O_2$ response for supra-threshold constant-load exercise differed from the NC response only in terms of magnitude for the first 160 sec approximately. The individual profiles obtained, enabled kinetic analysis for both NC and HC (Fig. 4.11); no significant differences were found between conditions for the estimated τ (Table 4.2), despite predictions of a decrease in the velocity constant of ATP splitting (Ishii et al. 1992). Slowing of the O_2 kinetics at the start of exercise may have been compensated for by the greater active muscle mass resulting from shivering contractions present during the initial stages of exercise.

Normalised for metabolic-acidaemic stress, it appears that the $\dot{V}O_2$ slow component characteristics were not appreciably influenced by environmental conditions. Thus, no further definitive information is provided for elucidation of the putative mediators of the excess $\dot{V}O_2$ and the precise functional significance in context of QO_2. Pulmonary gas exchange and cardiorespiratory variables showed essentially no variance between HC and NC; the few discernible differences for the $\dot{V}O_2$ and V_E responses were present only for the initial 160 and 120 sec respectively. The characteristically slow component of $\dot{V}O_2$ normally becomes superimposed upon the rapid increase associated with exercise onset after some 80-110 seconds (Barstow and Mole 1991; Paterson and Whipp 1991) and develops most rapidly between min 3 and 10 of exercise (Poole et al 1990; Poole et al. 1991). No meaningful inferences can therefore be made to account for the possible contribution of V_E, and the associated O_2 cost of an increase in pulmonary ventilation, to the excess $\dot{V}O_2$ observed during supra-threshold exercise.

An increase in core and muscle temperature has been proposed as a possible mechanism contributing to the slow component, via the Q_{10} effect (Gaesser and Poole 1996). In the present study, T_R (expressed as a change from baseline) was significantly lower in HC compared to NC throughout supra-threshold exercise, as was T_{sk}. By logical deduction, the present findings suggest that increased body temperature is unlikely to be quantitatively important in contributing to the slow component. Indeed, this has been shown by Rowell (1971), who could not demonstrate a discernible effect on exercise $\dot{V}O_2$ following changes in body temperature of 2-3° C. Koga et al. (1997) have demonstrated that if anything, the slow component (characterised by $\Delta \dot{V}O_{2\ (6-3)}$) was slightly, but significantly smaller when muscle temperature was elevated. This finding is inconsistent with the previously accepted hypothesis that an exercise-induced increase in muscle temperature may be the predominant mechanism behind the slow component.

There are, however, contra-indications to the deduction made above based on the present findings. For instance, the limited number and short duration of discernible differences for the measured variables during exercise above θ_L (in contrast to findings for sub-threshold exercise), suggest that the influence of the cold was not as striking at the heavier intensity. Therefore, although T_R and T_{sk} were reduced with respect to normothermic values, the thermogenic effects of supra-threshold exercise may have counterbalanced any metabolic alterations within the exercising musculature as a result of cooling. Further investigation is required, however, for definitive conclusions on the influence of cooling on the $\dot{V}O_2$ slow component and the consequent inferences on proposed mediators of this phenomenon.

Conclusions

In conclusion, the findings from the present study have demonstrated detrimental effects on sub-maximal and maximal exercise performance under the influence of reduced T_R and T_{sk}. Furthermore, the results offer support to the contention that shivering is inhibited with increasing exercise intensity and this consistent regardless of the form of exercise (i.e., incremental versus constant-load). The absence of differences for the $\dot{V}O_2$ slow component between HC and NC, tends to suggest that increased muscle temperature is unlikely to contribute significantly to its manifestation.

Chapter Five

General Discussion

General Discussion

The primary objective of Studies I, II and III was to provide an indirect evaluation of garment properties, incorporating certain aspects into the design that allowed for assessment of specific characteristics, in standardised environmental conditions. In this chapter, the findings are discussed in a wider context and their practical applications considered. Study IV investigated exercise metabolism under the influence of cold stress. The implications of the results on some of the current perspectives concerned with underlying control mechanisms are referred to in this chapter, alongside directions for future work in the related area of research.

Influence of garment properties on the physiological response to cold stress.

Studies I and II demonstrate that the degree to which a garment is permeable to wind, can exert considerable influence on the physiological response to cold stress. Furthermore, the findings showed that although air permeability was important in providing protection against the imposed environment, it was not the only discerning factor in the discrimination between suits. The fact that the suit with medium air permeability (MP) appeared to be the most favourable of the suits, suggests that other factors contribute to the overall protective capacity of MP in cold and windy environments such as the ones employed for these studies. The most plausible explanation from the given physical properties and characteristics of the suits appears to lie in the different thickness of LP and MP, which could theoretically have affected suit fit. The thinner fabric of LP may have resulted in looser fit on subjects (Gavhed et al. 1991), thus allowing for greater ventilation within the microclimate. The insulatory capacity (due trapped air) of the microclimate is also likely to have been diminished through compression of the suit against the body. It is conceivable that the force of the wind exerted a larger impact on the thinner material, compressing the suit against the body and effectively eliminating the still air layer.

The purpose of Study III was to compare the influence of different physical properties and wicking capacity of garments on the thermoregulatory responses and subjective perception of humans, during rest that was subsequent to a period of exercise in the cold. Significant cooling was observed in subjects as a result of the cold ambient in conjunction with the presence of moisture accumulated through the exercise sweating response. The differences found among the garments evaluated were likely due to differences in the drying process (heat being lost through evaporation from the surface of the skin or the clothing, depending on the transfer of moisture) (Bakevigg and Nilesen 1994). The preferred garment combined a high wicking capacity with greater thermal resistance and thickness, although it has been postulated that thicker constructions may slow the evaporation process by giving less moisture per volume and a lower temperature at the garment surface (Bakevigg and Nielsen 1994). Evaporation may be enhanced if the moisture remains close to the skin initially, since it has a higher temperature than the environment.

Technological constraints and equipment limitations for Study III excluded certain measurements that would have provided additional information on garment performance. These include quantification of the microclimate (in terms of temperature and humidity), estimation of the amount of moisture on the skin (skin wetness), as well as weighing of the garments to assess the amount of moisture present at a given time. A number of investigators, for instance, have measured humidity within the microclimate as well microclimate temperature at separate sites during garment assessments (Gavhed et al. 1989; Ha et al. 1998). Ha et al. (1998) conducted a study comparing two baselayer garments during rest subsequent to physical activity in cold. As well as quantifying the microclimate (in terms of temperature and humidity), the investigators attempted to estimate evaporative losses of moisture by incorporating body mass and garment weighing during the experimental protocol, thus providing information on the transient behaviour of moisture transport.

Clothing physiology - correct approach and future directions.

An adjacent outer-garment was included as part of the garment evaluation in Study III; the moisture is transported by vapour diffusion to this garment and condenses there. When the vapour condenses, the latent heat that is liberated results in a lower temperature gradient between the skin an the outer-layer; the effect, however, on heat loss from the skin (which will ultimately cause cooling and affect the body's thermoregulatory response) is likely to be minimal (Renbourn 1972). Incorporating a second layer into the design protocol of the present study emphasises a fundamental issue in the area of clothing physiology and its application to cold environments: the idea of a multi-layer clothing ensemble that allows the wearer to selectively control the degree of protection from garments, tailoring it to the demands of the environment (Lotens 1987; Dickinson 1995). No single garment can satisfy all the requirements presented during cold exposure e.g. there is no material that is a fine insulator, yet simultaneously offers effective protection from wind and rain. The basic multi-layered clothing system should incorporate a base-layer, where warmth and wicking ability are the principal prerequisites, insulation layers and an outer layer to protect against wind and moisture (Dickinson 1995). A layered system allows for more trapped air layers, thus increasing effective insulation by adding to the total value. Although not convenient at all times, adding or shedding items of clothing may prevent potentially hazardous situations like the accumulation of excess heat (and hence sweat) during exercise, an issue addressed in Study III. The layers can be varied according to ambient temperature, the presence (or not) of wind and rain, and activity (including intensity and duration). A review by Lotens (1987) contends that "... probably the largest design problem of cold weather clothing is not the achievement of high insulation, but rather the creation of possibilities for the adjustment of insulation to the difference in heat production between work and rest".

The garments assessed in the present studies were functionally designed to be used as a base-layer (Study III) and protective outer-layer (Studies I and II). It is logical to believe that the evaluation of any garment is only complete when tested as a part of a multi-layered system, thus allowing for interaction between the different garments and estimation of a resultant, as opposed to individual, insulation value. Holmer and Gavhed (1991) have shown that significant errors arise in predictions of thermal responses when basic insulation values are used in calculations instead of resultant figures. Furthermore, the assessment of the dynamic behaviour of clothing in terms of heat exchange should be incorporated into the design protocol (i.e. employing a rest/exercise cycle, such as for studies I, II and III) for comprehensive evaluation of any garment. An extended number of combinations are possible, and studies are required for determining the "optimal" combination in a given environment, taking into account ambient temperature, precipitation, activity status and duration of exposure.

Although manikin measurements provide values for the basic thermal properties of clothing (e.g. insulation, evaporative resistance etc.), they must be compared with measurements on human subjects to account for individual variability of thermal properties in a field situation. It makes sense, therefore, to combine measurements from both manikin and human trials. Reviews on the recent trends in clothing physiology (Lotens 1987; Holmer 1989; Dickinson 1995) accent the most significant problems to be addressed in both chamber and field experiments: a) the variability of intrinsic thermal properties under conditions of intended wear (i.e. posture, body movement, wind, etc.); b) the effect of clothing on heat exchange during transient conditions, like intermittent activity; c) the effects of moisture absorption in clothing, including transfer of sweat from the skin and re-evaporation in adjacent layers and d) validation of predictive models for specialised clothing (i.e. protective garments), as well as for models predicting basic and resultant thermal properties of clothing.

Influence of cold exposure on aerobic performance in exercising humans.

Study IV showed alterations in the metabolic response to progressive maximal exercise during exercise in the cold (and following body cooling) that are consistent with previous findings (Paton and Vogel 1984; Quirion et al. 1989). There was a significant reduction in time to exhaustion and a tendency for lowered $\dot{V}O_{2\,max}$, although this did not attain statistical significance. During the initial stages of the incremental exercise, however, $\dot{V}O_2$ was elevated in the cold compared to normothermic conditions. A number of investigators have proposed that increases in

$\dot{V}O_2$ in cold temperatures appear to relate to exercise intensity (Stromme et al. 1963; Hong and Nadel 1979; Quirion et al. 1989). It is likely that at high intensities, exercise substitutes for shivering thermogenesis, rather than adding to its effect. This hypothesis, derived from results obtained for incremental exercise, extended to the findings of the constant-load exercise tests.

$\dot{V}O_2$ during sub-threshold constant-load exercise was systematically higher in HC compared to NC. The elevated $\dot{V}O_2$ is likely to be principally a consequence of shivering (Nadel et al. 1973; Hong and Nadel 1979) which persisted throughout the duration of exercise, indicating that the thermogenic capacity of moderate intensity exercise was not adequate to offset heat loss. In three of the subjects the elevation in $\dot{V}O_2$ characteristically displayed an "overshooting" behaviour during the initial stages of the square-wave exercise transitions, implying that, possibly, there were contributions other than from shivering to the higher $\dot{V}O_2$ in HC. The possibilities include changes in fibre-type recruitment (Beelen and Sargeant 1991; Ferretti 1992; Ishii et al. 1992) and an additional energy requirement for overcoming an increased internal resistance within the muscle as a result of cooling (Beelen and Sargeant 1991).

In contrast to sub-threshold findings, the $\dot{V}O_2$ response for heavy-intensity constant-load exercise differed between HC and NC only during the initial stages of the square-wave transition (approximately 160 sec). The characteristic $\dot{V}O_2$ slow component appeared to be unaffected by the cooling, since there were no differences in its magnitude between HC and NC. The discrepancy in the $\dot{V}O_2$ response for HC between sub- and supra-threshold constant-load exercise can only be accounted for by an increase in metabolic heat generation. Evidently, the shivering response was abolished early on during supra-threshold exercise transition as a result of a greater thermogenic capacity and heat flux generated by the higher intensity exercise.

Despite the absence of significant differences for the $\dot{V}O_2$ slow component, T_R and T_{sk} were significantly lower during HC compared to NC. This observation has significant implications for the role of temperature as a potential mediator of the slow rise in $\dot{V}O_2$ typical of supra-threshold constant-load exercise in normothermia. Although proposed as a putative mechanism contributing to the "excess" O_2 component (Gaesser and Poole 1996), the findings of the present study implicate that an increased muscle temperature is unlikely to contribute by a significant amount. Previous findings by Koga et al. (1997) are also inconsistent with the contention that an exercise-induced elevation in muscle temperature is a predominant mechanism for the slow component, since the magnitude of the slow component was reduced with increased muscle temperatures. If an increased muscle temperature were to contribute significantly in the manifestation of the slow component, then the lowered T_R, T_{sk} and, by deduction, muscle temperatures during supra-threshold exercise in HC in the present study, would have been expected to decrease the magnitude of the slow component. It is, however, possible that although only significant during the initial part of the square-wave exercise transition, thermoregulatory adjustments (i.e. shivering) persisted, albeit diminished, for a longer duration and effectively "masked" the expected decrease in the $\dot{V}O_2$ slow component. Perhaps it is also unjustified to expect a reduction in the magnitude of the slow component at sub-normal temperatures; it is likely that the metabolic heat production of heavy intensity exercise is adequate to offset heat loss, and will thus diminish any thermoregulatory response acting in the same manner (as indicated by results from the present study). No definitive conclusions can, therefore, be drawn regarding the putative stimuli contributing to the $\dot{V}O_2$ slow component.

Limitations and constraints to the design of Study IV

The design of study IV demands certain caution in interpreting the results obtained. The primary limitations to interpretation of the findings are the utilisation of a single transition for constant-load exercise tests and the relatively low density of data obtained from these. Breathing, typically, has inherent irregularities that produce breath-by-breath fluctuations (i.e., "noise") during gas exchange; these must be accounted for when estimating values for the kinetic parameters, important for elucidation of physiological determinants related to kinetic modelling (Lamarra et al. 1987). The noise produces statistical uncertainty in the estimation of kinetic parameters and the more noisy the data, the lower the confidence of each estimation. Lamarra et al. (1987) derived an expression to determine *a priori* the number of square-wave repetitions required to reduce the uncertainty to a specified level (i.e., a 95 % confidence interval). The low density of data, the result of using Douglas bags for collection of expired gas, would surely require a number of repetitions (rather than a single transition) for an increased signal-to-noise ratio and, hence, accurate (or confident) parameter estimation. The well motivated subjects, however, participating in the present study were tested to their limits and indeed were extremely uncomfortable during HC experiments. Thus, the number of cold-exposures was limited to an absolute minimum.

Expired gas was collected in Douglas bags as the low environmental temperature employed for HC experiments rendered the use of a breath-by-breath system (typically utilised for determination of pulmonary gas exchange kinetics) impossible. In similar analogy to the work of Whipp et al. (1999), one could accommodate the system outwith the cold environment enabling pulmonary gas exchange measurement on a breath-by-breath basis. Whipp et al. (1999) conducted simultaneous determination of muscle ^{31}P metabolite and O_2 uptake kinetics during whole body NMR spectroscopy. This was accomplished by housing the mass spectrometer and the ventilation measurement module in a room adjacent to the magnet and extending the length of the sample-line. A similar set-up for the present experiments presented further technical challenges, however, as both the flow-head (connected to the mouth-piece) and sample line would be exposed to sub-zero temperatures and it is unlikely that they are robust enough to withstand such temperatures without fracturing.

The confidence of interpreting the present findings could be improved by introduction of several additional measurements to the design of present study. In addition to a breath-by-breath system that would allow for greater density of data, electromyogram (EMG) recordings, muscle temperature measurement and a heated sample line for frequent blood-sampling would improve the accuracy of result interpretation.

Integrated EMG recordings (Burton and Edholm 1995; Hong and Nadel 1979) have previously been used to estimate shivering activity. Hong and Nadel (1979) positioned the electrodes over the middle of the sternocleidomastoides muscle of neck; this muscle has been shown to be active during shivering and although it may serve as an accessory muscle in forced inspiration, any additional electrical activity due to exercise *per se* should be minimal (Hong and Nadel 1979). Thus, the integrated EMG response would accurately reflect the temporal and quantitative aspects of the shivering response.

Previous investigators looking at the effects of temperature on $\dot{V}O_2$ kinetics have all measured muscle temperature in addition to core and/or skin temperature (Beelen and Sargeant 1991; Ishii et al. 1992; Shiojiri et al. 1997; Koga et al. 1997). Needle thermocouples have been used for invasive muscle temperature measurement, inserted normally to a depth of approximately 3 cm. Muscle temperature measurement in the present study would have provided additional information for interpretation of results, especially findings on the $\dot{V}O_2$ slow component. Most of the evidence available concludes that the origin of the slow rise in $\dot{V}O_2$ at work-rates above θ_L lies within the working muscle (Whipp 1994; Gaesser and Poole 1996); any sound deductions, therefore, require measurements at the level of the muscle.

A heated sample line for arteriovenous blood sampling (as opposed to skinprick capillary samples obtained in the present study) would enable more frequent sampling, and quantification of blood constituents other than lactate e.g. plasma catecholamine concentration, glucose and free fatty acids (FFA) among others have been previously measured, providing information on metabolism during exercise at sub-normal temperatures. Plethysmographic techniques have also been employed for blood flow determination (Bancroft and Edholm 1943; Hardy and Sodestrom 1985; Shiojiri et al. 1997). Such techniques employed for the present study would provide information on the presence (or not) of a persisting vasoconstriction during exercise in

HC and thus inferences could be made on whether circulatory impairment of O_2 delivery contributed significantly to any of the findings.

Despite the limitations of the present study, the major trends showed that body cooling had a detrimental effect on exercise performance and that this was more pronounced at low exercise intensities. Further studies are required to assess the reproducibility of the present results and to provide more definitive information for elucidation of the underlying mechanisms responsible for the decrement(s) in performance. It is possible that the severity of the shivering response effectively masked any "true" physiological adjustments to cardiopulmonary and metabolic response profiles due to cold. Cooling by immersing the legs in cold water, can effectively minimise the shivering response (Shiojiri et al. 1997); further investigation, therefore, on both sub- and, especially, supra-threshold response profiles is required utilising this form of cooling. Finally, the inclusion of high ambient temperatures (e.g. ≥ 30° C) to the design of the present study would allow for comparison at the two temperature extremes.

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Appendix - Medical Questionnaire

CENTRE FOR EXERCISE SCIENCE AND MEDICINE

MEDICAL HISTORY

(CONFIDENTIAL)

Please read.

It is important to take a record of your medical history. You may have, or may have once had a condition that would make this type of testing unsuitable for you. For this reason we ask you to be as truthful and detailed as possible. At no point will this information be made available to any one other than the principal investigators for this study. If you have any doubts or questions, please ask.

SUBJECT DETAILS:

NAME:

AGE: D.O.B:

SEX (M/F):

SMOKING:

Never Smoked ......
Not for >6 months ......
Smoke <10 per day ......
Smoke >10 per day ......

ILLNESSES:

ALLERGIES:

HOSPITALISATIONS:

MUSCULO-SKELETAL DISORDER:
(Arthritis, Joint Pain, Fractures, Sports injury, Others)

CARDIOVASCULAR DISORDER: (Fever, Heart Murmurs, Chest Pain, Palpitations, High Blood Pressure, Others)

RESPIRATORY DISORDER: (Asthma, SOB, Cough, URTI, Others)

GASTROINTESTINAL DISORDER: (Jaundice, Bleeding, Others)

DIABETES:

CNS DISORDER: (Fits, Blackouts, Tremor, Paralysis, Epilepsy, Other)

PSYCHIATRIC TREATMENT:

FAMILY HISTORY: (Sudden death in a first degree relative under the age of 35 years)

ARE YOU CURRENTLY TAKING ANY MEDICATION? No / Yes*

(*Please specify)____

ARE YOU CURRENTLY TAKING ANY SUBSTANCES TO HELP IMPROVE YOUR TRAINING OR CONTROL YOUR WEIGHT i.e. CREATINE, PROTEIN SUPPLEMENT? No / Yes*

(*Please specify) ____

ARE YOU CURRENTLY TAKING ANY OTHER SUPPLEMENTS i.e. FOOD SUPPLEMENTS, VITAMINS? No / Yes*

(*Please specify) ____

CAN YOU THINK OF ANY OTHER REASON WHY YOU SHOULD NOT TAKE PART IN ANY OF OUR TESTS?

____

SYMPTOMS:

Do you experience any of the following, particularly on exercise?

Breathlessness	No / Yes
Chest Pain	No / Yes
Dizzy Fits/Fainting	No / Yes
Palpitations	No / Yes

Please note that if you feel unwell on the day of the proposed test, or have been feeling poorly over the preceding day or two, please inform the investigators and DO NOT TAKE PART in the exercise test.

DECLARATION:

I have completed this questionnaire fully and truthfully. I have not kept any information from the investigators that may put myself at risk during high-intensity exercise, or affect the results that they obtain. I understand that I may withdraw from any one test or the study as a whole if I feel unwell, or feel uncomfortable with any part of the testing procedure.

(Signature) ....

(Date) ....