THE EFFECTS OF PROTECTIVE CLOTHING AND ITS PROPERTIES ON ENERGY CONSUMPTION DURING DIFFERENT ACTIVITIES

By

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ABSTRACT

There are many situations where workers are required to wear personal protective clothing (PPC), to protect against a primary hazard, such as heat or chemicals. But the PPC can also create ergonomic problems and there are important side effects which typically increase with rising protection requirements. The most extensively studied side effect is that of increased heat strain due to reduced heat and vapour transfer from the skin. Less studied is the extra weight, bulk and stiffness of PPC garments which is likely to increase the energy requirements of the worker, reduce the range of movement and lead to impaired performance.

Current heat and cold stress standards assume workers are wearing light, vapour permeable clothing. By failing to consider the metabolic effects of actual PPC garments, the standards will underestimate heat production and therefore current standards cannot be accurately applied to workers wearing PPC. Information on the effect of the clothing on the wearer and the interactions between PPC, wearer and environment is limited.

Data was collected to quantify the effect of PPC on metabolic load based on the properties of the PPC for the EU THERMPROTECT project (G6RD-CT-2002-00846). The main objective of the project was to provide data to allow heat and cold stress assessment standards to be updated so that they need no longer exclude specialised protective clothing.

The aim of this thesis was to investigate the effect of PPC and its properties on energy consumption during work. For this purpose, the effects of a range of PPC garments (Chapter 3), weight (Chapter 4), number of layers and material friction (Chapter 5) and wet layers (Chapter 6) on energy consumption whilst walking, stepping and completing an obstacle course were studied. The impact of PPC on range of movement in the lower limbs was also investigated (Chapter 7).

The main findings were; a) Increased metabolic cost of 2.4 - 20.9% when walking, stepping and completing an obstacle course in PPC compared to a control condition. b) An average metabolic rate increase of 2.7% per kg increase in clothing weight, with greater increases with clothing that is heavier on the limbs and in work requiring greater ranges of movement. c) 4.5 to 7.9% increase in metabolic cost of walking and completing an obstacle course wearing 4 layers compared to a single layer control condition of the same weight. d) Changes in range of movement in PPC due to individual behavioural adaptations. e) Garment torso bulk is the strongest correlate of an increased metabolic rate when working in PPC ($r=0.828$, $p<0.001$). f) Garment leg bulk ($r=0.615$), lower sleeve weight ($r=0.655$) and weight of the garment around the crotch ($r=0.638$) are also all positively correlated with an increased metabolic rate. Total clothing weight and clothing insulation had r values of 0.5 and 0.35 respectively.

This thesis has confirmed the major effect of clothing on metabolic rate, and the importance of including this effect in standards and models.

Keywords: Protective clothing, energy consumption, metabolic rate, clothing weight, layers, friction, bulk, stiffness, range of movement

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Study 4, described in Chapter 6 represents work conducted jointly by the author and Mr D King. The author was responsible assisting with the supervision of Mr D King during his MSc dissertation work. The author re-analysed the raw data obtained in the study for inclusion in this thesis.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Preface

There are many industrial situations where workers are required to wear personal protective clothing and equipment (PPC), for example, firefighters, chemical workers, cold store workers, army personnel and those working in the steel and forestry industries. Although this protective clothing may provide protection from the primary hazard, for example heat or chemicals, it can also create ergonomic problems.

In recent years many PPC product standards have been introduced, these have helped to improve the quality of the protective clothing and so increased the safety of the workers. However, information on the effect of the clothing on the wearer and the interactions between PPC, wearer and environment are limited. Most PPC is designed for optimal protection against the hazard present, but this protection in itself can be a hazard.

There are important side effects to protective clothing and typically with increasing protection requirements, the ergonomic problems increase. Often the main problem is the added load on the body in terms of weight. Also reduced mobility due to garment stiffness reduces the freedom of movement and may increase the risk of falls or getting caught in machinery. Even worse, the extra load and discomfort due to the protective clothing may tempt workers not to wear it when the primary hazard risk is low, leaving them unprotected if the hazard unexpectedly reappears or increases in strength.

The problems of protective clothing can be seen as thermal, metabolic and performance issues. By creating a barrier between the wearer and the environment, clothing interferes with the process of thermoregulation, particularly reducing dry heat loss and sweat evaporation. The main metabolic effects come from the added weight of the clothing and the 'hobbling effect' due to garment bulk and stiffness, both of which increase metabolic cost so the worker has to expend more energy when carrying out tasks. Loss of freedom of movement and range of motion due to PPC can also lead to reduced performance.

Current heat and cold stress standards consider the balance of heat production and loss but focus on environmental conditions and work rate metabolism. They also assume workers are wearing light, vapour permeable clothing. By failing to consider the metabolic effects of actual protective clothing, the standards underestimate heat production and therefore current standards cannot be accurately applied to workers wearing PPC.

The effects of protective clothing on workers have been studied across a number of industries but studies have mainly concentrated on the thermal effects of clothing, such as heart rate, core temperature responses to different garments and on performance decrements caused by wearing PPC. Very few studies have considered the metabolic effects.

Quantifying the effect of PPC on metabolic load based on the properties of the PPC was one of the objectives of the European Union THERMPROTECT project and the work undertaken for this thesis made up work package 4 of the EU project. The main objectives of the project were to provide data and models which allow the heat and cold stress assessment standards to be updated so that they need no longer exclude specialised protective clothing.

This thesis will consider the effects of protective clothing and its properties on energy consumption during work. The following is a review of the relevant background literature on metabolic rate, protective clothing, work environments, and standards. Previous research on PPC and its effects is also presented and evaluated.

1. Human thermal environment

Humans are homeotherms and require a stable internal (core) temperature. That the internal temperature should be maintained at around 37 °C dictates that there is a heat balance between the body and its environment. So, on average, heat transfer into the body and heat generation within the body must be balanced by heat outputs from the body. This process is not a steady state but a dynamic balance. The heat balance equation for the human body can be represented in many forms, however all equations involve terms for the heat generation within the body, heat transfer and heat storage.

$$M - W = E + R + C + K + S$$

Heat generation within the body

M metabolic rate of the body

The metabolic rate is the rate at which the body converts chemical energy, into mechanical (used to produce work (W)) and thermal energy (remainder that is released as heat (M - W)).

Heat transfer from the body

W energy released outside the body as mechanical work

E evaporation

R radiation

C convection

K conduction

Heat can be transferred from the body to the environment and vice versa via these 4 pathways.

Heat storage

S rate of heat storage

For the body to be in heat balance (constant temperature) the rate of heat storage must be zero. If there is a net heat gain, storage will be positive and body temperature will rise. If there is net heat loss, storage will be negative and body temperature will fall.

There are numerous proposed system models of human thermoregulation. Although they are different in composition, for most practical purposes they are almost identical and can explain human thermoregulatory responses. All models recognise that when the body becomes hot it loses heat by vasodilation of blood vessels and, if required, sweating (sweat is secreted over the body to allow cooling by evaporation). If the body becomes cold then heat is preserved by vasoconstriction of blood vessels and, if necessary, generated by shivering. Shivering can vary in intensity from 'mild' to 'violent' and can greatly increase metabolic heat production (Parsons 2003).

Air temperature, radiant temperature, vapour pressure and air velocity are the four basic environmental variables that affect the human response to thermal environments. Combined with the metabolic heat generated by human activity and the insulation of the clothing worn by a person, they provide the six fundamental factors that define human thermal environments (Parsons 2003).

It can be seen from the previous equation that metabolic rate is an important influence on heat load and in the overall heat balance. There are a number of factors that can influence the metabolic rate (heat load) of the worker, these are illustrated in Figure 1.1.

When a person performs a task, some energy will be used to perform the external work but energy for mechanical work will vary from about zero to no more than 25 % of total metabolic rate, the rest of the energy is given off as heat (Parsons 2003). The amount of heat produced will depend on the number and size of muscle groups involved, (for example, just the arms or a whole body effort) and intensity of the work.

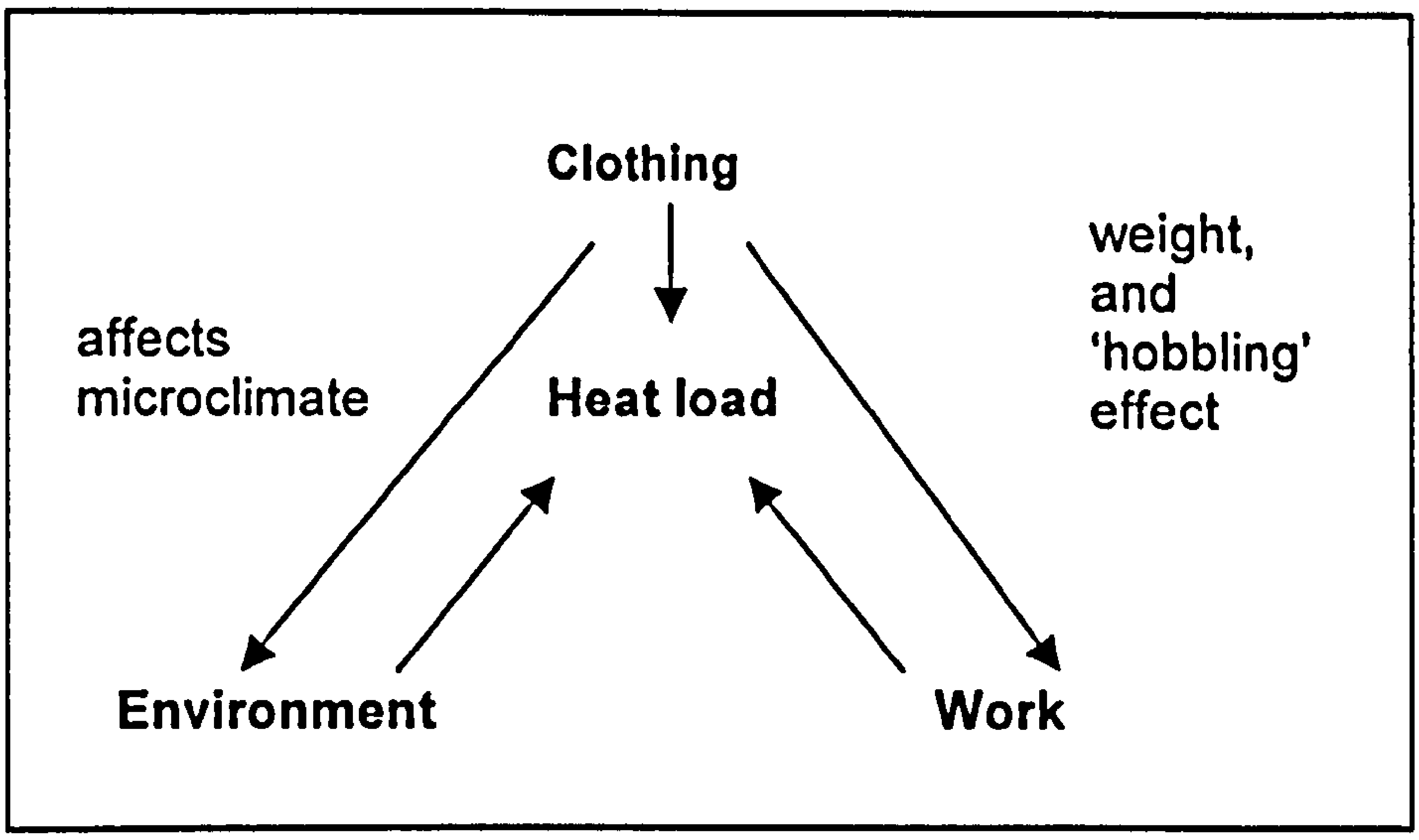


Figure 1.1. Factors affecting metabolic rate (heat load) of worker.

Clothing can influence the heat load as garments covering the body surface affect the microclimate of the body, interfering with the heat transfer pathways of conduction, convection, radiation and evaporation, the avenues through which excess heat is lost. Clothing also indirectly affects the heat load due to its properties. The weight of the clothing can increase the workload and the bulk/stiffness of the garments can have a 'hobbling effect', restricting movements and making them less efficient, and thus harder work.

These effects are detailed in BS 7963 'Ergonomics of the thermal environment - Guide to the assessment of heat strain in workers wearing personal protective equipment' (British Standards 2000), which states that although worn to protect against physical, chemical, biological and thermal hazards, PPC can negatively affect the heat balance of the body:

- metabolic rate can be increased by the weight of the PPC or by the restrictions it imposes on the movement of the wearer,
- convection to and from the skin can be affected by the amount of body covered by PPC and its thermal insulation properties. In general, the greater the proportion of the body covered and the greater the insulation, the less heat is lost by convection,
- evaporation of sweat from the skin is also an effective pathway for cooling the body but the more the body is covered and the greater

the evaporative resistance of the PPC, the less is the heat loss by evaporation,

- radiation to and from the skin can be affected by the coverage of PPC over the body.

The standard also includes a table of typical incremental increases in metabolic rates when selected items of PPC are worn, suggesting these increments should be added to the activity related metabolic rate (British Standards 2000).

In her paper 'Heat stress in protective clothing: Interactions among physical and physiological factors' Nunneley (1989) concludes that "a better understanding is needed of the interactions between the environment, clothing, task and worker to support the development of predictive models which are valid over the entire spectrum of thermal conditions encountered among industrial and military applications". The author goes on to suggest "particularly challenging areas needing improvement include quantification of changes to the metabolic cost of real-world tasks due to clothing, worker characteristics, thermal stress and fatigue".

In summary, the main effects of PPC on the heat balance of the worker are to increase the rate of metabolic heat production and reduce the convective, radiative and evaporative pathways for heat exchange.

2. Metabolic rate and its measurement

The metabolic rate, as a conversion of chemical into mechanical and thermal energy, measures the energetic cost of muscular load and gives a numerical index of activity. Metabolic rate is an important determinant of the comfort or the strain resulting from the exposure to a thermal environment (ISO 2004). Thus an estimate of metabolic heat production in the body is fundamental to the assessment of human thermal environments (Parsons 2003).

2.1 Basic principles

Humans require the substance, adenosine triphosphate (ATP) to supply energy for each cell, for use in membrane transport, chemical reactions and mechanical work. The ATP is generated from ADP (adenosine diphosphate) using the energy produced by combustion of glucose, ingested in food as carbohydrates, fats and proteins, and oxygen, with the release of carbon – dioxide (CO_2) and water. Carbohydrates are converted in the gut and liver to glucose before they reach the cell. Proteins are converted into amino acids and fats into fatty acids, which are then transported to the cell via the bloodstream. Within the cells, a number of enzyme driven reactions take place to produce ATP, which is steadily regenerated by 'burning' carbohydrates, fats and proteins with oxygen. The breakdown of ATP liberates energy, most of which is released as heat. The total energy produced is termed the metabolic rate (Parsons 2003).

2.2 Factors affecting metabolic rate

A number of factors are known to affect metabolic rate;

1. Activity level

   As the body shifts from rest to exercise, the energy needs increase, with the metabolic rate increasing in direct proportion to the increased rate of work (Wilmore and Costill 1999).

2. Environment

Metabolism is raised in the heat due to additional energy required for sweat gland activity and altered circulatory dynamics. Cold environments can also significantly increase energy metabolism during rest and exercise, with fivefold increases reported during extreme cold stress as shivering generates body heat to maintain a stable core temperature. The magnitude of the effect depends largely on body fat content and clothing (McArdle *et al.* 2001).

3. Body temperature

If the temperature of the body is increased the rate of cell chemical reactions increases by around 13 % for each 1 °C rise in temperature. (Parsons 2003).

4. Diet – induced thermogenesis

Food consumption generally increases energy metabolism due to the energy required digesting, absorbing and assimilating food nutrients, with the thermic effect of food generally reaching a maximum within an hour after a meal (McArdle *et al.* 2001).

5. Diurnal fluctuation

Even if other conditions are kept the same, e.g. food intake and environmental temperature, metabolic rate is subject to diurnal fluctuation, with an increase in the morning and a decline during the night (Frisancho 1993).

6. Pregnancy

An added energy cost to weight bearing locomotion, e.g. walking, jogging, stair climbing has been reported during pregnancy, resulting primarily from the additional weight of the foetus transported by the female (McArdle *et al.* 2001).

7. Body mass

Body mass determines the energy expended, particularly in weight bearing exercise like walking and running. The influence of body mass on energy metabolism occurs whether a person gains weight naturally as body fat or as an acute added load such as sports equipment or a weighted vest on the torso (McArdle *et al.* 2001).

8. Body composition and age

Metabolic rate is directly related to fat-free mass, with a greater fat-free mass resulting in a higher metabolic rate, because women tend to have a greater fat mass, they also tend to have lower metabolic rates than men of a similar weight. Metabolic rate tends to decrease with age, generally due to a decrease in fat-free mass (Wilmore and Costill 1999).

9. Stress and hormones

Stress increases the activity of the sympathetic nervous system, which increases metabolism. Thyroxine (from the thyroid gland) and epinephrine (from the adrenal medulla) are also known to increase metabolism (Wilmore and Costill 1999).

10. Drugs

Drugs taken may affect metabolic heat production, for example, antithyroids and hypoglycaemics are known to reduce metabolic heat production (Parsons 2003).

2.3 Measurement of metabolic rate

The different approaches, and levels of accuracy for the measurement of metabolic rate are detailed in ISO 8996 'Ergonomics. Determination of metabolic heat production' (ISO 2004) and summarised in Table 2.1. While measurement of metabolic rate via direct or indirect calorimetry is quite accurate for a specific condition, estimations of metabolic rate are prone to error. The main factors affecting the accuracy of the estimations are:

- Differences in work equipment and work speed
- Differences in work technique and skill
- Gender differences and anthropometric characteristics
- When using level 2, differences between observers and training
- When using level 3, accuracy of relationship between heart rate and oxygen uptake, as other stress factors also influence heart rate
- When using level 4, measurement accuracy (determination of gas volume and oxygen fraction).

The accuracy of the results, but also the costs of the study, increase from level 1 to 4. Measurement at level 4 gives the most accurate values. As far as possible, the most accurate method should be used (ISO 2004).

Table 2.1. Levels for the determination of metabolic rate (ISO 2004).

Level	Method	Accuracy
1. Screening	a)Classification according to occupation b)Classification according to activity	Rough information Very great risk of error
2. Observation	a)Tables of group assessment b)Tables for specific activities	High error risk Accuracy ± 20%
3. Analysis	Heart rate measurement under defined conditions	Medium error risk Accuracy ± 10%
4. Expertise	a)Measurement of oxygen consumption b)Doubly-labelled water technique c)Direct calorimetry	Errors within the limits of the accuracy of the measurement Accuracy ± 5%

At the 'screening' level the methods are easy to use and allow a mean workload for a given occupation or activity, to be estimated. The next level 'observation' details methods which could be used by people with a knowledge of the working conditions but no real training in ergonomics, to characterise an average working situation at a specific time. A procedure is described to record the activities with time and compute the time weighted average metabolic data, using tables of either group assessment or specific activities.

There are many tables and equations for calculating energy expenditure. In their book 'Energy, Work and Leisure', Durnin and Passmore (1967) provide detailed lists of energy expenditure values for various activities, particularly Chapter 4 which lists energy expenditure values (in kcal/min) for occupational activities, see also Spitzer *et al.* (1982) and Ainsworth *et al.* (1993). Givoni and Goldman (1971) using laboratory data and data from the literature on the energy cost of level or grade walking, with or without loads, also produced an empirical equation for the prediction of the metabolic cost of such activities.

The heart rate method described at the 'analysis' level is appropriate for people trained in occupational health and ergonomics of the thermal environment. It involves taking heart rate recordings over a representative period and allows an indirect determination of metabolic rate based on the relationship between oxygen uptake and heart rate which can be determined in the lab or for a specific individual. Finally at the 'expertise' level are the methods to be undertaken by experts to collect very specific measurements, (a) involves measuring oxygen consumption over relatively short periods 10-20 minutes, (b) uses doubly labelled water to characterise average metabolic rate over much longer periods of 1 to 2 weeks, (c) uses direct calorimetry.

For the work to be carried out in this thesis the 3 methods highlighted at the 'expertise' level were considered due to the need for highly accurate measurements. Direct calorimetry is based on the measurement of heat produced as all of the body's metabolic processes ultimately result in heat production. Various heat-measuring devices have been developed to measure heat production in an appropriately insulated calorimeter. However accurate measurements in a calorimeter require considerable time, expense and engineering expertise, so remain inapplicable for most sport, occupational and recreational energy determinations (McArdle *et al.* 2001). The doubly-labelled water technique provides an isotope-based method to estimate energy expenditure but the expense of the doubly-labelled water and spectrometric analysis of the isotopes and the long time constant for this type of measurement make this method unsuitable for comparisons of large numbers of conditions and short work periods (McArdle *et al.* 2001).

The oxygen consumption method is based on indirect calorimetry. As all energy-releasing reactions in the body ultimately depend on oxygen, and since the human body can only store very small amounts, it must be continuously taken up from the atmosphere by respiration. Muscles can work for a short time without being directly provided with oxygen (anaerobic work), but for longer periods of work, oxidative metabolism is the major energy source. Therefore measuring a person's oxygen consumption during physical activities can give an indirect, but accurate estimate of energy expenditure (ISO 2004). The absolute rate of oxygen consumption is typically given in the units litres per minute (l/min) and this can easily be converted to a rate of energy expenditure using the Weir formula as the consumption of 1 litre of oxygen results in the liberation of approximately 5 kcal (20.9 kJ) of energy.

The most common method followed in humans is the open-circuit method, which is based on the collection and analysis of expired air, allowing the changes in oxygen and carbon dioxide percentages to be compared to the inspired ambient air (20.93 % oxygen, 0.03 % carbon dioxide, 70.94 % nitrogen) and thus indirectly reflecting the ongoing process of energy metabolism (McArdle *et al.* 2001). At its simplest this method requires the volume of expired air to be recorded (and the time frame over which it was recorded) and the oxygen and carbon-dioxide content analysed.

Historically, the measurement of oxygen uptake has been restricted to the laboratory or clinical settings due to cumbersome equipment (Wideman *et al.* 1996). Early scientists often employed large canvas or plastic Douglas bags to collect the expired air together with separate Haldane chemical analyses, but the need for faster and more efficient techniques fuelled the development of semi- and fully-automated systems (Macfarlane 2001). Although the Douglas bag method is still considered the gold standard, it has several disadvantages and its own sources of error. No breath-by-breath data can be obtained and the method is also time consuming due to the requirement of sampling and analysis after collection (Carter and Jeukendrup 2002).

Over the last 40 years, a considerable number of automated systems have been developed, with over a dozen commercial manufacturers producing in excess of 20 different automated systems. The quality of modern flow-sensing devices and gas analysers can permit highly valid and reliable measurements of oxygen consumption ($\dot{V}O_2$) to be made, but considerable care must be taken in the maintenance and particularly the calibration of these machines to facilitate acceptable results (Macfarlane 2001). In summary the three main open circuit methods of measuring oxygen consumption and their key details are included in the Table 2.2.

Table 2.2. Specific characteristics of three alternative methods of respiratory gas analysis (adapted from Roecker *et al.* 2005).

Approach	Field of application	Benefits	Drawbacks
Douglas bag	• indirect calorimetry • reference method for steady state conditions	• gold standard • accuracy • robust due to low technical complexity • inexpensiveness • all-purpose method	• low temporal resolution • method is laborious • PVC material of bags permeable to certain gases • analysis of inspired air is not included • difficult handling • additional artificial deadspace due to breathing-valve • additional weight on subjects' head from valve and air tubes
Mixing chamber	• exercise stress testing with regard to maximum criteria • measurement of absolute and stable values in gas exchange and indirect calorimetry	• accuracy • method performed automatically	• volume of mixing chamber and other factors influence measured gas concentrations irregularly • average technical complexity • analysis of inspired air is difficult • high amount of maintenance for some systems • additional artificial deadspace due to breathing-valve • additional weight on

			subjects' head from valve and air tubes
Breath-by-breath	• exercise stress testing with regard to submaximal criteria • analysis of gas exchange kinetics • intra-breath calculations	• high temporal resolution • direct implementation of the mass balance equation by measurement of inspired air • low additional weight on subjects' head	• interpretation often equivocal due to breath-by-breath variability and artefacts • depends on sophisticated computer algorithms

For the determination of metabolic effects of clothing, freedom of movement is crucial, and static oxygen uptake measurement systems cannot be used. Several ambulatory systems have become available over recent years, of which most are based on breath-by-breath technology.

2.4 Portable breath-by-breath systems

The validity of portable devices for gas exchange measurements has been evaluated by comparisons to Douglas bag measurements, by comparisons to other validated stationary devices, by assessing the reproducibility during repeated measurements and by quantifying the influence of the apparatus' weight during exercise (Meyer *et al.* 2005).

The two systems that are in most widespread use are those from Cosmed and Cortex, whose current models are the K4 b^2 and MetaMax 3B respectively. Accuracy of gas exchange measurements has most often been investigated using determinations from Douglas bags as a criterion measure (Meyer *et al.* 2005). Kawakami *et al.* (1992) found no significant difference in the calculated $\dot{V}O_2$ between the Cosmed K2 system and the Douglas bags when subjects were cycling to exhaustion. They also succeeded in using the Cosmed K2 to measure a variety of activities in the field, including playing soccer and rowing on the water. However, Peel and Utsey (1993) found that oxygen consumption measurements were significantly lower using the K2 system compared with a metabolic measurement cart, the respiratory rate was also lower for measurements made with the metabolic cart. The Cosmed systems use a different formula to calculate $\dot{V}O_2$ as the carbon dioxide content of expired air is not measured. The authors also suggest subjects breathe slower and deeper when using a mouthpiece system (as is common with most metabolic cart and Douglas bag systems) compared to a face mask (as is common with most of the portable systems), they conclude that exercising with the K2 system may facilitate a more natural breathing pattern because subjects are less affected by the gas collection system (Peel and Utsey 1993).

McLaughlin *et al.* (2001) compared a Cosmed system (K4 b^2) to Douglas Bags during cycle ergometry. Although they found no significant differences in $\dot{V}O_2$ at rest and cycling at 250 W, at work rates of 50 to 200 W the K4 b^2 values were significantly higher, although the magnitude of the differences were small. As McLaughlin *et al.* (2001) state the ideal experimental design would use simultaneous expired air collections, but when they tried during a pilot it proved too problematic. Also employing a cycling protocol but using submaximal exercise levels, Hausswirth *et al.* (1997) found no significant differences in $\dot{V}O_2$ between the Cosmed K4 system and a metabolic cart and they concluded that the K4 system was accurate for all oxygen uptake measurements from rest to maximal exercise levels.

Schulz *et al.* (1997) tested an earlier Cortex model, the Cortex X1 and concluded that it accurately measured oxygen uptake and carbon dioxide output, when compared with a standard breath-by-breath system. Using a graded cycle test with subjects exercising to volitional fatigue, the Cortex X1 accurately measured ventilation, even up to 288 l/min with no loss of linearity. They noted the main disadvantage of the Cortex system seemed to be the relatively high weight of the equipment. Similar studies have also been carried out on the Aerosport system (Wideman *et al.* 1996, McLaughlin *et al.* 2001) and Oxycon-Pro system (Rietjens *et al.* 2001, Carter and Jeukendrup 2002).

In their review of the literature on portable devices used for the measurement of gas exchange during exercise Meyer *et al.* (2005) conclude that the results from the validity studies are comparable to those for corresponding stationary systems. The mean differences to Douglas bag measurements are reported to be around 0.1 – 0.2 l/min in $\dot{V}O_2$, reach an acceptable accuracy and are not inferior to metabolic carts (Meyer *et al.* 2005).

The review of Meyer *et al.* (2005) highlights the lack of investigations addressing the reliability of gas exchange measurements from portable devices but they suggest the available evidence indicates that the devices produce sufficiently reproducible results, with no obvious inferiority compared to stationary metabolic carts. However, in contrast to stationary systems an additional factor that needs to be considered in portable devices is the extra weight that has to be carried by the subject (Meyer *et al.* 2005). But with current modern systems weighing as little as 1 kg and improvements in weight distribution, Meyer *et al.* (2005) highlight the superior weight distribution of the Cortex MetaMax 3B which hangs around the athletes' shoulders distributing weight more symmetrically to the front and back, the systems can be tolerated well.

In summary, Meyer *et al.* (2005) conclude that the two most often tested portable devices, the Cortex MetaMax and Cosmed K2/K4b[2] can be regarded as valid and reliable.

3. Personal Protective Clothing (PPC)

3.1 PPC overview

Millions of people world-wide work in environments which expose them to specific risks. In many industrial sectors, military and energy services, hospital environments, human beings are subjected to various types of risks and each setting has its own requirements for protective clothing (Shishoo 2002).

The end-use applications for protective clothing include:

- Chemical splash and vapour protection
- Clean-room apparel
- Cut resistant gloves
- Dirt and dust
- Fire fighting
- Heat and cold protection
- Ballistic protection
- Paint spray
- Puncture-resistant clothing
- Hospital textiles
- Dry chemical handling (Shishoo 2002).

The growing concern regarding health and safety of workers in various industrial sectors has generated regulations and standards, environmental and engineering controls, as well as tremendous research and development in the area of personal protective equipment. All clothing is protective to some extent, it is the degree of protection from a specific hazard that is of major concern (Raheel 1994).

3.2 PPC and thermoregulation

Clothing can protect workers from hazardous or unpleasant environments. The prime physiological objective for protective clothing is to enable the wearer to maintain their body temperature within acceptable limits (Parsons 1988). Successful protective clothing must allow the functions of the body to be maintained and account for its responses as well as protect it from environmental hazards and agents (Parsons 1994). Clothing functions as a resistance to heat and moisture transfer between the skin and environment by acting as a barrier, formed by the clothing materials, the air they enclose and the still air that is bound to its outer surfaces (Havenith 1999). So the clothing provides a microclimate between the body and the external environment and the nude body exists within and responds to this microclimate. To provide for thermal comfort and health, protective clothing should maintain an internal body temperature within acceptable limits and allow skin temperature and skin wettedness to be within comfort limits. That internal body temperature should be relatively constant at 37 - 38°C implies that heat production and any heat transfer into the body must be balanced by heat loss from the body, including that through clothing. The thermoregulatory responses of the body and the heat transfer and vapour permeation properties of the clothing determine the microclimate (Parsons 1994).

As most protective clothing, by definition of its purpose, will be less permeable to heat and vapour than normal work clothing it is obvious that thermal stress is quite likely with these types of garments (Havenith 1999). Impermeable clothing prevents any sweat evaporation and is a potential hazard to the wearer even at moderate environmental temperatures (Nunneley 1989).

It is usually thought that heat strain only occurs in warm or hot conditions. This is incorrect. Any heat generated by working which cannot escape because protective clothing is being worn, is stored in the body, and as a consequence the body temperature rises. Heat strain therefore occurs whenever the body generates more heat than it can lose, even in cold conditions (Crockford 1999). Working in NBC clothing can cause variations in core and skin temperatures even at –10°C (Rissanen and Rintamaki 1994). That said performing work in a warm or hot environment is in general more stressful than in a neutral or cool environment. The physical load of the work, added to the heat exposure, can increase the risk to the worker's health and safety. If protective clothing is worn in such conditions it may have a detrimental effect on the workers ability to lose heat to the environment and lead to intolerable heat strain. Protective clothing causes a downward shift in the temperature level at which heat stress occurs. Military data on soldiers wearing chemical protective garments undertaking medium heavy to heavy work indicate the temperature threshold above which heat stress is observed falls well below 20°C (Havenith 1999).

Firefighters, workers engaged in toxic cleanup, foundry workers, miners and soldiers on the chemical-biological battlefield may all be exposed to uncompensable heat stress. This occurs when working in oppressively hot and/or humid areas, or when working in protective clothing. Uncompensable heat stress exists when the evaporative cooling requirement exceeds the environment's cooling capacity. Under these conditions, individuals are unable to achieve thermal steady state and will continue to store heat until exhaustion occurs (Montain *et al.* 1994). Evaporation of sweat normally provides a powerful physiological cooling mechanism for humans under warm work conditions, but clothing inhibits evaporation by creating a humid microclimate (Nunneley 1989).

3.3 PPC and energy cost

Protective clothing also increases the metabolic cost of performing a task by adding weight and by otherwise restricting movement. The binding or hobbling effect of multilayered clothing adds measurably to work. Clothing can also require added movement to compensate for problems such as restricted visual fields and failure of communication due to a gas mask or loss of manual dexterity due to gloves. The effect of added weight on work load depends in part upon the task, e.g. a heavy suit poses little problem for a stationary worker but presents a severe handicap for a firefighter climbing a ladder or stairwell (Nunneley 1989).

There is a very limited number of papers considering the influence of PPC on metabolic rate / energy expenditure. Studies on the energy expended by the soldier were among the earliest non-clinical investigations in the area of applied physiological research (Goldman 1965) and because of the need to wear protective clothing and still be able to perform tasks effectively much of the research is still military based.

3.4 PPC, task and environment

Nunneley (1988) introduced the 'heat stress triad' arguing that heat stress may result from one or more of three factors; work rate, clothing, environment. The triad can also be applied to effects other than heat stress, such as reduced productivity and comfort, and increased physiological strain (Adams *et al.* 1994).

Montain *et al.* (1994) tried to determine the influence of exercise intensity, protective clothing level and climate on physiological tolerance to uncompensable heat stress. 7 subjects attempted 180 minute treadmill walks at metabolic rates of approximately 425 and 600 W (representing moderate and heavy exercise for soldiers wearing chemical protective clothing) while wearing full or partial protective clothing (US military MOPP 4 and 1 level protection respectively) in both a desert and tropical climate. The study found that full encapsulation of subjects in protective clothing reduced physiological tolerance and partial encapsulation of subjects resulted in a physiological tolerance similar to that reported for unclothed persons. Increasing the metabolic rate from approximately 400 to 600 W when dressed in full clothing did not alter physiological tolerance, with the rectal temperature at exhaustion, 38.5 – 38.7°C when subjects were wearing protective clothing in desert and tropical climates with the same wet bulb globe temperature (WBGT) (Montain *et al.* 1994).

However predicting garment effects on worker performance is difficult because relationships of garment properties and human responses are not well understood. In an expanded model by Adams *et al.* (1994), a systematic approach for studying the effects of PPC properties on various aspects of worker performance is presented with thermal balance being affected by four causal factors; clothing, task requirements, environmental conditions and worker traits.

(i) clothing

It is necessary to identify those garment properties that potentially affect worker performance, from the subcomponents (yarn, seams, openings) to the garment components (fabric, design and fit), and the garment properties (stiffness, weight, insulation and vapour permeability).

(ii) task requirements

It is necessary to identify what movements must be made for each task and the characteristics of the movements. Worker movement also causes clothing to move or change form. Resistance to change in form imposes additional force requirements on the wearer and may compromise movement capability.

(iii) environmental conditions

Environmental conditions often require the use of PPC, but may also affect the wearer's performance directly.

(iv) worker traits

Differences among workers in three characteristics help determine the effects of PPC on performance, these are anthropometry (how well the garment fits), physiology (rate of metabolic heat generation and level of sweating) and motivation (affects the rate and duration of work and the choice of movements involved).

Three of these factors; clothing, task requirements and worker traits also determine changes in garment form and position that accompany movement. The processes of maintaining thermal balance and changing garment form cause immediate effects on movement capability, physiological balance and sensory feedback. These immediate effects may in turn produce the net effects of reduced productivity, increased physiological strain and reduced comfort (Adams *et al.* 1994). It is also known that working in a hot environment creates greater physiological strain than working in a thermoneutral environment and greater strain is also apparent when working in protective clothing than in normal clothing (Smith and Petruzello 1998).

4. Work environment

The previous section established that the human body responds to the microclimate between the skin and the clothing and any risk of heat strain will be as a response to that climate (Parsons 2000). The microclimate is the primary environment that impacts the body and it is altered by humans when adding or removing clothing with different properties. When any material, such as encapsulating protective clothing covers the body the microclimate quickly becomes warmer and more humid than the ambient environment. Therefore a worker can experience heat strain even in a cold environment if he/she is producing a high metabolic heat load and wearing heavy insulative clothing (Bishop *et al.* 2000).

Metabolic heat production is directly proportional to the work demands, so metabolic rate and clothing characteristics may combine with environmental factors to cause heat stress (Bernard and Matheen 1999). High levels of activity with protective clothing should always be regarded as high risk. The ability to vary the pace of the work will provide a major method for reducing thermal strain. However, there will be some jobs with a limited exposure time and hot environment, where protective clothing must be worn and the task completed, which will obviously be high risk (Parsons 2000).

Three possible contributing factors to heat stress were highlighted in the previous section; work rate, environment and clothing. Unacceptable heat stress may be produced by one of these factors or by two or three of them in combination. For example, the rise in core temperature which normally accompanies sustained work is not in itself a threat, but problems develop when environmental conditions and/or clothing prevent dissipation of excess metabolic heat and thus interfere with achievement of a tolerable steady-state condition (Nunneley 1988).

Working in a hot environment such as in a foundry, glass works, mine or in the ceramics industry can put considerable heat stress on workers. The greater risks occur in this country with indoor workers. Generally a comfort zone exists which is the range of environmental conditions in which it is possible to work without undue strain or discomfort. Temperatures of between 16 and 24 °C appear to be acceptable with heavier workloads at the lower end of the temperature range and sedentary tasks at the upper end. But this temperature zone needs adjustment for heavy physical work or work requiring the use of protective equipment (Williams 1993).

The human body compensates well for moderate climatic heat stress, but artificial environments often block or overwhelm physiological defence mechanisms. Examples from industry include combinations of high air temperature and extreme radiant load in smelters, foundries and glassworks or elevated humidities which cause problems in very deep mines (coal and gold), ship engine compartments and textile drying rooms (Nunneley 1988).

MacDougall *et al.* (1974) had subjects treadmill running under three thermal conditions; a condition in which the active hyperthermia induced by the exercise would be similar to that experienced by an individual undergoing heavy exercise in a non-laboratory setting at a "normal" ambient temperature (23±1 °C). A "hyperthermal" condition was induced by infusing a water-perfused suit worn by the subject with hot water to accelerate the rate of active hyperthermia, cold water was then used for the "hypothermal" condition. While treadmill speed was identical under each condition, work tolerance was significantly reduced in the hyperthermal condition and significantly prolonged in the hypothermal. Slight but significant increases in $\dot{V}O_2$ occurred over time under each condition, the greatest increase in $\dot{V}O_2$ occurred in the hyperthermal condition, where it became higher than in the hypothermal condition after only 15 minutes of running. In summary, it is apparent that during exercise where normal heat dissipation mechanism are curtailed, or when heavy exercise under comfortable ambient conditions (where no restrictions are made on heat dissipation mechanisms) is prolonged, a condition of metabolically induced hyperthermia develops, becoming a limiting factor to performance time (MacDougall *et al.* 1974).

Consolazio *et al.* (1963) also had subjects exercise at three levels of physical activity in three different temperatures, and compared metabolic rates. Results indicated that as the environmental temperature increases there was also an increase in metabolic rate when performing a fixed activity. As no significant difference was seen in metabolic rates between temperatures of 21.2 °C and 29.4 °C, the significant threshold must occur in temperatures above 29.5 °C. The authors cite work by Eichna *et al.* (1950) and Christensen (1933) who suggest there is an approximate increase of 11.6 % in the metabolic rate for every 1 °C rise in body temperature.

So working in a hot environment creates greater physiological strain than working in a thermoneutral environment and greater strain is also apparent when working in protective clothing than in normal clothing (Smith and Petruzello 1998).

5. Standards

The heat balance equations are used in a number of standards to assess heat and cold stress for the worker in various climatic conditions. Typically these standards use climatic data (temperature, humidity, radiation, wind), clothing data (insulation and vapour resistance), and data on the work activity (metabolic heat production) to determine the heat/cold stress level. They deal with these factors in a relatively simple way, one insulation value for the clothing ensemble, an estimate for metabolic rate based on the work load and environmental conditions. However, they do not consider any effect the clothing may have on the metabolic heat production of the wearer.

This simple approach reduces the applicability of these standards, e.g. ISO 7933 'Ergonomics of the thermal environment. Analytical determination and interpretation of heat stress using calculation of the predicted heat strain' (ISO 2004) includes a disclaimer "in its present form, this method of assessment is not applicable to cases where special protective clothing is worn". The paradox is that it is these types of clothing, for example that include impermeable protection, that induce the most strain and therefore would benefit most from an accurate standard that could help to determine safe working limits.

Where heat stress may pose a risk to the worker, it must be assessed. Different methods for estimating potential heat stress have been developed including the Wet Bulb Globe Temperature (WBGT) index and the Required Sweat Rate index. However, these methods, covered in International Standards such as ISO 7243 (ISO 1989) and ISO 7933 (ISO 2004), assume that the worker is wearing light, vapour permeable clothing. As most forms of protective clothing (PPC) either have a higher insulative value or are water vapour impermeable, these standards cannot be accurately applied to workers wearing PPC (Hanson 1999). Thus whilst the method should apply to protective clothing and PPC use, further work is needed to provide guidance. As the WBGT index provides most weight to the natural wet bulb value, it is considered a representation of the response of a sweating worker in saturated clothing with free evaporation to the environment, therefore when impermeable clothing is worn it is debatable whether the WBGT index is appropriate (Parsons 1999). As many researchers have recognised that clothing plays an important role in heat stress, some adjustments and correction factors to the WBGT have been put forward for when different types of clothing are worn (Hanson 1999, Bernard *et al.* 2005).

All the heat and cold stress standards that have metabolic rate as an input parameter refer to ISO 8996 'Ergonomics. Determination of metabolic heat production' (ISO 2004) for detailed guidance on how to measure or estimate metabolic rate. However no reference is made to the effects of PPC on metabolic rate in ISO 8996. Furthermore, little information is provided concerning the insulative characteristics or moisture permeability of items of PPC in ISO 9920 'Ergonomics of the thermal environment. Estimation of the thermal insulation and evaporative resistance of a clothing ensemble' (ISO 1995) (Hanson 1999).

A working group from BSI identified a need to develop a British Standard which would allow interpretation of the existing standards for workers wearing PPC. Hanson and Graveling (1999) from the Institute of Occupational Medicine (Edinburgh) conducted the research comprising a literature review, discussions with experts, a questionnaire survey and consideration of reported physiological data, and produced a report "Development of a draft British Standard; The assessment of heat strain for workers wearing personal protective equipment".

The authors highlighted a number of studies which had considered the effects of PPC on metabolic heat production rate. But they also state that studies of the metabolic cost of clothing interpreted from heart rate data are difficult to interpret because heart rate is an indirect measure of metabolic heat production and it is very difficult to differentiate between heart rate increases attributable to increased metabolic heat production from clothing and increases due to thermal stress. Even where oxygen consumption data is available, the observed increase in metabolic cost may only be partly associated with the energy cost of the PPC (Hanson and Graveling 1999).

Based on the available literature, Hanson and Graveling (1999) produced a table of various forms of PPC and the magnitude of their effect on metabolic heat production, with values for individual items of PPC (where more than one item is worn, values should be added together), but the table is limited. They conclude that the effect of PPC on metabolic heat production rate will vary with the activity, but as the metabolic heat production rate due to the activity increases, the effect of the PPC will also increase. They suggest that ideally a series of percentage based corrections would be utilised to relate the metabolic cost of PPC to the metabolic heat production rate of the activity. But the data available to them was not considered sufficient to allow these to be compiled.

6. Previous research on PPC

A detailed review of the literature highlighted a significant lack of consideration of the effects of PPC on energy cost and metabolic rate. The existing papers focus particularly on the thermal effects of wearing PPC and comparisons of different garment designs / ensembles and are dominated by work on firefighting and Nuclear, Biological and Chemical (NBC) protective clothing.

6.1 Specific effects of PPC on energy cost

Teitlebaum and Goldman (1972) investigated the possible increased energy cost with multiple clothing layers. They used 8 subjects walking on a treadmill at 5.6 and 8.0 km/hr either wearing an additional 5 layers of arctic clothing over their standard fatigues or carrying the 11.2 kg equivalent weight of the five layers as a lead-filled belt. For every subject the energy cost at a given speed was always higher with the clothing than the weight belt. In conclusion, the authors suggest the significant increase on average of approximately 16 % in the metabolic cost of working in the clothing compared to the belt can most probably be attributed to 'friction drag' between the layers and/or a 'hobbling effect' of the clothing.

So during walking, multilayered clothing ensembles have been reported to increase oxygen uptake (VO_2), equivalent to metabolic rate, by an amount significantly in excess of that which can be accounted for by the increases in the clothed weight of the subjects. A study by Duggan (1988) investigated the effect of protective clothing ensembles (chemical agent and cold weather) on the energy cost of a bench stepping task. Using a step height of 0.305m and rate of 20 steps/min, subjects performed the task in military combat clothing and with long underwear, cold weather quilted thermal jackets/trousers and chemical agent protection as extra layers. To prevent subjects from overheating the task was performed at a controlled ambient temperature of 10 °C and was limited to 6 minutes duration. When corrected for clothing weight, $\dot{V}O_2$ was greater by an average of 9 %. The author also concludes that when protective clothing ensembles are worn, the increased energy cost of physical performance will reduce the time to the onset of fatigue and because of the increased metabolic heat production, could exacerbate problems of heat dissipation and thus increase the risk of overheating (Duggan 1988).

6.2 Firefighter PPC

The effects of work in heavy, impermeable clothing has been illustrated well by studies on men wearing firefighter outfits under mild and hot conditions (Nunneley 1989). Many studies have been conducted in the laboratory setting; Duncan *et al.* (1979), Skoldstrom (1987), Faff and Tutak (1989), Ilmarinen *et al.* (1994) and Smith *et al.* (1994). The effects of different garments, conditions and tasks have also been studied in the field; Romet and Frim (1987) used a training facility and Ilmarinen and Makinen (1992) a flashover facility with small burning houses. Smith *et al.* (1997) and Smith and Petruzello (1998) used fire houses whilst Budd (2001) looked at suppression of experimental bush fires. Shipboard fire fighting was also simulated in the studies of Bennett *et al.* (1995) and Bilzon *et al.* (2001).

Studies in the laboratory have tended to look at performance in cycling and walking exercises. The most common protocol is walking at a set speed and gradient over a specified time period with and without the fire fighting protective clothing (Duncan *et al.* 1979, Skoldstrom 1987, Ilmarinen *et al.* 1994, Smith *et al.* 1994, Baker *et al.* 2000). However maximal exercise tests (Louhevaara *et al.* 1995) and cycling to exhaustion (Gavhed and Holmer 1989) have also been employed by researchers. Simulated fire fighting tasks have been studied, especially in the field settings, Romet and Frim (1987) provided a scenario which required a group of fire-fighters with a truck to respond to an alarm, subjects were classified into 4 activity categories; crew captain, lead hand, secondary help and exterior fire fighting. Smith *et al.* (1997) simulated a ceiling overhaul whilst Smith and

Petruzello (1998) got subjects to complete 3 sets of 4 tasks; dragging a hose, carrying a 5 gallon pump, hoisting a hose and chopping on a block of wood. During shipboard fire fighting simulations Bennett *et al.* (1995) had subjects complete the following objective; to contain and extinguish a Class A material fire, whilst Bilzon *et al.* (2001) used tasks including a drum carry and boundary cooling.

Many of the studies also compared performance in sports kit and a fire fighting clothing ensemble (Duncan *et al.* 1979, Skoldstrom 1987, Baker *et al.* 2000) or between different garments (House 1994, Ilmarinen *et al.* 1994, Smith *et al.* 1994, Smith and Petruzello 1998, Ftaiti *et al.* 2001, Taylor *et al.* 2001, Rossi 2003).

The literature can best be divided into those studies that have looked at

1. Physiological effects of wearing firefighter PPC
2. Comparisons of different firefighter PPC ensembles

The studies have focused on physiological responses (cardiovascular and thermoregulatory) including; heart rate, core temperature, oxygen uptake, skin temperature, ECG, energy expenditure, body mass loss, blood pressure, sweat loss and ratings of perceived exertion.

6.2.1 Physiological effects of wearing firefighter PPC

The physiological strain inherent in fire fighting activities is a result of the combination of physical activity, heavy clothing and/or thermal stress. The physical workload is dependent on the task being done, tools used and protective gear worn (Smith *et al.* 1997). The thermal strain results from the external stress of heat radiating from the fire and the exercise-induced metabolic heat stress that is trapped due to the encapsulation provided by protective clothing (Skoldstrom 1987, Smith *et al.* 1997). It is known that working in a hot environment creates greater physiological strain than working in a thermoneutral environment. Greater cardiovascular and thermal strain is also apparent when working in protective clothing than in normal clothing (Smith and Petruzello 1998).

Modern firefighters' clothing appears to be very effective in fulfilling its primary purpose, that of protecting the firefighter against the direct effects of the severe environments in which they may have to work. But research by Graveling and Hanson (2000) has, however, demonstrated and quantified the negative aspect of this protection, that the clothing itself increases the physiological cost of working whilst wearing it, and that the clothing can create a risk of heat stress through its considerable disruption of the thermoregulatory pathways. In summary, during the laboratory trials, standard firefighter clothing typically increased physiological cost (oxygen consumption) by 15 % over control sessions (Graveling and Hanson 2000).

UK fire fighting clothing weighs approximately 10 kg (excluding breathing apparatus) which inevitably incurs an energy cost (Baker *et al.* 2000). According to previous findings and the reports of other authors, protective equipment weighing 15-26 kg causes a rise in energy cost of walking or climbing by about 20 % or more (Faff and Tutak 1989). Ftaiti *et al.* (1989) state that the weight of protective clothing and equipment can increase energy demands by as much as 40 %. Also Goldman (1990) quotes a weight of 10.9 kg for the full fire fighting ensemble plus 10.5 kg for the self-contained breathing apparatus (SCBA) and asserts that the hobbling effect of arm and leg movement in such thick, heavy clothing can increase the working heat production by about 30 % over that of the same task done wearing only a station uniform. Previous research has found that the energy cost of moderate work while wearing the fire fighting clothing and protective equipment was elevated 33 % over that required to perform the same work without protective clothing and equipment (Davis *et al.* 1982). Bilzon *et al.* (2001) note the increase in energy cost of moderate intensity work of 33 % and explain that the high metabolic demand of fire fighting is a result of intrinsic metabolic and physical demands of various tasks combined with additional extrinsic stressors (clothing, equipment and environment).

In the field of fire fighting, the insulation of the clothing is so high that storage of heat can often not be avoided, with the weight of the equipment representing an additional load for the fire-fighter. The structure of the clothing and number of textile layers also increase the energy consumption and thus the required heat loss (Rossi 2003).

Duncan *et al.* (1979) reported significant ($p<0.01$) increases in oxygen uptake when subjects wore a turnout uniform compared to wearing a blue uniform (lightweight shirt and trousers) walking at 4 km/hr, 10 % gradient on a treadmill. After 15 minutes of exercise, mean oxygen uptake values were 7.13 ± 0.41 and 10.47 ± 0.75 ml/kg/min for the blue and turnout uniform respectively. The authors concluded that the additional weight and insulating properties of the turnout clothing imposed significant stress on firefighters especially while working in the heat. Skoldstrom (1987) also compared treadmill walking, 60 minutes at 3.5 km/hr, with and without turnout gear (standard 'blue' uniform of shirt and cotton trousers plus thick sweater, impermeable trousers, coat, boots, helmet and breathing apparatus) in a 15°C and 45°C climate. Oxygen uptake without turnout gear and breathing apparatus was 0.8 l/min, with the influence and weight of the additional clothing and equipment significantly increasing oxygen uptake by 0.4 l/min to 1.2 l/min. There was no significant effect on oxygen uptake when increasing the ambient temperature from 15°C to 45°C. Heart rate and rate of perceived exertion were significantly affected by both temperature ($p<0.001$) and equipment ($p<0.001$). Although the lack of a significant effect with increasing temperature is perhaps surprising it should be noted that absolute workloads were very low in this study.

Baker *et al.* (2000) compared the cardiorespiratory and thermal responses of two intensities (5 km/hr and 7 km/hr) of treadmill exercise over brief periods (12 minutes). Sports kit composed one ensemble (SE); shorts, vest and sports footwear and the firefighter kit (FE) of helmet, flash hood, GoreTex tunic and breeches, cotton underwear, gloves and leather boots the other. When walking at 7km/hr, heart rate (171 bpm and 146 bpm) and

$\dot{V}O_2$ (39.9 ml/kg/min and 36.1 ml/kg/min) were significantly ($p<0.05$) higher when wearing the FE compared to the SE respectively. The results of this study showed that walking at a moderate intensity in FE in a temperate environment (21 °C, 55 % RH) can involve up to 75 % of maximal oxygen consumption.

Faff and Tutak (1989) used a different work mode (cycle ergometry) but two clothing conditions (standard uniform (SU) and fire fighting protective clothing (FE)) The FE was aluminised, fire-resistant, impermeable clothing with self contained breathing apparatus. Subjects were instructed to cycle with a work load of 1.5 W/kg until a point of subjective fatigue and overheating that would cause them to stop working during real fire fighting. Heart rate recorded at the end of the exercise was independent of clothing but the working time until fatigue was much shorter for the FE trials, approx 15 minutes compared to the SU, approx 27 minutes (durations read off graph in the paper). Throughout the trial FE heart rate was higher than SU, the difference ranging from 5–19 bpm, the heart rate rose progressively throughout the exercise, but the increase in the SU condition was consistently smaller than in the FE (Faff and Tutak 1989).

6.2.2 Comparisons of different firefighter PPC ensembles

Smith and Petruzello (1998) compared different configurations of protective fire fighting gear. On separate days subjects wore (a) the NFPA (National Fire Protection Agency) 1500 (1987) standard configuration and (b) a hip-boot configuration and completed 3 firefighting drills. The NFPA 1500 configuration included bunker pants with low boots compared to ¾ hip boots and full length turnout coat. The NFPA 1500 gear did not perform as well as the hip-boot configuration, on average the subjects took 38 secs, 35 secs and 51 secs longer to complete the tasks in the NFPA gear than in the hip-boot configuration (time to complete trials 5:39, 5:34 and 5:38 minutes respectively). A repeated measures ANOVA for tympanic temperature revealed a significant effect for time ($p<0.001$) and a significant gear x time interaction effect ($p<0.042$) as it rose by 0.9 °C above pre-task levels in the hip-boot configuration and 1.5 °C in the NFPA gear (Smith and Petruzello (1998).

Five jackets were compared by Ftaiti *et al.* (2001), one leather and four textile ones, during treadmill running. In general, exercise in the jackets resulted in a higher tympanic temperature, heart rate and body mass loss compared to a condition in which no jacket was worn, with the magnitude of these changes dependent on the type of jacket. Exercise in the leather jacket resulted in the highest tympanic temperature (2.2 °C increase compared to 0.7 °C increase for no jacket, 1.6 - 1.9 °C for the textile jackets) and heart rate (end of test HR, 161 bpm for no jacket, 176–187 bpm other jackets, highest recorded in leather jacket), which was significantly ($p<0.001$) different from all the other conditions. The textile jackets induced less heart rate and tympanic temperature stress than the leather one and the magnitude of the physiological responses induced by the textile jackets could be correlated to jacket weight.

Ilmarinen *et al.* (1994) found no significant differences in cardiorespiratory or thermal strain during submaximal work in the heat wearing a turnout suit with or without a microporous water barrier. Regardless of the suit worn, heart rate and rectal temperature increased steadily during the work period, up to individual tolerance limits.

While protective clothing is being continually improved and lightened, the requirement for adequate environmental protection is generally contradictory. One option that has been implemented by the New York City Fire Department and is being considered for implementation by the Toronto Fire Service is the replacement of the long pants that are worn under the protective overpants with shorts, tested by McLellan and Selkirk (2004). To the authors knowledge the findings are the first to document the reductions in cardiovascular and thermal strain for firefighters while wearing shorts under their protective overpants during exercise in a warm environment.

It should be noted that differences between suits observed in these studies often represent the combined effects of variations in insulation, vapour resistance, clothing weight and their effect on the metabolic rate.

6.2.3 Summary

The physiological strain experienced by fire-fighters results from several factors a) metabolic heat produced by working muscles, b) heavy insulative protective gear that adds to metabolic work that must be done, c) insulative properties of clothing that trap metabolic heat next to body, d) radiant heat associated with the fire. However firefighters spend a considerable amount of time attending to tasks other than fighting fires, although required to wear the fire fighting ensemble, little attention has been directed at the energy cost and thermoregulatory changes that occur while working in fire kit in a non-fire environment.

6.3 Nuclear Biological Chemical (NBC) clothing

It is well reported that wearing chemical warfare (CW) protective combat clothing (often made up of an encapsulating protective garment, overboots, rubber gloves and gas mask) may protect the wearer but also results in impairment of human performance. Many studies including combined arms exercises, field trials, and laboratory studies have documented the degradation of both individual and unit performance, these have been thoroughly reviewed by Taylor and Orlansky (1993) in their comprehensive overview of the literature. Even when heat stress was not an important factor, the performance of many combat and combat support tasks was degraded when CW clothing was worn. The performance degradation was due to reduced manual dexterity, reduced vision, reduced communication, respiratory stress and psychological stress. The degree to which the combat effectiveness of an individual or a unit will be degraded by wearing CW clothing is a function of a number of variables including;

1. the ambient conditions of the workplace
2. the type and extent of the protective clothing

3. the length of time the protective clothing is worn
4. the level of physical activity
5. the physical conditions of the individuals in the unit
6. the work/rest cycles
7. the training level of the unit (Taylor and Orlansky 1993).

The protective clothing ensemble worn by the US forces, known as the 'Mission Orientated Protective Posture' (MOPP) provides 4 levels of increasing chemical (and some biological) protection ranging from slight (MOPP-I) to complete encapsulation (MOPP-IV). MOPP-IV consists of a chemical protective overgarment (suit), hood, gloves, boots and mask with special filter (Fine 2002). There are two main areas of concern regarding functional efficiency of troops clad in the MOPP-IV configuration; limitations imposed by the climate in which the protective clothing is worn and limitations imposed by the design of the clothing itself. Of necessity, the protective garment must be impenetrable by outside agents, chemical or biological. Thus the wearer is enclosed in an artificial environment that severely limits the evaporation of body sweat and thus reduces the body's ability to maintain normal thermoregulation (Fine 2002).

There are a number of different acronyms and abbreviations for different types and levels of chemical protective garments. Most provide chemical protection and some also protection against nuclear and biological threats. As the descriptor NBC (nuclear, chemical, biological) is probably better known this will be the term used for the protective garments described in this section.

The literature can best be divided into those studies that have looked at

1. Physiological effects of wearing NBC garments
2. Comparisons of different NBC ensembles

The energy cost and metabolic demands of wearing NBC clothing have been considered (Henane *et al.* 1979, Patton *et al.* 1995, Murphy *et al.* 2001), although these parameters are not always measured, with heart rate and core temperature more commonly reported. Implications of wearing NBC clothing in the cold (Rissanen and Rintamaki 1994, Young *et al.* 2000) and the added issues of armoured vehicles (Millard 1994) and fighter jet pilots (Frim *et al.* 1992) with their poor ventilation and confined spaces, can also be found in the literature.

6.3.1 Physiological effects of wearing NBC garments

White *et al.* (1991) examined the physiological and subjective responses when wearing light work clothing with a self contained breathing apparatus (SCBA) or a chemical protective ensemble (NBC) with a self contained breathing apparatus in three different thermal environments (cool, neutral and hot). The results of this investigation demonstrate the interaction of thermal environment and clothing ensemble on the physiological and subjective responses, and the ability to perform low intensity work. While working at a fixed low work rate in the cool environment work performance did not appear to be limited nor did heat stress appear to be a problem in either ensemble. In the neutral environment work performance was not significantly limited wearing the NBC clothing, however the observed increases in heart rate, skin temperature, rectal temperature and subjective ratings suggest the ensemble does cause additional stress to the worker. The shortest total work time was in the hot environment wearing the NBC ensemble (White *et al.* 1991).

Using two work rates, two environmental conditions and three levels of clothing protection, the effects on work tolerance time were also studied by McLellan *et al.* (1993). The various levels of NBC protective clothing exerted a minimal impairment on work times when the metabolic rate of the task was light and the environmental temperature was cool (less than 20°C). As the metabolic rate and/or the environmental temperature increased, work times were progressively reduced while wearing the different levels of protective clothing with the greatest reduction in the full NBC ensemble.

6.3.2 Comparisons of different NBC ensembles

Possible solutions to the problem of heat strain associated with wearing protective clothing include implementing work/rest schedules, using microclimate cooling or designing new protective clothing layers (McLellan *et al.* 1994).

Cadarette *et al.* (2001) evaluated the physiological heat strain from two developmental toxic agent protective systems (Self-Contained Toxic Environment Protective Outfit–STEPO) compared with the standard Toxicological Agent Protective suit (TAP) during exercise-heat stress. STEPO was designed for personal protection in highly toxic, unknown or oxygen deficient environments, it is totally encapsulated and self contained, not relying on filtered air (like the TAP suit). A new generation of STEPO was designed in terms of reduced heat stress, improved load carriage and improved flame resistance, as well as both industrial chemical and chemical warfare agent protection. The study compared 2 STEPO suits, one with a tethered airline and one with a self-contained breathing apparatus. Although the thermal and performance parameters; heat storage, core temperature and endurance time were favourable for the STEPO suits compared to the TAP, the time weighted mean energy costs were higher in the STEPO suits (298 W and 299 W compared to 222 W).

The new generation of toxic chemical protective uniform systems can effectively reduce heat strain and increase work capabilities, because of the micro-climate cooling. It has not yet been determined what cooling system will provide the most favourable ratio of heat removal to equipment weight. All of the improvements to the STEPO systems, which make them a safer alternative to wearing the TAP suit, also come with a significant weight and therefore metabolic burden to the wearer (Cadarette *et al.* 2001).

The findings of an investigation from McLellan (1996) revealed a very significant reduction in heat strain associated with the removal of the combat clothing layer (normally worn under NBC garments) during light intermittent exercise. Therefore, the removal of the combat clothing prior to donning an NBC overgarment, gloves, boots and respirator would be recommended for extended operations in hot environments. The data also showed further reductions in heat strain associated with wearing a new protective NBC-BDU but these additional changes are small in comparison to the effect of removing the combat layer by itself.

6.3.3 Energy cost of NBC clothing

Despite the large body of knowledge on the performance effects of chemical protective clothing, little quantitative information exists about the energy cost and related physiological changes during dynamic exercise under conditions where heat stress is not a significant factor. Wearing standard BDU (battledress uniform), BDU with a M17 protective mask or NBC clothing (chemical protective clothing with a mask, overgarment, gloves and boots) Patton *et al.* (1995) had subjects walk at 5.6km/hr on a treadmill at 3 grades; 0, 5 and 10 %. Laboratory environmental conditions were maintained at 18-22°C and 40-55 % relative humidity to minimise the possible effects of heat on the physiological and perceptual responses to exercise in the NBC clothing (Patton *et al.* 1995). $\dot{V}O_2$ was significantly ($p<0.01$) increased in NBC clothing compared to BDU at all grades. No differences were seen between the BDU and BDU with mask conditions at any level of exercise. Over the range of exercise intensities (approximately 30-60 % $\dot{V}O_{2max}$), $\dot{V}O_2$ increased between 13 and 18 % while wearing NBC clothing. Since the contribution of the mask to this response was slight, the increased energy cost was assumed to be due to the overgarment, overboots and gloves. $\dot{V}O_2$ was corrected for clothing weight but was still greater by 6–11 % across exercise intensities in the NBC clothing suggesting that factors other than clothing weight were responsible for the increase.

The high insulation and low permeability of NBC clothing is an inherent problem that compromises the body's evaporative and convective cooling mechanism. The physical and psychological performance decrements while wearing NBC have also been extensively documented; decreased task performance, decreased work tolerance, increased time for task completion (Murphy *et al.* 2001). The study by Murphy *et al.* (2001) was conducted in a thermoneutral environment where heat stress was not a factor. Energy cost ($\dot{V}O_2$) was measured during the performance of physical tasks, categorised as stationary, intermittent or continuous, whilst wearing BDU or NBC. As the exercise intensity and mobility of the tasks increased so did the physiological impact of wearing NBC, with the difference in the energy cost between NBC and BDU significantly ($p<0.05$) higher in the continuous task category. After normalising the data for clothing weight, approximately 8 -10 % of the additional energy cost was attributed to the hobbling effect and the weight NBC added to the extremities.

Rissanen and Rintamaki (1997) had subjects dressed in an impermeable rubber suit (IP) or a semipermeable activated carbon suit (SP) performing work/rest cycles in an ambient temperature of -10°C. During work they found the oxygen consumption was 13 % higher in the IP ensemble than in the SP ensemble, with $\dot{V}O_2$ 30 % higher in the IP ensemble during rest periods.

6.3.4 Summary

A number of studies have considered the physiological effects of working in NBC ensembles, however few have considered the metabolic implications, with a greater focus on the thermal consequences of the protection.

For the NBC clothing the major contributing factor to the increased heat load and energy cost is probably the encapsulation of the wearer, creating a microenvironment that severely compromises the ability of the body to thermoregulate, particularly through evaporation of sweat. By inhibiting the dissipation of internally produced metabolic heat, NBC garments can be seen to cause heat stress and illness at relatively moderate ambient temperatures.

6.4 Other Personal Protective Clothing

In hot working environments thermal radiation often accompanies high air temperature and in such conditions it is necessary to use protective clothing against radiation. This type of clothing is typically aluminized and therefore greatly disturbs heat dissipation from the human body, resulting in excessive heat strain. In many industrial operations, radiation protective clothing is often used in resting conditions during surveillance tasks like the quality control of molten metals. Marszalek *et al.* (1999) studied the effect of wearing aluminized protective clothing, which when worn at rest in the heat (WBGT 29°C) caused a higher sweat rate and higher subjective ratings of sweating and thermal sensation. The aluminized clothing was impermeable to water vapour, hampering sweat evaporation, the greater sweating in the protective clothing condition represented the failure to dissipate the heat by evaporation due to the clothing barrier.

Due to the asbestos exposure risk, workers in the asbestos removal industry are also advised to wear protective clothing. Respiratory protective devices prevent inhalation of asbestos fibre and protective clothing prevents contamination of personal clothing. Moreover asbestos removal workplaces are characterised by a very high air humidity resulting from covering the floor, ceiling and walls with vinyl sheets and spraying water to reduce the amount of asbestos in the air. To be able to work safely and effectively, Threshold Limit Values (TLV) for work in the heat are widely used. Since these TLV's are applicable to normally clothed workers, TLV's should be adjusted when applied to the asbestos removal workers who wear extra impermeable protective clothing. Although abbreviated guidelines for heat stress exposure have been proposed including characteristics of the clothing, literature advocating their use in the asbestos removal industry is limited (Ohnaka *et al.* 1993).

The study by Ohnaka *et al.* (1993) looked at wearing disposable asbestos removal clothing during work/rest cycles in varying environmental conditions. They reported a five-fold increase in sweat rate in the hot compared to the cool conditions, rectal temperature increased after the first work period in both the hot and hot/cool conditions, and positive heat storage during recovery in the hot condition suggested body temperature was increasing even during recovery. They concluded it is necessary not only to take a rest when working in the heat but also to consider using a countermeasure of passive cooling, for example cool rooms in the workplace.

Heat stress can also be a significant problem for pilots wearing protective clothing during flights, because the extra insulation they provide prevents evaporative heat loss. As heat stress can influence human cognitive activity this might be critical in a flying situation, requiring efficient and error-free performance. Sea King helicopter pilots are obliged to wear survival suits all year round when operating in areas with low sea temperatures, but wearing a survival suit results in higher discomfort ratings and significant rises in skin temperatures and sweat rates (Faerevik and Reinertsen 2003).

Protective clothing can be as simple as waterproof jackets. Australian soldiers may be required to perform prolonged activity in tropical conditions. It is important that soldiers be supplied with wet weather jackets which offer protection while still allowing for heat loss. A study by Malcolm *et al.* (2000) has shown that during physical activity in tropical conditions any design of wet weather garment worn over a standard uniform will impair heat loss and increase physiological stress. Comparing no jacket to a poncho and a ¾ length wet weather jacket, both layers caused increased body temperature and physiological work load with decreased thermal comfort. Measures of oxygen consumption and metabolic rate were significantly higher when wearing the poncho compared to the jacket and when wearing the jacket compared to no jacket. In conclusion wearing any form of wet weather garment in hot, humid conditions restricts heat loss and results in greater body heat storage, it seems when wearing the poncho, the heat trapped between the poncho and the skin, despite being circulated by the pumping action of the arms did not contribute to additional heat loss but rather resulted in increased body heat storage (Malcolm *et al.* 2000).

In summary, protective clothing decisions in many industries are based on the need to reduce the risk of skin contact with chemical or physical hazards. But sometimes over-protection of the skin results in a secondary hazard, heat stress.

6.5 Summary of previous research on PPC

The physiological effects of protective clothing have been well studied. The volume of research reviewed illustrates a focus in the literature on firefighter and NBC garments, with considerably fewer papers on other workers and industries, for example those working in asbestos removal.

It is the thermal effects of the protective clothing that have been emphasized with the most commonly reported physiological parameters: core temperature, heart rate and sweat loss. It is known that wearing protective garments and/or performing in the heat causes greater increases in these parameters, indicating a degree of heat stress. Although some studies have reported energy cost or oxygen consumption, there is limited data on the pure metabolic effects of protective clothing and the data that is available is confined to a narrow range of protective garments, most notably fire fighting and NBC ensembles.

A wider knowledge is required of the metabolic costs of protective clothing worn in other industries, e.g. steel workers, cold store workers, those working in asbestos removal and with industrial kilns, for example in the ceramics industry. This information is crucially important as the heat and cold stress standards currently being used in industry to assess the working environment may be significantly underestimating the heat stress workers are exposed to as they assume light, vapour permeable clothing. More data on the metabolic costs of a wider range of protective garments with different properties will allow a greater understanding of the causes of the extra energy costs. Predicting garment effects on worker performance up to now has been limited because the relationships between garment properties and human responses are not well understood

7. Conclusions

From the literature review the following conclusions can be drawn:

- Information on the effect of PPC on the wearer and the interactions between PPC, wearer and environment is limited.
- There are important side effects to PPC, including added weight of the clothing and reduced mobility due to garment bulk and stiffness, which are not well understood.
- Current heat and cold stress standards assume workers are wearing light, vapour permeable clothing.
- Metabolic rate is the rate at which the body converts chemical energy into mechanical and thermal energy and is an important influence on heat load and in the human heat balance.
- The main effects of PPC on the heat balance are to increase the rate of metabolic heat production and reduce the convective, radiative and evaporative pathways for heat exchange.
- Measuring a person's oxygen consumption during work can give an indirect, but accurate estimate of energy expenditure (metabolic rate).
- Newer portable breath-by-breath analysis systems have been well validated against the gold standard Douglas bag method for measuring oxygen consumption.
- Studies of the effects of PPC on workers have concentrated predominantly on the thermal implications of the clothing, little quantitative information exists about the energy costs.
- Literature on the effects of PPC is dominated by studies on firefighting and NBC garments.
- Clothing weight, a binding or hobbling effect and friction drag between clothing layers have all been put forward by authors in an attempt to try and explain increased energy costs with PPC, but none of these theories have been thoroughly investigated.
- Predicting garment effects on worker performance is difficult because relationships between garment properties and human responses are not well understood.

A number of research questions are raised from the literature,

- How much of an effect does PPC have on metabolic rate?
- Do different garments have greater effects on the wearers metabolic rate?
- Is the effect on metabolic rate the same across a number of activities?
- What is the relationship between garment weight and metabolic rate?
- Does clothing bulk have a 'hobbling' effect, reducing the range of movement for the wearer?
- Can wearing a number of layers increase metabolic rate due to friction between layers?
- Can we predict the metabolic effect of a PPC garment from its properties, for example, weight, stiffness, number of layers?

The aim of the work conducted in this thesis is to quantify the effects of wearing a range of PPC garments on metabolic rate whilst performing different activities. Further work will then consider the properties of the PPC such as weight, bulk, stiffness, number of layers and the scale of their contributions to increases in metabolic rate recorded.

It is important to establish the effects of PPC on metabolic rate as current heat and cold stress standards do not take this into account and so currently cannot accurately be applied to situations in which PPC is worn. It is hoped that the results from this thesis will provide a greater understanding into the interactions between the clothing and the wearer and that the data collected will be used to improve the application of heat and cold stress standards when PPC is worn.

CHAPTER 2

EQUIPMENT AND METHODOLOGY

1. Introduction

This chapter introduces the experimental research methods used to investigate the issues in the thesis. It introduces the selection of the clothing and work modes used and methods for measuring energy consumption and subjective responses. It also describes the experimental protocol and procedures. Finally a pilot study is described in detail.

1.1 Research considerations

The nature of the research requires participants to wear a range of protective clothing garments whilst performing different activities and for their metabolic rate to be measured and compared to their performance in a control suit. The testing environment needs to be cool to minimise any thermal effects on the metabolic rate. In subsequent experiments participants will be required to wear clothing of different weights, layers, materials etc. But there will always be a control to which the test garment can be compared back to in order to study the metabolic rate increase.

1.2 Experimental design considerations

- **clothing :** a range of protective clothing garments that are worn in industrial and military settings, with suitable underwear and footwear. A set of reference clothes to wear in the control condition, for example, cotton tracksuit trousers and sweatshirt with trainers.

- **work modes :** a range of activities that simulate some of the work tasks that would be carried out in industrial and military settings by those wearing protective clothing.

- **measurement of metabolic rate :** a method of measuring metabolic rate accurately whilst participants are completing the work modes.

- **subjective responses :** a set of scales to measure perceived exertion and thermal sensation of participants.

- **experimental area :** an area must be established where the testing will take place. This area must have adequate space for the experimenter and participants and have a thermal environment in which temperature and humidity can be maintained at a steady state.

- **participants :** will be recruited from the student body at Loughborough University. Participants to be healthy (as determined by Health Screen Questionnaire), within a normal height and weight range and have an active lifestyle (not sedentary).

2. Equipment

2.1 Clothing

Due to the desire to test protective clothing ensembles from a range of industries and professions sourcing the garments proved a very time consuming process. Following a market survey and extensive conversations with manufacturers (Gore), representatives in industry (Tempex), military (Ministry of Defence) and fire departments (Leicestershire Fire Service), the garments were eventually sourced. Table 2.1 gives the garments details and the sources from which they were borrowed, donated or bought. Figure 2.1 includes photographs of all the garments.

Table 2.1. Clothing details and sources.

Label (used in tables / graphs)	Ensemble description	Sourced from	Garment details
A Workwear (insulated)	Workwear suit with insulation	donated by WL Gore and Associates GmbH (Germany)	Jacket; Goretex workwear (medium), langjacke ID # 80. Conforms to EN 471, ENV 343, EN 533. Jacket included zip in fleece inner jacket. Trousers; Goretex workwear (extra large), latzhose ID #' 8011796.
B Grey fire	Grey firefighters suit (jacket and trousers)	borrowed from Leics Fire and Rescue Service (garments previously used)	GLOBE firefighters suits (made in the USA). Garment meets NFPA 1971 standard on protective ensemble for structural firefighting.
C Workwear	Workwear suit (jacket and trousers)	donated by WL Gore and Associates GmbH (Germany)	Goretex workwear by Bardusch. Jacket; size 50-52 (1 chest pocket, lower pockets x 2). Trousers (dungaree style) size 50-52, 1 upper leg pocket, 1 lower leg pocket.
D Gold fire	Gold firefighters suit (jacket and trousers) plus gloves	borrowed from Leics Fire and Rescue Service (garments previously used)	Second hand, no details.

E Chemical	Chemical clean up suit (jacket and trousers)	from lab clothing stores	Alpha Solway Chem master chemical protective clothing, conforms to EN 467 : 1995. Jacket; model type CMJC, size medium. Trousers; model type CMTE, size medium.
F ArmyNBC	Army combat gear and NBC protection (jacket and trousers) plus gloves and overboots	borrowed from DLO Caversfield, Ministry of Defence	NBC Protective suit by Remploy Ltd. Jacket; Mk IV DPM smock size 170/100 (height/breast) with hood, 2 chest pockets, I upper arm pocket. Trousers; Mk IV DPM size 180/100 (height/breast) with 2 thigh pockets and woven cotton braces.
G Welding	Welding protection clothing (jacket, apron and gaiters)	bought new from Arco Leicester, 127 Scudamore Rd, Leicester, LE3 1UQ	Jacket; Arco Large 34" Chrome Leather Welders Jacket (1812505) with flame retardant velcro fastening. Apron; Arco 38" x 24" Chrome Leather Split Leg Apron (1813000) with flame retardant velcro. Gaiters; Arco 14" Heat Resistant Leather Gaiter (1813400), chrome leather lined with velcro.
H Coldsuit black	Black coldstore suit (all in one suit) plus gloves	donated by Tempex Industrial Safety Products Ltd. (garment previously worn)	Tempex Protectline Coldstore Mentmore Range coverall rated to -25. 6oz shell, fur collar, knitted cuffs, 2-way zips, knee length side zips, elasticated back.
I Coldsuit green	Green chill suit (jacket and trousers)	donated by Tempex Industrial Safety Products Ltd. (discontinued line)	Tempex Protectline Coldstore Mentmore Range jacket and trousers rated to -25. Jacket; 6oz tear resistant nylon shell, lock over fur collar, knitted cuffs, high rise zip baffle. Trousers; 6oz shell, knee length side zips, adjustable braces, kidney guard.
J Chainsaw	Chainsaw protection clothing (jacket and trousers)	bought new from Arco Leicester, 127 Scudamore Rd, Leicester, LE3 1UQ	Jacket; Oregon Extreme Protective Chainsaw Jacket 111119. Size medium. Restriction to chainsaw cutting, Class O - chain speed 16m/s. Conforms to prEN 381-11. Trousers; Oregon Extreme Chainsaw Type C (protection covering all

			around leg) Wet Weather Trousers p/n 111047. Size large. Restriction to chainsaw cutting, Class 1,chain speed 20m/s. Conforms to EN 381-5.
K ChemBio	Dutch Chem Bio clothing (jacket and trousers)	borrowed from TNO Soesterberg, The Netherlands	No details.
L ArmyVEST	Army combat gear and body armour (vest)	borrowed from DLO Caversfield, Ministry of Defence	Cover combat body armour I/w Mk 1 UN blue (size 180/100, height/chest) to be used with filler combat armour I/w Mk 1. Dashmore Clothing Ltd.
M ArmyH2O	Army combat gear and waterproof jacket	borrowed from DLO Caversfield, Ministry of Defence	Jacket; liner, DPM, MVP size 180/104 (height/chest).
N Mountain rescue	Mountain rescue (jacket and trousers)	donated by WL Gore and Associates GmbH (Germany)	Jacket; Save Pro Life size 48 (hood, side pockets x 2 and chest pockets x 2). Trousers; Save Pro Life size 50, full length side zips and velcro storm flaps.
	Work trousers	bought new from Arco Leicester, 127 Scudamore Rd, Leicester, LE3 1UQ	Work King 9oz Trousers Navy Regular Leg, sizes 44" and 46".
	Sweatshirt	from lab clothing stores	Fruit of the Loom sweatshirt, 70% cotton, 30% polyester
	T-shirt	bought new	Kustom Kit t-shirt, 100% cotton
	Tracksuit trousers	bought new	Originals, 65% polyester, 35% cotton
	Army thermals	borrowed from DLO Caversfield, Ministry of Defence	Top; vest W U/W, chest 92-99cm. Bottoms; drawers winter underwear olive, size 97-108cm
	Army trousers	borrowed from DLO Caversfield, Ministry of Defence	DPM combat lightweight size 85/100/116 (leg/waist/seat) with thigh pockets x 2 and back pocket x 1
	Army Norwegian shirt	borrowed from DLO Caversfield, MOD	Shirt, man's, field, extreme cold weather. Size 100.

Figure 2.1. Photographs of protective garments.

A Workwear (insulated)

B Grey fire

C Workwear

D Gold fire

E Chemical

F ArmyNBC

G Welding

H Coldsuit black

I Coldsuit green

J Chainsaw

Photo not available

K ChemBio

L ArmyVEST

M ArmyH2O

N Mountain rescue

Tracksuit trousers / sweatshirt

Work trousers / t-shirt

Army thermals

Army trousers / Norwegian shirt

As can be seen in Figure 2.1 the garments selected were realistic protective ensembles and served to protect the wearer from a range of hazards. As the functions of the protective garments differed (e.g. protection from fire, cold or chemicals) so did their weight, insulation, material and design. So in selecting garments from such a range of industries, further analysis could be made of the contribution to any measured increase in metabolic cost of garment bulk, weight, stiffness etc.

As it proved very difficult to establish and acquire the exact undergarments and footwear that would be worn with each protective ensemble, it was decided to use a standard package of cotton work trousers and a t-shirt, and army boots (a range of sizes were borrowed from the Load Carriage Lab within the department). The only exception to this was with the army ensembles which were worn with the correct underwear / base layers.

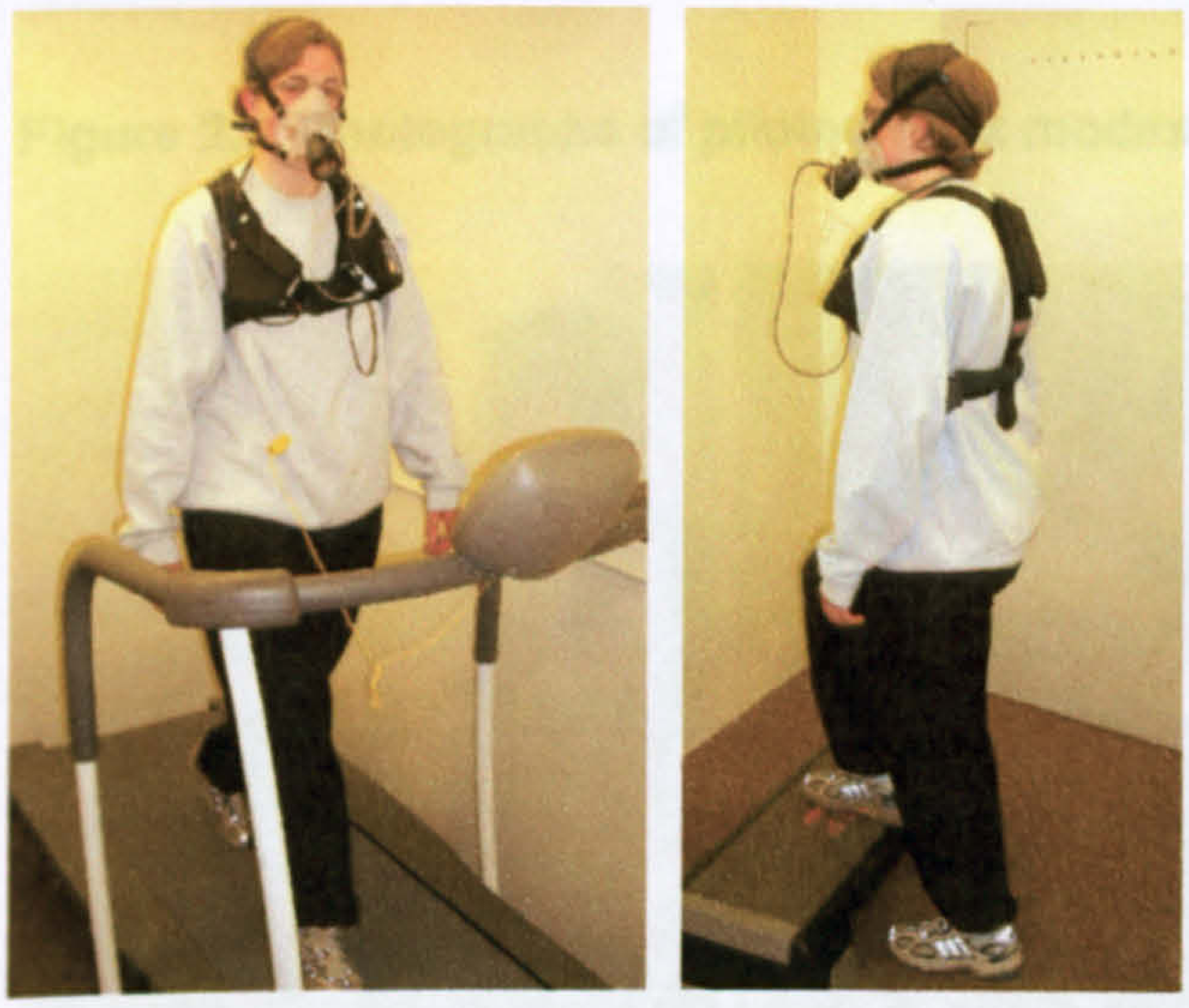
In order to establish if the protective garments had a significant effect on the metabolic rate of the wearer, the results when wearing the protective ensembles would have to be compared to a control condition. The control clothing needed to allow full freedom of movement, be comfortable and comprise of one layer. The options were shorts or tracksuit trousers and a t-shirt or sweatshirt. Shorts and a t-shirt are often used in studies but as the environment would be cooled to minimise thermal effects whilst wearing the protective ensembles, tracksuit trousers and a sweatshirt were worn by the participants to ensure they did not find it too cold and to protect their knees during the obstacle course.

2.2 Work modes

A number of work modes had to be defined that would simulate the sort of work demands made on the protective clothing when worn in the field. Many of the studies reported in the literature used very simple tasks e.g. walking and stepping, or very specific tasks to the clothing e.g. firefighters dragging a dummy, unrolling a hose, climbing a ladder. As garments from such a wide range of industries were to be used in the present work and as typical work in the clothing used required quite diverse tasks, ranging from firefighting, tree cutting and welding, it was difficult to decide on the tasks to be carried out. In order to compare the garments, the tasks would have to be the same for all garments, involve upper and lower body work, carried out in the lab, not in the field, with the speed controlled.

Walking and stepping were to be used to allow comparison of the results to the literature. A number of speeds / stepping rates were piloted based on reports in the literature. 3.5 and 5 km/hr treadmill walking and 25 steps/min on a 20 cm aerobic step were used, photos can be seen in Figure 2.2.

Figure 2.2. Photographs of piloted work modes, walking and stepping.



Finally a work mode that required the upper body was considered. Using an arm ergometer was dismissed as it was felt the action was not representative of normal work movements. The 'ideal' task needed to force participants to use their arms and shoulders but also incorporate some twisting of the trunk in order to stress the clothing. For a pilot study participants were required to move plastic crates containing 5 kg across a room and place them / pick them up from 3 levels (the floor, a table 72.5 cm high and another table 145 cm high), this was rotational and repeated with the speed controlled by a metronome, photographs can be seen in Figure 2.3.

This work mode was developed following the pilot study to include stepping over and crawling under an obstacle. Two height adjustable wooden hurdles were made, they can be seen in Figure 2.4, details are provided in Table 2.2. After piloting different heights it was decided to use a hurdle 55 cm high, which required participants to lift their legs over and another hurdle 100 cm high, which required participants to crawl and bend their upper body under. These heights increased the range of movement required of the participants and forced some more extreme movements e.g. kneeling down, crawling, higher leg lift to step over hurdle.

The work modes were developed further for the later studies with the stepping combined with moving crates and going over and under hurdles, into a continuous obstacle course. Full details are provided in Table 2.3.

Figure 2.3. Photographs of piloted work modes, moving crates.

Figure 2.4. Photographs of piloted work modes, moving over and under hurdles.

It was very important to control the speed of the participants when lifting crates and completing the obstacle course. Some studies have used total time to complete tasks, for example timing how long it took to complete in each clothing ensemble. If this was then compared to the time it took in control clothing, one could look at performance decrements, assuming it would take longer in the heavier, bulkier, more restrictive garments. This method would probably result in greater effects seen between garments. However, this would make comparisons of metabolic rates very difficult and is not very realistic to work situations, except perhaps soldiers and firefighters who may be trying to complete tasks as quickly as possible.

In this set of studies the intensity and speed of moving the crates and completing the obstacle course was controlled by a metronome and verbal counting. This proved quite hard to do without disjointing the movements, as occurred if participants were instructed to step on every beep (from the metronome). Counting was employed to ensure the movements through the course were more fluid but still kept in time. Participants were given a demonstration of the activity with the metronome and counting and then given a chance to practice prior to the first condition. During the obstacle course they also started with moving the crates which followed the rhythm the easiest. The rate of the metronome and timing was also important as participants needed to reach a steady state. Pilot work showed that working them too hard warmed them up and created a cardiovascular drift in heart rate and meant it took longer for them to return to baseline resting conditions. By contrast if the movements were too slow the participants did not increase their $\dot{V}O_2$ significantly and could complete the movements with minimal effort. The rate eventually decided upon was 50 beeps a minute, or 1 beep every 1.2 seconds. The counting was in 3's, so 1 (1.2 secs), 2 (2.4 secs), 3 (3.6 secs), 1, 2, 3, etc. Each obstacle took a 3 count to complete, moving a crate, walking to the steps, moving over the high step, moving over the steps, moving over the hurdle etc. these are shown in full in Table 2.3.

Table 2.2. Details of equipment used in the obstacle course including photographs.

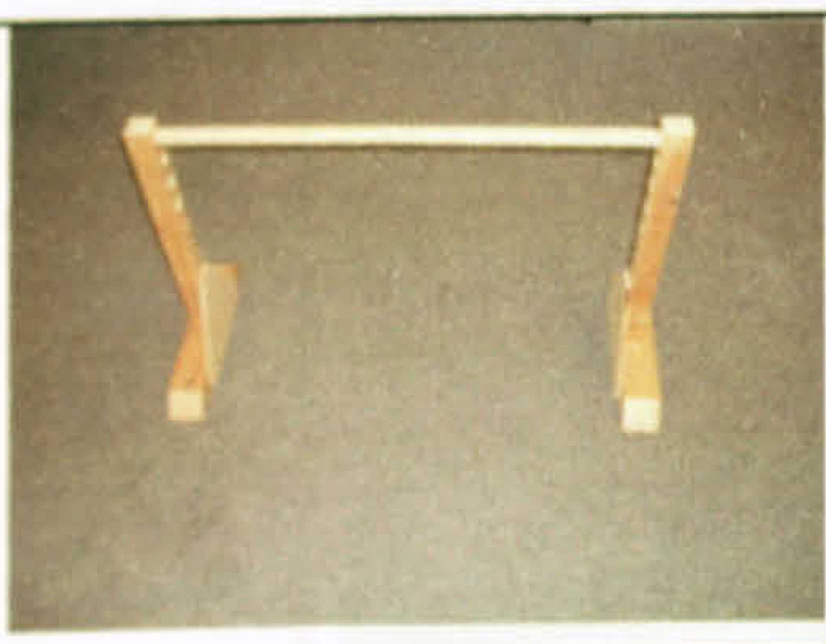
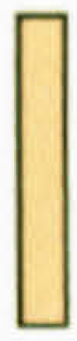
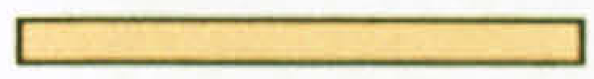
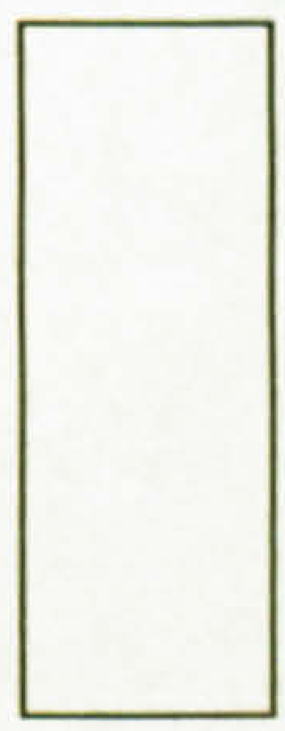
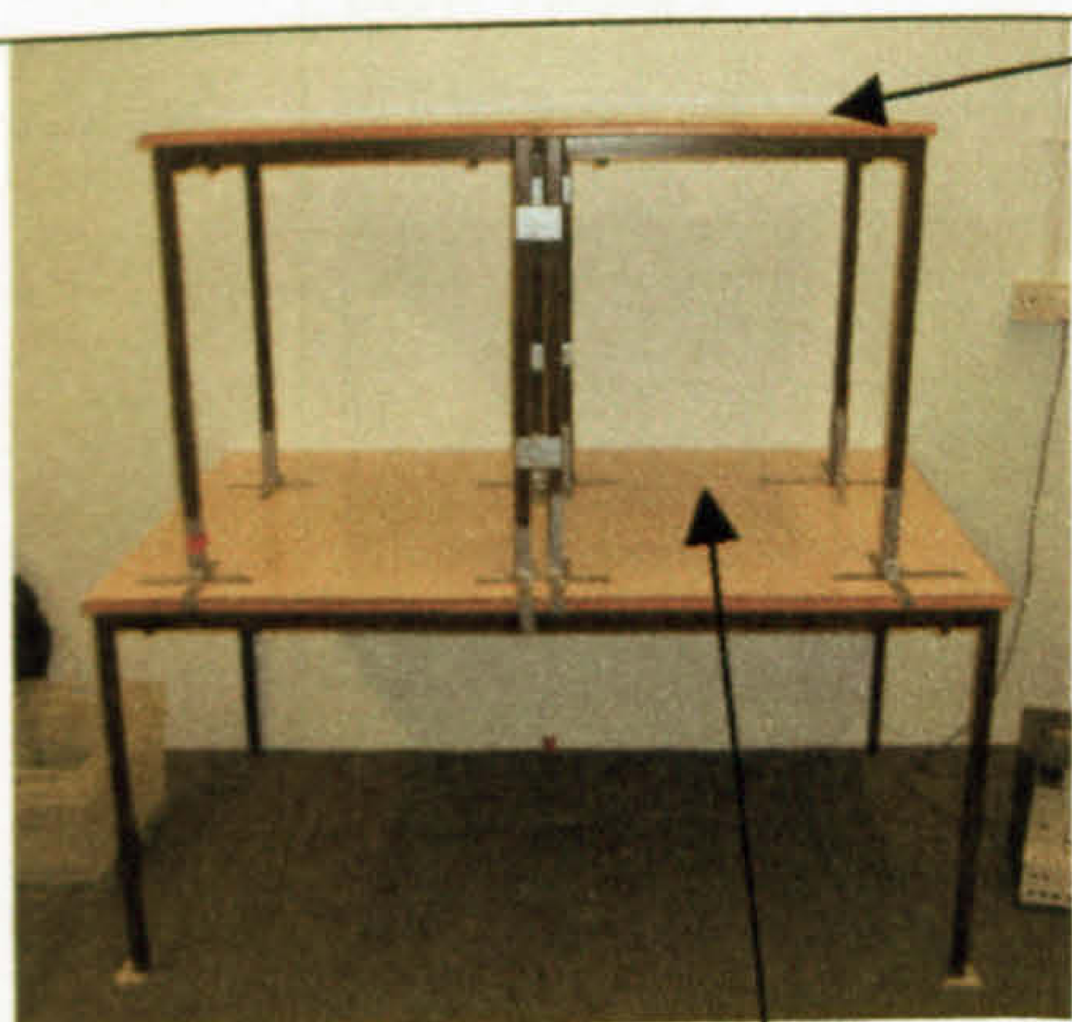
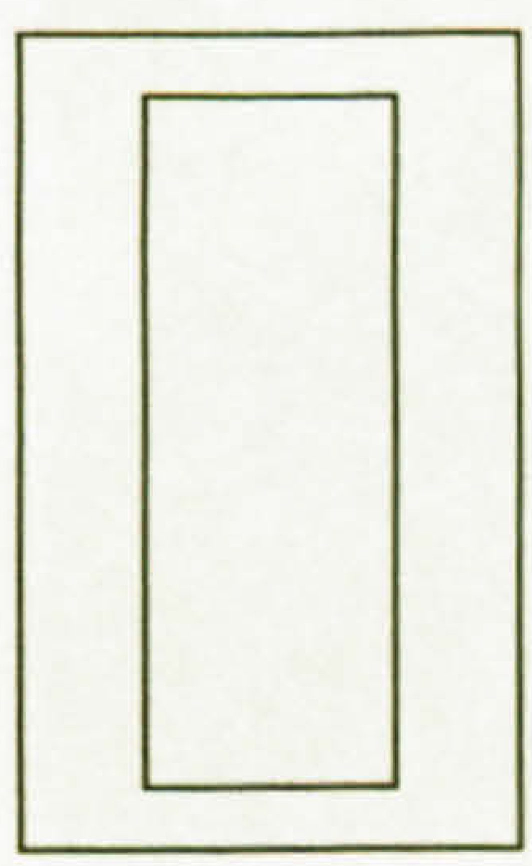
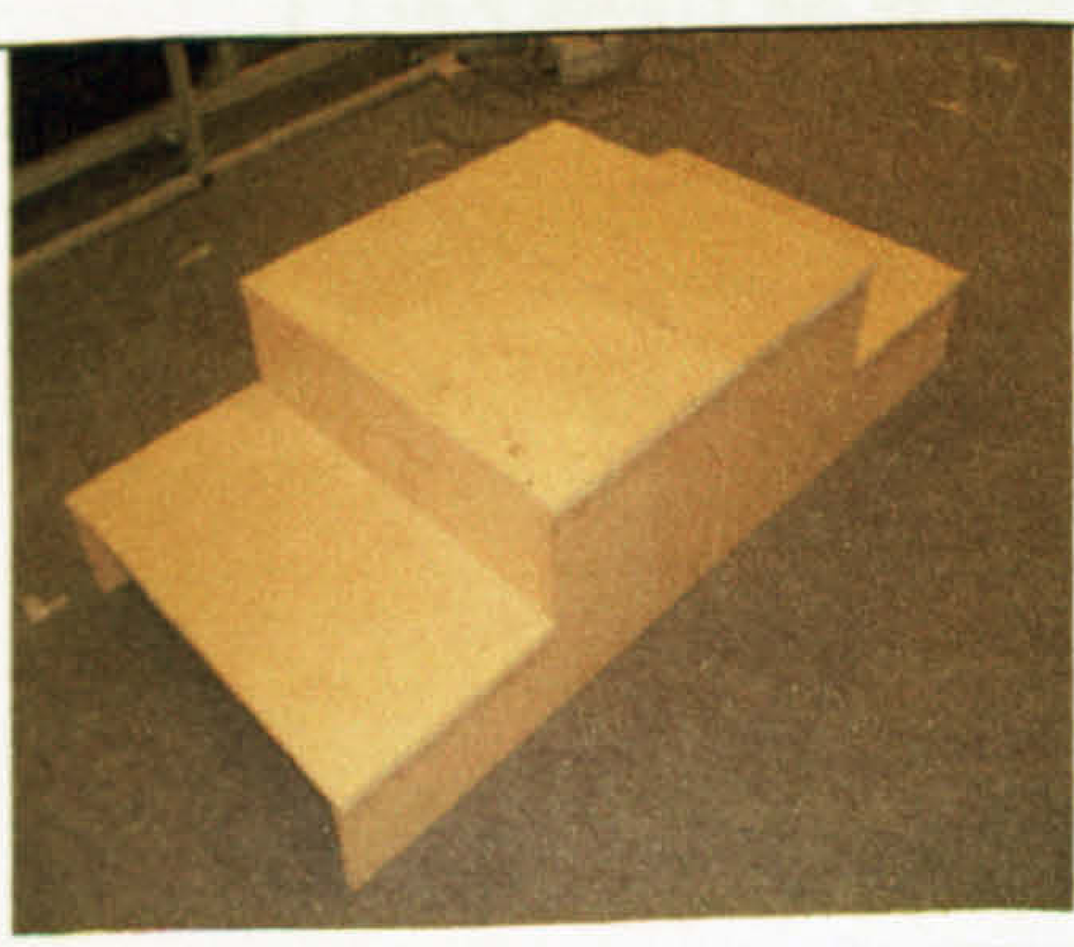
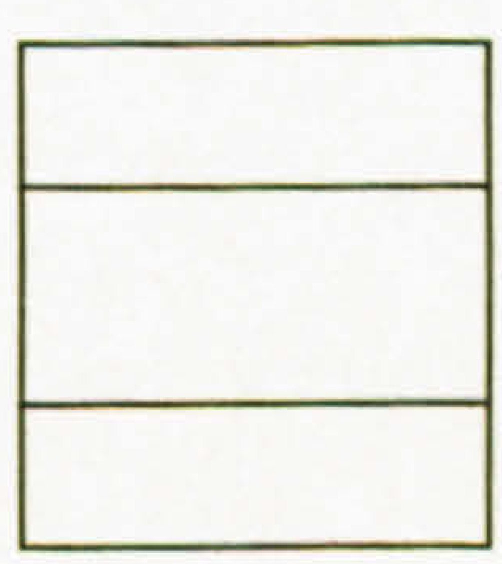
Photographs	Key used in floor plans	Details
		**LOW HURDLE** - wooden hurdle - 55cm high - 90cm long
		**HIGH HURDLE** - wooden hurdle - 100cm high - 100cm long
		**TABLE 2** - wooden table with metal legs - 120cm by 60cm - height of table surface from floor 82.5cm
 **Table 1 (lower part)**	**Table 3 (higher part)** 	**TABLE 1 and 3** - 2 wooden tables with metal legs (smaller one sits on top of larger one) - small table; 120cm by 60cm - large table; 150cm by 90cm - both tables 72cm high
		**STEPS** - two stage wooden step - bottom steps x 2, 20cm high, 80cm wide, 40cm depth - top step x1, 40cm high (20cm higher than bottom step), 80cm wide, 80cm deep

Table 2.3. Full details of final obstacle course including timing in seconds; course description and photographs.

Task	Count (cumulative time) Task description		
A Crates			
	1 (1.2 secs) Pick up Crate 1 from Table 1	2 (2.4 secs) Turn with Crate 1	3 (3.6 secs) Put Crate 1 down on Table 2
			
	1 (4.8 secs) Pick up Crate 2 from Table 1	2 (6 secs) Turn with Crate 2	3 (7.2 secs) Put Crate 2 down on Table 2
			
	1 (8.4 secs) Pick up Crate 1 from Table 2	2 (9.6 secs) Bend down	3 (10.8 secs) Put Crate 1 down on floor

			
	1 (12 secs) Pick up Crate 2 from Table 2	2 (13.2 secs) Bend down	3 (14.4 secs) Put Crate 2 down on floor
			
	1 (15.6 secs) Pick up Crate 1 from floor	2 (16.8 secs) Turn with Crate 1	3 (18 secs) Put Crate 1 down on Table 3
			
	1 (19.2 secs) Pick up Crate 2 from floor	2 (20.4 secs) Turn with Crate 2	3 (21.6 secs) Put Crate 2 down on Table 3

			
	1 (22.8 secs) Pick up Crate 2 from Table 3	2 (24 secs) Lower Crate 2	3 (25.2 secs) Put Crate 2 down on Table 1
			
	1 (26.4 secs) Pick up Crate 1 from Table 3	2 (27.6 secs) Lower Crate 1	3 (28.8 secs) Put Crate 1 down on Table 1
Walk to steps			
	1 (30 secs)	2 (31.2 secs)	3 (32.4 secs)
B Steps			
	1 (33.6 secs) Step up onto high step	2 (34.8 secs) Step off	3 (36 secs) Step round

			
	1 (37.2 secs) Step onto lower step	2 (38.4 secs) Step over middle step	3 (39.6 secs) Step off
C Hurdles			
	1 (40.8 secs) Step over low hurdle	2 (42 secs) Trailing leg over hurdle	3 (43.2 secs) Turn
			
	1 (44.4 secs) Bend under high hurdle	2 (45.6 secs) Stand up	3 (46.8 secs) Touch wall

			
	1 (48 secs) Crawl under high hurdle	2 (49.2 secs)	3 (50.4 secs) Stand up
			
	1 (51.6 secs) Step over low hurdle	2 (52.8 secs) Trailing leg over hurdle	3 (54 secs) Step up to steps
D Steps			
	1 (55.2 secs) Step onto lower step	2 (56.4 secs) Step over middle step	3 (57.6 secs) Step off last step and round

			
	1 (58.8 secs) Step up onto high step	2 (60 secs) Second foot onto high step	3 (61.2 secs) Step off
Walk to crates			
	1 (62.4 secs)	2 (63.6 secs)	3 (64.8 secs)

Details of all the equipment used in the obstacle course is included in Table 2.2. Floor plans of the experimental set-up are included in the experimental chapters as the location of the experiments varied slightly.

2.3 Measuring energy cost

A method for quantifying increased energy usage due to wearing the clothing was required. As has already been discussed in the literature review, changes in energy usage are reflected in heart rate, oxygen consumption and metabolic rate. There are a number of different methods for measuring these variables which vary in the level of detail they provide and accuracy of the results collected. The methods have been discussed in detail in the literature review. In summary, to insure the accuracy, a method of indirect calorimetry had to be considered. Metabolic rate can be calculated using indirect calorimetry, as measuring a person's oxygen consumption and carbon dioxide production can give an indirect but accurate estimate of energy expenditure. The Douglas bag method (collecting expired air in large bags which is sampled for oxygen and carbon-dioxide post collection and then the volume of the bag measured) is still considered the gold standard method. However it can only provide an average value over the collection period and is not very practical when participants are moving around and going through an obstacle course.

A number of automated breath-by-breath systems are now capable of producing highly valid and reliable measurements due to the quality and reduced sizes of gas analysers and modern flow-sensing devices (Macfarlane 2001). There is a growing number of systems on the market and of studies in the literature reporting their reliability. The lab was in a position to purchase one of these newer breath-by-breath systems so research was undertaken to investigate the leading systems. A review of the literature was conducted as well as discussing the pros and cons of a number of systems with other labs verbally and by posting on relevant discussion forums. Important requirements for the system to be purchased included a lightweight unit, as extra weight to be carried may inflate metabolic rate. The system also had to be worn comfortably over clothing and allow the wearer full range of movement. As the work modes would not all be stationary it was preferable that the system need not be tethered to a base unit or computer.

2.4 Cortex MetaMax 3B

A MetaMax 3B (Cortex, Germany) portable breath-by-breath system was purchased. It is a lightweight (600 grams) portable system that is worn in a harness around the shoulders and is available with a telemetry system that can be used in combination with a laptop. Prior to use in the testing it was evaluated against Douglas bags. This was achieved with 3 participants completing two 30 minute tests in the same session (rest/recovery period in between), one in which the Douglas bags were used to collect their expired air and a Polar belt and watch system worn for the heart rate data, and one in which the MetaMax was worn. Participants sat at rest for 6 minutes before completing three 8 minute stages on the treadmill at 3.5, 5 and 7.5 km/hr. These levels were set to represent the intensities of the walking and other activities required for the main testing. For both tests participants wore the MetaMax system in its shoulder harness, with the MetaMax mask used in the MetaMax test session and a mouthpiece and nose-clip used for the Douglas bag test, expired air was collected for the last 4 minutes of each stage. Data was analysed from the final 2 minutes of each stage.

Figure 2.5 shows the $\dot{V}O_2$ results for the 2 systems over the different intensities and Figure 2.6 the data points for heart rate and $\dot{V}O_2$ with regression lines fitted for the 2 systems. The data shown in Figures 2.5 and 2.6 show a very close relationship between the values recorded on the different systems. The data provided by the MetaMax system (recorded using a telemetry system) was accurate and reliable.

Before every test period the MetaMax system was calibrated for pressure (atmospheric pressure reading), volume (using a 3 litre Hans Rudolph gas syringe) and gas concentration (using ambient air and a BOC calibration gas 4.04 % carbon dioxide, 16.13 % oxygen, 20.12 % argon and balanced with nitrogen). The MetaMax 3B is compatible with a Polar heart rate belt which was also worn by participants. Photographs of the MetaMax unit and calibration equipment can be seen in Figure 2.7.

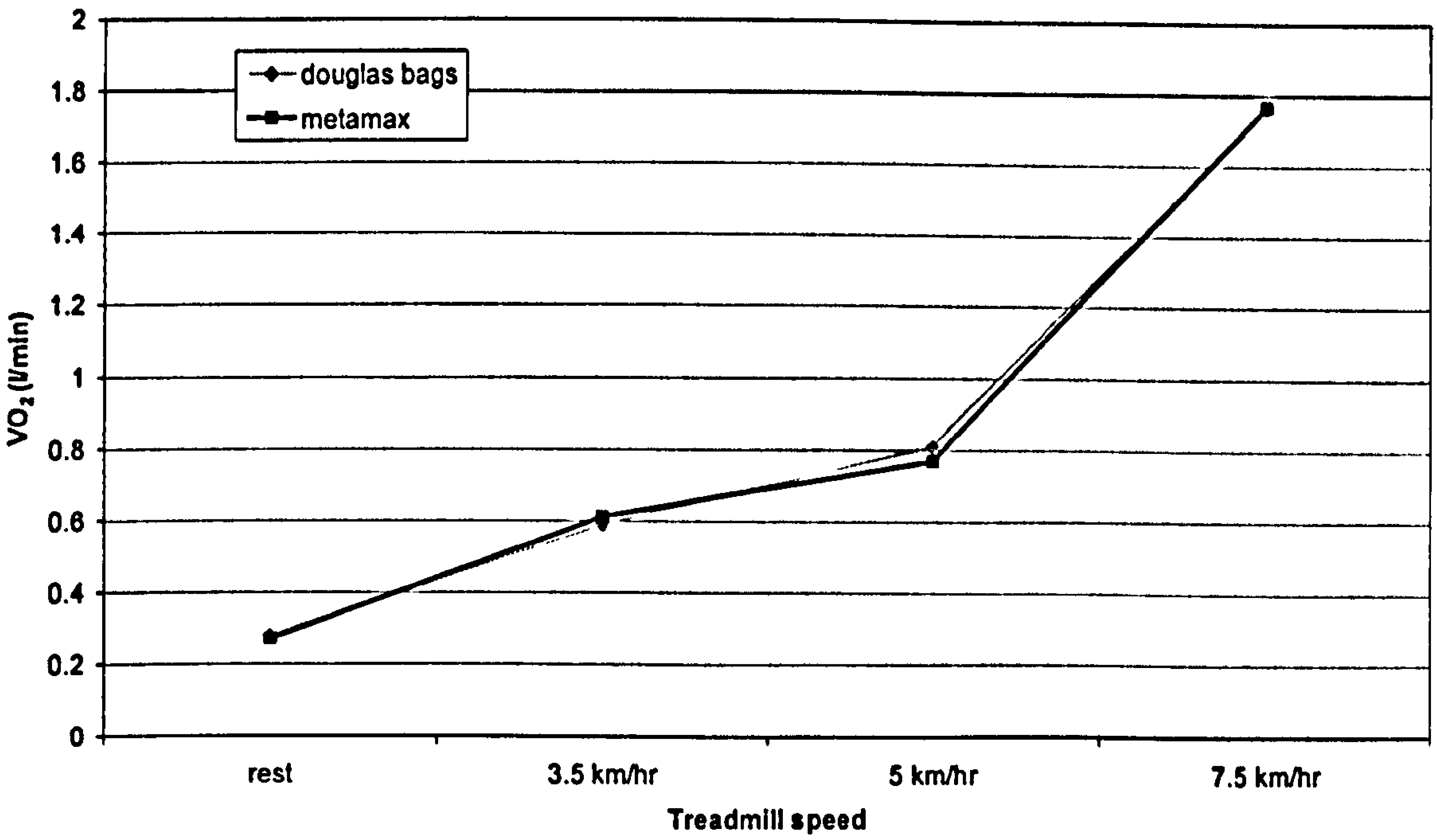


Figure 2.5. Oxygen consumption data collected with Douglas bags and MetaMax at rest and over 3 different treadmill speeds.

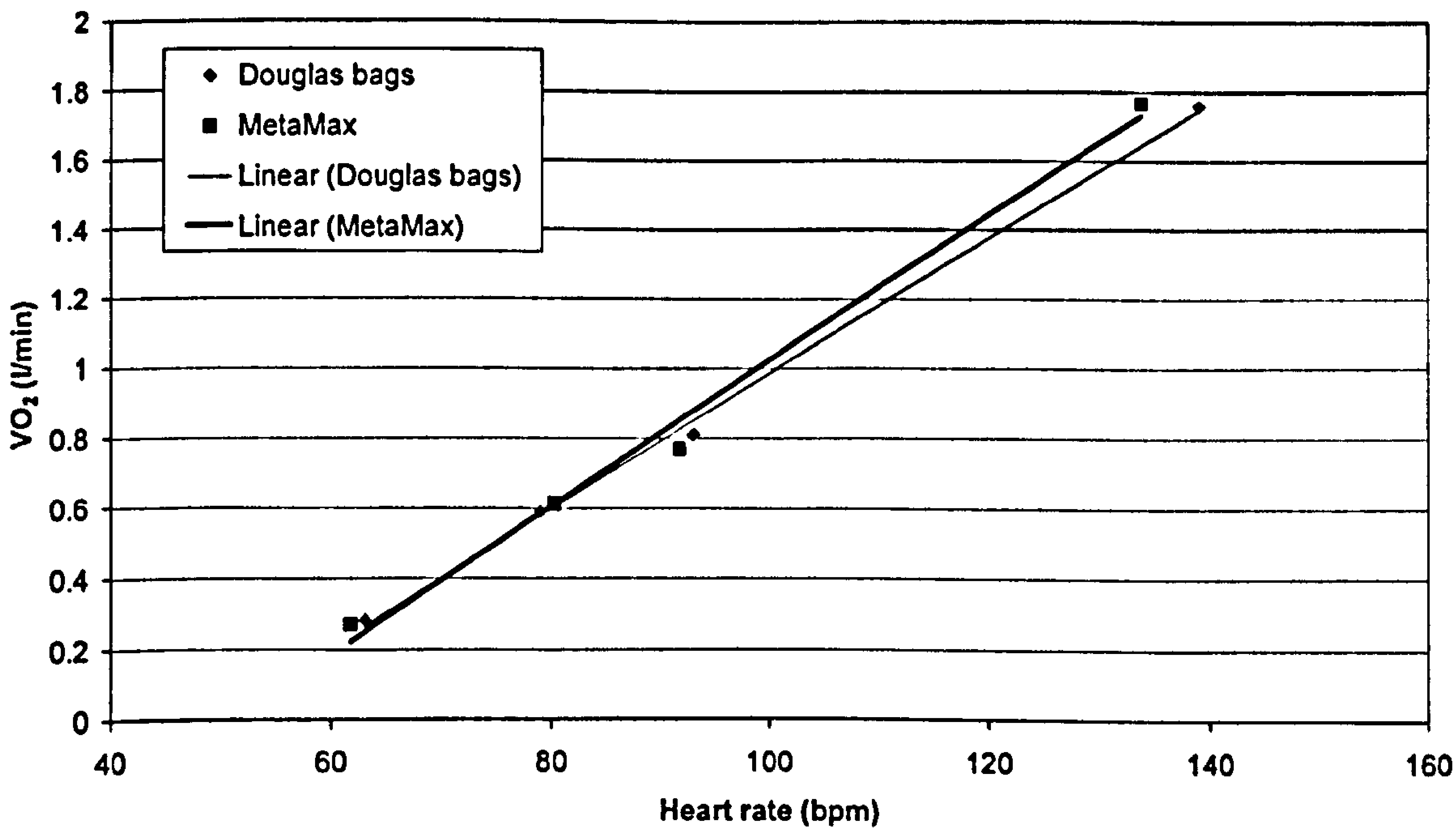
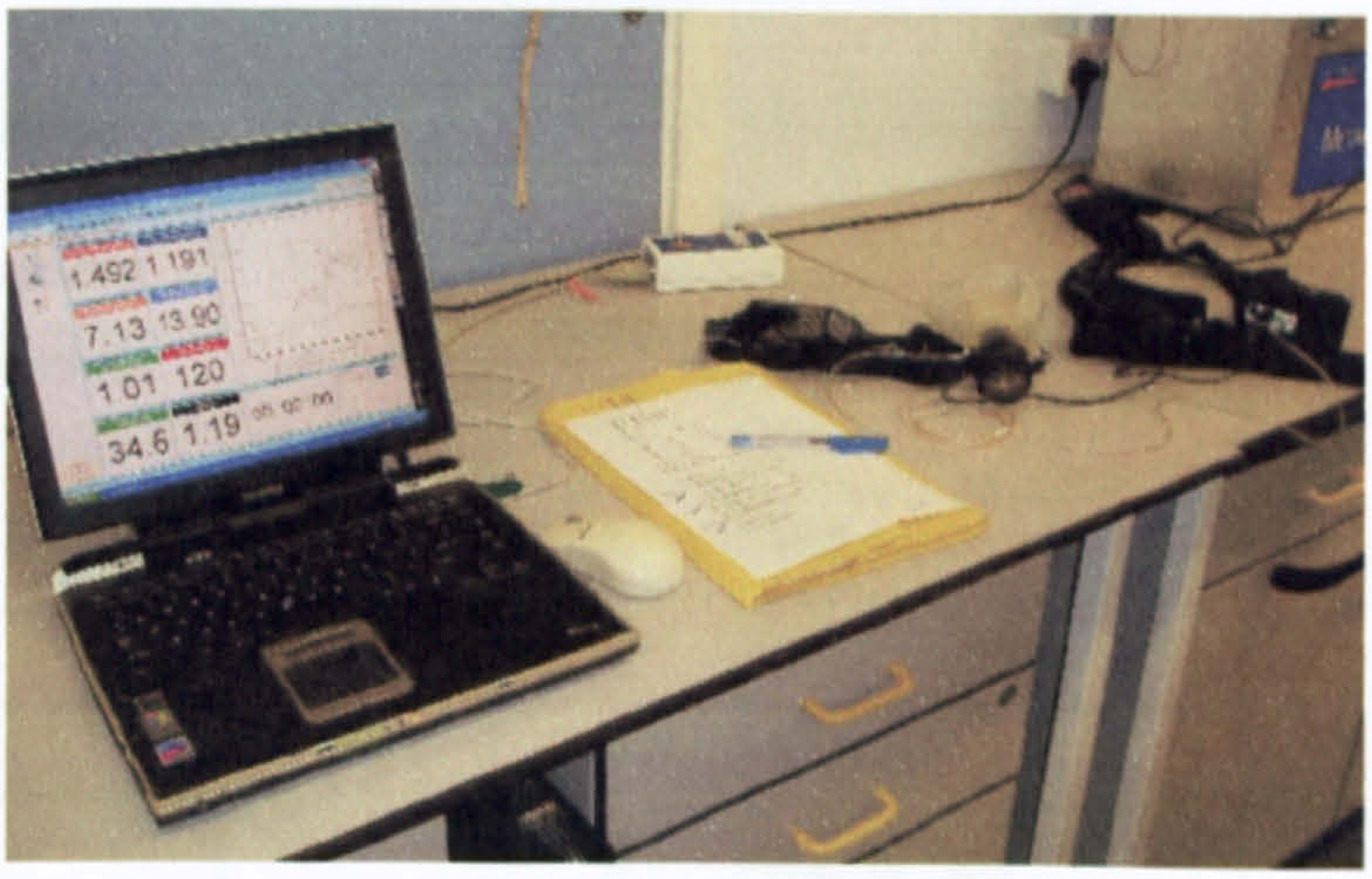


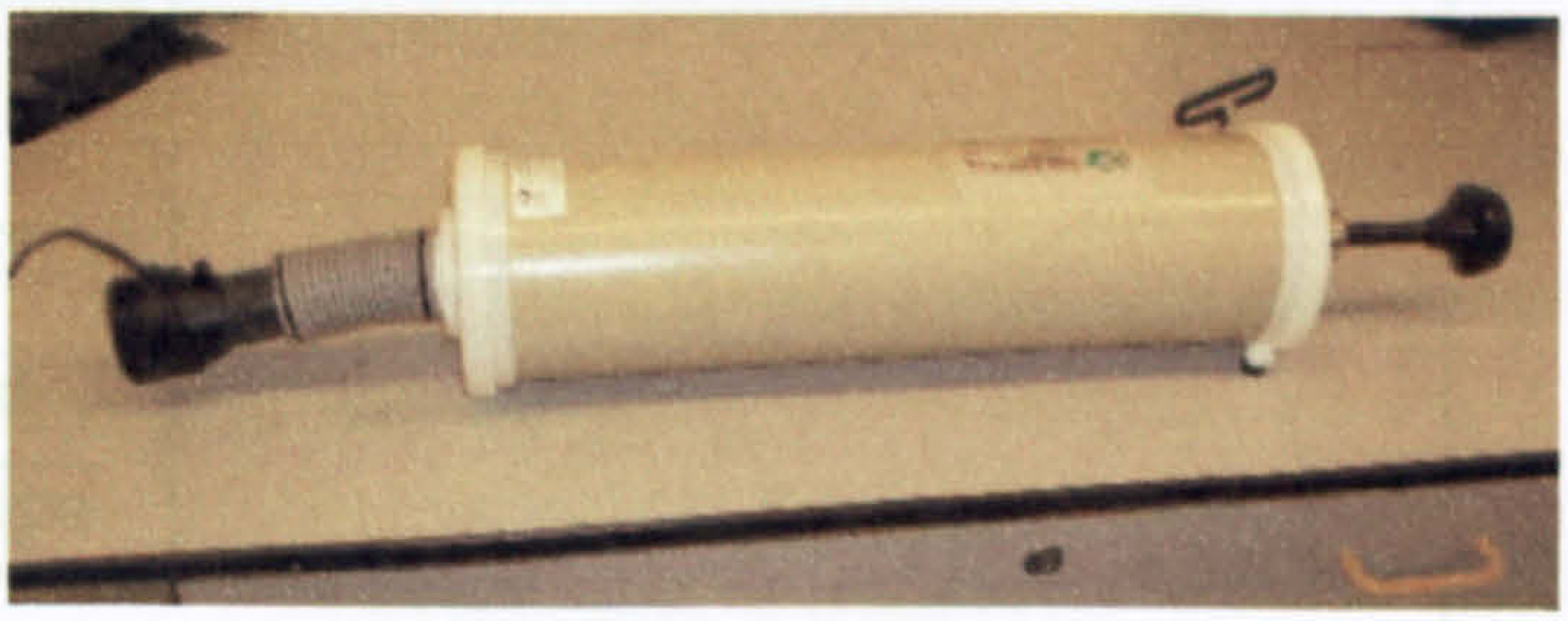
Figure 2.6. Heart rate and oxygen consumption data collected with Douglas bags and MetaMax fitted with regression lines.

a. MetaMax unit



b. MetaMax unit, telemetry box and laptop

c. Gas calibration



d. Volume calibration with gas syringe

Figure 2.7. Photographs of MetaMax and calibration equipment.

2.5 Measuring subjective responses

To complement the objective measures already discussed, subjective responses of 'Rate of Perceived Exertion' (RPE) and 'Thermal Sensation' (TS) were taken. One form of the Borg scale was used for RPE (taken from "Borg's Perceived Exertion and Pain Scales" Human Kinetics, Champaign, IL). The ASHRAE Thermal Sensation scale was also used (taken from "Human Thermal Environments" Parsons 2003). A copy of the scales are included in Table 2.4. Responses were recorded after each work period.

Table 2.4. RPE and TS scales used to measure subjective responses.

RPE scale

Rating	Description
6	no exertion at all
7	extremely light
8	
9	very light
10	
11	light
12	
13	somewhat hard
14	
15	hard (heavy)
16	
17	very hard
18	
19	extremely hard
20	maximal exertion

TS scale

Rating	Description
7	Hot
6	Warm
5	Slightly warm
4	Neutral
3	Slightly cool
2	Cool
1	Cold

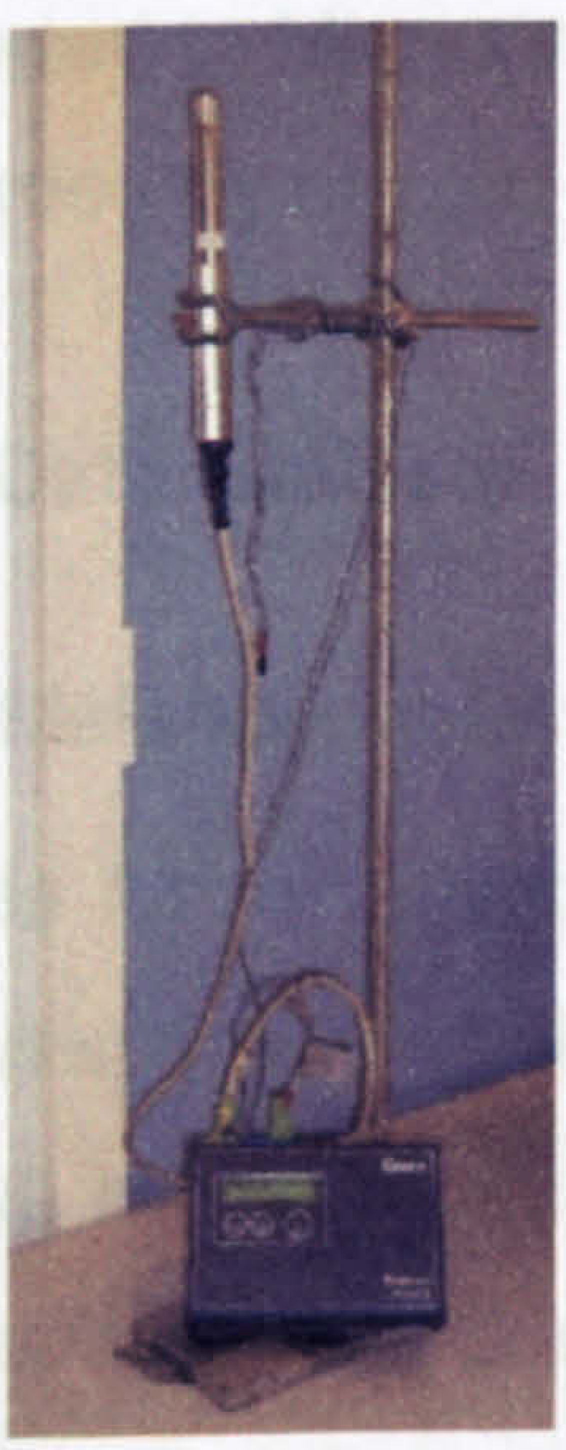


Figure 2.8. Photograph of Vaisala temperature and humidity probe connected to Squirrel logger to record environmental conditions.

2.6 Measuring environmental conditions

Data on the environmental conditions in the room in which the testing took place was measured by Vaisala HMP35DGT humidity and temperature probe which was connected to a 1000 series Squirrel meter/logger (Grant Instruments, Cambridge), shown in Figure 2.8. It was set to log the room temperature and relative humidity every 5 minutes, measured to 2 decimal places.

2.7 Data acquisition

The MetaMax 3B came with its own software Metasoft 2.6 which was installed on a Toshiba Tecra S1 laptop. The Metasoft program allowed participants to be monitored in real time. The MetaMax 3B could be used hardwired to the laptop or in a telemetry mode with a telemetry receiver connected to the laptop. On completion of each session, data could be exported into a Microsoft Excel file for analysis.

The Squirrel data logger was downloaded using Filewise software and then exported to Microsoft Excel files for analysis. The subjective responses were recorded by hand.

2.8 Data analysis

The MetaMax data was exported into Microsoft Excel files for analysis. The values for metabolic rate were derived from the oxygen consumption ($\dot{V}O_2$) and respiratory exchange ratio (RER) raw data using the Weir formula, as shown in Equation 1. The RER is the ratio of the amount of carbon dioxide produced by the body to the amount of oxygen consumed. At rest it ranges from 0.6 to 1.0 depending on what fuels the body is using.

Equation 1.

$$metabolic\ rate\ (kcal/\mathrm{min}) = ((1.1 * RER) + 3.9) * VO_2$$

These metabolic rate values were then converted to watts (W) and watts per metre (W/m^2) squared of body surface area, using the formulae in Equation 2 and 3.

Equation 2.

$$metabolic\ rate\ (watts) = \frac{(met\ rate\ (kcal/\min) * 4200)}{60}$$

Equation 3.

$$metabolic\ rate\ (watts\ /\ m^2) = \frac{met\ rate\ (watts)}{body\ surface\ area\ (m^2)}$$

The percentage increase in metabolic rate for each test garment from the control garment was based on Equation 4 below, with the control metabolic rate being the value measured in the same session as the garment metabolic rate.

Equation 4.

$$\%\ increase = \left[\frac{test\ garment\quad met\ rate}{control\ garment\quad met\ rate} * 100\right] - 100$$

The exported Excel spreadsheet for the Squirrel datalogger gave a value for temperature and humidity every 5 minutes. After each session the ambient conditions for the time period of testing were copied into a summary spreadsheet. At the end of a trial the average temperature and relative humidity was calculated as the average of all the time periods during which testing was carried out.

2.9 Statistical analysis

In order to establish if working in the protective garments significantly increased the metabolic rate above a control condition, single sample t-tests were carried out for each garment. Wilcoxon signed rank tests were carried out on the subjective data. Issues of multiple comparisons were considered and will be discussed.

2.10 Experimental area

Details of the experimental set-up are included in each chapter as the location varied slightly between studies as more room became available in the lab. For all locations the ambient conditions were kept stable and cool with air-conditioning units. The ambient temperature needed to be kept cool to minimise any thermal effects on metabolic rate.

3. Experimental design

A within-subjects design with each participant acting as their own control, is used. It was decided to add a control condition to each session. The alternative would have been to run sessions at the same time of day, on consecutive days. However there is evidence of daily variation in metabolic rate and any differences due to clothing worn might have been lost in daily noise. Having a control in each session increased testing time and number of sessions per participant but provided a greater degree of reliability in the data collected. The order in which the participants completed all of the garments / conditions in each experiment was balanced, full details are given for each experiment in the relevant chapters.

3.1 Procedure

The general health and fitness of each participant was checked when they arrived at the laboratory before each session. The study was explained to them and they were shown the clothing and equipment. A demonstration of the work modes was also provided. They were also familiarised with the subjective scales. They were asked to fill out a Generic Health Screen Questionnaire and sign a Declaration of consent, a copy of which is included in Appendix 1. They were reminded of their right to withdraw from the experiment at any time without having to provide a reason.

They were then provided with the first set of clothing to be tested and given time to dress and put on the heart rate monitor. Following instrumentation with the MetaMax, they sat at rest and data collection began. Once the resting time period had elapsed they began the first work mode. At the end of the work period subjective responses were recorded.

Between conditions the MetaMax was removed and participants had time to rest and get changed for the next condition. The procedure was then repeated for the remaining conditions. At the end of the session, the MetaMax was removed and participants removed the final set of clothing.

4. Safety

4.1 Ethical clearance

In order to obtain ethical clearance for the research, amendments were made to a generic protocol 'Measurement of ventilated gas volumes, oxygen uptake and energy expenditure' that had already been accepted. This was submitted to the Loughborough University Ethical Advisory Committee, the proposal was passed and cleared by the committee in May 2004, reference number G04/P2.

4.2 Health Screen Questionnaire and Informed Consent

Participants completed the 'Generic Health Screen for Study Volunteers' form before undertaking any testing. Participants were also given a comprehensive information sheet on the nature of the experiment, what would be required of them and the exact protocol. They were also given the opportunity to have a look round the laboratory and ask questions before any testing began. They were asked to sign a 'Declaration of consent' form.

4.3 Withdrawal criteria

All parts of the experiment were to be carried out at a sub-maximal intensity with heart rate and oxygen consumption continually monitored through the MetaMax output. Participants were made aware that some of the protective garments would be heavy and working in them they may cause them to get a bit hot and sweaty. The participants were of course reminded of their right to withdraw at anytime without having to give a reason.

5. Pilot study

Extensive preliminary work was carried out to determine work modes, work intensity and duration. These have been detailed thoroughly in this chapter. Time was also spent learning how best to use the MetaMax system for the testing requirements. Much of this preliminary testing was carried out on a single participant. A pilot study was then conducted to try out work modes and timings.

5.1 Participants

Five participants (all female) took part in the pilot study. They were all volunteers drawn from the student population at Loughborough University. Their physical characteristics are detailed in Table 5.1.

Participants were made fully aware in writing of all experimental details (including time demands, measurements to be taken, protocol and all other procedures). Before participating each was required to complete an 'Informed Consent' form and a 'Generic Health Screen for Study Volunteers' which provided more information regarding their general health and fitness.

Table 5.1. Participant details for pilot study.

Participant no.	Gender M / F	Age years	Height cm	Weight kg
1	F	28	168	59
2	F	24	169	68
3	F	27	164	72
4	F	25	150	59
5	F	24	172	70
Average $\pm$ SD		25.6 $\pm$ 0.2	164.6 $\pm$ 8.6	65.6 $\pm$ 6.2

5.2 Clothing

Four protective clothing ensembles were tested, a description and weight of the garments is provided in Table 5.2 below. Each was worn with cotton tracksuit trousers and a t-shirt underneath (provided) and trainers (participants own). For the control conditions participants wore cotton tracksuit trousers and sweatshirt with trainers.

Table 5.2. Clothing details for pilot study.

Protective garments	Underwear	Footwear	Total weight inc footwear
1. Navy firefighters suit (jacket and trousers)	tracksuit trousers and t-shirt	trainers	3.98kg
2. Army NBC protection (jacket and trousers)	tracksuit trousers and t-shirt	trainers	2.66kg
3. Workwear suit (jacket and trousers)	tracksuit trousers and t-shirt	trainers	3.39kg
4. Mountain rescue (jacket and trousers)	tracksuit trousers and t-shirt	trainers	3.04kg
Control	**tracksuit trousers and sweatshirt**	**trainers**	**1.45kg**

5.3 Work modes

Participants completed 4 work modes. The details of the work modes and the equipment used are provided in Table 5.3 below. The work modes lasted 8 minutes each separated by a 6 minute rest period. In the first session participants walked at 3.5 km/hr and then stepped and in the second session participants walked at 5 km/hr and then lifted crates containing 5 kg across a room and placed them / picked them up from 3 levels (the floor, a table 72.5 cm high and another table 145 cm high), this was rotational and repeated, with the speed controlled by a metronome, see section 2.2 for more detail.

Table 5.3. Details of work modes and equipment for pilot study.

Work mode	Details	Equipment used
1. Walking	3.5 and 5 km/hr	Tunturi T-track Gamma 300 treadmill (Finland)
2. Stepping	25 steps/min on a 20cm step, rate controlled by metronome	Reebok Aerobics Step Birkbeck Laboratory Timer and Signal Source (metronome)
3. Lifting two crates	Lifting and moving two 5kg crates to/from different heights, rate controlled by metronome	Tables 72.5cm high and 145cm high

5.4 Measurements

Metabolic rate was measured with a MetaMax 3B (Cortex, Germany) portable breath-by-breath system. Participants also wore a heart rate belt (Polar Electro, Finland) which was compatible with the MetaMax system.

The environmental conditions in the testing room were measured by a Vaisala HMP35DGT humidity and temperature probe which was connected to a 1000 series Squirrel meter/logger (Grant Instruments, Cambridge).

Subjective responses of 'Rate of Perceived Exertion' (RPE) and 'Thermal Sensation' (TS) were also recorded.

5.5 Experimental design

The experiment was a within-subjects design with each participant acting as their own control, the garment order was randomised. All test sessions were conducted at the same time of day and within 2 days of each other. Within each session participant completed the activities in the control clothing and wearing 2 protective garments.

5.6 Results

5 participants (all female, age 25.6$\pm$0.2 years, height 164.6$\pm$8.6 cm, weight 65.6$\pm$6.2 kg) completed the test in 4 protective garments. The average environmental conditions for the room were 15.3$\pm$0.5 °C and 57$\pm$4 % relative humidity (RH).

5.6.1 Absolute results

The absolute values for all conditions (4 garments and control) are grouped according to work mode and shown in Tables 5.4 to 5.7. For each condition average and standard deviations are given for $\dot{V}O_2$, RER and metabolic rate (in kcal/min, W and W/m^2). The averages and standard deviations for each condition are based on the final 3 minutes data for each work period from each of the 5 participants.

Table 5.4. Absolute results for pilot study when walking at 3.5 km/hr in control and 4 protective clothing ensembles.

WALK 3.5 km/hr		$\dot{V}O_2$	RER	Met rate	Met rate	Met rate
		[l/min]		[kcal/min]	[W]	[W/m^2]
control	ave	0.70	0.85	3.4	236.0	138.0
	SD	0.03	0.01	0.1	9.9	5.8
army NBC	ave	0.76	0.81	3.6	254.0	148.6
	SD	0.08	0.05	0.4	27.8	16.3
workwear	ave	0.72	0.87	3.5	244.2	142.8
	SD	0.07	0.04	0.3	23.6	13.8
firefighter	ave	0.72	0.85	3.5	244.8	143.2
	SD	0.03	0.08	0.2	12.0	7.0
mountain rescue	ave	0.74	0.81	3.5	247.8	144.9
	SD	0.05	0.04	0.2	17.5	10.2

Table 5.5. Absolute results for pilot study when walking at 5 km/hr in control and 4 protective clothing ensembles.

WALK 5 km/hr		$\dot{V}O_2$	RER	Met rate	Met rate	Met rate
		[l/min]		[kcal/min]	[W]	[W/m^2]
control	ave	0.92	0.85	4.4	310.8	181.8
	SD	0.03	0.02	0.2	11.8	6.9
army NBC	ave	1.01	0.83	4.9	340.2	199.0
	SD	0.10	0.11	0.4	29.5	17.3
workwear	ave	1.02	0.87	5.0	348.3	203.7
	SD	0.10	0.05	0.5	33.4	19.5
firefighter	ave	1.02	0.81	4.9	341.9	199.9
	SD	0.10	0.04	0.5	33.1	19.4
mountain rescue	ave	1.00	0.82	4.8	336.3	196.7
	SD	0.12	0.02	0.6	42.5	24.9

Table 5.6. Absolute results for pilot study when stepping in control and 4 protective clothing ensembles.

STEPPING		$\dot{V}O_2$	RER	Met rate	Met rate	Met rate
		[l/min]		[kcal/min]	[W]	[W/m^2]
control	ave	1.45	0.94	7.1	499.0	291.8
	SD	0.04	0.01	0.2	14.6	8.5
army NBC	ave	1.54	0.91	7.5	527.2	308.3
	SD	0.16	0.07	0.8	54.2	31.7
workwear	ave	1.47	0.96	7.3	508.8	297.5
	SD	0.14	0.03	0.7	46.1	26.9
firefighter	ave	1.51	0.94	7.4	520.6	304.4
	SD	0.12	0.06	0.6	43.8	25.6
mountain rescue	ave	1.55	0.91	7.6	531.7	310.9
	SD	0.12	0.01	0.6	41.2	24.1

Table 5.7. Absolute results for pilot study when lifting crates in control and 4 protective clothing ensembles.

LIFTING		$\dot{V}O_2$	RER	Met rate	Met rate	Met rate
		[l/min]		[kcal/min]	[W]	[W/m²]
control	ave	1.29	0.87	6.3	438.3	256.3
	SD	0.01	0.02	0.0	0.5	0.3
army NBC	ave	1.29	0.88	6.3	439.1	256.8
	SD	0.13	0.09	0.6	44.8	26.2
workwear	ave	1.26	0.90	6.4	447.1	261.4
	SD	0.13	0.04	0.6	44.5	26.0
firefighter	ave	1.33	0.85	6.4	450.7	263.6
	SD	0.14	0.06	0.7	52.4	30.6
mountain rescue	ave	1.26	0.86	6.1	438.8	249.6
	SD	0.22	0.03	1.1	76.0	44.5

A summary of the absolute change in metabolic rate for all garments and all work modes from the control is shown in Figure 5.1. Looking at the work modes the changes in metabolic rate when walking at 5 km/hr compared to 3.5 km/hr is much greater. Walking at 5 km/hr increased the metabolic rate by at least 25 W compared to the control in all garments. Stepping also had a large effect, with increases of over 20 W for 3 of the 4 garments. The largest change in metabolic rate when lifting compared to the control is seen in the firefighter suit, but is only 13 W and in the mountain rescue suit no change was recorded.

The figures in the tables above are not the same as those that will be seen in Figures 5.2 to 5.6. The numbers in the tables are an average of for example the metabolic rate of all participants when walking wearing the mountain rescue garment. However the figures in the graphs take account of the specific control conditions measured in the same individual session as the test suit and are thus based on an average of each participants % increase data for the individual session.

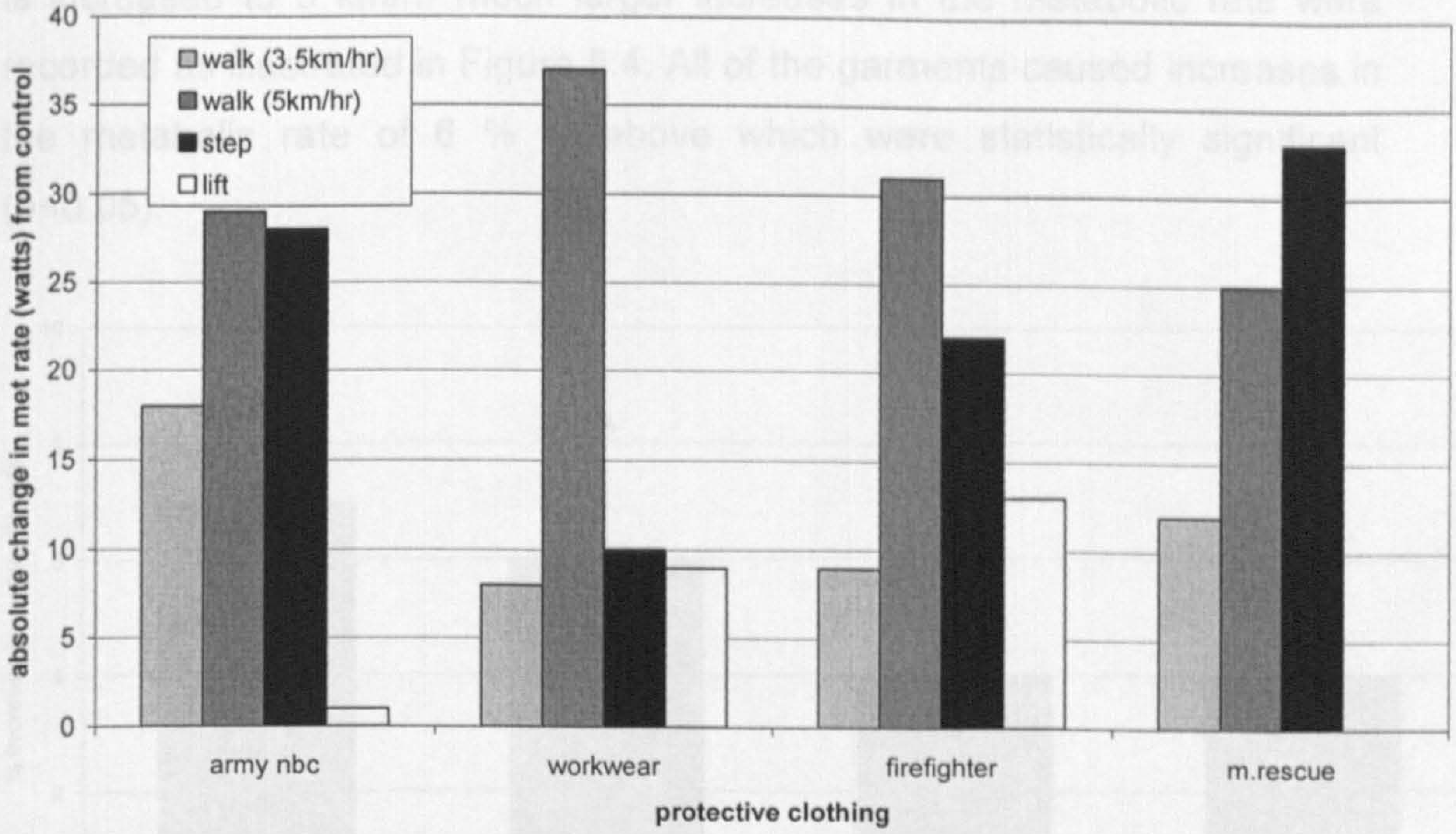


Figure 5.1. Graph of absolute change in met rate (W) from control for all garments and all work modes.

5.6.2 Metabolic rate results

Overall results

The percentage increases in metabolic rate have been plotted for the 4 protective garments and the results are presented in Figures 5.2 to 5.6. The overall average percentage increase is shown first in Figure 5.2. So when working (walking, stepping, lifting crates) the Army NBC and Workwear garments significantly ($p<0.05$) increased the metabolic rate by 7 % and 6 % respectively when compared to a control condition in which lightweight cotton clothing was worn. The Firefighter and Mountain Rescue garments both increased the metabolic rate by approximately 4 % although these increases were not statistically significant.

Walking results

The results for walking at 3.5 km/hr and 5 km/hr are presented in Figures 5.3 and 5.4 respectively. The only significant ($p<0.05$) result in Figure 5.3, walking at 3.5 km/hr was for the Army NBC ensemble with an increase of 8 %. The increases in the other three garments were 5 % (Workwear) or below (Firefighter and Mountain Rescue). However when the walking speed is increased to 5 km/hr much larger increases in the metabolic rate were recorded as illustrated in Figure 5.4. All of the garments caused increases in the metabolic rate of 6 % or above which were statistically significant ($p<0.05$).

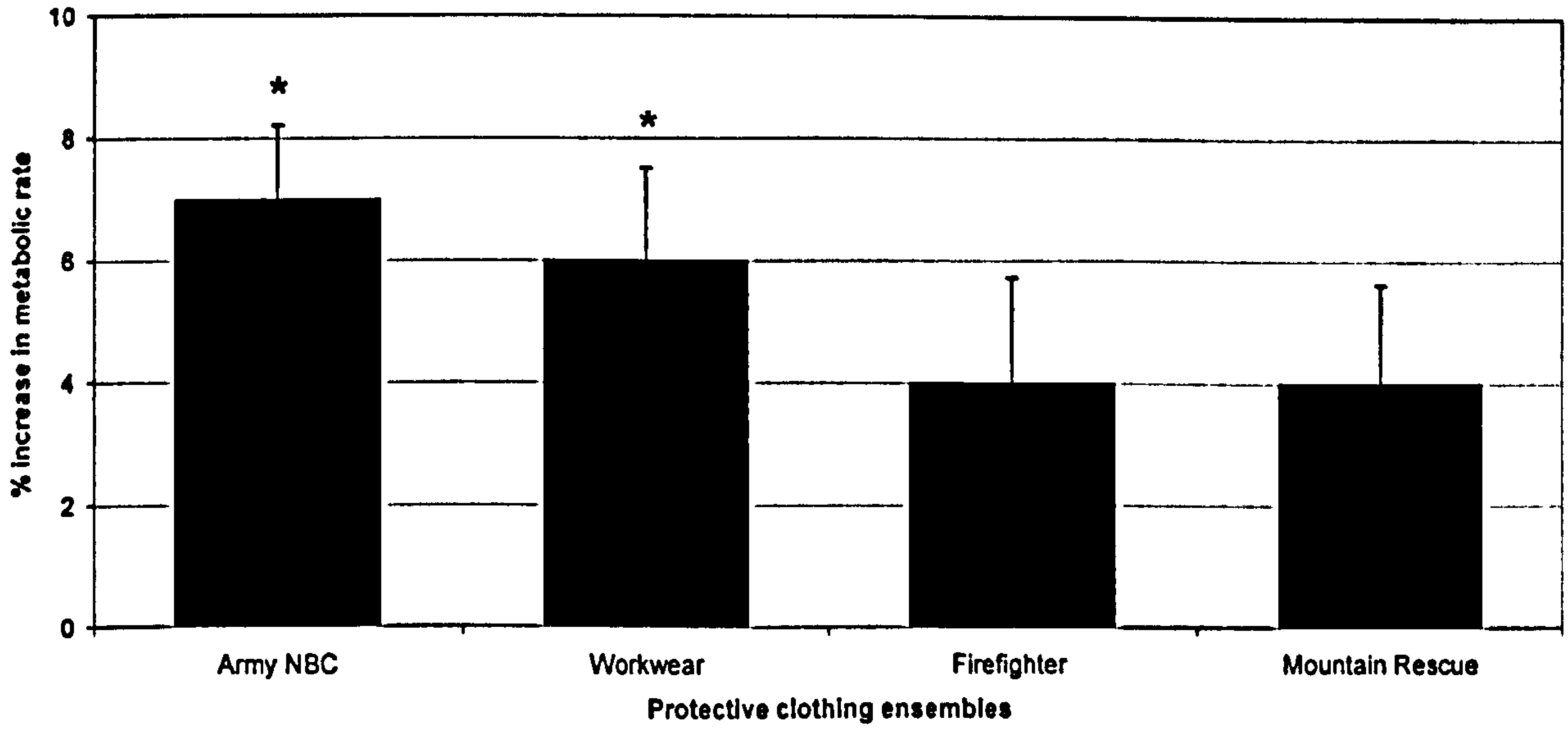


Figure 5.2. Overall average (n=5) percentage increase in metabolic rate when wearing protective clothing relative to the control condition during work (average of walking, stepping and lifting). Significance of p<0.05 indicated by *.

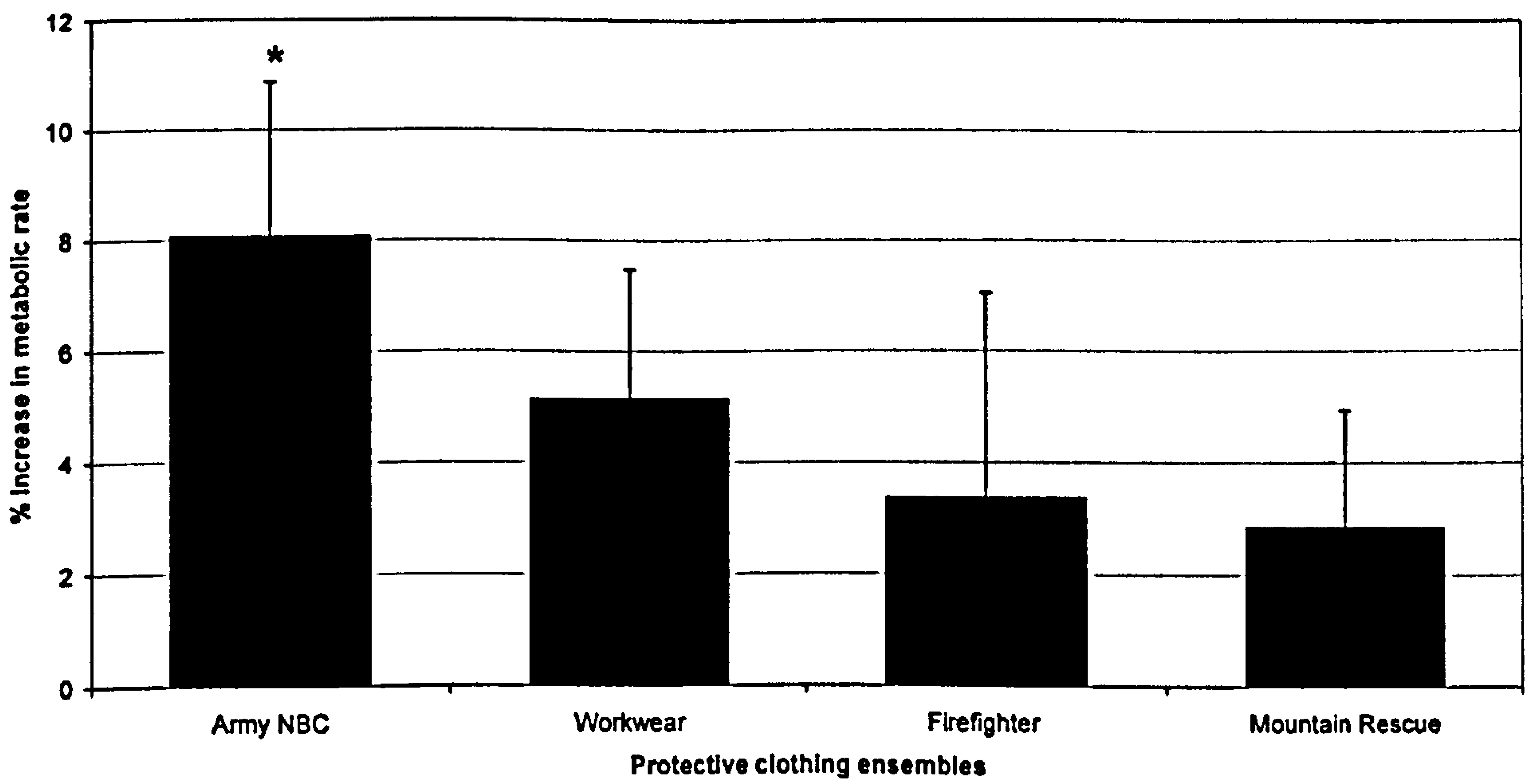


Figure 5.3. Average (n=5) percentage increase in metabolic rate when wearing protective clothing relative to the control condition during walking at 3.5 km/hr. Significance of p<0.05 indicated by *.

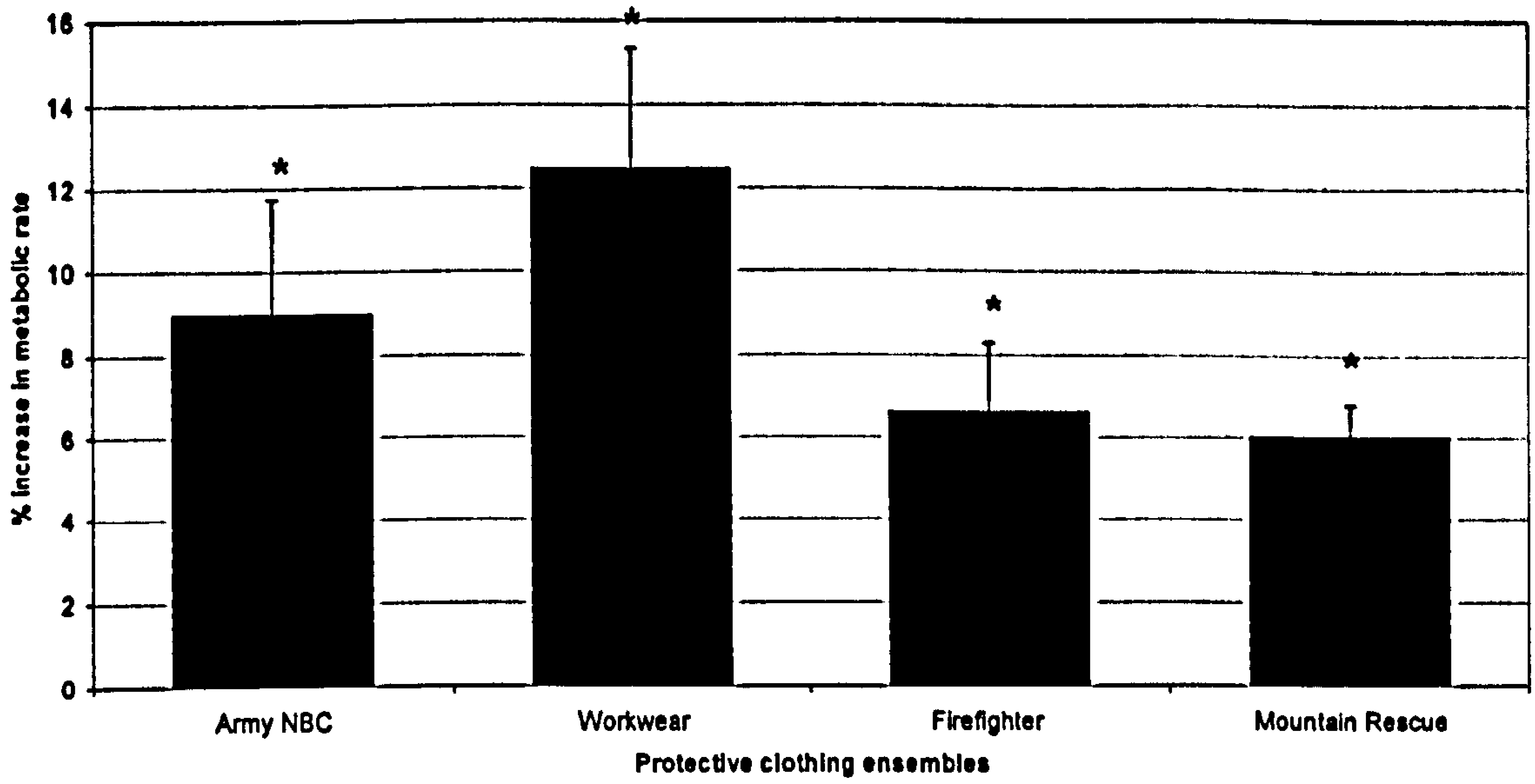


Figure 5.4. Average (n=5) percentage increase in metabolic rate when wearing protective clothing relative to the control condition during walking at 5 km/hr. Significance of p<0.05 indicated by *.

Stepping results

Figure 5.5 illustrates the trend for the stepping work mode. The increases in the Army NBC and Workwear garments of just over 6 % and just under 4 % respectively, were significant ($p<0.05$). The Firefighter garment with an increase of 4 % narrowly missed significance ($p<0.07$) and although the Mountain Rescue garment had an average increase of almost 6 %, the increase was not significant due to a high standard deviation.

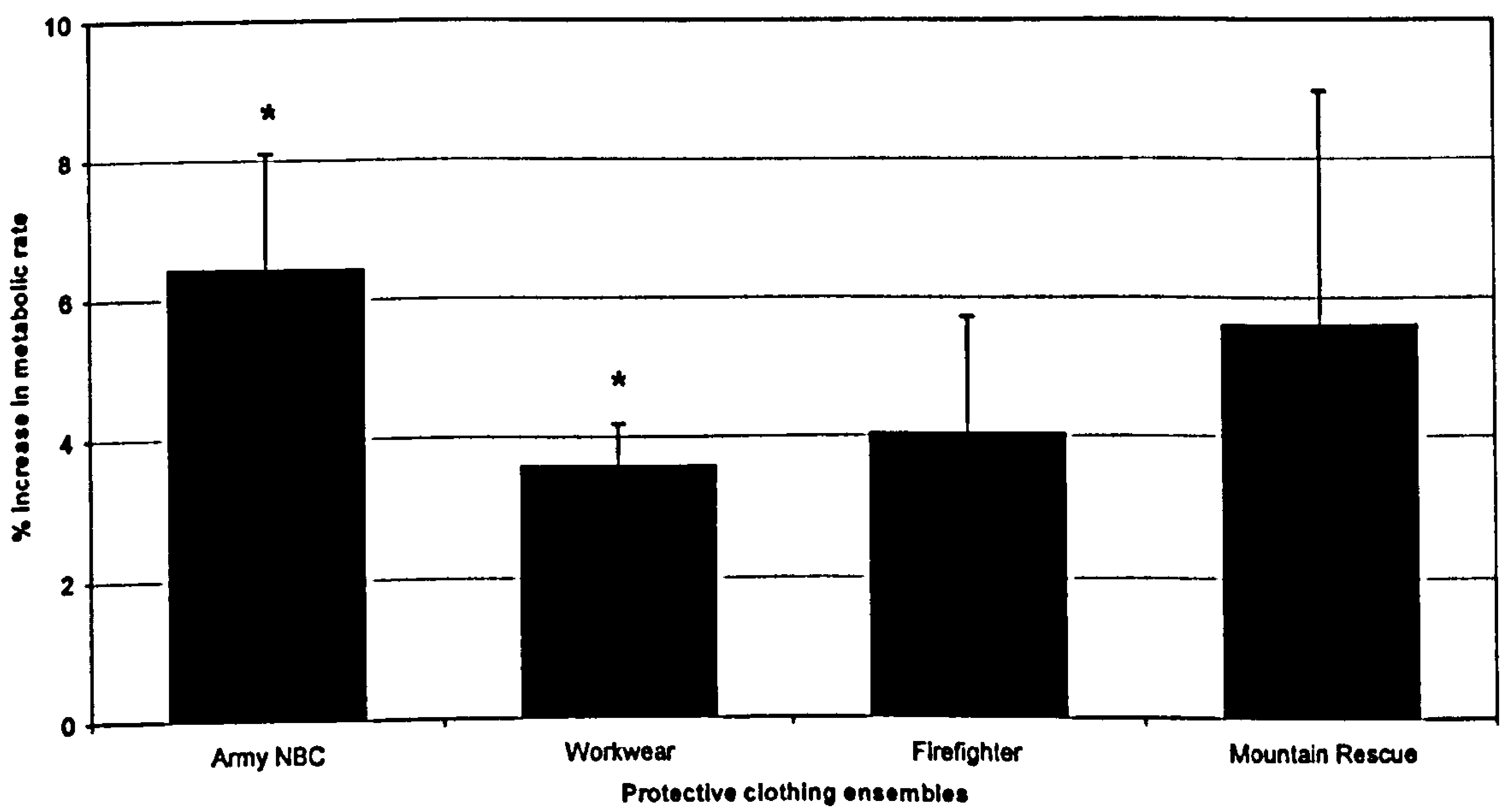


Figure 5.5. Average (n=5) percentage increase in metabolic rate when wearing protective clothing relative to the control condition during stepping. Significance of p<0.05 indicated by *.

Lifting results

The lifting task had no significant effect on the metabolic rate of participants, as can be seen in Figure 5.6, with much smaller increases than the other work modes. The Mountain Rescue garment did not show any increase above resting and the largest increase was only 3 % for the Army NBC ensemble.

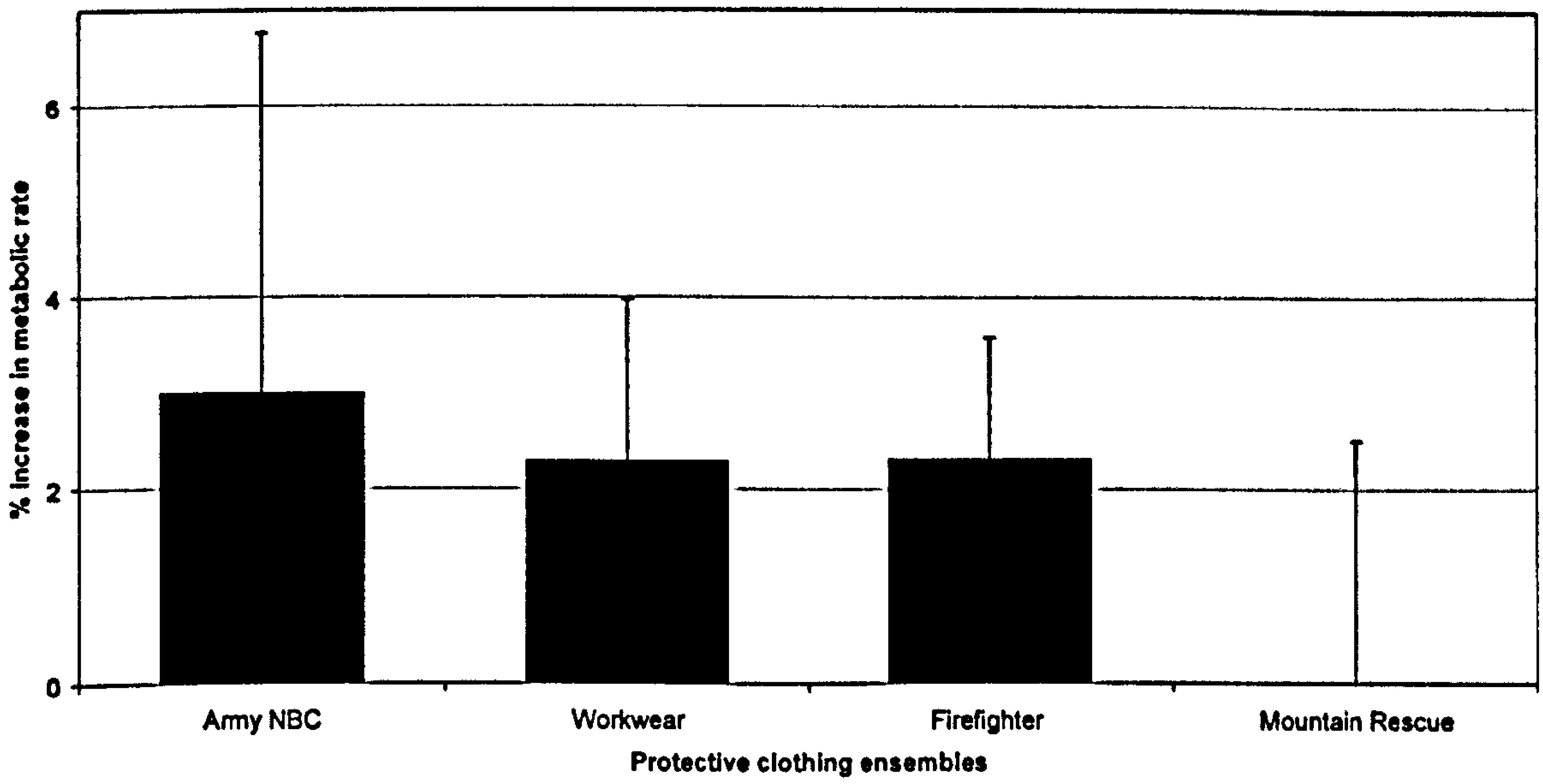


Figure 5.6. Average (n=5) percentage increase in metabolic rate when wearing protective clothing relative to the control condition when lifting crates. Significance of $p<0.05$ indicated by *.

5.6.3 Subjective results

Rate of perceived exertion results

Two subjective measures were also recorded in the final minute of each work period. Figure 5.7 illustrates the Rate of Perceived Exertion responses, the scale ranges from 6, no exertion at all, to 20, maximal exertion, however responses recorded during this experiment only ranged from 9, very light, to 13, somewhat hard, hence the abbreviated scale on the y-axis of Figure 5.7.

Both walking speeds were perceived on average as very light by the participants, with a marked increase in subjective rating when stepping and lifting crates. The 8 minutes of stepping at a rate of 25 steps/min was perceived as much harder by the participants and having to move the crates up and down with 5 kg in them also increased the subjective rating. When wearing the protective garments the subjective ratings were also elevated compared to the control as can be seen by the coloured lines in Figure 5.7. Stepping and walking at 5 km/hr required a higher subjective effort compared to the control condition than walking at 3.5 km/hr and lifting crates, although none of the increases were significant.

Overall the highest subjective ratings were recorded when participants were wearing the fire suit. For the walking the army suit showed the smallest perceived increases in exertion required compared to the control.

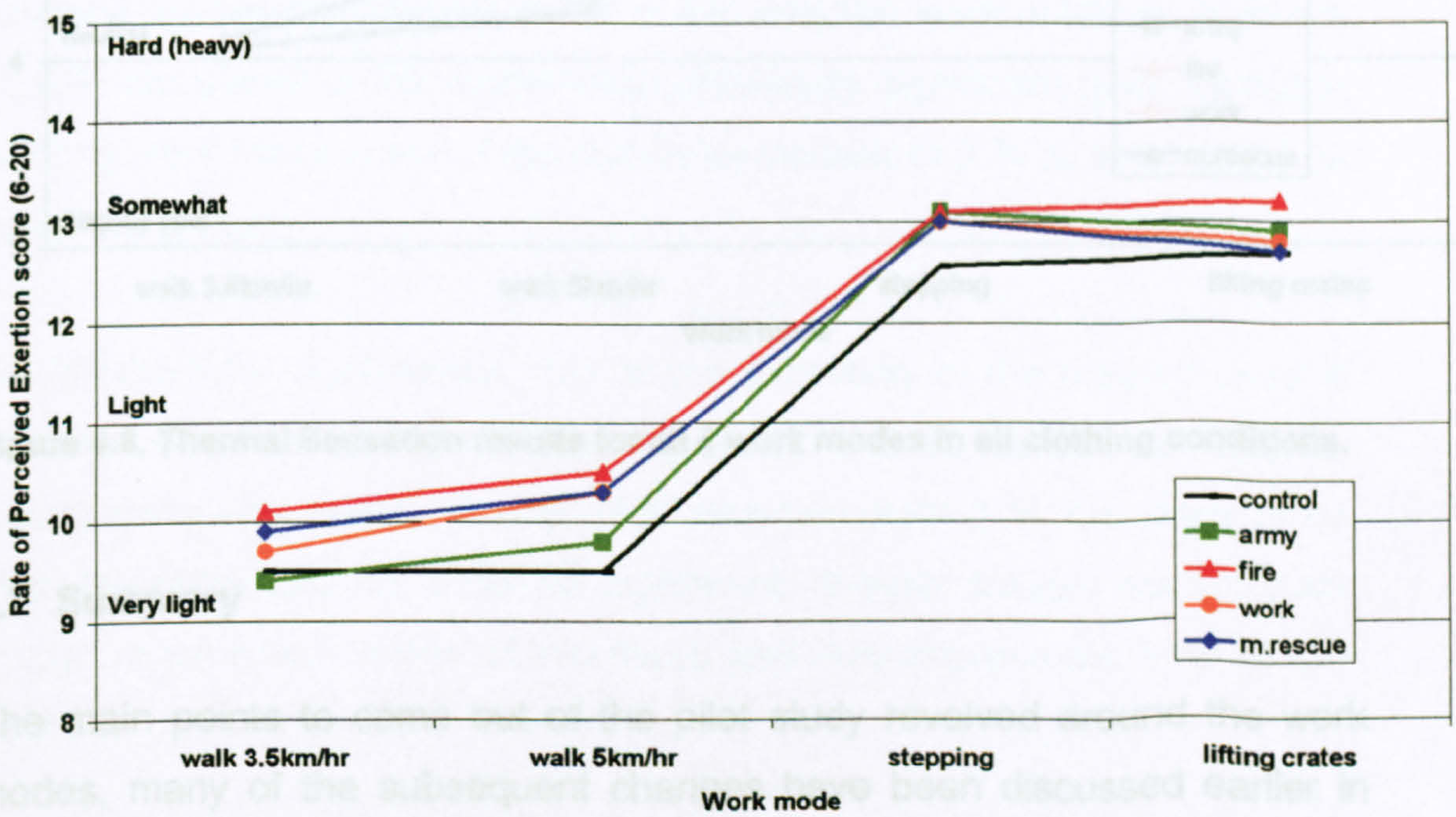


Figure 5.7. Rate of perceived exertion results for all 4 work modes in all clothing conditions.

Thermal sensation results

The thermal sensation responses are detailed in Figure 5.8. The walking work modes had a minimal effect on participant thermal sensation with the average responses between neutral and slightly warm. The most elevated responses (warm) were recorded when participants were stepping and lifting the crates. Thermal sensations were increased in all garments compared to the control, with the fire garment having the greatest effect on thermal sensation overall. Stepping in the fire garment caused participants to rate their thermal sensation significantly ($p<0.05$) higher than in the control condition.

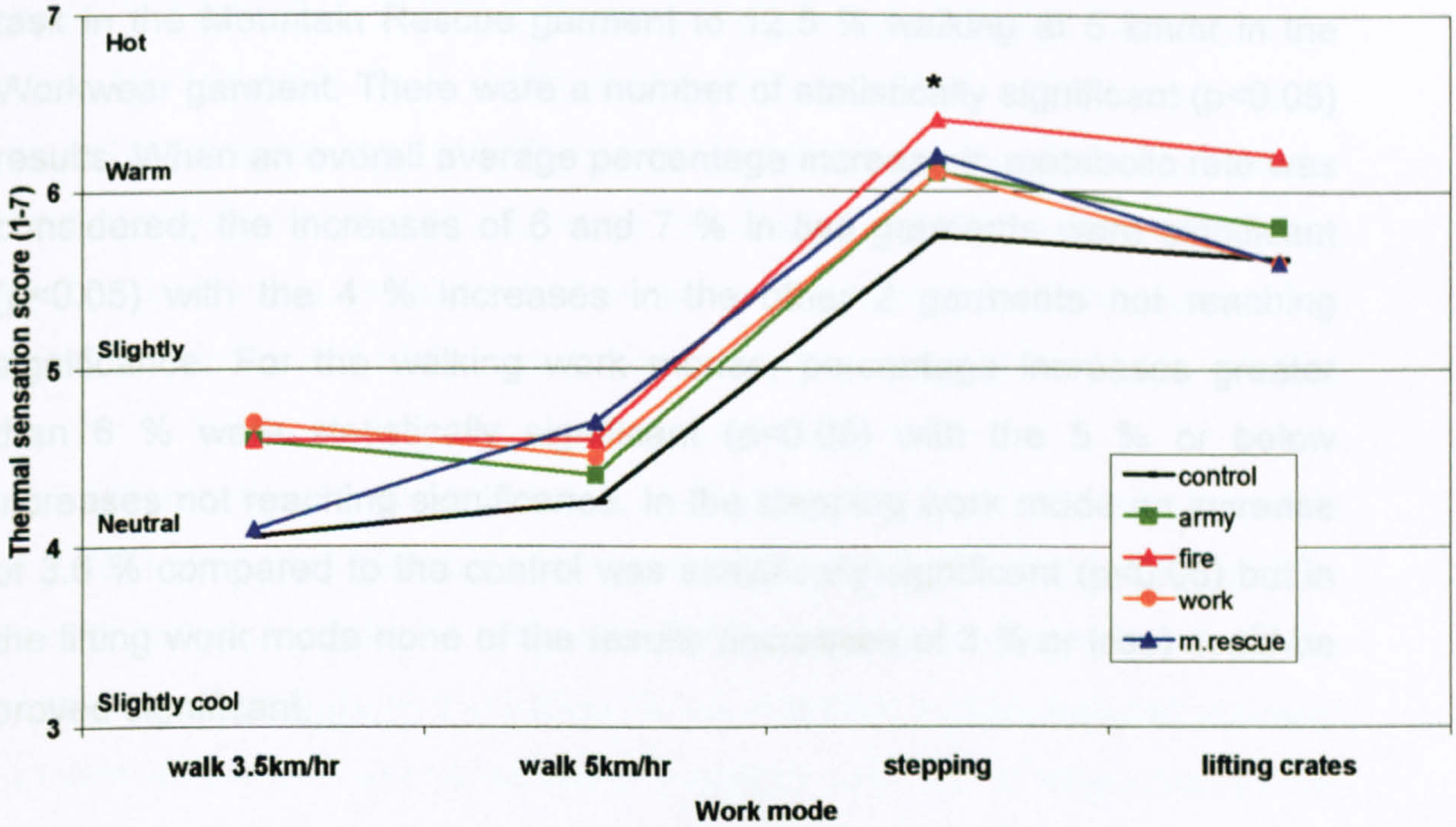


Figure 5.8. Thermal Sensation results for all 4 work modes in all clothing conditions.

5.7 Summary

The main points to come out of the pilot study revolved around the work modes, many of the subsequent changes have been discussed earlier in this chapter. In summary, particularly important was the finding that walking at 5 km/hr promoted a significant increase in metabolic rate in all garments compared to only one significant result walking at 3.5 km/hr. The lifting task employed in the pilot did not promote any significant increase in metabolic rate when wearing any of the 4 garments. These findings led into further development of the work modes for the main testing, as detailed earlier.

Practice in explaining the procedures and putting on / taking off the MetaMax mask and unit was also invaluable.

5.8 Discussion of sensitivity of metabolic rate measurement

The percentage increase in metabolic rate for 4 garments from a control condition across 4 work modes in the pilot ranged from 0 % for the lifting task in the Mountain Rescue garment to 12.5 % walking at 5 km/hr in the Workwear garment. There were a number of statistically significant ($p<0.05$) results. When an overall average percentage increase in metabolic rate was considered, the increases of 6 and 7 % in two garments were significant ($p<0.05$) with the 4 % increases in the other 2 garments not reaching significance. For the walking work modes, percentage increases greater than 6 % were statistically significant ($p<0.05$) with the 5 % or below increases not reaching significance. In the stepping work mode an increase of 3.6 % compared to the control was statistically significant ($p<0.05$) but in the lifting work mode none of the results (increases of 3 % or less) could be proved significant.

The threshold for significance, due to the sensitivity of the method used is therefore assumed to be in the region of 3-4 %, for 5 participants. Consequently any effects smaller than approximately 3 % are likely to be lost in the noise and not show up significant. Greater subject numbers will be used in the main studies of this thesis and may improve the level of this threshold.

The results of the pilot study were all positive, i.e. increases in metabolic rate, apart from the no change for the Mountain rescue garment during the lifting work mode. If the non-significant increases observed would occur purely by chance, one would expect these results to be randomly scattered above and below zero. This however was not the case. Thus, despite the lower observed increases not reaching statistical significance, it can be assumed that the trend of a systematic positive difference from the control illustrates a realistic effect, even for these low values.

The signal to noise ratio in this testing, represented here in this within-subjects experiment as the effect size in relation to the day to day variation in metabolic rate for each individual person is crucial to the statistical power of the test.

Intra-individual coefficients of variation (CV) in metabolic rate for repeated measurements have been reported in the region of 0.4 to 7.2 % (Murgatroyd *et el.* 1987, Fredrix *et al.* 1990, Adriaens *et al.* 2003). In the most recent paper by Adriaens *et al.* (2003) mean within-subject CV in metabolic rate for three measurements with 2 week intervals was found to be 3.3 %, representing the expected noise levels in the experiment. In contrast the mean inter-individual CV in metabolic rate was reported to be 18 %.

The within-subjects design of the studies in this thesis, requirement for participants to attend the lab at the same time of day for all of their sessions and written instructions to eat, sleep and exercise as normal and refrain from alcohol, caffeine and smoking 12 hours before testing, were all planned to minimise the average variations in metabolic rate, which may increase the noise of the data.

CHAPTER 3

STUDY 1

ESTABLISHING THE EFFECTS OF PROTECTIVE CLOTHING ON METABOLIC RATE DURING DIFFERENT ACTIVITIES

1. Introduction

The problems of protective clothing can be split into thermal and metabolic issues. The thermal effects of protective clothing have been studied by looking at heart rate and core temperature responses to different garments and performance decrements in the heat. However very few studies have considered the metabolic effects. Generally the current literature on protective clothing is also characterised by a focus on firefighting and NBC garments.

Protective clothing can increase the metabolic cost of performing a task by adding weight and by otherwise restricting movement. The binding or hobbling effect of multilayered clothing also adds measurably to work. The extra bulk and stiffness of protective clothing may require additional movement to compensate for problems such as restricted visual fields, failure of communication or loss of manual dexterity. The effect of added weight on work load depends in part upon the task, e.g. a heavy suit poses little problem for a stationary worker but presents a severe handicap for a firefighter climbing a ladder or stairwell (Nunneley 1989).

1.1 Previous research

As detailed in the literature review Teitlebaum and Goldman (1972) investigated the possible increased energy cost with multiple clothing layers. Subjects walked on a treadmill at 5.6 and 8.0 km/hr on 2 occasions wearing a 5 layer arctic clothing ensemble over standard fatigues or an 11.2 kg lead-filled belt (equivalent to the weight of the five extra clothing layers). For every subject the energy cost at a given speed was always higher with the clothing than the weight belt, with a significant increase on average of approximately 16 % in the metabolic cost of working in the clothing, compared to the belt. The design of the study with the same weight worn as clothing or as a weight belt allowed the authors to conclude that the 16 % increase in metabolic cost can most probably be attributed to a 'friction drag' between clothing layers or a 'hobbling' effect due to the bulk of the layers.

Duggan (1988) investigated the effect of protective clothing ensembles on the energy cost of a bench stepping task, with subjects performing the task in 4 different ensembles. Standard military combat clothing was worn for the control condition. Chemical agent protection garments were added for the second ensemble, with cold weather protective clothing added to the chemical layers for the third ensemble. The final ensemble included thermal trouser liners on top of those previously described to give 3, 4, 6 and 6 layers on the torso respectively for the 4 conditions (with 1, 2, 3 and 4 layers on the legs). External work rate and clothed subject weight increased with the amount of clothing worn, being 3.9, 5.6 and 6.0 % higher in the 3 ensembles respectively compared to the control. $\dot{V}O_2$ (expressed in l/min) during stepping was significantly greater in all 3 ensembles compared to the control, with a mean increase of 9, 12 and 16 % in the 3 ensembles respectively. These increases were proportionately greater than the increases in clothed subject weights, and when corrected for clothing weight the $\dot{V}O_2$ in the last ensemble was still significantly increased by 9 %.

Graveling and Hanson (2000) concentrated on modern firefighters' clothing demonstrating and quantifying the negative aspect of the protection, the physiological cost of working whilst wearing it, and the risk of heat stress through its considerable disruption of the thermoregulatory pathways. In summary, during the laboratory trials (involving treadmill walking in ambient conditions), standard firefighter clothing typically increased physiological cost (oxygen consumption) by 15 % over control sessions wearing shorts and t-shirt. Although this increase is much higher than the 9 % quoted by

Duggan (1988), in this study the increase in $\dot{V}O_2$ was not corrected for the weight of the firefighter clothing and no details of weight were given, so it is not possible to say how much of the increase is due to the weight of the clothing and how much might be due to other factors.

With modern UK fire fighting clothing weighing in at approximately 10 kg (excluding breathing apparatus) there will inevitably be an increase in energy cost (Baker *et al.* 2000). The weight of the equipment (30 kg) in a study by Skoldstrom (1987) increased the physical workload, resulting in a 0.4 l/min increase in oxygen uptake. According to previous findings, protective equipment weighing 15-26 kg causes a rise in energy cost of walking or climbing by about 20 % or more, not corrected for weight (Faff and Tutak 1989). Ftaiti *et al.* (1989) also comment that the weight of protective clothing and equipment can increase energy demands by as much as 40 %. Also Goldman (1990) quotes a weight of 10.9 kg for the full fire fighting ensemble plus 10.5 kg for the self-contained breathing apparatus (SCBA) and asserts that the hobbling effect of arm and leg movement in such thick, heavy clothing can increase the working heat production by about 30 % over that of the same task done wearing only a station uniform. Previous research has found that the energy cost of moderate work while wearing the fire fighting clothing and protective equipment was elevated 33 % over that required to perform the same work without protective clothing and equipment (Davis *et al.* 1982). Bilzon *et al.* (2001) note the increase in energy cost of moderate intensity work of 33 % and explain that the high metabolic demand of fire fighting is a result of intrinsic metabolic and physical demands of various tasks, combined with additional extrinsic stressors (clothing, equipment and environment).

Despite the large body of knowledge on the performance effects of chemical protective (CP) clothing, little quantitative information exists about the energy cost and related physiological changes during dynamic exercise under conditions where heat stress is not a significant factor. Wearing standard battledress uniform (BDU), BDU with a M17 protective mask or CP clothing (with a mask, overgarment, gloves and boots) subjects walked on a treadmill at 3 grades; 0, 5 and 10 % in a study by Patton *et al.* (1995). Laboratory environmental conditions were maintained at 18 – 22 °C and 40 - 55 % RH to minimise the possible effects of heat on the physiological and perceptual responses to exercise in the CP clothing. $\dot{V}O_2$ was significantly increased in CP clothing compared to BDU at all grades, with no differences seen between the BDU and BDU with mask conditions at any level of exercise. Over the range of exercise intensities (approximately 30-60 % $\dot{V}O_{2max}$), $\dot{V}O_2$ increased between 13 and 18 % while wearing CP clothing. Since the contribution of the mask to this response was slight, the increased energy cost was obviously due to the overgarment, overboots and gloves. $\dot{V}O_2$ corrected for differences in clothed weight was 6-11 % greater in CP clothing across the range of exercise intensities (Patton *et al.* 1995).

In summary, the previous work has seen a focus on firefighting and chemical protective clothing. Very few studies have investigated the effects of the clothing on energy consumption / metabolic rate. Of those that have, for example, Teitlebaum and Goldman (1972), Duggan (1988) and Patton *et al.* (1995), very few garments have been studied and only whilst walking or stepping.

1.2 Aims

The aim of this study is to establish whether wearing a range of protective clothing garments significantly increases metabolic rate when performing different types of work compared to performance in a control (tracksuit) condition. The protective garments to be tested shall cover a wide range of industries with participants completing tasks requiring lower and upper body movements. Participants will also be asked to rate their level of perceived exertion when completing the tasks to see if wearing the garments also has an effect on their subjective perceptions of effort.

2. Methods

2.1 Participants

There were seven participants (4 male, 3 female), all volunteers drawn from the student population at Loughborough University. Their physical characteristics are detailed in Table 2.1 below. Participant 5 completed the first 3 sessions but had to be replaced for the last 3 sessions, details for both participants are shown.

Table 2.1. Participant details.

Participant no.	Gender M / F	Age years	Height cm	Weight kg
1	F	29	168	59
2	F	20	169	66
3	F	24	172	70
4	M	23	180	65
5	M	23	180	75
5	M	24	185	85
6	M	21	179	75
Average ± SD		**23.4 ± 0.3**	**176.1 ± 6.5**	**70.7 ± 8.5**

2.2 Clothing

Fourteen protective clothing ensembles were selected for the study, photographs of the garments can be seen in Chapter 2 (Methodology). The background to their selection and details of the garments and sources are also provided in Chapter 2 (Methodology). All garments were worn with work trousers, t-shirt and army boots, except ensembles F, L and M, worn with army specific layers.

A description and weight of the garments is provided in Table 2.2. The underwear and footwear worn is also detailed. For the control conditions participants wore cotton tracksuit trousers and a sweatshirt (provided) with trainers (participants own), details in Table 2.3.

Table 2.2. Clothing details and weights for each protective garment worn.

Protective garments	Underwear worn	Footwear worn	Total weight of ensemble including footwear
A Workwear (insulated)	work trousers and t-shirt	army boots	5.86 kg
B Grey fire	work trousers and t-shirt	army boots	7.00 kg
C Workwear	work trousers and t-shirt	army boots	4.36 kg
D Gold fire	work trousers and t-shirt	army boots	6.66 kg
E Chemical	work trousers and t-shirt	army boots	3.66 kg
F ArmyNBC	trousers, norwegian shirt	army boots	5.27 kg
G Welding	work trousers and t-shirt	army boots	5.58 kg
H Coldsuit black	work trousers and t-shirt	army boots	4.92 kg
I Coldsuit green	work trousers and t-shirt	army boots	4.83 kg
J Chainsaw	work trousers and t-shirt	army boots	5.68 kg
K ChemBio	trousers, norwegian shirt	army boots	4.87 kg
L ArmyVEST	thermals, trousers, norwegian shirt	army boots	5.32 kg
M ArmyH2O	thermals, trousers, norwegian shirt	army boots	3.51 kg
N Mountain rescue	work trousers and t-shirt	army boots	4.14 kg
Control	**tracksuit trousers and sweatshirt**	**trainers**	**1.4kg**

Table 2.3. Clothing details and weights for the control clothing and underwear worn.

Control clothing	Weight
trainers	0.65 kg
army boots	1.57 kg
tracksuit trousers and sweatshirt	0.75 kg
work trouser and t-shirt	0.63 kg

2.3 Work modes

Details of the work modes can be found in Chapter 2 (Methodology), a summary of the details and equipment used is provided in Table 2.4.

Table 2.4. Work mode details and equipment used.

Work mode	Details	Equipment used
1. Walking	5 km/hr	Tunturi T-track Gamma 300 treadmill (Finland)
2. Stepping	25 steps/min on a 20cm step, rate controlled by metronome	Reebok Aerobics Step Birkbeck Laboratory Timer and Signal Source (metronome)
3. Obstacle course	Lifting 5kg crates and moving over and under hurdles, rate controlled by metronome	Wooden hurdles (55cm and 100cm high) and tables 72cm high, 82.5cm high and 150cm high

2.4 Floor plan and details

A detailed floor plan for the obstacle course is included in Figure 2.1 with the shapes used in the plan detailed in Table 2.2 in Chapter 2 (Methodology). As previously explained, participants completed the obstacle course circuit continuously for 6 minutes. The arrows show the direction of movement. Following the white arrows first, participants stepped over a low hurdle then moved the crates between the two tables and the floor (the timing and order in which the participants moved the crates is given in detail with photographs in Table 2.3 in the Equipment section of Chapter 2). They then crawled under a hurdle, touched the wall and bent down to come back under the hurdle. The black arrows now show that they walked around the table and back to the start. Although the order of the obstacles completed as described here is not exactly the same as illustrated in Table 2.3 in the Equipment section of Chapter 2 (the details given there are for the final obstacle course developed after this study and including stepping), photographs show the technique and timing of each of the movements made, e.g. bending down to go under the hurdle. Speed was controlled by a metronome and counting, as described in Chapter 2 (Methodology).

2.5 Experimental design

The experiment was a within-subjects design with each participant acting as their own control, the garment order was randomised. Two protective garments could be completed with a control in each session, so the protective garments were divided into 7 random pairs and labelled a and b, and then to prevent order effects for the 7 sessions put into a Latin Square. Within the sessions participants 1–3 completed garment a first then a control then garment b while participants 4–6 completed garment b first then a control then garment a, with the control always in the middle.

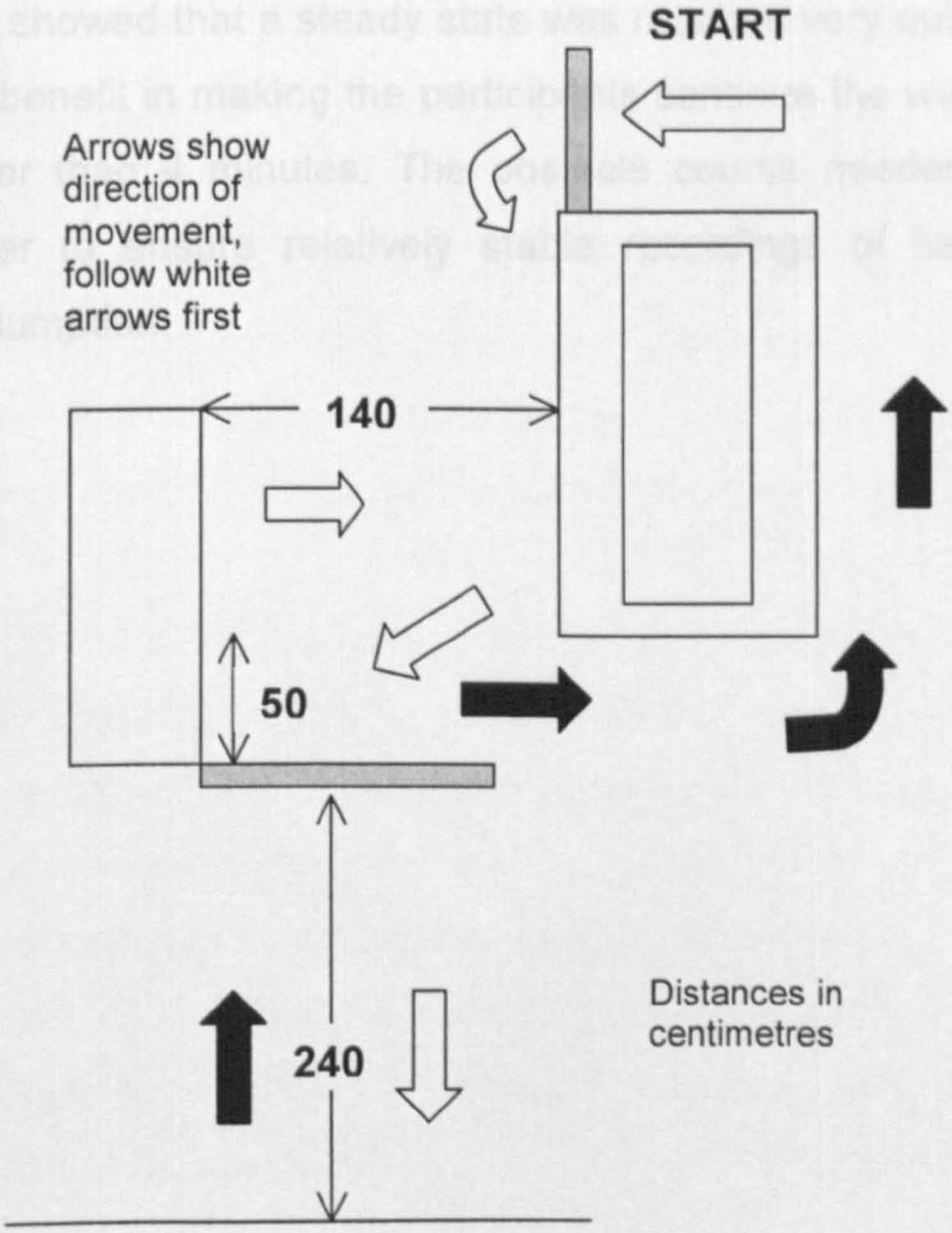


Figure 2.1. Floor plan for the obstacle course.

2.6 Procedure

Following a 3 minute seated rest, participants completed the first work mode (walking on a treadmill at 5 km/hr) which lasted 4 minutes, being asked for their Rate of Perceived Exertion (RPE) and Thermal Sensation (TS) scores in the final minute. They sat at rest for 3 minutes before completing the second work mode (stepping) for 4 minutes, again they were asked for their RPE and TS scores in the last minute. They rested for a further 4 minutes before the final work mode, the obstacle course with moving crates, and going over and under hurdles, which lasted 6 minutes. The duration of work and rest periods were adjusted following the pilot study. Analysis of the pilot data showed that a steady state was reached very quickly and there was no real benefit in making the participants continue the walking and stepping for longer than 4 minutes. The obstacle course needed to be continued for longer to ensure relatively stable recordings of heart rate and oxygen consumption.

3. Results

3.1 Participants and environment

7 participants (4 males, 3 females, age 23.4±0.3 years, height 176.1±6.5 cm, weight 70.7±8.5 kg) completed the sessions in 14 protective garments. The average environmental conditions for the room were 18.7±1.1 °C and 40±4 % relative humidity.

3.2 Absolute results

The absolute values for all conditions (14 garments and control) are grouped according to work mode and shown in Tables 3.1 to 3.3. For each condition average and standard deviations are given for oxygen uptake ($\dot{V}O_2$), respiratory exchange ratio (RER) and metabolic rate (in W and W/m^2). The averages and standard deviations for each condition are based on the final 2 minutes of steady state data from each of the 7 participants for the walking and stepping work modes and final 3 minutes of steady state data from each of the 7 participants for the obstacle course.

The figures in the tables are not the same as those that will be seen in the graphs that follow. The figures in the tables are an average of, for example, the metabolic rate of all participants when walking wearing the Mountain rescue garment. However the figures in the graphs take account of the control conditions, and are based on an average of each participants % increase data (which is derived from comparing the protective garment condition to the control condition in the same session). The graph data is included in Appendix 2.

Table 3.1. Absolute results for walking in control and 14 protective clothing conditions.

WALK		Heart Rate [bpm]	$\dot{V}O_2$ [l/min]	RER	Met Rate [W]	Met Rate [W/m²]
control	ave	97	0.96	0.86	325.0	174.7
	SD	6	0.03	0.03	11.2	6.0
A Workwear (insulated)	ave	107	1.14	0.88	385.6	207.3
	SD	9	0.21	0.09	67.8	36.5
B Grey fire	ave	110	1.15	0.87	379.0	203.7
	SD	11	0.23	0.05	99.2	53.3
C Workwear	ave	107	1.09	0.86	368.0	197.8
	SD	7	0.17	0.06	56.2	30.2
D Gold fire	ave	107	1.16	0.77	383.6	206.2
	SD	12	0.14	0.12	45.6	24.5
E Chemical	ave	109	1.04	0.86	354.8	190.8
	SD	13	0.31	0.08	107.5	57.8
F ArmyNBC	ave	109	1.07	0.86	360.8	194.0
	SD	8	0.30	0.06	98.8	53.1
G Welding	ave	106	1.09	0.91	371.2	199.6
	SD	12	0.18	0.10	54.2	29.2
H Coldsuit black	ave	110	1.12	0.82	375.6	202.0
	SD	14	0.15	0.14	44.7	24.0
I Coldsuit green	ave	105	1.09	0.85	368.7	198.2
	SD	11	0.31	0.08	106.1	57.0
J Chainsaw	ave	109	1.04	0.90	355.5	191.1
	SD	12	0.14	0.05	43.7	23.5
K ChemBio	ave	104	1.06	0.87	358.8	192.9
	SD	7	0.13	0.10	39.5	21.2
L ArmyVEST	ave	105	1.09	0.90	374.6	201.4
	SD	9	0.13	0.09	45.1	24.2
M ArmyH2O	ave	101	1.07	0.90	365.9	196.7
	SD	8	0.21	0.09	74.3	40.0
N Mountain rescue	ave	102	1.08	0.84	365.7	196.6
	SD	6	0.08	0.06	26.9	14.5

Table 3.2. Absolute results for stepping in control and 14 protective clothing conditions.

STEP		Heart Rate	$\dot{V}O_2$	RER	Met Rate	Met Rate
		[bpm]	[l/min]		[W]	[W/m2]
control	ave	114	1.21	0.89	413.3	222.2
	SD	2	0.05	0.04	14.6	7.8
A Workwear (insulated)	ave	124	1.41	0.91	484.7	260.6
	SD	7	0.26	0.06	84.3	45.3
B Grey fire	ave	129	1.37	0.92	470.0	252.7
	SD	8	0.17	0.05	54.4	29.2
C Workwear	ave	125	1.38	0.89	471.3	253.4
	SD	7	0.24	0.06	81.6	43.9
D Gold fire	ave	123	1.38	0.81	460.5	247.6
	SD	11	0.14	0.13	42.1	22.6
E Chemical	ave	125	1.33	0.88	455.0	244.6
	SD	11	0.18	0.06	64.2	34.5
F ArmyNBC	ave	124	1.27	0.92	438.0	235.5
	SD	9	0.44	0.06	152.7	82.1
G Welding	ave	122	1.20	0.94	415.3	223.3
	SD	8	0.12	0.06	38.9	20.9
H Coldsuit black	ave	127	1.37	0.84	462.9	248.9
	SD	15	0.19	0.15	57.3	30.8
I Coldsuit green	ave	119	1.42	0.92	488.7	262.7
	SD	13	0.17	0.09	63.0	33.9
J Chainsaw	ave	128	1.17	0.96	415.7	223.5
	SD	9	0.12	0.07	36.8	19.8
K ChemBio	ave	121	1.22	0.91	417.4	224.4
	SD	7	0.30	0.09	96.1	51.7
L ArmyVEST	ave	122	1.37	0.94	472.9	254.3
	SD	6	0.21	0.07	73.5	39.5
M ArmyH2O	ave	112	1.24	0.92	425.6	228.8
	SD	16	0.24	0.08	81.1	43.6
N Mountain rescue	ave	117	1.28	0.87	436.2	234.5
	SD	9	0.09	0.05	30.9	16.6

Table 3.3. Absolute results for the obstacle course in control and 14 protective clothing conditions.

OBSTACLE COURSE		Heart Rate [bpm]	$\dot{V}O_2$ [l/min]	RER	Met Rate [W]	Met Rate [W/m2]
control	ave	117	1.21	0.90	412.3	221.6
	SD	4	0.09	0.04	29.4	15.8
A Workwear (insulated)	ave	125	1.42	0.93	487.9	262.3
	SD	10	0.31	0.08	102.4	55.1
B Grey fire	ave	135	1.38	0.92	474.7	255.2
	SD	8	0.24	0.06	80.8	43.5
C Workwear	ave	126	1.32	0.87	446.9	240.3
	SD	9	0.23	0.08	80.4	43.2
D Gold fire	ave	131	1.34	0.81	449.1	241.4
	SD	10	0.25	0.12	75.8	40.8
E Chemical	ave	130	1.39	0.89	475.3	255.5
	SD	9	0.22	0.08	80.0	43.0
F ArmyNBC	ave	126	1.32	0.92	453.8	244.0
	SD	11	0.27	0.03	93.2	50.1
G Welding	ave	132	1.17	0.94	403.7	217.0
	SD	12	0.14	0.09	46.9	25.2
H Coldsuit black	ave	137	1.52	0.85	511.2	274.9
	SD	13	0.32	0.14	102.2	54.9
I Coldsuit green	ave	123	1.44	0.91	492.9	265.0
	SD	11	0.24	0.09	87.0	46.8
J Chainsaw	ave	133	1.19	0.94	410.1	220.5
	SD	6	0.13	0.08	41.1	22.1
K ChemBio	ave	124	1.26	0.89	429.4	230.8
	SD	10	0.25	0.11	81.3	43.7
L ArmyVEST	ave	117	1.42	0.93	490.1	263.5
	SD	20	0.21	0.06	73.9	39.7
M ArmyH2O	ave	120	1.17	0.91	400.1	215.1
	SD	10	0.32	0.09	109.2	58.7
N Mountain rescue	ave	121	1.27	0.87	432.7	232.6
	SD	9	0.16	0.06	55.9	30.0

3.3 Metabolic rate results

3.3.1 Overall results

The percentage increases in metabolic rate have been plotted for the 14 protective garments and the results are presented in Figures 3.1 to 3.4. The overall average percentage increase (when all work modes are weighted evenly to produce an average) is shown first in Figure 3.1. The highest recorded increase in metabolic rate (18.7 %) was seen in the Workwear (insulated) (A) garment, with the other Workwear (C) and the two fire suits, Grey fire (B) and Gold fire (D) also showing increases of 14 –16 %. All suits showing an increase in metabolic rate of 10 % or more over the control proved to be significant ($p<0.05$). At just under 7 % the ArmyH2O (M) ensemble increase also proved to be significant ($p<0.05$). The only 2 garments whose increases did not reach significance were the ArmyVEST (L) and Mountain rescue (N) ensembles.

3.3.2 Walking results

The work modes are now considered individually starting with the 5 km/hr treadmill walking results illustrated in Figure 3.2. The order of the garments on the x-axis of the graphs will remain the same for the next 3 figures and follow the overall ranked increase in metabolic rate from Figure 3.1. The graph shows that the garment with the highest percentage increase when walking was the Grey fire (B) suit which caused a 21 % increase in metabolic rate, the lowest increase was 4 % for the Mountain Rescue (N) uniform. Increases in the metabolic rate of 12 % or above proved to be significant ($p<0.05$) although it is difficult to give a specific threshold as there is a gap from the ArmyH2O (M) at 11.9 % (significant $p<0.05$) to the next lowest, ArmyVEST (L) (not significant) with a 8.7 % increase. Due to a large standard deviation, the Chemical (E) suit, with an average 13.4 % increase in metabolic rate, did not prove to be significant.

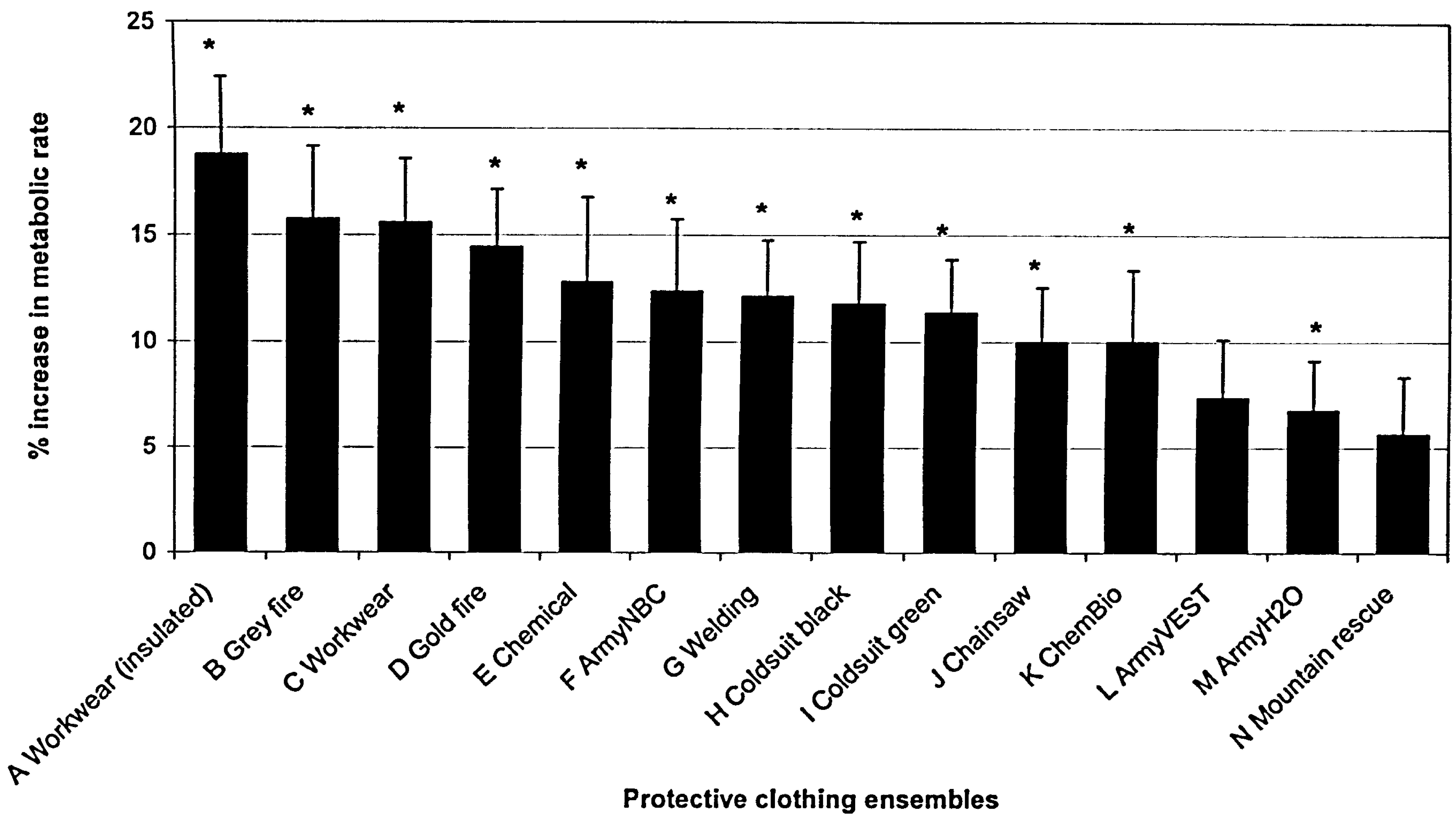


Figure 3.1. Overall average (n=6) percentage increase in metabolic rate relative to a control condition when wearing protective clothing during work. Significance ($p<0.05$) indicated by *.

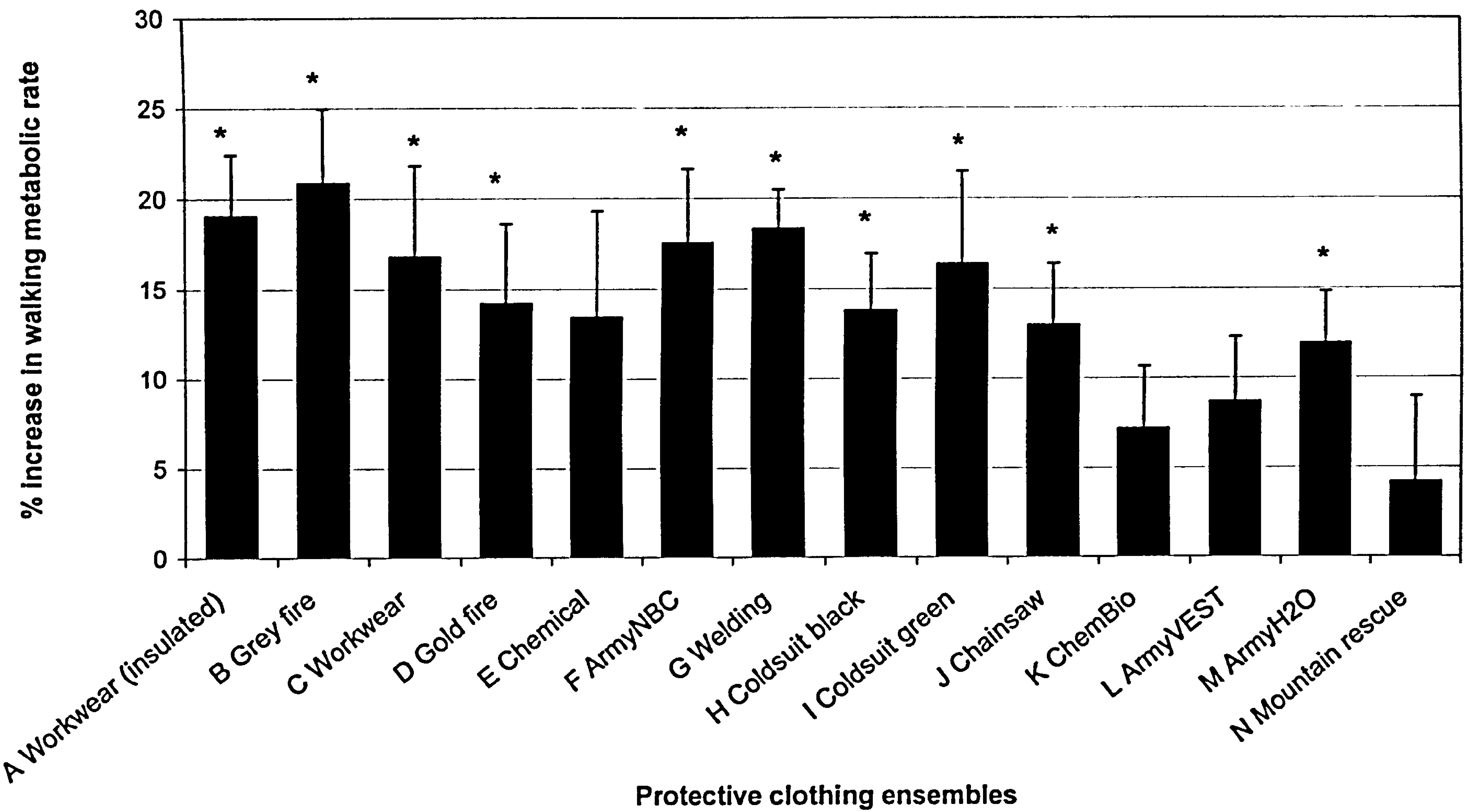


Figure 3.2. Average (n=6) percentage increase in metabolic rate relative to a control condition during walking. Significance ($p<0.05$) indicated by *

3.3.3 Stepping results

The results for the stepping work mode in Figure 3.3 show a similar pattern of increase to the overall results in Figure 3.1, with the highest increase recorded for the two workwear garments, Workwear (insulated) (A) and Workwear (C), 19.8 % and 14 %, and Grey fire ensemble (B) 14.5 %. The increases recorded for 6 other ensembles also reached significance, Gold fire (D) and Chemical (E), 12.2 % and 12.6 % respectively, Black coldsuit (H) and Green coldsuit (I), 11.1 % and 10.2 % respectively. A 10.1 % increase for the ArmyNBC (F) and 8 % for the Chainsaw (J) also proved to be significant but the 9.4 % increase from the Welding (G) ensemble did not reach significance probably due to a larger standard deviation.

3.3.4 Obstacle course results

In Figure 3.4 the results are presented, considering the percentage increase in metabolic rate for the garments when completing an obstacle course, which as detailed earlier included moving crates and moving under and over hurdles, all at a set pace. The pattern of increases is quite different to those seen in the above figures, especially Figures 3.1 and 3.3. The error bars are also larger with the individual increases recorded showing a wider range.

The Workwear (A, C) and Fire (Grey B, Gold D) ensembles, again proved to be significant, even though the increase recorded in the Grey fire (B) suit was only 11.8 %. The 17.1 % increase in metabolic rate noted for the ChemBio (K) ensemble, although in the range of the 15.9 – 17.4 % increases which were significant for the Workwear (A, C) and Fire (B, D) ensembles, was not significant, perhaps again due to a large standard deviation. Statistical analysis also returned significant differences (8.8-10.3%) in three other garments, Welding (G), Chainsaw (J) and Mountain rescue (N).

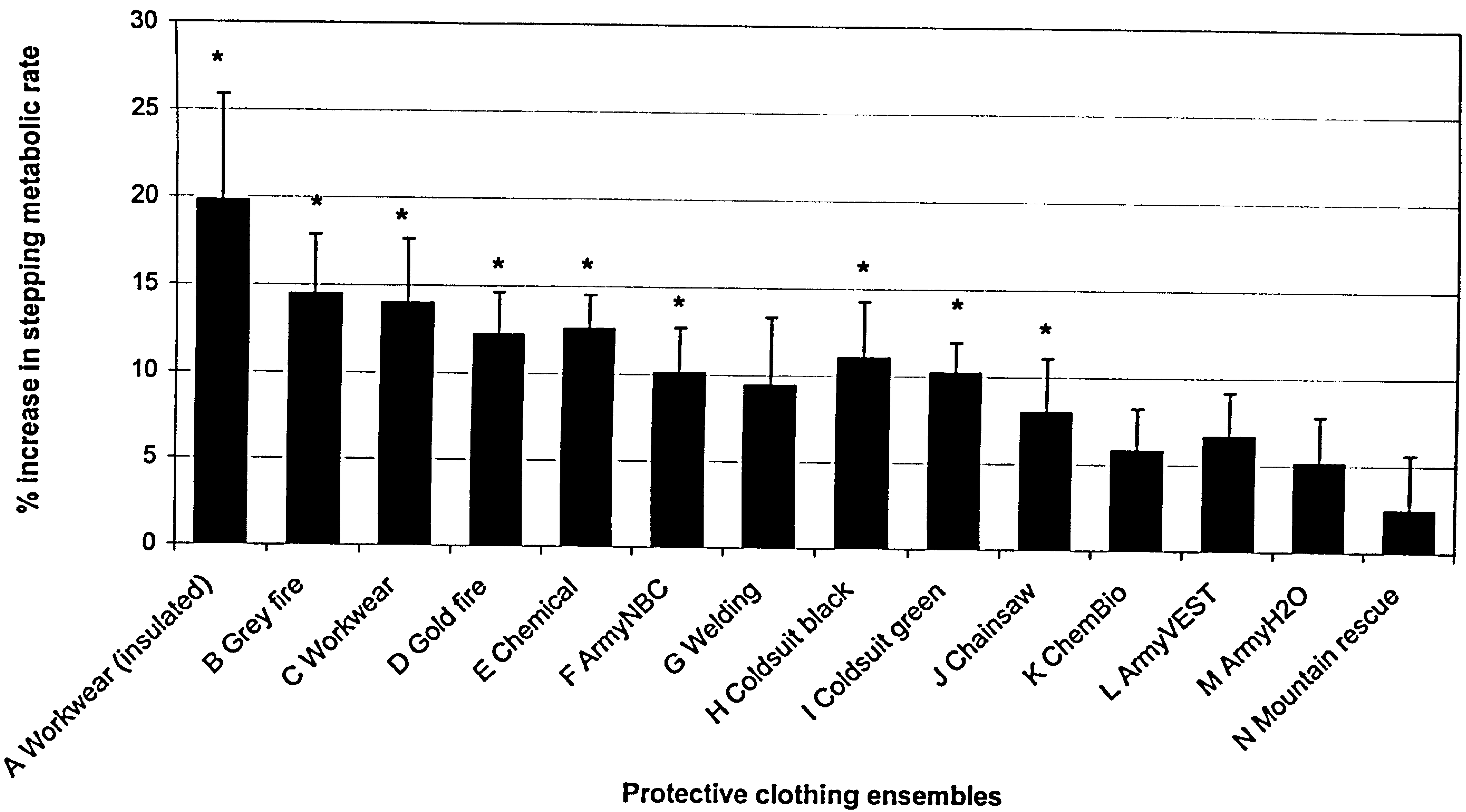


Figure 3.3. Average (n=6) percentage increase in metabolic rate relative to a control condition during stepping. Significance ($p<0.05$) indicated *.

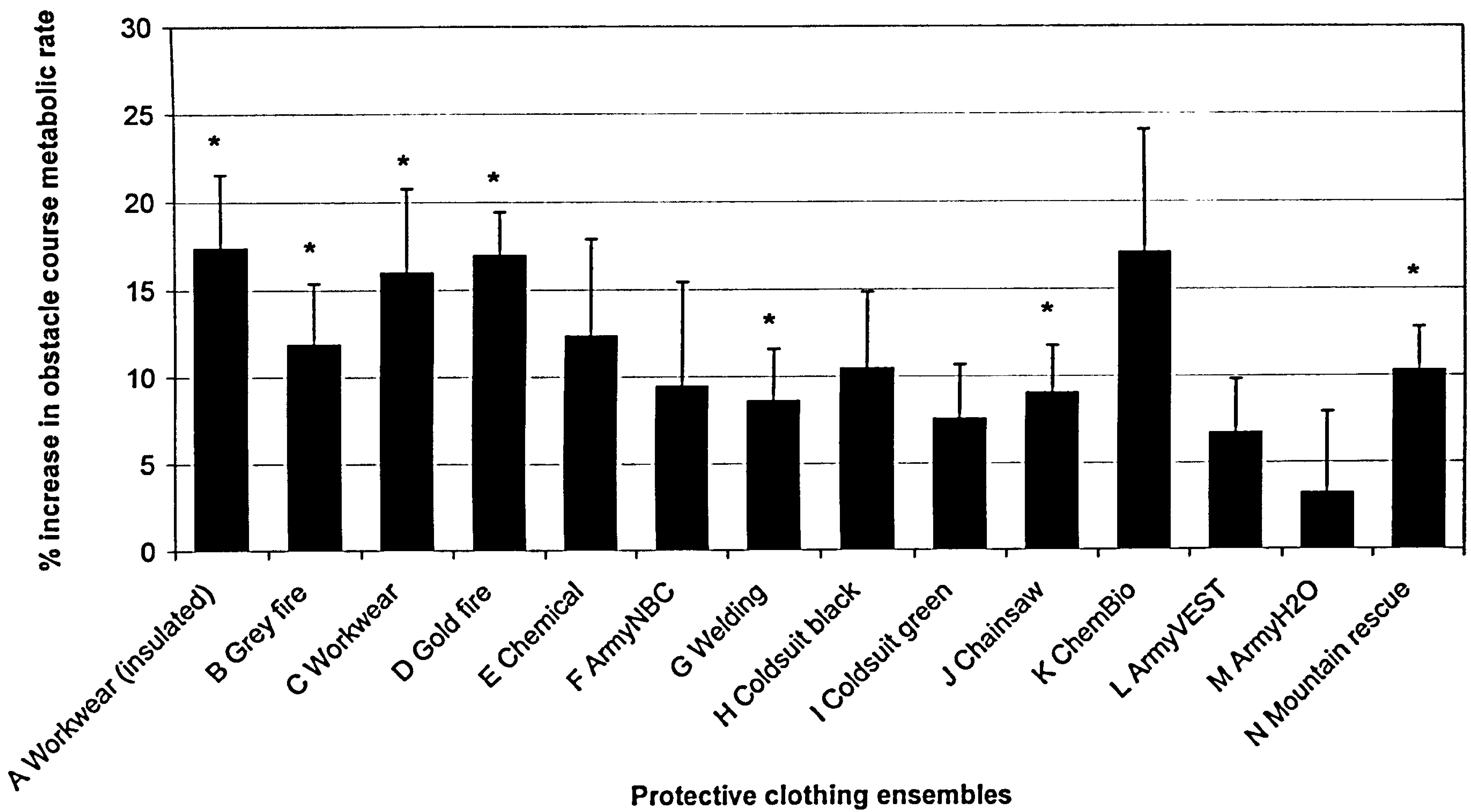


Figure 3.4. Average (n=6) percentage increase in metabolic rate relative to a control condition during obstacle course. Significance ($p<0.05$) indicated by *.

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In summary, the protective garments tested caused metabolic rate increases of 2.4–20.9 % above those recorded in a control condition. When walking the increases ranged from 4.2 % for the Mountain rescue (N) garment up to 20.9 % for the Grey fire (B) ensemble. For the stepping work mode the increases ranged from 2.4 % (Mountain rescue N) to 19.8 % (Workwear (insulated) A). The obstacle course caused increases in the region of 3.2 % for the ArmyH2O (M) combination to 17.4 % for the Workwear (insulated) (A) garment.

When the overall increase in metabolic rate is considered, the garments ranged from 5.6 % for the Mountain rescue (N) ensemble to 18.7 % for the Workwear (insulated) (A). Increases in metabolic rate of 10 % and above when compared to a control condition proved to be significant ($p<0.05$). When walking at 5 km/hr the threshold for significance was 11.9 %, but this was lower for the stepping and obstacle course work modes being 8 % and 8.8 % respectively.

The thresholds for significance can be seen to differ slightly with work mode. In Figures 3.1 to 3.4 there were 18 results in which the increase in metabolic rate in the clothing compared to the control were not significant, 2 for the overall average, 4 for the walking work mode, 5 for the stepping and 7 for the obstacle course. The statistical analysis was repeated, doubling the dataset to establish the effect of a larger sample (with the same spread in the data). Only 3 results remained non-significant, the 4.2 % and 2.4 % increases seen in the Mountain rescue (N) garment when walking and stepping respectively and the 3.2 % increase in the ArmyH2O (M) ensemble during the obstacle course.

The Workwear (insulated) (A), Workwear (C), Grey fire (B), Gold fire (D) and Chainsaw (J) ensembles caused significant ($p<0.05$) increases in the metabolic rate for all work modes and overall. The ArmyNBC (F), Coldsuit black (H) and Coldsuit green (I) produced significant ($p<0.05$) increases with the walking and stepping work modes and overall but not for the obstacle course activity. The Welding (G) ensemble produced significant increases when walking, carrying out the obstacle course and overall but not when stepping. The only garment not to show any significant increases with any of the work modes was the ArmyVEST (L).

3.4 Subjective results

As detailed in Chapter 2 (Methodology), participants were asked to rate their level of perceived exertion and thermal sensation in the final minute of each work period, these results are presented in Figures 3.5 and 3.6 respectively (the data is also given in table form in Appendix 2).

3.4.1 Rate of perceived exertion results

Figure 3.5 illustrates the Rate of Perceived Exertion responses, the actual scale ranges from 6, no exertion at all, to 20, maximal exertion, however responses recorded in this study fell in the range, 7 (extremely light) to 15 (hard), hence the abbreviated scale on the y-axis. During the control condition walking was on average perceived as very light (8.8), stepping as light (11) and the obstacle course between light and somewhat hard (11.9). The results for each protective ensemble are then plotted and a few will be highlighted. The general trend when wearing the protective clothing was the same as the control condition with the perception of exertion increasing for walking, stepping and the obstacle course respectively. However the levels of perceived exertion recorded were shifted upwards as perceived exertion was higher when the protective clothing was worn.

The 2 Fire suits, Grey fire (B) and Gold fire (D) caused the greatest shift in perceived exertion with the ratings recorded for walking, stepping and the obstacle course rising to 11.5, 13 (somewhat hard) and 14.5 – 15 (hard) respectively. The Chainsaw (J) and Coldsuit green (I) also caused large increases in the perceived exertion with values of 11.3, 13, 14 for each work mode respectively. At the other end of the spectrum, the ArmyH2O (M) and Mountain rescue (N) garments caused the smallest increases in perceived exertion, with ratings rising to only 10, 11.5 and 12.5 for the walking, stepping and obstacle course work modes compared to the control values of 9, 11 and 12 respectively. For the RPE ratings during the stepping all the garments except the ArmyH2O (M) and Mountain rescue (N) caused a significantly higher exertion rating than the control, these results are also highlighted in Figure 3.5. The ArmyH2O (M) and Mountain rescue (N) garments did not cause significantly increased RPE ratings during the obstacle course either.

3.4.2 Thermal sensation results

The results for Thermal Sensation seen in Figure 3.6 show that in the control condition, participants rated their thermal sensations as slightly cool – neutral (3.5) when walking, neutral – slightly warm (4.5) when stepping and slightly warm (5) when completing the obstacle course. When completing these activities in protective clothing the thermal sensations recorded were higher but followed the same trend, with the stepping increasing the participants thermal sensation above the values for walking and participants rating their thermal sensation the highest (warmest) during the obstacle course. For all the protective ensembles and all the work modes, the thermal sensations recorded were significantly higher than those recorded in the control conditions.

When walking in the protective clothing the range of thermal sensations recorded was 4.3 to 5.3, with 4 being neutral and 5 being slightly warm on the scale. For the stepping the range of thermal sensations recorded was 5 to 6.4, with 5 being slightly warm and 6 being warm. The thermal sensations were highest for the obstacle course ranging from 5.8 to 6.9 when wearing the protective clothing corresponding with 6 as warm and 7 as hot on the thermal sensation scale. The physiological stress of this perceived increase in thermal sensation is believed to be minimal as the duration of the work periods was 4 minutes for the walking and stepping, 6 minutes for the obstacle course and observation of the heart rate showed no significant upward drift, therefore a significant thermal effect on metabolic rate can be excluded.

The Gold fire (D) and 2 Coldsuit garments (black H and green I) were reported as increasing thermal sensation the most, slightly warm (5.3) when walking, and warm – hot (6.5 – 7) for stepping and the obstacle course.

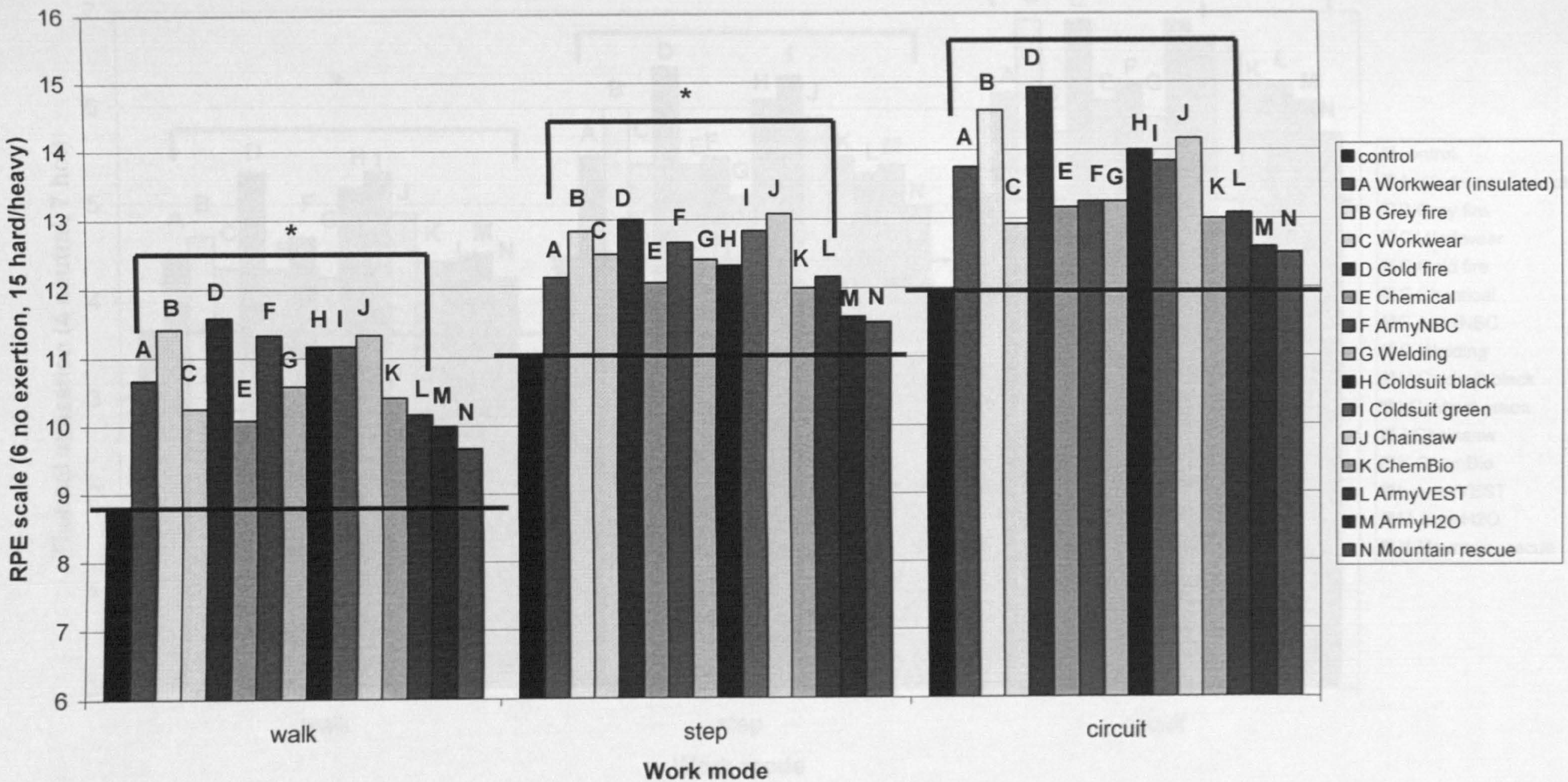


Figure 3.5. Rate of Perceived Exertion scores recorded for 3 work modes for all protective clothing. Significant difference from control ($p<0.05$) marked *.

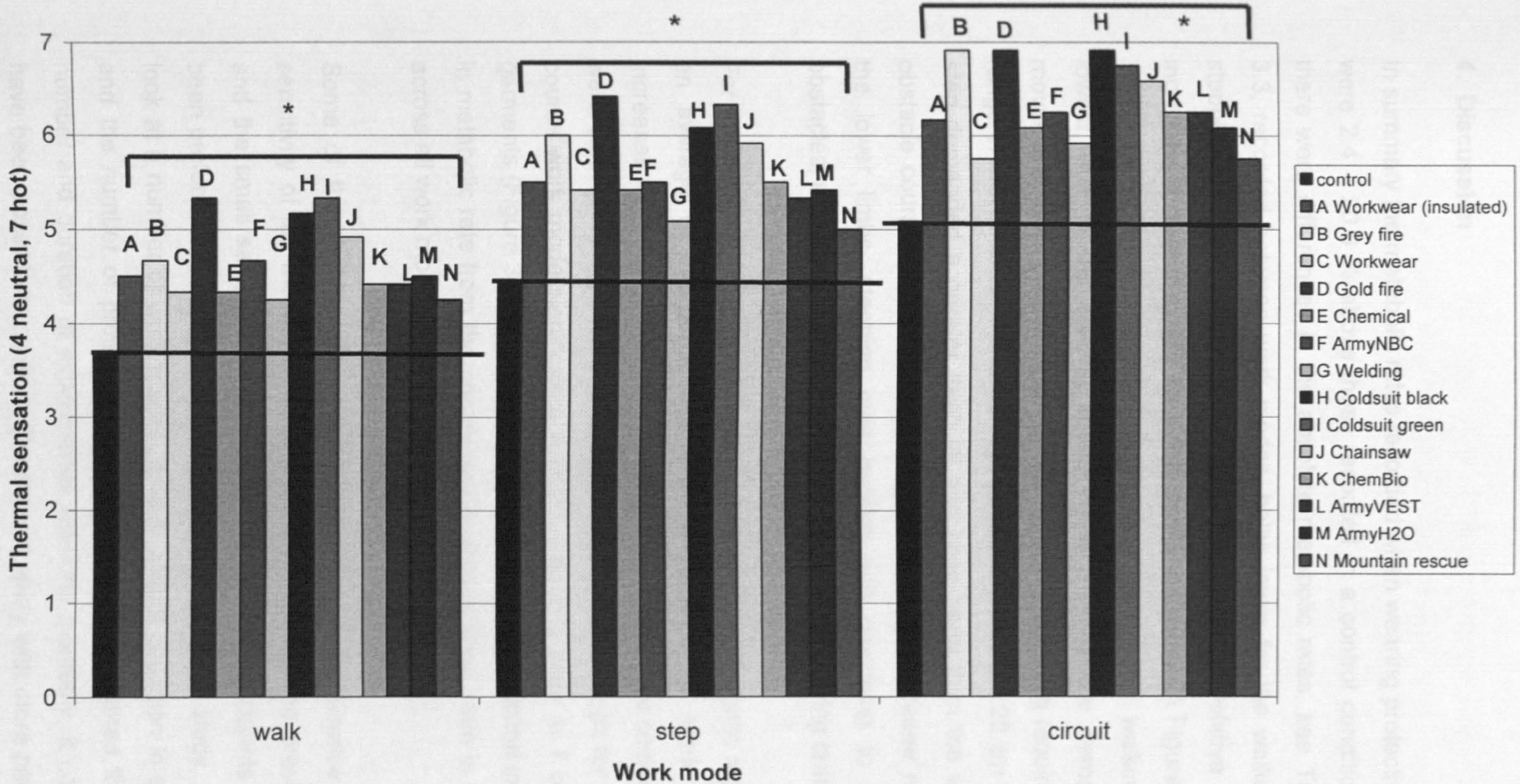


Figure 3.6. Thermal sensation scores recorded for 3 work modes for all protective clothing. All results significantly ($p<0.05$) different from control*.

4. Discussion

In summary the metabolic rates recorded when wearing protective garments were 2.4 – 20.9 % above those recorded in a control condition. Although there were differences in the absolute metabolic rates, see Tables 3.1 to 3.3, recorded between work modes, being lower for the walking than the stepping and obstacle course, the range in the relative percentage increases in metabolic rate were very similar as shown in Figures 3.1 to 3.4. The absolute metabolic rate results recorded for the walking were the lowest, due to the walking speed being 5 km/hr the demands of the movements were predominantly in the legs. The stepping required a greater range of movement in the lower legs as moving onto the 20 cm high aerobic step demanded a greater thigh lift and knee bend than the walking. The obstacle course was purposely designed to demand greater movement in the lower limbs, stepping over hurdles and crouching to bend under obstacles, as well as involving the upper body when moving crates.

For the calculated overall percentage increase in metabolic rate, based on an average of the percentage increase seen in all work modes, the increases from the control for 12 out of the 14 protective clothing garments were statistically significant ($p<0.05$) (Figure 3.1). Although for the obstacle course work mode significance ($p<0.05$) was only seen in 7 out of the 14 garments (Figure 3.4), wearing each of the garments resulted in an increase in metabolic rate from the control and increases were seen in all garments across all work modes (Figures 3.1 to 3.4).

Some of the results may have failed to reach significance due to the sensitivity of the method as discussed at the end of the previous chapter and the small sample size. A greater number of participants would have been preferred however the within-subject design of the study, the desire to look at a number of work modes, have a control condition in each session and the number of protective garments to be investigated increased the number and duration of experimental sessions markedly. It could certainly have been possible to continue the present study with more participants but it was decided on the basis of the number and size of the systematic positive results found that the aim of the present study had been met, significant increases in metabolic rate when wearing protective clothing compared to a control had been shown and the focus would now move forward to new studies that would try and investigate the factors contributing to the increases.

The two fire suits, Grey fire (B) and Gold fire (D) had significant ($p<0.05$) effects on the metabolic rate of the wearer in all work modes. They were also the two heaviest garments to be tested. Walking in the Grey fire (B) suit (7.00 kg) elicited a 21 % increase, 14 % in the Gold fire (D) suit (6.66 kg), whilst stepping increased the metabolic rate by 15 % in the Grey fire (B) and 12 % in the Gold fire (D). These figures are similar to those reported by Graveling and Hanson (2000) from laboratory trials where standard firefighter clothing typically increased physiological cost (oxygen consumption) by 15 % over control sessions.

The ArmyNBC (F) and ArmyVEST (L) garments also showed interesting results. The ArmyNBC (F) ensemble was made up of a shirt, combat trousers and army boots with NBC jacket and trousers over the top plus overboots and gloves, total weight 5.27 kg. The ArmyVEST (L) ensemble was made up of base layer (top and bottoms), combat trousers, shirt, protective vest and army boots and weighed 5.32 kg. Even with very similar total clothing weights the percentage increase values for the ArmyVEST (L) ensemble were only 9 % when walking and 7 % when stepping compared to the significant ($p<0.05$) increases of 18 % when walking and 10 % when stepping in the ArmyNBC (F). The ArmyNBC (F) ensemble is made up of a number of layers which increase the weight where as the vest accounts for 2.45 kg of the total weight in the ArmyVEST (L) ensemble, and this weight is centred around the torso. So the distribution of the clothing weight and the number of clothing layers may also be important factors which affect how easily and efficiently work can be performed. In the above example it seems that when the weight was carried around the torso in the ArmyVEST (L) ensemble it had a smaller impact on movement and the effect on the metabolic rate was much lower than the ArmyNBC (F) where the extra bulk and layers may have caused increases in metabolic rate due to a hobbling effect or friction drag which have been proposed by other authors, this was discussed in the literature review (Chapter 1).

Experimental studies have demonstrated that the metabolic cost of walking, without external load, is linearly related to the weight of the body. These studies have also demonstrated that the metabolic cost of carrying normal loads on the trunk is the same as that of carrying an equivalent additional weight of the body itself. If bodyweight and the weight of external loads are combined, the metabolic cost of walking at any speed is then expressed as a linear function of the total weight (Givoni and Goldman 1971).

Givoni and Goldman (1971) devised an equation for calculating metabolic rate (M) which is included below and has been used to calculate a theoretical line for the increase in metabolic rate when walking at 5 km/hr carrying an additional weight from 1 to 10 kg (using participant average bodyweight of 70.7 kg, see Table 2.1), the results are shown in Table 4.1 and the theoretical line is included in Figure 4.1, along with the clothing data points from the present study and a line of best fit.

$$M = 1.5\,(wgt) + 2(wgt + @load) * \left(\frac{@load}{wgt}\right)^2 + 1.5 * \# * \left((wgt + @load)(V^2) + 0.35(V * G)\right)$$

wgt	=	**NUDE BODY WEIGHT in kg**
@load	=	**Added load weight in kg**
V	=	**SPEED in meters per second**
#	=	**1 if terrain is treadmill**
G	=	**GRADE in % rise; level = 0**

Givoni and Goldman (1971).

Table 4.1. Theoretical metabolic cost of carrying added load calculated using the equation of Givoni and Goldman (1971) and using a body weight of 70.7 kg.

added load (kg)	met rate (W)	% increase in metabolic cost
0	314	
1	317	1.0
2	320	1.9
3	323	2.9
4	326	3.8
5	330	5.1
6	333	6.1
7	336	7.0
8	340	8.3
9	343	9.2
10	347	10.5

In Figure 4.1 the percentage increase in metabolic rate and weight of all 14 protective garments are plotted, a linear regression line for this relationship is provided. There is a clear trend in Figure 4.1 that heavier garments cause a greater increase in walking metabolic rate. It is evident that the weight of the protective garments has an effect on the metabolic rate as the % increase per kg for the clothing (based on the linear regression line) is higher than the line for the theoretical relationship for just the weight. The clothing increases corrected for clothing weight are detailed in Table 4.2.

The slope of the linear regression line for clothing in Figure 4.1 shows that for the present study, an increase in energy consumption of 2.7 % per kg of clothing weight was observed while a theoretical prediction purely on weight would predict only 1 % per kg added weight (Table 4.1). The observed value is close to that found by Rintamaki (2005) of 3 % per kg.

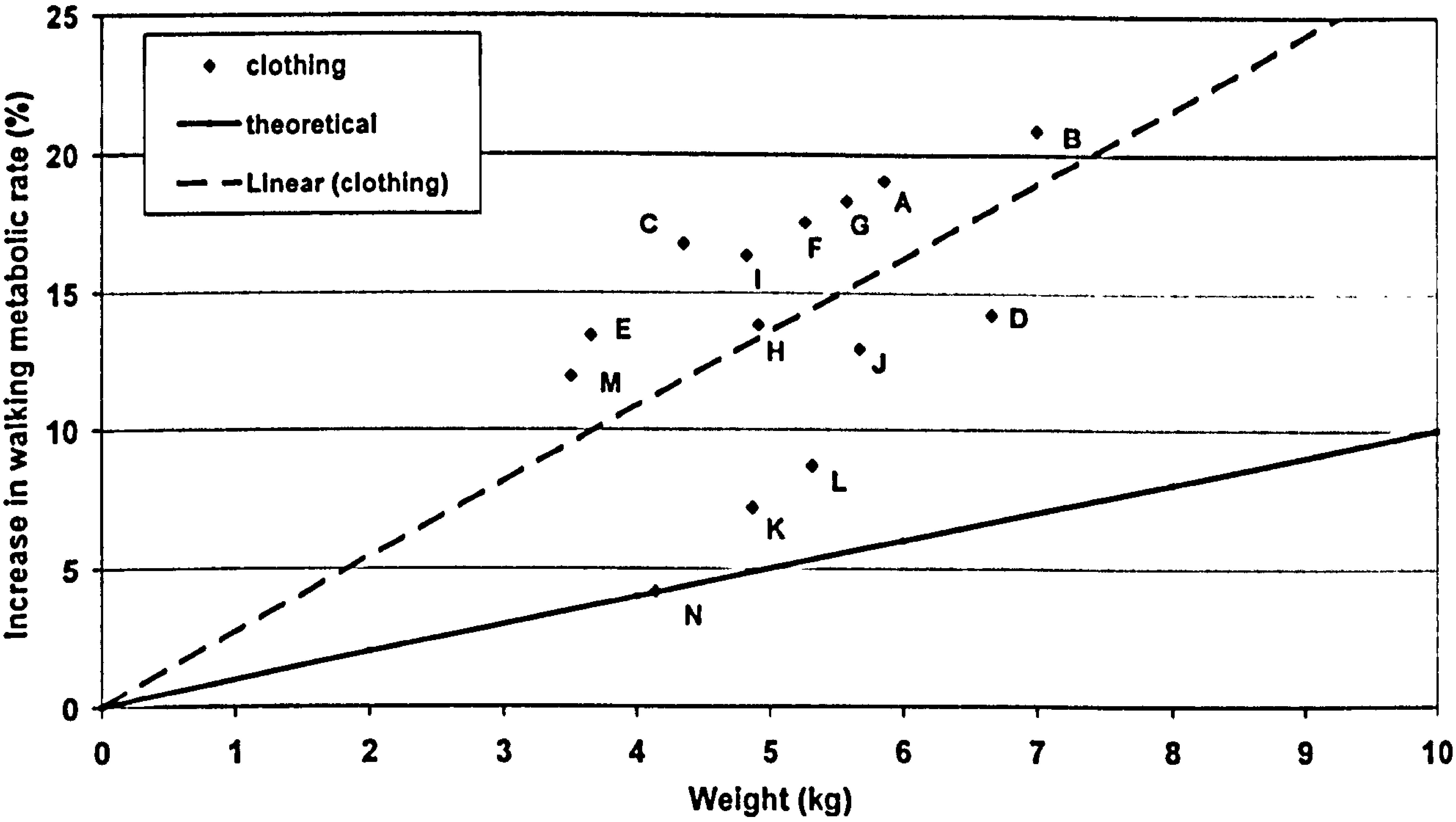


Figure 4.1. Graph to illustrate metabolic rate increase recorded in relation to the weight of protective clothing garments, as well as the theoretical implication (using Givoni and Goldman (1971) equation) of carrying additional weight to metabolic rate. See Table 4.2 for garment labels.

It was observed that heavier garments tended to cause higher metabolic rate values and further analysis showed a positive relationship between the garment weight and metabolic rate increase of 2.7 % per kg clothing weight. This is considerably higher than the calculated theoretical cost of an additional 1 % per kg of added load. Some garments seem to be more expensive in terms of metabolic cost for their weight than others, for example, the ChemBio garment (K) had a much lower increase in metabolic rate than the Coldsuit garments (H and I), with all being a similar weight.

The significant values recorded in this study can be compared with the results of a number of studies highlighted in the introduction. The values in Table 4.2 are very comparable to the to 6-11 % weight corrected $\dot{V}O_2$ increases reported by Patton *et al.* (1995), the 9 % increase in $\dot{V}O_2$ during stepping of Duggan (1988) and the 16 % increase in metabolic cost during walking in a 5 layer arctic ensemble (11.2 kg) found by Teitlebaum and Goldman (1972).

Table 4.2. Weight corrected values for increase in metabolic rate from control.

A Workwear (insulated)	13 %
B Grey fire	14 %
C Workwear	12 %
D Gold fire	8 %
E Chemical	10 %
F ArmyNBC	12 %
G Welding	13 %
H Coldsuit black	9 %
I Coldsuit green	12 %
J Chainsaw	7 %
K ChemBio	2 %
L ArmyVEST	3 %
M ArmyH2O	8 %
N Mountain rescue	0 %

5. Chapter summary

The present study has shown that protective clothing ensembles from a variety of industries increase the metabolic cost of walking, stepping and completing an obstacle course including lifting and moving crates, crawling on hands and knees, and moving under and over obstacles. The garments tested caused metabolic rate increases of 2.4 to 20.9 % compared to a control condition. In addition, significant ($p<0.05$) increases were seen in the Rating of Perceived Exertion and Thermal Sensation when wearing many of the protective garments. The results for the fire and army ensembles have been explored as these are the types of garments that have been previously studied. The results in the present study fit with those documented in the literature.

More detail is needed to assess the contribution of the garment weight and its distribution to the observed increases in metabolic rate wearing the protective clothing ensembles. This will allow a better understanding of the scale of the contribution weight makes to the overall increases in metabolic rate recorded.

CHAPTER 4

STUDY 2

EFFECTS OF SIMULATED WEIGHT DISTRIBUTIONS ON METABOLIC RATE

1. Introduction

Protective clothing is worn in many industrial and military situations. Although worn for protection from one or more hazards, the clothing can have secondary effects which may limit the ability of the worker to perform the tasks required of the job. As demonstrated in the previous chapter, increases in energy consumption of 10 to 20 % are not uncommon. A small number of other results in this range have been reported in the literature along with suggestions that the additional clothing weight of the protective garments may be contributing to the observed increases. However, despite these proposals little investigation has been undertaken. In the previous chapter a plot of the percentage increases in metabolic rate in relation to the garment weight, fitted with a linear regression line resulted in a 2.7 % increase in metabolic rate per kg of clothing weight, which is considerably higher than would be predicted for carrying load.

1.1 Previous research

A number of studies have shown that various protective clothing ensembles increase the metabolic cost of walking and stepping by adding weight (Teitlebaum and Goldman 1972, Duggan 1988, Patton *et al.* 1995). Murphy *et al.* (2001) also cited the additional weight and bulkiness of chemical protective clothing contributing to performance degradation in stationary, intermittent and continuous tasks, when wearing chemical protective clothing (CPC) weighing 9.3 kg compared to standard battledress uniform (BDU) weighing 3.7 kg. They report the difference in energy cost between the CPC and BDU was significantly higher in the continuous tasks. Even after normalising $\dot{V}O_2$ for clothing weight, the differences between the garments for the continuous tasks was still significant. The CPC garment had little impact on the tasks of a stationary or intermittent nature. Nunneley (1989) also commented on the fact that the effect of added weight on work load depends in part upon the task, citing the example of a heavy suit posing little problem for a stationary worker but presenting a severe handicap for a firefighter climbing a ladder or stairwell.

Experimental studies have demonstrated that the metabolic cost of walking, without external load, is linearly related to the weight of the body (Goldman and Iampietro 1962; Givoni and Goldman 1971). When dressed in protective clothing the energy cost of walking is dependent on various aspects; weight, number of layers and motion restriction (Lotens 1982). Heavy fabrics will show their impact in several ways. The weight of the garment has to be carried and increases the energy cost. With clothing it is obvious that some weight is moved out on to the extremities towards the hands and feet (Lotens 1988b). Soule and Goldman (1969) have demonstrated that the metabolic cost of load carriage increases when the load is placed in the hands or on the feet, i.e. away from the centre of gravity of the body. Weight on the extremities of the body has to be accelerated and decelerated at every step, causing an even higher increase in energy cost. As Nunneley (1989) suggests, the increased metabolism when weight is carried on the legs and feet is probably due to the cyclic up-and-down displacement of the lower limbs, which produces internal heat without measurable external work.

In the Soule and Goldman study (1969) they used 20 minutes of treadmill walking at 4, 4.8 and 5.6 km/hr. Subjects carried 1) no load, 2) 4 or 3) 7 kg on each hand, 4) 6 kg on each foot or 5) 14 kg on the head. The energy cost (expressed as millilitres of oxygen per minute per kg of total weight (man+clothing+load)) of carrying the load on the hands at 4 and 4.8 km/hr was 1.4 times the expected cost per kg of the no load condition for the 4 kg condition and 1.9 times for the 7 kg condition. At 5.6 km/hr the cost per kilogram of the 4 and 7 kg loads on the hands was 1.9 times higher. The cost expressed per kg of load carried on the feet was 4.2 times higher at 4 km/hr, 5.8 times at 4.8 km/hr and 6.3 times at 5.6 km/hr (Soule and Goldman 1969). Soule and Goldman (1969) note that loads 3), 4) and 5) represented a maximum for their subjects. Overall the loads used in their study are unrealistic in relation to clothing weights. However it is important to remember this study was carried out 35 years ago and there had been no careful comparison of the energy costs of carrying weights on the head, hands and feet. The authors describe developments in wrist / helmet radios, and helmet-suspended binoculars which explains the loads and sites they studied (Soule and Goldman 1969).

In the sports science literature a number of studies have looked at the aerobic responses of walking and running with hand, wrist and ankle weights, including Francis and Hoobler (1986), Auble *et al.* (1987), Graves *et al.* (1988) and Claremont and Hall (1988). However research findings regarding the effects of handweights are mixed. There are ambiguous findings due to variations in the combinations of walking or running speed and handweight used. The magnitude of the effect of handweights on the energy costs of exercise are most closely related to variations in arm movement patterns.

Clothing and other protective garments decrease performance due to their weight, bulkiness and friction. Clothing can therefore impair manual dexterity, decrease the range of movements and increase energetic costs of work. Each additional kg in clothing weight increases energy costs by approximately 2.7 % (previous chapter) to 3 % (Rintamaki 2005). Increased energy costs are associated with a decrease in physical performance, which is often task specific, and roughly equal to the changes in energy costs. The decrement in performance can be minimised by decreasing clothing weight and bulkiness (Rintamaki 2005).

For the military, one of the most relevant aspects of clothing is the decrement in performance but many of the trials that have tried to investigate these issues have done so in very artificial environments (Lotens

1988a). However, in general, tests show a dependency of performance on clothing / load weight and a strong correlation between performance decrement and increased energy cost (Lotens 1988a).

In summary, there has been very little investigation of the effects of load / weight distribution on energy cost, since Soule and Goldman highlighted the issue in their paper in 1969. However the loads employed in their study were extreme and planned to represent the weight of wrist and helmet mounted equipment rather than clothing.

1.2 Aims

The purpose of this trial, was to look at the effects of carrying more realistic simulated clothing weight distributions close to the body centre of gravity (using a weight belt) and at the extremities (weights worn around the wrists and ankles). The metabolic rate was measured as participants walked, stepped and completed an obstacle course.

Therefore the aims of this study are;

- To investigate the energy cost of carrying simulated clothing weight on combinations of the ankles, wrists and waist with the hypothesis that the further away from the body core the weight is positioned, the higher the resulting energy cost during work. The most expensive position for the weight in terms of energy cost is expected to be the ankles, followed by the wrists and then the waist.
- To investigate the effect of carrying the simulated clothing weights during different work modes, for example walking and completing an obstacle course. The hypothesis is that the energy cost of the extremity weight conditions (ankles and wrists) will be higher in activities requiring greater ranges of movement of the limbs supporting the weight, in this case the obstacle course compared to walking.

2. Methods

2.1 Participants

Eight participants (4 male, 4 female) completed the trial. They were all volunteers drawn from the student population at Loughborough University. Their physical characteristics are detailed in Table 2.1 below.

Table 2.1. Participant details.

Participant no.	Gender M / F	Age years	Height cm	Weight kg
1	F	29.6	168	57
2	M	18.8	183	106
3	F	26.8	150	59
4	F	21.9	171	59
5	M	21.0	171	63
6	M	24.3	180	67
7	M	21.6	180	75
8	F	25.3	172	70
Average ± SD		**23.7 ± 3.5**	**171.9 ± 10.4**	**69.5 ± 16.0**

Participants were made fully aware in writing of all experimental details (including time demands, measurements to be taken, protocol and all other procedures). Before participating each participant was required to complete an 'Informed Consent' form and a 'Generic Health Screen for Study Volunteers' which provided information on their general health and fitness.

2.2 Weight simulations

For the waist the weight simulations were achieved using a simple diving belt and diving weights (Tribord, Decathlon). As it was easy to alter the weight, the weights could be positioned and taped in such a way that they did not move about and it was a comfortable fit around the waist. An army webbing system was also trialled however some of the weight carried in that way is supported by the shoulders and the webbing pouches were too bulky and got in the way during the crawling and bending phases of the obstacle course.

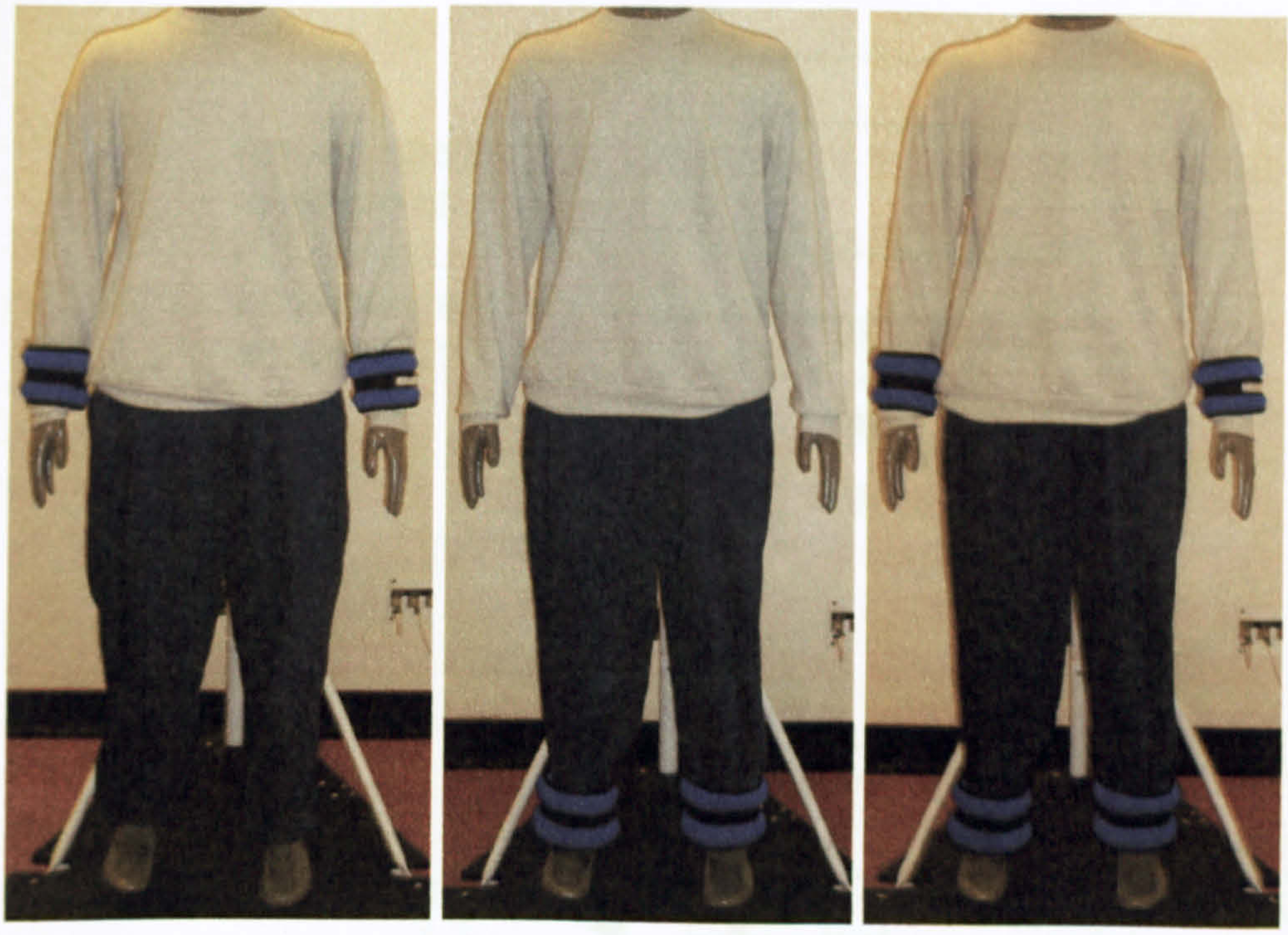
11 weight conditions were defined for the study. Weights of 2, 4, 6, 8, 10 kg were carried around the waist. 1 and 2 kg weights with velcro fastenings (Domyos, Decathlon) were carried around the ankles and wrists, the conditions being ankles 2 (1 kg on each ankle), ankles 4 (2 kg on each ankle), wrists 2 (1 kg on each wrist), wrists 4 (2 kg on each wrist), ankles/wrists 4 (1 kg on each ankle and wrist) and ankles/wrists 8 (2 kg on each ankle and wrist). For all conditions including the control (unweighted condition) participants wore lightweight tracksuit trousers and a sweatshirt which were provided, and their own trainers. See Figure 2.1 for photographs of the weight distributions.

2.3 Work modes

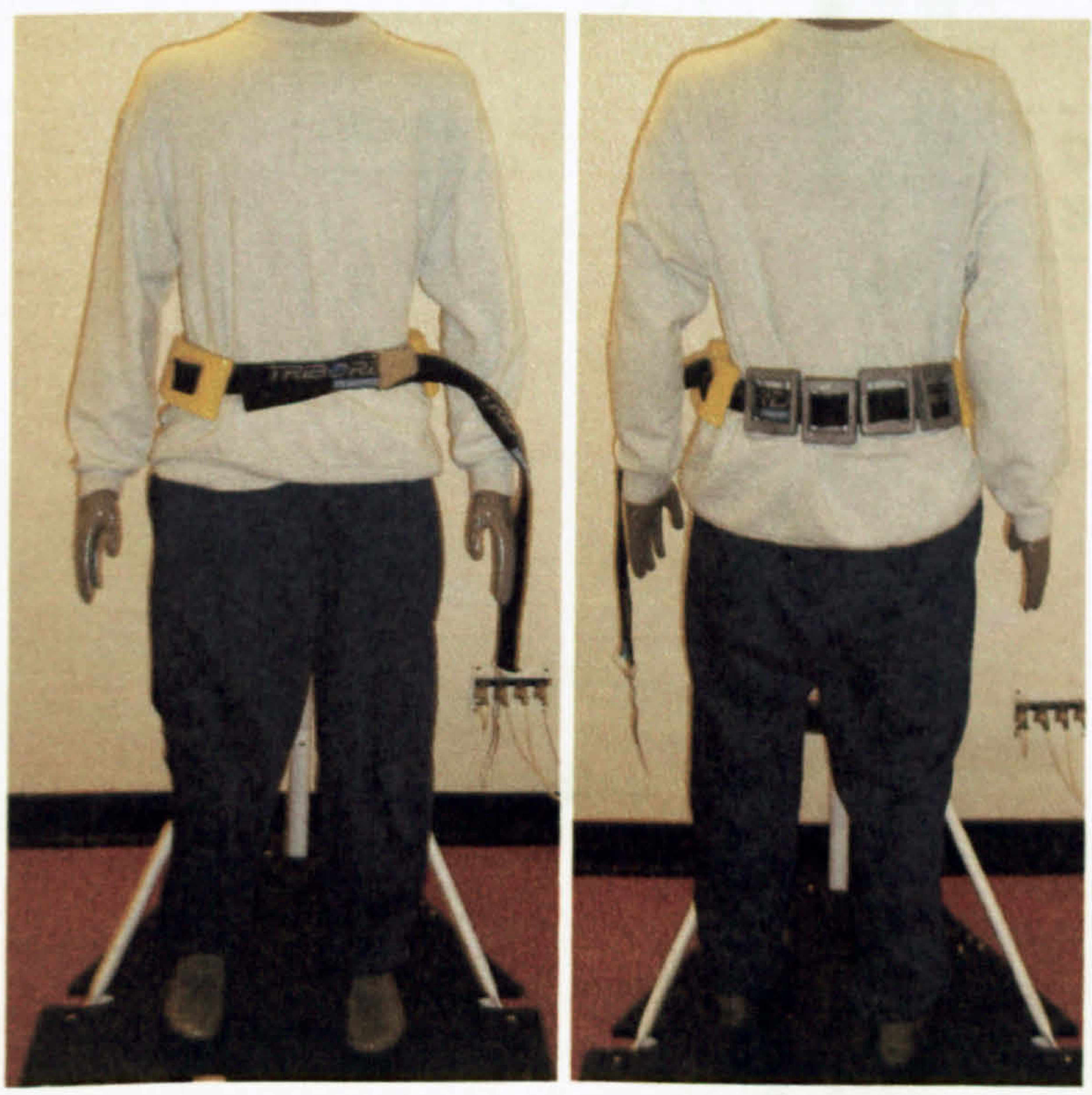
Participants completed 2 work modes for each condition. They were required to walk on a treadmill (h/p/cosmos mercury, Germany) for 4 minutes set at a speed of 5 km/hr, then complete 6 minutes of an obstacle course circuit. The circuit included moving crates containing 5 kg, walking over some steps, ducking and crawling under a hurdle and stepping over another hurdle. This was repeated for 6 minutes with participants speed controlled by a metronome and verbal counting. Photographs and descriptions of the work modes are provided in Chapter 2 (Methodology).

2.4 Floor plan and details

A detailed floor plan for the obstacle course is included in Figure 2.2 with the shapes described in Chapter 2 (Methodology). As previously explained participants completed the obstacle course circuit continuously for 6 minutes. The arrows show the direction of movement, following the white arrows first, participants moved the crates between the tables and floor as detailed in Table 2.3 in Chapter 2, they then stepped over the two stage step, stepped over a low hurdle, crawled under the high hurdle and touched the wall. The black arrows now show that they passed back under the high hurdle, over the low hurdle and the two stage step before walking back to the start.



Wrist weights | Ankle weights | Ankle and wrist weights



Waist weights (front view) | Waist weights (back view)

Figure 2.1. Photographs of the weight distributions used.

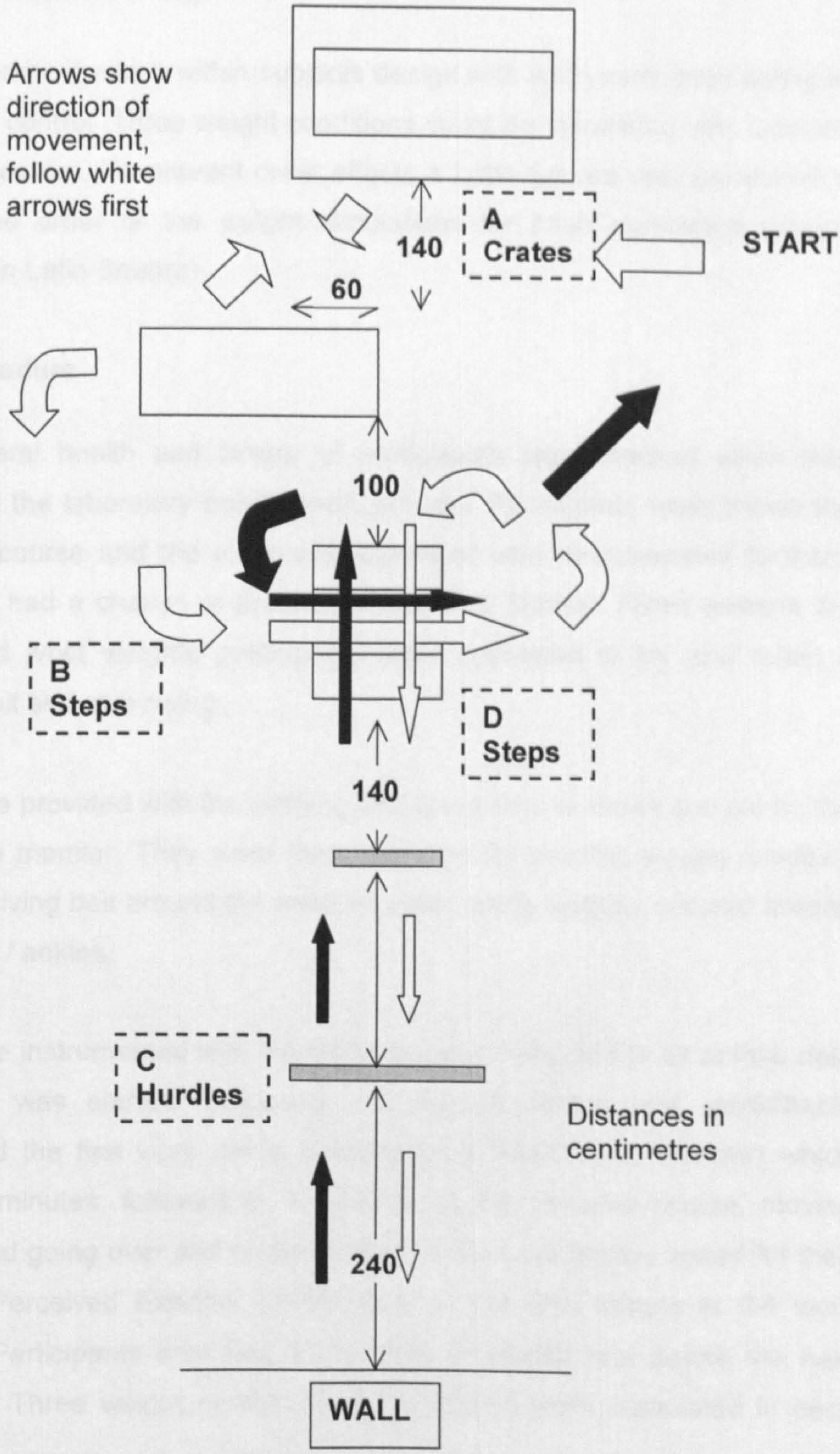


Figure 2.2. Floor plan for the obstacle course completed. A key for the shapes used can be found in Table 2.3, Equipment section, Chapter 2. For extra explanation of boxes with dashed lines, see detailed task descriptions in Table 2.3, Equipment section, Chapter 2, including photographs.

2.5 Experimental design

The experiment was a within-subjects design with each participant acting as their own control. Three weight conditions could be completed with a control in each session. To prevent order effects a Latin Square was generated to assign the order of the weight simulations for each participant (control included in Latin Square).

2.6 Procedure

The general health and fitness of participants was checked when they arrived at the laboratory before each session. Participants were shown the obstacle course and the route was described and demonstrated to them, they also had a chance to practice before they started. When wearing the ankle and wrist weights participants were instructed to try and retain a normal gait and arm swing.

They were provided with the clothing and given time to dress and put on the heart rate monitor. They were then prepared for the first weight condition with the diving belt around the waist or wrist / ankle weights secured around the wrists / ankles.

They were instrumented with the MetaMax and instructed to sit at rest, data collection was started. Following a 5 minute seated rest, participants completed the first work mode (walking on a treadmill at 5 km/hr) which lasted 4 minutes, followed by 6 minutes of the obstacle course, moving crates, and going over and under hurdles. They were always asked for their Rate of Perceived Exertion (RPE) score in the final minute of the work periods. Participants then had 10 minutes of seated rest before the next condition. Three weight conditions and a control were completed in each session.

3. Results

3.1 Participants and environment

8 participants (4 males, 4 females, age 23.7±3.5 years, height 171.9±10.4 cm, weight 69.5±16 kg) completed the test for 11 weight conditions. The average environmental conditions for the room were 17.9±0.1 °C and 43±2 % relative humidity.

3.2 Absolute results

The absolute values for all the weight conditions for walking and the obstacle course are shown in Tables 3.1 and 3.2 respectively. For each condition average and standard deviations are given for heart rate, oxygen consumption ($\dot{V}O_2$), respiratory exchange ratio (RER) and metabolic rate. The averages and standard deviations are for each condition are based on the final 2 minutes of steady state data from each of the 8 participants.

The figures in the tables are not the same as those that will be seen in subsequent graphs. The figures in the tables are an average of, for example the metabolic rate of all participants when walking with 4 kg on the wrists. However the figures in the graphs take account of the control conditions, and are based on an average of each participants % increase data (which is derived from comparing the weight condition to the control condition of the same experimental session).The graph data is included in Appendix 3.

Table 3.1. Absolute results when walking at 5 km/hr for control and 11 weight conditions.

WALK		Heart Rate	$\dot{V}O_2$	RER	Met Rate	Met Rate
		[bpm]	[l/min]		[W]	[W/m^2]
control	ave	97	0.89	0.87	303.4	167.2
	SD	10	0.18	0.08	58.4	23.7
waist 2	ave	97	0.89	0.85	299.7	165.7
	SD	13	0.16	0.08	54.3	23.4
waist 4	ave	102	0.98	0.84	328.3	179.4
	SD	6	0.19	0.11	59.3	19.7

waist 6	ave	98	0.93	0.85	314.6	173.7
	SD	15	0.20	0.08	63.3	25.9
waist 8	ave	101	1.00	0.84	337.4	186.7
	SD	6	0.17	0.09	55.3	22.7
waist 10	ave	103	1.00	0.87	338.8	187.9
	SD	9	0.20	0.09	64.9	31.8
ankles 2	ave	99	0.96	0.83	323.6	178.1
	SD	12	0.22	0.09	70.5	26.8
ankles 4	ave	102	0.97	0.87	328.0	181.0
	SD	9	0.22	0.07	71.3	29.8
wrists 2	ave	100	0.92	0.84	309.5	176.3
	SD	6	0.20	0.11	61.4	20.8
wrists 4	ave	100	0.93	0.83	313.6	173.5
	SD	9	0.16	0.09	49.9	20.4
ank/wris 4	ave	102	0.99	0.82	331.2	182.4
	SD	10	0.22	0.05	72.0	28.1
ank/wris 8	ave	106	1.04	0.84	350.5	192.7
	SD	8	0.16	0.08	52.0	23.9

Table 3.2. Absolute results when completing an obstacle course in control and 11 weight conditions.

OBSTACLE COURSE		Heart Rate [bpm]	$\dot{V}O_2$ [l/min]	RER	Met Rate [W]	Met Rate [W/m^2]
control	ave	123	1.31	0.87	444.5	245.5
	SD	10	0.21	0.06	70.1	27.1
waist 2	ave	123	1.33	0.86	451.6	250.6
	SD	12	0.16	0.06	54.1	23.0
waist 4	ave	127	1.43	0.86	482.6	264.5
	SD	11	0.26	0.06	85.2	35.1
waist 6	ave	133	1.44	0.88	490.6	272.4
	SD	16	0.18	0.08	58.3	26.4
waist 8	ave	127	1.47	0.89	503.5	279.0
	SD	9	0.21	0.07	72.0	30.7
waist 10	ave	126	1.47	0.91	502.6	279.4
	SD	12	0.23	0.08	76.3	41.2
ankles 2	ave	128	1.43	0.87	487.0	269.5
	SD	15	0.26	0.05	82.8	36.0
ankles 4	ave	127	1.42	0.92	487.3	270.4
	SD	11	0.24	0.06	76.2	37.1
wrists 2	ave	125	1.34	0.86	455.4	260.6
	SD	8	0.23	0.06	74.6	31.2
wrists 4	ave	131	1.41	0.90	481.3	265.7
	SD	11	0.29	0.08	95.1	38.6
ank/wris 4	ave	131	1.44	0.87	488.4	270.3
	SD	13	0.26	0.04	85.6	37.8
ank/wris 8	ave	134	1.49	0.90	507.9	280.2
	SD	10	0.17	0.08	55.0	32.8

3.3 Metabolic rate results

The following graphs illustrate the results for the walking, obstacle course and overall (average of data collected when walking and completing obstacle course) data, in Figures 3.1, 3.2 and 3.3 respectively.

3.3.1 Walking

As weight carried around the waist increased in 2 kg increments from 2 kg up to 10 kg there was a stepped increase in metabolic rate. Figure 3.1 shows that 2 kg around the waist caused a 3 % increase in metabolic rate, with the increase rising to 6, 8 and 9 % for 4, 6 and 8 kg respectively, with the highest increase of 10 % for the 10 kg condition.

When the weight was carried on the ankles the increases in metabolic rate were recorded as 8 and 11 % for 2 and 4 kg respectively. These increases were higher than the 3 and 6 % increases for the same weight when distributed around the waist. The increases for the ankle conditions were also higher than those recorded when the weight was carried around the wrists, 7 and 6 % for the 2 and 4 kg conditions respectively.

When the weight was distributed over the ankles and wrists the increases in metabolic rate were recorded as 9 % for 4 kg (1 kg on each limb) and 17 % for 8 kg (2 kg on each limb). The increase for the 4 kg condition is larger than when the weight is distributed on the waist or around the wrists but smaller than when it is carried only on the ankles.

The metabolic rate recorded in all conditions was significantly ($p<0.05$) higher than in the control.

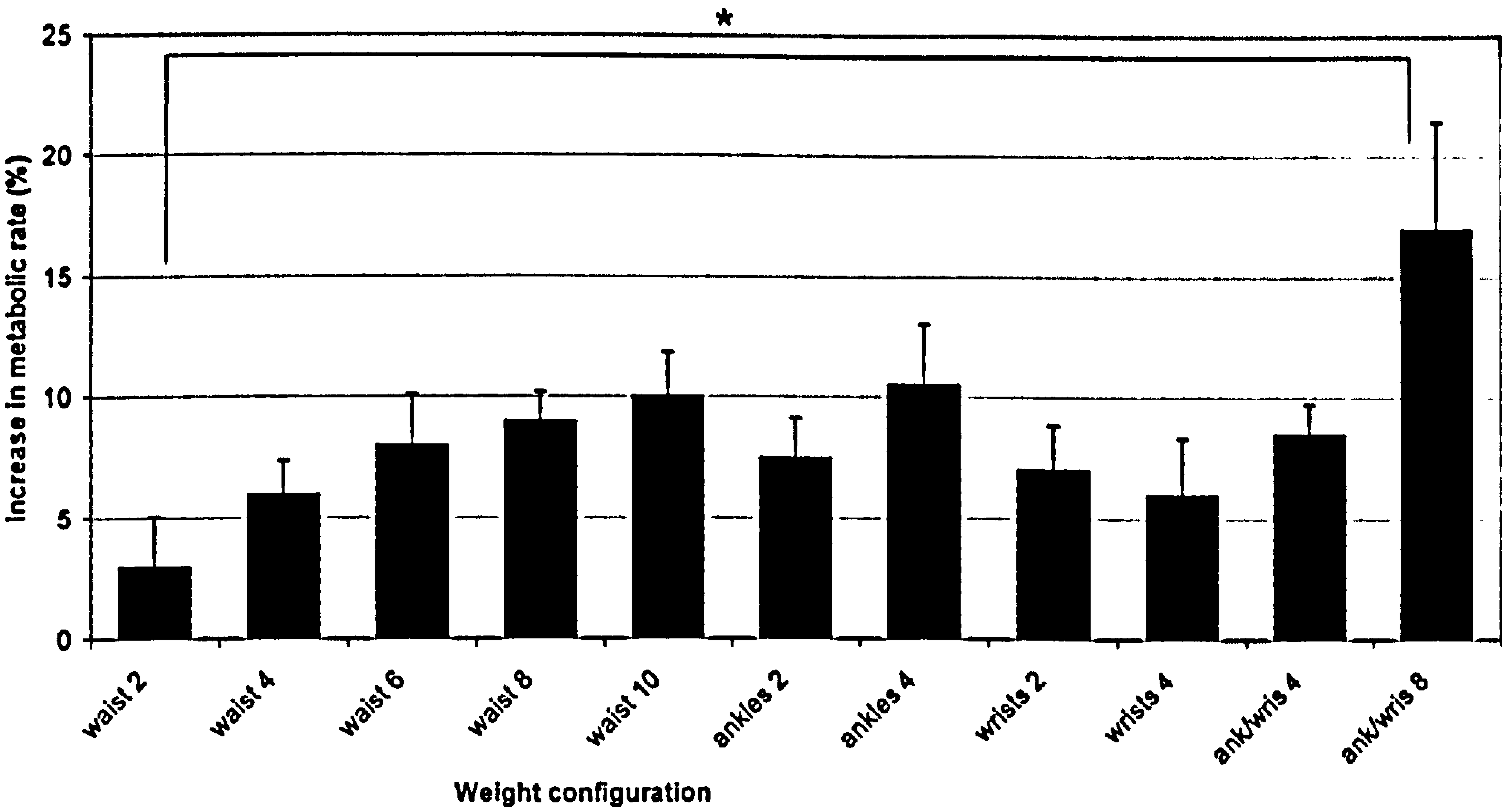


Figure 3.1. Increase in metabolic rate when carrying weight simulations around the waist, ankles and wrists (ank/wris; weight split between sites) when walking at 5 km/hr on a treadmill compared to an unweighted control, significance ($p<0.05$) marked by *. (weights in kgs on x-axis).

3.3.2 Obstacle course

The order of the conditions on the x axis in Figure 3.2 has been kept the same as in Figure 3.1, and on average the increases in metabolic rate recorded for the obstacle course were slightly higher than for the walking work mode. The increases in metabolic rate for the waist were 8, 4, 10, 11 and 13 % for the 2, 4, 6, 8 and 10 kg loads respectively. As for the walking the increase in metabolic rate for the 2 kg ankle weight condition, just under 10 % was much higher than for the 2 kg wrist weight condition (4 %). However, the results for the 4 kg conditions were very similar, 9 % for the ankles, 10 % for the wrists and 9 % for the ankles/wrists. As the obstacle course requires upper body movements including lifting and moving crates the added weight on the wrists had a much greater effect on the metabolic rate than during the walking work mode, except for the wrists 2 condition.

The results for the ankle/wrists conditions are similar to those seen in Figure 3.1, although for the maximum weight condition of 8 kg the metabolic rate increase is 4 % higher than that recorded for the walking work mode, this can most probably be attributed to the additional demands on the upper body of the obstacle course as previously highlighted. The metabolic rate recorded in all conditions was significantly ($p<0.05$) higher than in the control.

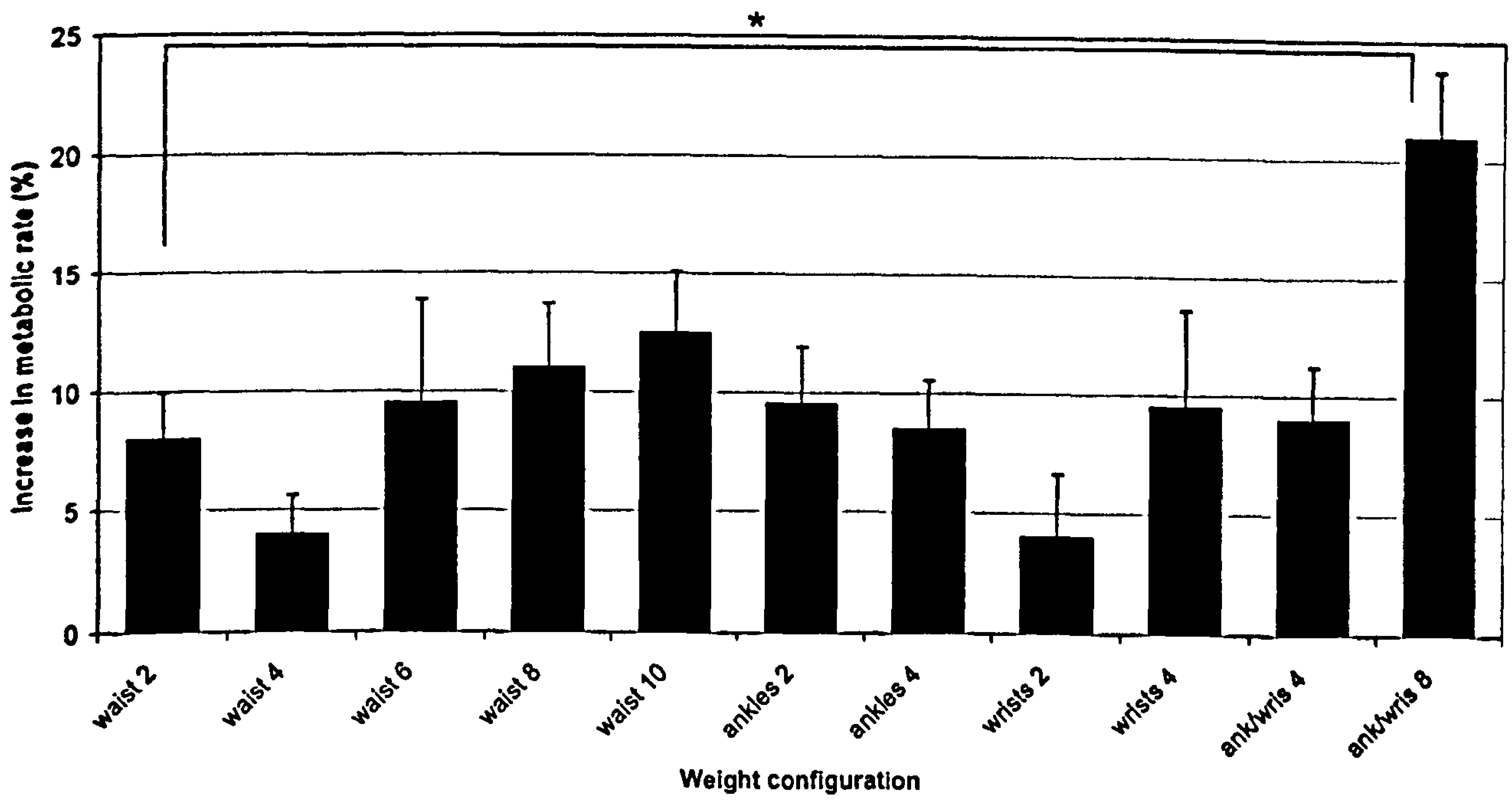


Figure 3.2. Increase in metabolic rate when carrying weight simulations around the waist, ankles and wrists (ank/wris; weight split between sites) when completing the obstacle course, compared to an unweighted control, significance ($p<0.05$) marked by *. (weights in kgs on x-axis).

3.3.3 Overall

The graph for the overall results, Figure 3.3, shows very similar trends to Figure 3.1, greater increases with more weight on the waist, greater increases on the wrists and even greater increases on the ankles. The percentage increases in metabolic rate are slightly higher than those for walking only, but the obstacle course requires movements of the upper body when lifting crates and a greater range of movement in the lower body when stepping and moving over hurdles. The metabolic rate recorded in all conditions was significantly ($p<0.05$) higher than in the control.

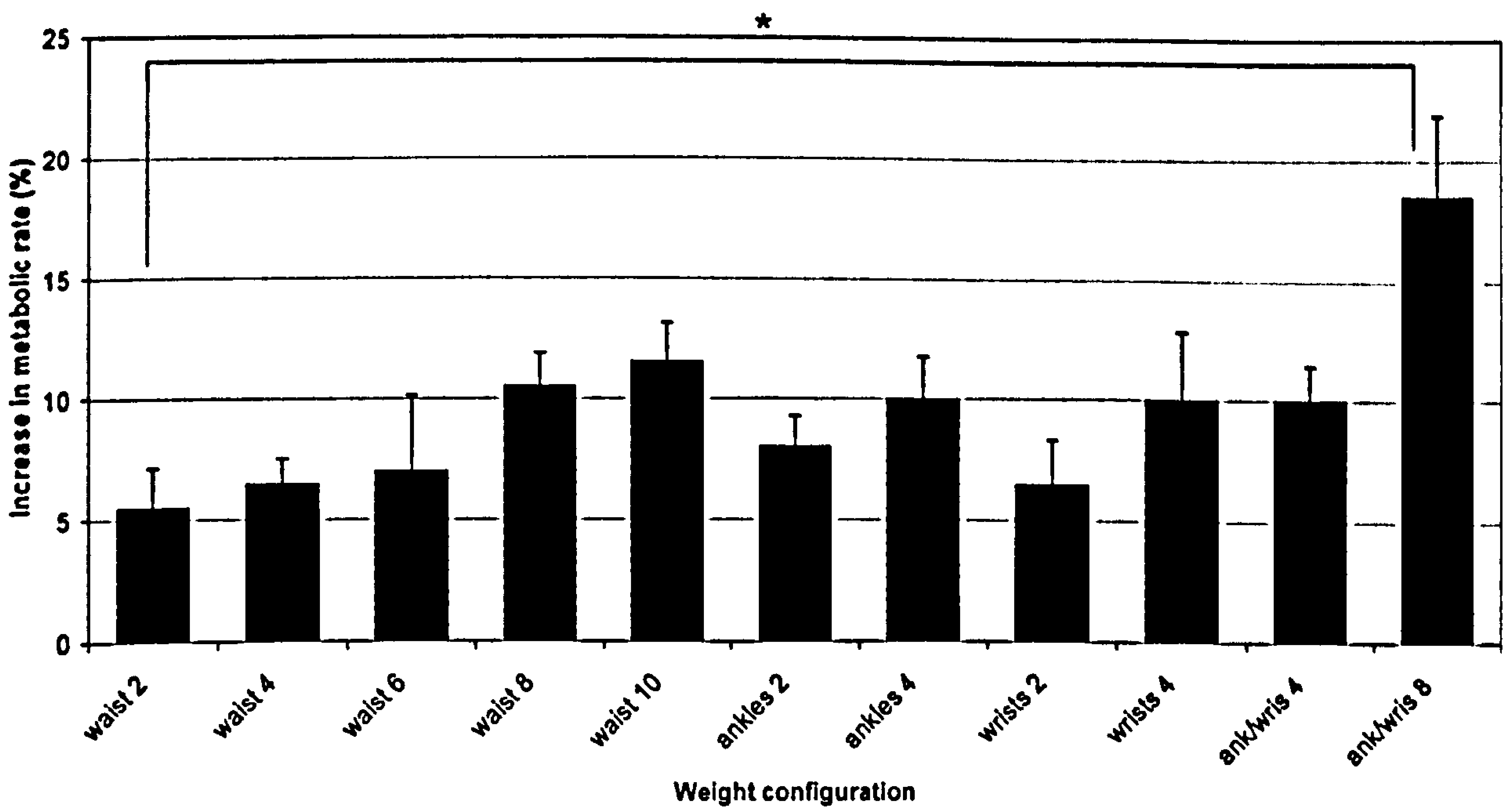


Figure 3.3. Overall increase in metabolic rate when carrying weight simulations around the waist, ankles and wrists (ank/wris; weight split between sites), based on average of data collected when walking and completing an obstacle course, compared to an unweighted control, significance ($p<0.05$) marked by *. (weights in kgs on x-axis).

3.4 Weight comparisons

When the data is grouped according to the weight carried as in Figure 3.4 some of the trends described above become more obvious. For the 2 kg conditions, carrying the weight around the waist induced a 3 % increase in metabolic rate when walking, this compares to 7 % and 8 % increases for both activities when the same weight is carried on the wrists and ankles respectively. The results for the obstacle course do not fit this trend as the induced metabolic rate increases were 8 % for the waist condition, 4 % for the wrists and 10 % for the ankles.

For the 4 kg weight conditions, walking caused a 6 % increase in metabolic rate, 7 % overall. Walking with the weight on the wrists also caused only a 6% increase in metabolic rate which jumped to 10 % overall (when the data for obstacle course was included in the average). For the ankles the increases were 11 % for walking, 10 % overall and for the ankles and wrists the increases were 9 % for walking, 10 % overall. For the wrists condition clearly the obstacle course required a greater range of movement than just walking hence the increase in metabolic rate from 6 % to 10 %. For the obstacle course weight carried on the ankles and wrists caused metabolic rate increases of 9-10 %, compared to only 4 % for the waist weight. With weight carried wholly or partly on the ankles the increases are consistently 9-11 % for all activity. Doubling the weight carried on the ankles and wrists from 4 kg (1 kg on each limb) to 8 kg (2 kg on each limb) doubled the metabolic rate increase overall from 10 % to 19 %. This increase was greater for the obstacle course (12 %) than the walking condition (8 %) .

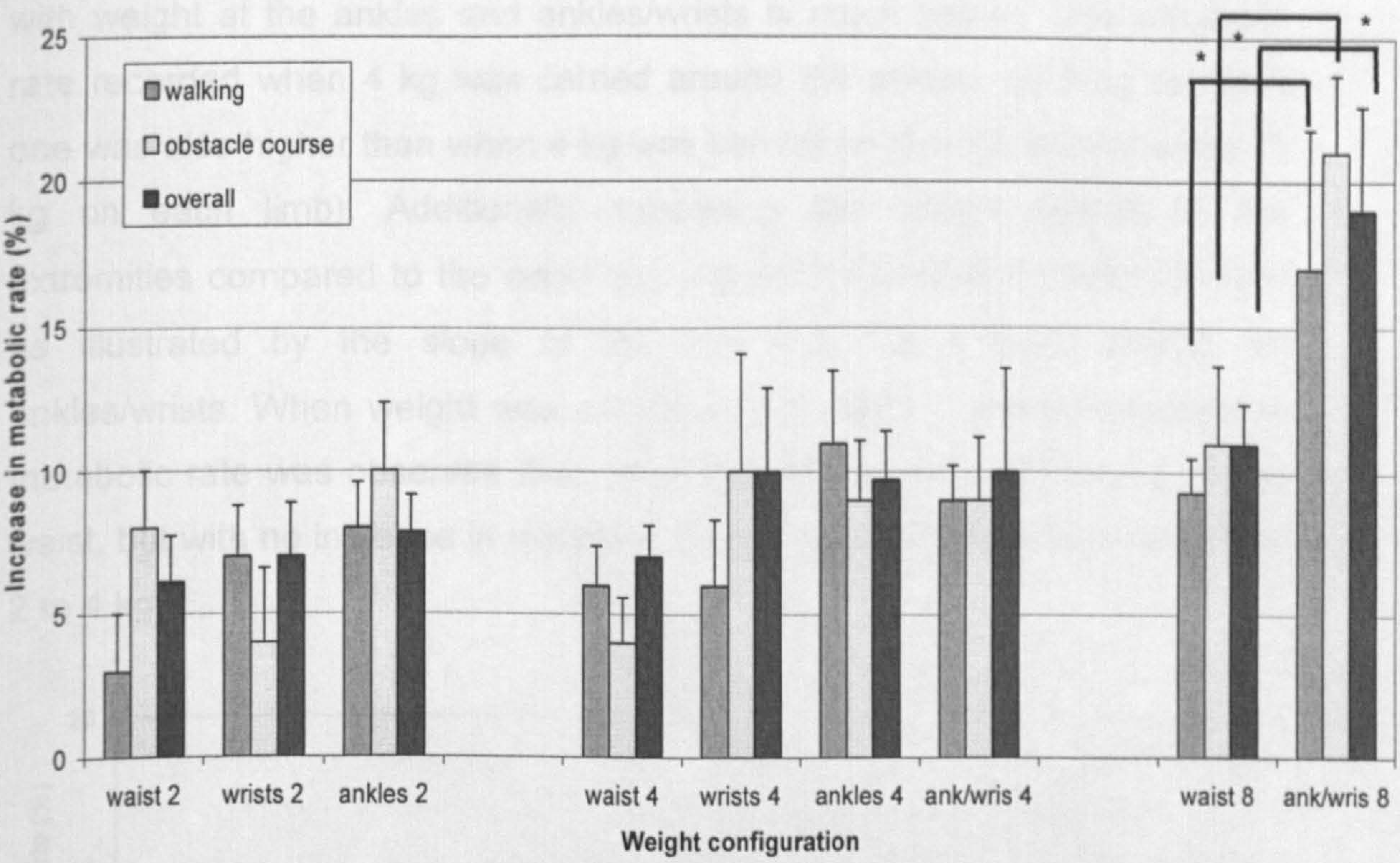


Figure 3.4. Increase in metabolic rate due to carrying weight around the waist, ankles, wrists or ankles and wrists (ank/wris) for two work modes, walking (light grey bars) and obstacle course (white bars) and overall (average of data collected when walking and completing an obstacle course (dark grey bars)). Significant ($p<0.05$) differences between sites for same weight indicated by *.

The only statistically significant differences in the increase in metabolic rate depending on the site of the weight (tested with a one way anova and Tukey post-hoc tests) were seen in the 8 kg conditions, carried either around the waist or on the ankles and wrists (2 kg on each limb). There was a significant increase ($p<0.05$) from 9 % for the waist to 17 % for the ankles and wrists when walking, 11 % to 21 % for the obstacle course and from 11 % to 19 % overall.

In Figure 3.5 the data has been expressed in a different way, the weight configurations have been plotted against the increase in walking metabolic rate. The relationship between increasing weight carried on the waist and increasing metabolic rate can be seen to be fairly linear. There are also clear positive relationships between increased weight carried on the ankles and the ankles/wrists, and increased metabolic rate. Compared to the same weight carried around the waist the increase in metabolic rate when walking with weight at the ankles and ankles/wrists is much higher. The metabolic rate recorded when 4 kg was carried around the ankles, as 2 kg on each one was also higher than when 4 kg was carried on the ankles and wrists (1 kg on each limb). Additionally increasing the weight carried at the extremities compared to the waist has a greater increase in metabolic rate as illustrated by the slope of the line with the circular symbol for ankles/wrists. When weight was carried at the wrists a greater increase in metabolic rate was observed than when the weight was carried around the waist, but with no increase in metabolic rate when the weight increased from 2 to 4 kg.

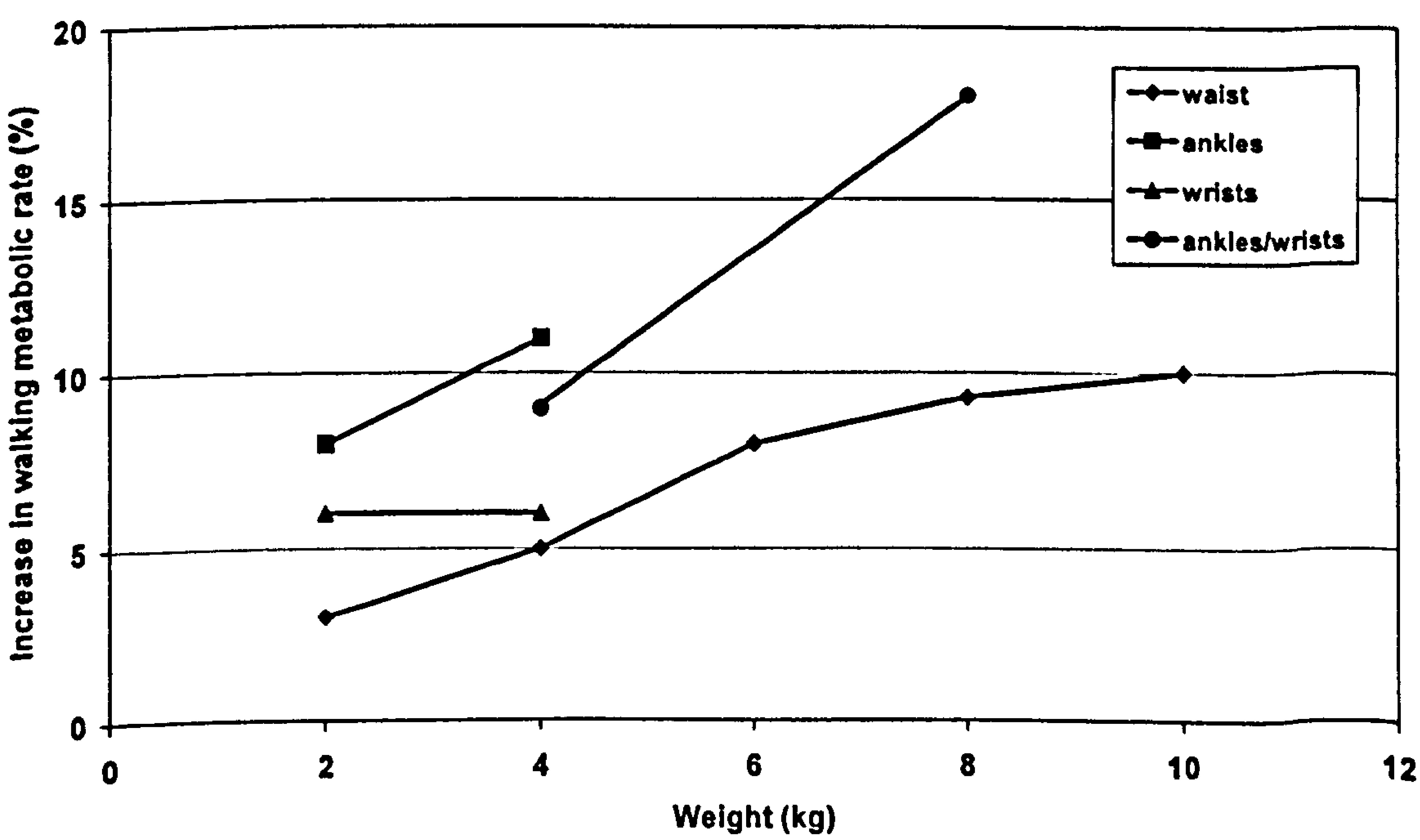


Figure 3.5. Graph of metabolic rate increase in relation to weight carried when walking for the 4 weight distribution sites (waist, ankles, wrists, ankles/wrists).

When the same graph is plotted for the metabolic rate increase during the obstacle course, as in Figure 3.6 the trends are not quite as linear as those seen in the walking data. With the exception of the 4 kg waist condition there is a gradual increase in metabolic rate with increasing weight carried. For the wrists conditions. 2 kg has very little effect, less than 5 % on metabolic rate but when the weight carried is doubled to 4 kg the extra energy cost is also doubled to 10 %. There is very little change when weight is carried around the ankles, with actually a drop in the % increase in metabolic rate from 10 % to 9 % for 2 and 4 kg respectively. The highest increases in metabolic rate can again be seen in the ankles / wrists conditions. The obstacle course requires a much greater range of motion and activities including upper limb movements. The contrast between Figures 3.5 and 3.6 illustrates what happens when testing occurs in the laboratory under idealised conditions, for example, walking on a treadmill, as opposed to incorporating more realistic tasks into the testing as in the obstacle course.

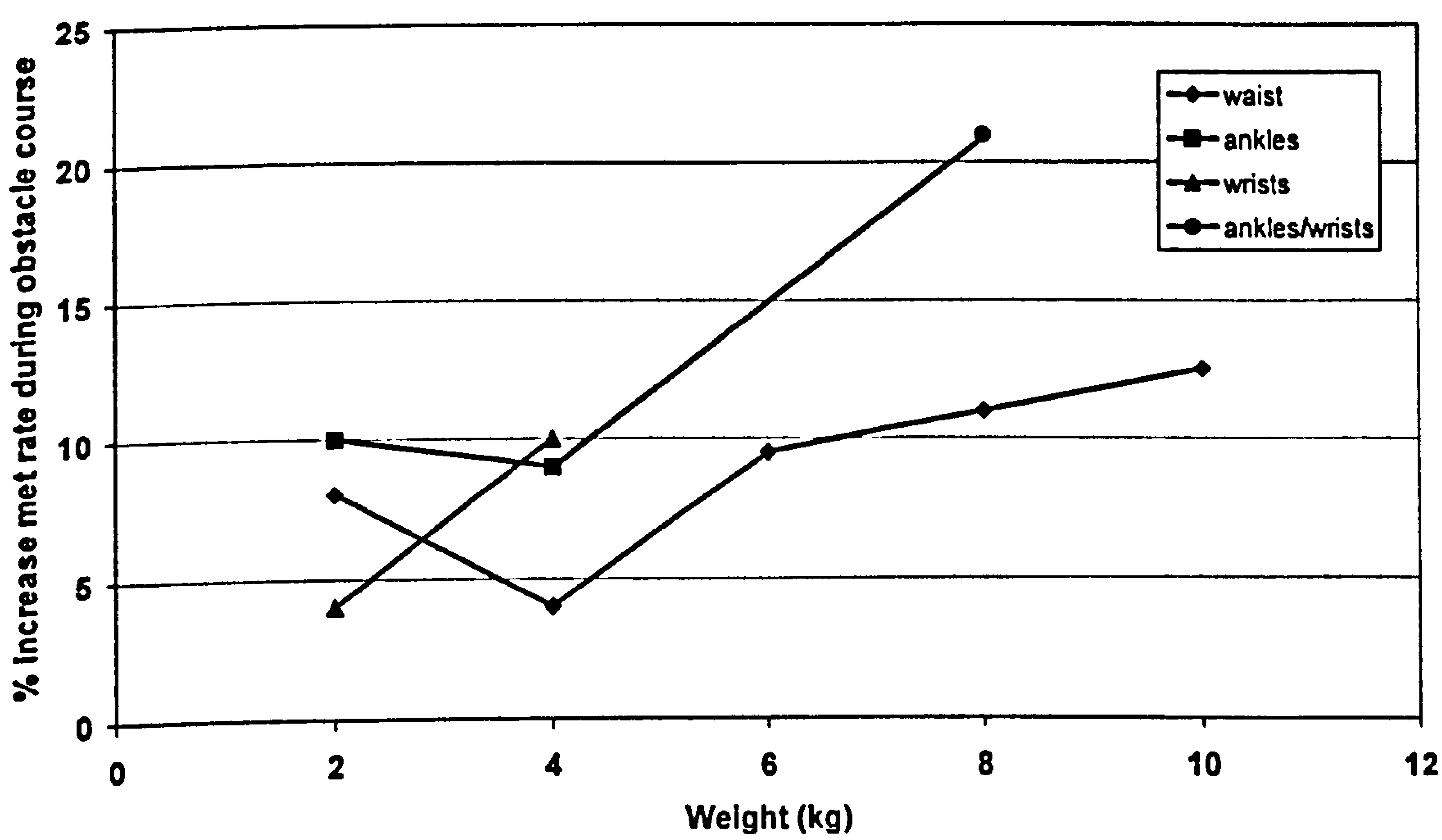


Figure 3.6. Graph of metabolic rate increase in relation to weight carried during the obstacle course for 4 weight distribution sites (waist, ankles, wrists, ankles/wrists).

3.5 Rate of Perceived Exertion results

Participants also recorded their 'Rate of Perceived Exertion' in the final minute of the work periods and the results are summarised in Figure 3.7. For the control (no weight) condition participants rated their exertion at 9 (very light) for the walking and just under 12 (between light and somewhat hard) for the obstacle course.

For the walking work mode most values for the weighted conditions were rated around 10 except waist 2 which was perceived closer to 9, the same value as the control, and ankles/wrists 8 perceived as 11 (light). For the obstacle course 7 of the conditions were perceived between 12 and 13 (somewhat hard) and the wrists 4, ankles/wrists 4, ankles/wrists 8 and waist 10 conditions perceived closer to 14. However, none of the observed values were significantly different from the control.

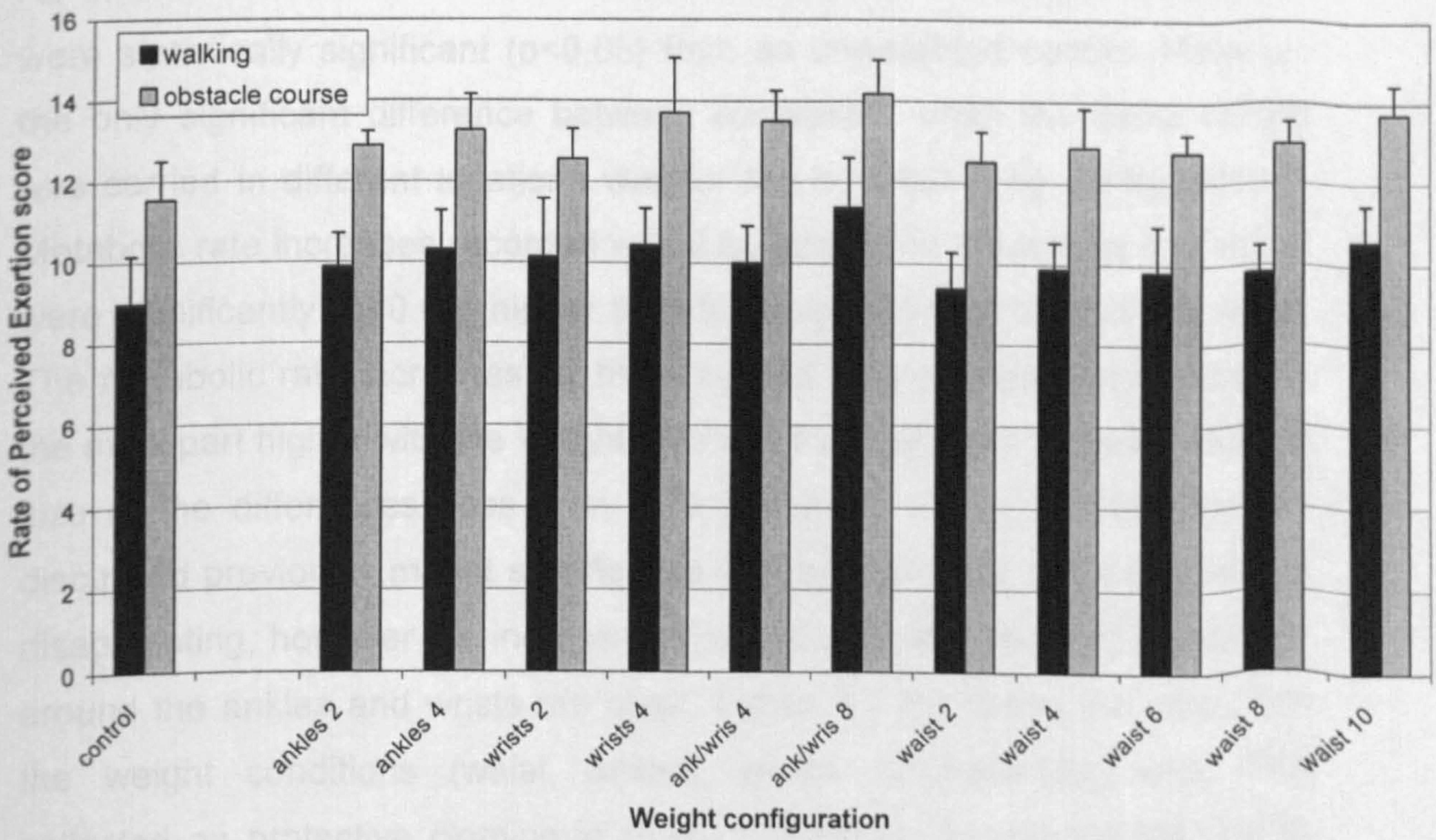


Figure 3.7. Graph of results of 'Rate of Perceived Exertion' responses taken during last minute of walking and obstacle course work modes for all weight simulations and control.

4. Discussion

The resulting increases in energy costs of walking and completing an obstacle course with additional weight around the waist, ankles and wrists compared to a control condition with no weight have been described. When walking with weight carried around the waist and increasing in 2 kg increments from 2 kg to 10 kg there was a stepped rise in the increase in metabolic rate percentages from 3 to 10 %. The increases in metabolic rate were highest for the ankle / wrists conditions, 17 % and 9 % for the 8 kg and 4 kg conditions respectively, followed by the ankles, 11 % and 8 % and the wrists, 6 % and 7 % (4 kg and 2 kg respectively). For the obstacle course work mode the general trend in the results was very similar with all the extremity conditions being higher than the metabolic rate recorded with the same weight around the waist, except the wrists 2 kg result.

All of the increases seen in metabolic rate across the weight simulations were statistically significant ($p<0.05$) from an unweighted control. However the only significant difference between conditions, when the same weight was carried in different locations was for the heaviest 8 kg configurations. Metabolic rate increases recorded with 8 kg carried on the ankles and wrists were significantly ($p<0.05$) higher than for weight carried around the waist. The metabolic rate increases for the 4 kg and 2 kg configurations were for the most part higher with the weight on the extremities than the waist but the size of the differences, less than 5 % and the sensitivity of the method discussed previously meant significance was not achieved. This outcome is disappointing, however the increased metabolic costs of carrying the weight around the ankles and wrists are clear, Figure 4.1 combines the data from the weight conditions (waist, ankles, wrists, ankles/wrists) with data collected on protective clothing in Study 1 (Chapter 3) and the theoretical data calculated from the equation of Givoni and Goldman (1971), also presented in the previous chapter. The data collected in this study for weight carried around the waist fits well with Givoni and Goldman (1971), whose equation gives an increase in energy cost of 1 % per kg for load carried. The increase in metabolic rate when carrying the weight around the ankles/wrists is 2.25 % per kg (taken from the slope of the line for ankles/wrists data) and the increase in energy cost per kg of the clothing from the clothing linear regression line is 2.7 % per kg, as described previously. Therefore the metabolic costs of carrying the clothing weight could be well explained if the majority of the clothing weight was concentrated around the extremities, however this is unrealistic and thus factors other than clothing weight must be contributing to the metabolic rate increases observed.

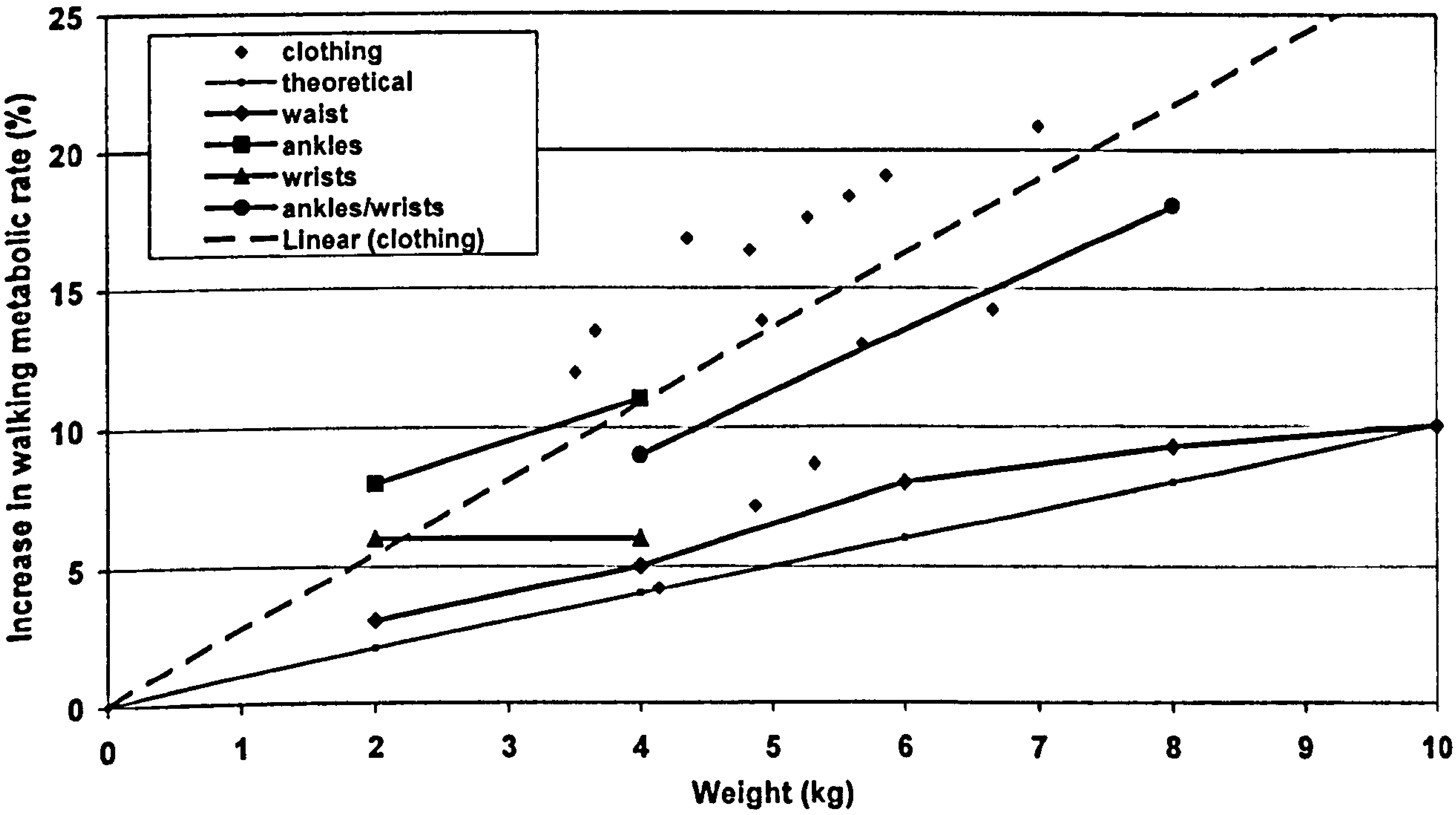


Figure 4.1. Increase in metabolic rate in relation to clothing weight or load carried on the waist, ankles, wrists, ankles/wrists. Theoretical line based on equation of Givoni and Goldman (1971).

The 2.7 % increase in energy cost per kg of clothing weight fits very well with Rintamaki (2005) who suggests that each additional kg in clothing weight increases energy costs by approximately 3 % and Oksa *et al.* (2004) who detail increases in energy cost per extra kg of clothing of 2.7 – 3.3 %. In the study of Oksa *et al.* (2004) subjects jogged at 50 % of their $\dot{V}O_2$ max on a treadmill for 60 minutes, the environmental conditions were 20 °C, 0 °C and –15 °C and subjects wore 1 (weighing 1 kg), 2 (3.6 kg) or 3 (4.9 kg) layers of clothing respectively. Although the study was complicated by the fact that the different clothing layers were worn in different temperatures the authors assert that as mean skin temperatures were stabilised at 31.5°C, 29.5°C and 30.0°C in the 20°C, 0°C and –15°C environments respectively, the observed increase in energy cost was not directly related to the body cooling but rather reflected the effect of clothing. The final oxygen consumption values of 1.67, 1.78 and 1.88 l/min correspond to increases in energy cost per extra kg of clothing of 2.7 – 3.3 % (Oksa *et al.* 2004).

The trend for greater increases in metabolic rate when performing the obstacle course compared to walking as seen in Figures 3.1 to 3.4 can be explained by the greater range of movements required. Walking on the treadmill obviously requires a degree of leg and arm swing but the range of movement is quite small. In contrast, the obstacle course required participants to squat with the crates, step, crawl and bend in the lower body and lift, carry and place the weighted crates at different levels involving the upper body. This explanation fits with both Nunneley (1989) and Murphy *et al.* (2001) who observed greater effects of heavy clothing in tasks that required greater movements. In the study of Murphy *et al.* (2001) the tasks of a continuous nature (load carriage and obstacle course), requiring more mobility demonstrated a greater increase in oxygen consumption and thus metabolic cost than stationary tasks. It would also follow from these studies that heavier loads cause greater increases in metabolic costs but in terms of the treadmill walking data in Figure 4.1 for this study there was a different finding. When weight was carried at the wrists there was a greater increase in metabolic rate than when the weight was carried around the waist, but in this study there was no increase in metabolic rate when 4 kg was carried on the wrists compared to 2 kg. This is a slightly surprising finding, however it can be explained by the fact that the participants were instructed to keep their arm swing as natural as possible and swinging the arms was not enforced. In hindsight they may actually have reduced their arm movements when carrying the heavier weights to reduce the impact and energy cost of the increased load. Soule and Goldman (1969) discuss compensation mechanisms that may be functioning when the load is carried on the hands. Shortening the swing of the arms, reduces the physical work so conserving energy which is balanced against the extra energy cost of fixing the extremities. They suggest this could be occurring at lower walking speeds with lighter weights but the results for this study suggest a smaller arm swing when more weight is carried.

Auble *et al.* (1987) reported that carrying hand weights caused only small increases in the aerobic energy requirement of normal walking, increases that could have been achieved by increasing walking speeds. In contrast pumping handweights (arms fully flex, swing upwards and fully extend downwards) while walking substantially increased the energy cost of normal walking. So the authors suggest that the most likely cause of variability in the effects of handweights is the amount of arm movement used when walking. In many of the studies that have assessed the use of hand, wrist and ankle weights for aerobic training, arm swinging has been strictly controlled and often exaggerated. This has led to findings of substantially greater energy costs when carrying weights on the hands and wrists than the ankles (Claremont and Hall 1988, Graves *et al.* 1988) and in comparison to the present study.

As explained in the introduction, the study by Soule and Goldman (1969) was one of the first to consider the effects of weight carried on energy costs. However the loads used in their study were extreme, up to 7 kg in each hand and 6 kg on each foot. The increased energy cost for their data can be calculated as in this study using the data presented in Table 2 of their paper which details the energy cost (expressed as millilitres of oxygen consumption per minute) of carrying the loads at 3 different speeds. When walking at a speed of 4.8 km/hr the increase in energy cost compared to a no load condition is 14 % and 34 % for the hands, 4 kg and 7 kg respectively and 95 % for the feet (6 kg).

It is also important to emphasize the different sites used, in the present study the weight was attached to the ankle but in the Soule and Goldman (1969) study the load for the feet was made by filling standard US Army double-walled "vapour barrier" with mercury until each boot weighed 6 kg. The authors discuss the fact that some of the increase in energy cost may be attributable to the fact that with 6 kg added to each foot, there was some immobilisation of the ankle joint, preventing the normal flexion-extension of the ankle. The different footwear used is also important to the scale of the differences found. In the present study, trainers were worn with the weight attached to the ankle as opposed to the army boots used by Soule and Goldman (1969). It is well known that the weight of footwear can influence the energy cost of walking and running (Jones *et al.* 1984, Legg and Mahanty 1986).

Energy cost was found to be significantly higher, 0.7 % per 100 g increase in the weight of boot, over a range of walking speeds when wearing boots than compared to lightweight athletic shoes by Jones *et al.* (1984). They attribute a large portion of the increase to the weight of the footwear, also noting that the increased energy cost of locomotion with boots appears to place a limiting stress on untrained subjects (Jones *et al.* 1984). Legg and Mahanty (1986) also clearly showed increasing the weight of a pair of boots significantly increased the energy cost of treadmill walking, a mean increase of 0.96 % in $\dot{V}O_2$ for each 100 g increase in boot weight. Applying the figures of 0.7 – 0.96 % per 100 g of boot weight to the present study would increase energy cost by 7–9.6 % and 14–19.2 % for the ankles 2 and ankles 4 conditions. However the increased energy costs recorded in the present study were lower, 8 % and 9–11 % for the ankles 2 kg and 4 kg conditions respectively. It must be remembered that in the present study trainers were worn by the participants and weights carried around the ankle therefore it is not surprising that the results are slightly lower than predicted by the results of the 2 studies that used military boots (Jones *et al.* 1984, Legg and Mahanty 1986) but otherwise they are rather close.

Although Legg and Mahanty (1986) did not carry out gait analysis, variations in the regional discomfort ratings they did record suggest increasing boot weight may influence gait and this links with observations from Soule and Goldman (1969). Therefore adopting a different walking stance/style that is more rigid and less efficient could potentially increase energy cost.

5. Chapter summary

The purpose of this trial, was to look at the effects of carrying more realistic simulated clothing weight distributions close to the body's centre of gravity (using a weight belt) and at the extremities (weights worn around the wrists and ankles). The findings confirmed the hypotheses put forward at the beginning of the chapter, i) the further away from the body core the weight is positioned the higher the resulting energy cost during work and ii) the energy cost of the extremity weight conditions (ankles and wrists) will be higher in activities requiring greater ranges of movement of the limbs, in this case the obstacle course compared to walking.

The results provide additional data about the energy costs of carrying weights of 2 – 10 kg around the waist and on the extremities. The energy cost of carrying weight on the ankles and wrists was shown to be 2.25 % per kg compared to 1 % per kg for weight carried around the trunk. Additionally work requiring greater ranges of movement in all limbs, in this instance completing an obstacle course also incurs a greater energy cost compared to a less demanding activity, for example, walking.

The weight of protective garments and the distribution of that weight can therefore clearly have a significant effect on the metabolic cost of work as the wearer has to carry the additional load of the garment on their body. The effect of the load is dependent on where the extra weight is present, being particularly costly if the material on the arms and trousers of the garment is heavy, as weight on the limbs has to be accelerated and decelerated with each step. Data from Chapter 3 of a 2.7 % increase in energy cost per kg of clothing also corresponds very well with previously documented values.

Although the % increase in energy cost per kg values observed for carrying load at the ankles and wrists resemble those for clothing, in the later case obviously not all weight is concentrated at the extremities which leaves a role for other factors such as clothing bulk and stiffness, number and friction of layers, which will be investigated in subsequent chapters.

CHAPTER 5

STUDY 3

INVESTIGATING THE EFFECT OF LAYERS AND THEIR FRICTIONAL PROPERTIES ON METABOLIC RATE

1. Introduction

The effects of protective clothing (PPC) on metabolic rate were investigated in the first study of this thesis. Significant increases in the metabolic cost of work were found wearing a range of PPC and a number of suggestions put forward, following observations from the study and the literature, as to the possible factors that might be contributing to this increase. Subsequently weight and its distribution on the waist and limbs was studied, with results suggesting that the weight of the protective garments would have had an effect on the metabolic rate. However the results from the weight study could not account for all of the metabolic rate increases recorded in the PPC garments, unless it would be assumed all weight was located at the wrists and ankles, which seems rather unrealistic.

Another concept suggested by a number of authors who also found similar increases in energy cost / oxygen consumption in PPC is that of a friction drag between layers, frictional resistance as one layer slides over another during movement. Despite being mentioned in the discussion and conclusions of a number of papers only one study has been found on the contribution of clothing friction and its effects on performance. However the study predominantly looked at task performance measures rather than energy cost / metabolic rate.

1.1 Previous research

The work of Teitlebaum and Goldman (1972) is the earliest paper to have investigated the effects of protective clothing (they used arctic clothing) on energy cost. In a well designed study they had subjects walk on a treadmill wearing 2 layers (shorts and t-shirt, fatigues) and a weighted belt or 7 layers (5 extra layers of arctic clothing). The belt worn with the 2 layer ensemble weighed the equivalent of the 5 extra layers and subjects wore identical footwear throughout. The authors report mean values of 514±12.4 W at a walking speed of 5.6 km/hr for the 7 layer ensemble compared to 435±12.9 W for the 2 layers plus weighted belt. At 8 km/hr the results were 995±32.3 W and 873±24.9 W for the 7 and 2 layers respectively. These increases of 18% and 14% when walking at 5.6 and 8 km/hr were highly significant ($p<0.001$) and are according to the authors most probably attributed to friction drag between layers (frictional resistance as 1 layer slides over another during movement) and hobbling. However, they conclude their paper with the sentence "we are still unable to distinguish between these two possibly different although perhaps related factors associated with multilayer clothing" (Teitlebaum and Goldman 1972).

The following year Amor *et al.* (1973) ran an experiment to confirm the validity of Teitlebaum and Goldman's observations over a range of 'more-appropriate' walking speeds using British multi-layer military clothing. Subjects wore a) an arctic assembly (9 kg) with 6 layers on the body and arms, 4 layers on the legs and arctic (mukluk) boots, b) a tropical assembly (4 kg) with 3 layers on the body and arms, 2 layers on the legs and military boots (of a similar weight to the mukluk boots), c) Physical Training kit (1 kg) consisting of shorts and sports shoes. The weight of the tropical assembly and PT kit was corrected to the weight of the arctic assembly with the additional weight carried in a webbing belt. Walking speeds ranging from 3.6 to 6 km/hr were used. The energy cost wearing the arctic and tropical ensembles averaged 21 % and 8 % above the PT kit with the differences highly significant ($p<0.001$). The authors make no attempt to identify the cause of the increased energy cost but suggest 3 possibilities; hobbling, friction between clothing layers and an increased effort possibly required to walk in the loose fitting arctic (mukluk) boots compared with the better fitting footwear in the other 2 conditions (Amor *et al.* 1973).

These 2 studies were summarised by Lotens (1982) in a rule of thumb that energy cost increases with 4 % for each clothing layer, at marching speed (5.6 - 6 km/hr) and 3 % per layer at a slower pace (3.6 km/hr). But he agrees that the source of the effect is not well understood, reiterating friction between layers and hobbling gait as possible explanations (Lotens 1982).

Duggan (1988) also cites the above studies and calculates his increases in oxygen uptake ($\dot{V}O_2$) during stepping per layer worn. Ensemble A was normal military combat clothing, Ensemble B added an extra layer in the form of chemical agent protection, Ensemble D had 2 extra layers, cold protective layers and quilted jacket and trouser liners for further thermal protection (all ensembles were corrected for clothing weight). Ensembles B and D differed by 2 layers and although not significant there was a mean increase in $\dot{V}O_2$ / kg clothed weight, during stepping of 4.8 % or 2.4 % per layer (Duggan 1988).

There are a few other studies and authors who have found increases in $\dot{V}O_2$ which are still significant after correcting for clothing weight. This has led them to speculate that a hobbling / binding effect, or frictional resistance of layers is contributing to the elevated energy costs. Patton *et al.* (1995) and Murphy *et al.* (2001) compared a 1-layered battledress uniform (BDU) weight 3.7 kg, to a chemical protective clothing (CP) ensemble, made up of 2 layers, battledress plus CP overgarment, rubber butyl gloves with cotton inserts and rubber boots worn over combat boots, total weight 9.3 kg. Patton *et al.* (1995) found that $\dot{V}O_2$ corrected for clothing weight was still 6 –11 % greater in the CP clothing across a range of walking speeds. The percentage increase when completing continuous tasks in the study of

Murphy *et al.* (2001) was reduced from 13.7 % to 8 % after correction for weight in the CP clothing condition, leaving an 8 % difference in energy cost due to factors other than weight.

Another study to look at multiple clothing layers and treadmill walking is that of Oksa *et al.* (2004) using 2 exercise intensities, 25 % and 50 % $\dot{V}O_{2max}$. Unfortunately the number of layers was not the only variable to change as the environmental conditions and weight of the layers were different as well. 1 layer (weight of 1 kg) was worn at 20°C, 2 layers (3.6 kg) at 0°C and 3 layers (4.9 kg) at –15°C. The $\dot{V}O_2$ was higher in the 2 and 3 (significant $p<0.05$) layer conditions after 55-60 minutes at 25% $\dot{V}O_{2max}$, with values of 1 and 1.1 l/min respectively compared to 0.95 l/min in the 1 layer condition. After 55-60 minutes at 50% $\dot{V}O_{2max}$, the $\dot{V}O_2$ was significantly ($p<0.05$) higher for both the 2 (1.8 l/min) and 3 (1.85 l/min) layer conditions compared to 1 layer (1.65 l/min), however it is not possible to isolate the significance of the number of layers or clothing weight to the overall increase in $\dot{V}O_2$ (Oksa *et al.* 2004).

In a summary paper on 'Protective Clothing and Performance in Cold Environments', Rintamaki (2005) writes that clothing and other protective garments decrease performance (decreasing the range of movements and increasing energetic costs of work) due to weight, bulkiness and friction. The decreases in performance are task specific and roughly equal to the changes in energy cost. Rintamaki (2005) also suggests the decrements in performance can be minimised by reducing clothing weight and bulk, the number of layers and friction between layers.

So there are a number of studies that have found increased energy costs in multilayered protective clothing. The authors have taken steps to correct the conditions or results for clothing weight, but still find increases which must be due to factors other than weight. Many have then concluded that clothing bulk, a hobbling or binding effect and friction between layers may be involved but they have been unable to isolate the extent of these effects and have not tried to investigate it further. There is also a need for more information to feed into standards as Meinander *et al.* (2004) completed manikin measurements and wear trials for the 'subzero' project on cold protective clothing and found that the metabolic rates of test subjects were higher than predicted using ISO / CD –11079 IREQ standard. They suggest this may in part be due to friction between layers which is unaccounted for (Meinander *et al.* 2004).

Huck (1991) did design a study to look at alternative designs and liner configurations in fire-fighter protective clothing to determine restrictions to wearer movements. She found no research that attempted to determine the extent to which, if any, use of smooth fabric layers between protective ensemble layers might reduce frictional forces and so increase wearer flexibility. Multiple fabric layers in fire-fighter turnout gear provide excellent thermal protection but the fabric layers can be bulky, heavy, inflexible and have relatively rough surfaces which can cause loss of mobility and increased energy costs (Huck 1991). The liner configurations she tested were; a) traditional, b) 1 extra liner on top of thermal liner, c) 2 extra liners as b) plus liner between outer shell and moisture barrier (liner patterns taken from existing designs in turnout jacket, and made out of polyester satin fabric). The dependent variables were range of motion (ROM) in 4 upper body joints using a Leighton flexometer and a subjective scale. Although the liners did not significantly improve ROM, subjectively 1 liner did improve the mean score of acceptability compared to no liner (Huck 1991).

The only other study attempting to look at friction of clothing and its effect on performance was conducted by Anttonen *et al.* (2001). They were trying to develop optimal low friction clothing for the defence forces and used low friction test clothing layers for underwear, middle wear and outerwear (the material selection was based on earlier friction tests) compared to standard M91 military clothing. Material measurements of all the layers and combinations were done with the Kawabata Evaluation System KES-FB4 (for surface test). They used Coolmax / Thermastat for the underwear, quilted fabric for the middle wear and satin lining for the overgarment. In the material tests values of up to 50 % lower friction were recorded for the low friction test clothing (Anttonen *et al.* 2001). Physical performance tests were studied including ball throwing (velocity of ball measured), step test, walking test, counter movement jump (time and maximal height of jump), crawling and running stairs. They conclude that the decrease in friction improves performance by up to 7 %, especially in the cases of wide movement ranges and in whole body movements (Anttonen *et al.* 2001).

So despite being mentioned as possible causes for increased energy costs, the problem of multiple layers and friction between layers has not been well investigated in the ergonomics and physiology literature. This lack of literature is highlighted by Adams *et al.* (1994) who reviewed 118 studies that isolated or defined a given garment property and dependent measure. Coefficient of friction was a poorly studied garment property and of the studies that had focused on it, the dependent measure was most likely to be subjective, for example comfort and psychophysical quantification.

Adams *et al.* (1994) provides a good introduction into the effects of garment properties that potentially affect worker performance. They highlight a number of garment subcomponents; fibre, yarn, construction and finish, which help define the fabric. The fabric used then potentially affects a number of garment properties; stiffness, hand, coefficient of friction, vapour permeability and insulation. Worker movement also causes clothing to move and change form, clothing must slide (displace), stretch (expand), fold (bend) and bunch-up (compress) as the body moves. These mechanisms all resist changes in garment form, with level of resistance determined by garment characteristics. Resistance to change in form imposes additional force requirements on the wearer (Adams *et al.* 1994).

A search of the clothing, textile and materials literature was undertaken to try and gain further insight in to the possible effects of fabric friction. There are a number of methods for assessing the properties of fabrics, perhaps the most well known is the concept of 'fabric hand' and the work of Kawabata (1980). Hand is perhaps the most rapid assessment that can be made of the quality of a fabric but previously the only guide was past experience, so it was desirable that the hand of a fabric be measurable, at least in relation to other fabrics (Thorndike and Varley 1961).

The hand of materials is a combination of subjective and objective properties of a fabric, as the subjective assessment and feel of a fabric are based on its mechanical properties (Kawabata 1980). However it was Peirce (1930) who first identified a number of simply measured fabric properties that correlate with judging the feel or handle of the material. Peirce's landmark research provided a foundation for simple and useful measurement of handle predicting fabric properties that are still used today, particularly fabric bending length (Barker 2002).

The earliest form of testing instrument for fabric friction used a simple inclined-plate tester consisting of a cloth covered glass plate and a cloth covered brass block. The glass plate was then tilted until the brass block began to slide, the coefficient of static friction was calculated from the angle of tilt from the glass plate to the horizontal (Thorndike and Varley 1961). Wilson (1963) went on to design apparatus to investigate the dynamic friction of fabric.

Although fabric friction has gained much significance, Das *et al.* (2005) explain that there is still no suitable instrument in the textile industry to measure it. Kawabata developed the KES – FB4 for measuring surface friction and surface roughness but this is not available to most due to the high cost. Most researchers use the Instron Tensile Tester with attachments (Das *et al.* 2005). Others, including Das *et al.* (2005) and Lima *et al.* (2005) have come up with their own equipment, see papers for more detail. The Kawabata System of Evaluation (KES) is still the most well developed system for evaluating the fabric hand. The unique feature of the KES is the ability to measure fabric mechanical properties at small strains with high sensitivity, and a capability to isolate the contribution of individual fabric properties (Barker 2002).

One of the most important characteristics of fabrics for clothing subjective and technological assessments is the coefficient of friction (Wilson 1963, Das *et al.* 2005, Lima *et al.* 2005). Friction coefficient is not an inherent characteristic of a material or surface, but results from the contact between 2 surfaces, a resistance to motion that can be detected when a fabric is rubbed mechanically against itself or tactfully between finger and thumb (Das *et al.* 2005, Lima *et al.* 2005). Any fabric that offers little frictional resistance to motion and possesses a low coefficient of friction is likely to be described as a smooth fabric (Ajayi 1992b). In contrast high friction usually equals a harsh feel as friction depends on the characteristics of surfaces in mutual contact (Chattopadhyay and Banerjee 1996).

Fabric friction can be affected by the type of fibre, type of blend, blend proportion, yarn structure, fabric structure, compressibility, crimp and crimp height (Das *et al.* 2005). Structurally protruding yarn crowns and fibre tufts from the fabric surface also influence fabric smoothness and friction, so frictional properties of woven fabrics may be interpreted from geometric consideration of their component yarns (Ajayi 1992a).

As early as 1963, Wilson was identifying the problems with multilayers of fabric and the friction of garments on other garments and expressing surprise at the lack of papers dealing with the general subject of fabric friction, and the intervening years have failed to provide many clear answers.

1.2 Aims

The potential contribution of friction between layers in multilayer clothing ensembles has been suggested by a number of authors who are still trying to explain the increased energy costs when wearing protective clothing after correcting for weight. However despite these suggestions of a possible effect no studies have been found that attempt to investigate it solely in relation to energy costs. Therefore the aims of this study are;

- To investigate if friction caused by wearing a number of layers has an effect on the metabolic cost of activity with the hypothesis that working in a number of layers will result in a higher energy cost than a single layered control weighing the same due to friction between layers.
- To investigate if making layers out of low friction compared to high friction material can reduce the effects on the metabolic cost of activity. The hypothesis is that if the material is matched for weight, thickness, bulk and stiffness, reduced energy cost measured in the low friction clothing would be due to decreased friction generated by the material layers moving across each other.

2. Methods

2.1 Participants

Eight male participants took part in the study. They were all volunteers drawn from the student population at Loughborough University. Their physical characteristics are summarised in Table 2.1.

Table 2.1. Participant details

Gender	Age (yrs)	Height (cms)	Weight (kg)
M	25.4	180	67
M	25.3	183	75
M	23.2	180	71
M	27.8	171	62
M	23.8	177	60
M	28.6	178	70
M	23.3	181	76
M	22.7	179	75
ave	25.0	178.6	69.5
SD	2.2	3.6	6.1

2.2 Clothing

In order to study the effect of wearing layers, a number of scenarios were considered, including multiple layers of underwear, disposable protective suits, coveralls and army layers. However piloting the underwear identified multiple layers were a very tight fit and when 3 to 4 layers were worn, the layers failed to move over each other and restricted movement due to tightness around the joints. The disposable suits were very baggy and as such the layers did not seem to have an effect. The coveralls were considered but it was not possible to find coveralls made of sufficiently different materials to look at the effects of low and high friction materials.

The main issues with wearing a number of layers are fit of the layers and movement of the layers, so they do not stick together and act as one, causing bulk and movement restriction. It was decided to aim for 4 – 6 layers in order to try and see an effect, this was confirmed by a number of reports in the literature, discussed above.

After considering the layers and materials available it was decided to make test suits, rather than using existing garments. Two materials were required, for low friction and high friction suits. Ideally the two materials selected would differ in their frictional properties but be of a similar weight and bulk. The design for the suits was based on an overall (all-in-one style with a zip up the front). A number of males were measured and their measurements along with a cotton overall were the basis of the pattern from which the test suits were produced. Prototype suits were made out of fleece and silk. However the fleece suit proved to be much bulkier (and had more give in the fabric) than the silk suit, which was good but very thin. A number of other fabrics were compared for example brushed cotton and egyptian cotton, which had similar weighting but not enough difference in the frictional feel. A number of fabric shops were visited to try and find two suitable materials for the suits. Contact was also made with the Textile Department at the School of Art and Design at the University. Eventually it was decided to use a polyester (100 %) material with a crepe finish for the high friction suits and a satin finish for the low friction suits. Five suits were made of each fabric, small, medium, large, x-large and xx-large, the low and high friction suits were identical sizes.

Due to the sizing of the suits, only male participants were recruited and they were screened for waist and chest measurements as it was essential the suits were not too tight (as this may cause movement restriction). The suits came out quite long in the body, so for each layer adjustable 'belts' were made out of elastic with a button to ensure a good fit and make sure the legs of the suits were not too long. Normal belts were too bulky if one was worn with every layer, the elastic belt was both light and thin. A deliberate decision was made to not have cuffs at the wrists and ankles of the suits because these may have caused the layers to ride up together when the arms or legs were bent.

Unfortunately the high friction suits did turn out to be heavier than their low friction equivalents so a method of correcting for the weight differences was required, this is detailed below.

For this study participants were required to complete two sessions.
The layers session consisted of the following conditions;
a) underwear and 4 low friction layers,
b) underwear and 4 high friction layers,
c) control condition (cotton sweatshirt and tracksuit trousers).

The overalls session consisted of the following conditions;
d) underwear, low friction layer, overall layer, low friction layer, overall layer,
e) the same combination but with high friction layers,
f) control condition (cotton sweatshirt and tracksuit trousers).
These ensembles are illustrated in Figure 2.1.

Tight underwear was worn as the base layer in all conditions except the control. As this underwear was tight to the skin, it is assumed that any movement of the clothing package will be between the layers, overalls and underwear, not between the underwear and skin.

2.3 Weight corrections

As mentioned above due to the differences in weight between the high and low friction suits, additional weight had to be added to the low friction ensembles. Extra weight was also added to the control condition, so in each session all ensembles weighed the same as the heaviest (high friction) condition.

The extra weight could have been easily placed around the waist however this would not have reflected the actual situation in the garments, where the weight is also distributed along the limbs. It is well documented that carrying weight around the body core (waist and torso area) is the most efficient in terms of metabolic cost, so placing all the extra weight around the waist may understate the effect. For further discussion of the weight distribution and its effects on metabolic rate see Chapter 4. As the garments were not tight to the body, if the weight had been spread over the limbs, for example in small pockets in the sleeves and legs, it would have moved as the sleeves and legs of the garments moved, for example during walking. This also proved the case when weight was sewn into cuffs and hems in the garments during pilot work. In that situation the cuffs and hems flapped around too much and it was also uncomfortable to have the weight hanging there.

underwear layer | low friction layer | high friction layer | overall

a) low friction layers | b) high friction layers | d) overalls low friction | e) overalls high friction

Figure 2.1. Photographs of the clothing layers used and clothing ensembles worn

For this study the weight was placed on the waist, wrists and ankles where it could be secured to prevent unnecessary movement. Weights were made out of lead and duct tape and attached to a belt for the waist and sweatbands for the wrists and ankles, as shown in Figure 2.2. Putting the sweatbands over the top of the garments caused restriction of the layers during the larger movements of the joints such as when the elbow was fully bent so the sweatbands were placed on the skin under the layers. Sweatbands were worn in all conditions.

1. weights made up for the ankles and wrists using lead weight and tape (top of the photo) and belts for the waist with weights taped on (bottom of the photo).

2. sweatbands

3. sweatbands with weights attached

4. sweatbands

5. sweatbands with weights attached

Figure 2.2. Photographs of the weights used to correct for garment weight.

In order to calculate the weight distribution required for the test garments a cotton overall was weighed and then cut up to ascertain the percentage of the garment weight that was carried around the torso, on the legs and arms. A photograph of the cut-up overall is illustrated in Figure 2.3. The 2 arm segments accounted for 5.5 % of the total garment weight each, the 2 leg segments accounted for 12 % of the total garment each, with the torso section making up 65 % of the total garment weight.

The weight of each layer and ensemble to be used was noted and is given in Table 2.2. However further corrections had to be made as the weight of the arm and leg segments would be placed at the end of the extremities during the testing and not spread across the limb. In the worked example shown in Figure 2.3, if the sleeve weighed 110 grams and the weight to compensate for this had to be placed on the wrist, the actual weight at the end of the limb (lever) should be less (due to its greater distance from the shoulder (pivot) and momentum) than the actual sleeve. Arbitrarily a method to compensate for this was developed. If the weight is split evenly along the arm in 3 segments the weight of each segment is then multiplied by its distance from the shoulder (in this case arbitrary units are used for the segments) so 1 x 37g plus 2 x 37g plus 3 x 37g, totalled and then divided by the total length (3 units) which in this example gives 74 grams for the wrist weight to compensate for the 110 gram total sleeve weight. The corrected weights for each ensemble are also included in Table 2.2.

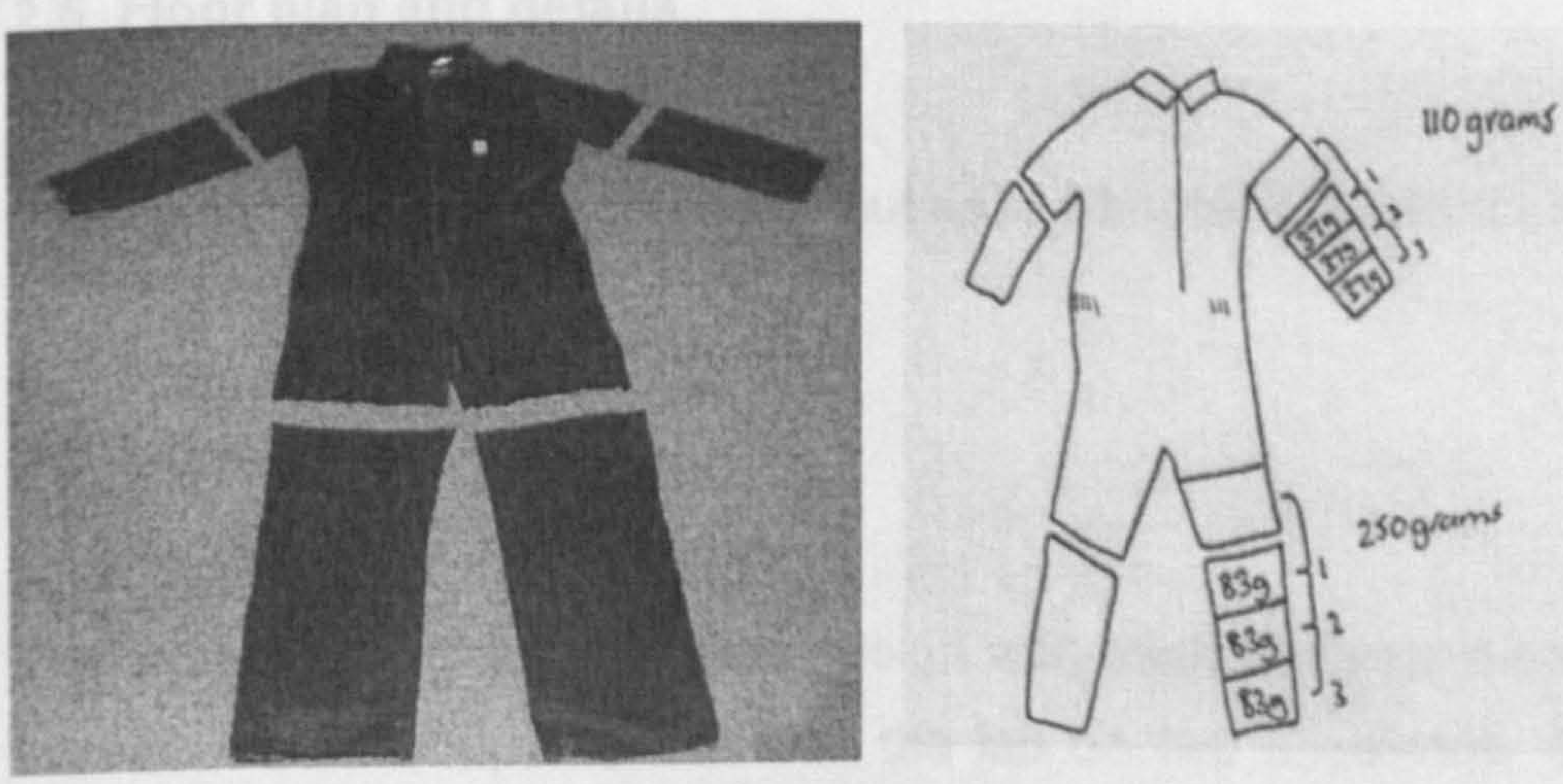


Figure 2.3. Photograph of cut-up overall to determine weight distribution of garment weight and diagram to illustrate methodology of calculating weight corrections applied using wrist and ankle weights.

Table 2.2. Weight details for ensembles and layers.

High friction layers underwear (0.559kg) layers x 4 (2.818kg)	**3.377kg**	**No correction**
Low friction layers underwear (0.559kg) layers x 4 (1.094kg)	**1.653kg**	**correction 1.724kg** waist 1.12kg ankles 0.140kg wrists 0.06kg
Control top and bottoms	**0.814kg**	**correction 2.563kg** waist 1.67kg ankles 0.206kg wrists 0.094kg
Overall high friction underwear (0.559kg) layers x 2 (1.396kg) overalls x 2 (1.309kg)	**3.264kg**	**No correction**
Overalls low friction underwear (0.559kg) layers x 2 (0.534kg) overalls x 2 (1.309kg)	**2.402kg**	**correction 0.862kg** waist 0.56kg ankles 0.066kg wrists 0.034kg
Control top and bottoms	**0.814kg**	**correction 2.45kg** waist 1.59kg ankles 0.200kg wrists 0.086kg

2.4 Work modes

Walking and obstacle course as detailed in Chapter 2 (Methodology).

2.5 Floor plan and details

Floor plan and obstacle course layout as in Chapter 4 (Weight simulations).

2.6 Experimental design

The study was a within-subjects design with each participant acting as their own control. Participants attended the lab on two occasions. One session was made up of the layers condition; a) 4 low friction layers worn over underwear, b) 4 high friction layers worn over underwear and c) control. The other session was made up of the overalls condition; d) 2 low friction layers in between 2 overalls over underwear, e) 2 high friction layers in between 2 overalls over underwear and f) control. The control condition was always the middle of the 3 conditions completed in each session. The garment order was fully balanced, so half of the participants started with the layers in the first session, half with the overalls. Within the sessions, half of the participants started with the low friction ensembles and half with the high friction ensembles, to prevent any order effects.

2.7 Procedure

On arrival at the lab participants were shown the treadmill and obstacle course and the route was described and demonstrated to them, they also had a chance to practice before they started. They were asked to fill out a Health Screen Questionnaire and sign an informed consent form. They were reminded of their right to withdraw from the experiment at any time without having to provide a reason.

They were provided with the first set of clothing and given time to dress and put on the heart rate monitor. Weights were attached around the waist, wrists and ankles if necessary in that condition, sweatbands were worn in all conditions.

Subsequently they were instrumented with the MetaMax oxygen analyser and instructed to sit at rest, data collection was started. Following a 5 minute seated rest, participants completed the first work mode (walking on a treadmill at 5 km/hr) which lasted 4 minutes, followed by 6 minutes of the obstacle course with moving crates, and going over and under hurdles. Both work modes are described in detail in Chapter 2 (Methodology) with the floor plan for the obstacle course included in Chapter 4 (Weight simulations). Participants were asked for their Rate of Perceived Exertion (RPE) score in the final minute of the work periods. Participants then rested and got changed for the next condition, with 2 layers conditions and a control completed in each session.

2.8 Analysis

A univariate analysis of variance was used for the metabolic rate data. Two analyses were completed one on the data from the layers session, one on the data from the overalls session, to establish possible significant differences from the control condition and between the high and low friction layers. Tukey post-hoc tests were carried out to establish where the significance lay.

For the subjective data Wilcoxon Signed Ranks tests were used to establish if the Rate of Perceived exertion recorded in the different layers and conditions were significant.

2.9 Material testing

The material testing was undertaken by Dr Harriet Meinander and colleagues at the Tampere University of Technology, Finland. A Kawabata Evaluation System (KES – FB4) was used as shown in Figure 2.4. For the friction test, the friction sensor was placed on the fabric to be tested, and the fabric moved 3 cm in one direction and 3 cm back, the measuring time being 1 minute. The friction coefficient was recorded with a printer, and the friction values integrated. The results were given as MIU (friction coefficient) and MMD (mean deviation of MIU).

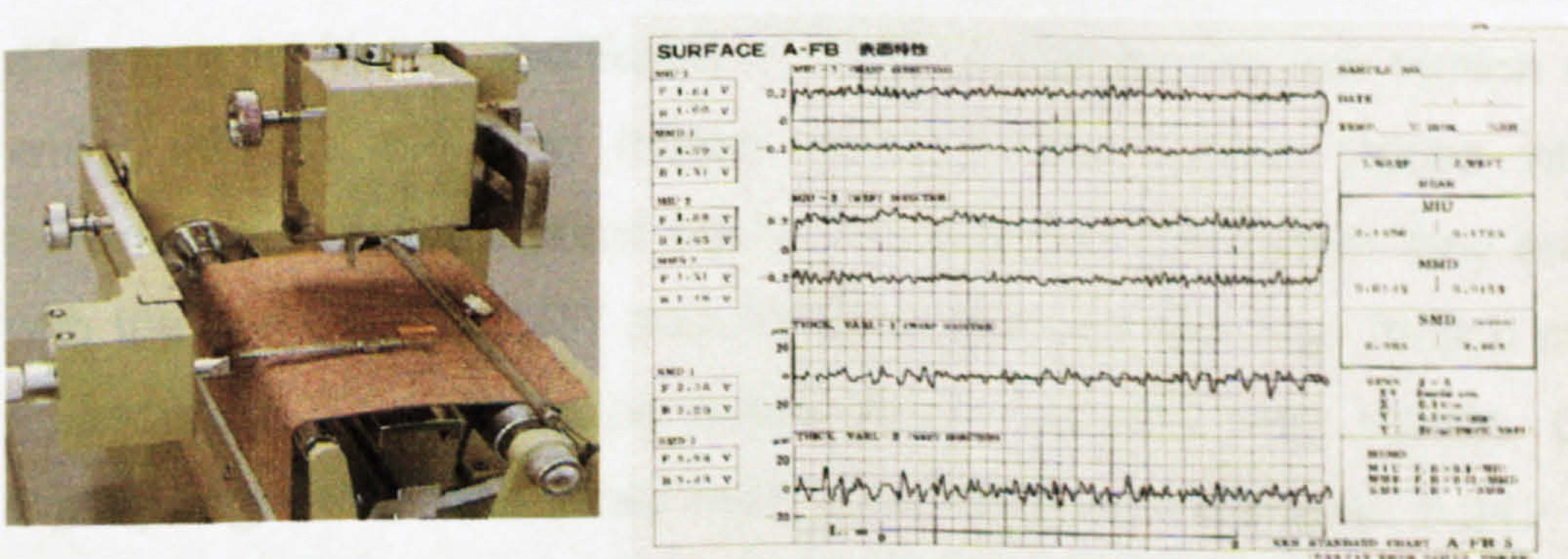


Figure 2.4. Photograph showing Kawabata Evaluation System (KES – FB4), the friction sensor is on the fabric and surface roughness sensor in the air. In the testing carried out for this study the standard friction sensor was replaced by a circular fabric covered sensor. Example of results for illustration only.

3. Results

3.1 Participants and environment

Eight male participants (age 25.0±2.2 years, height 178.6±3.6 cm, weight 69.5±6.1 kg) completed all sessions. The average environmental conditions for the room were 16.1±0.3 ^{0}C and 52±2 % relative humidity.

3.2 Material results

As explained previously, tight underwear was worn close to the skin, so any friction due to clothing movement would be between the clothing layers, not the clothing and the skin. The material tests were then carried out for the different layer interactions that would occur when worn. The interface with the lowest frictional resistance will always move first. The results from the material tests for the different layer combinations are shown in Figure 3.1. The combinations of materials tested reflect the interactions of the layers worn;

- Underwear v low and high friction layers
- Low friction layer v low friction layer
- High friction layer v high friction layer
- Overall v low and high friction layers

When comparing the underwear with low or high friction material the difference in friction coefficient is 0.242, 0.426 for the low friction material and 0.668 for the high friction material. The friction values when the materials are tested against each other are less than when they are tested with the underwear, 0.237 and 0.523 for the low and high friction materials respectively. The difference between the low and high results, 0.286 is slightly larger than when they were tested against underwear, 0.242.

For the overalls condition, the first 2 layers worn were the same as in the layers condition, underwear followed by a low or high friction layer. The subsequent layers were an overall, friction layer and another overall, so the friction coefficients between the friction layers and the overall were tested. The values measured were 0.266 for the low friction material and 0.461 for the high friction material as shown in Figure 3.1.

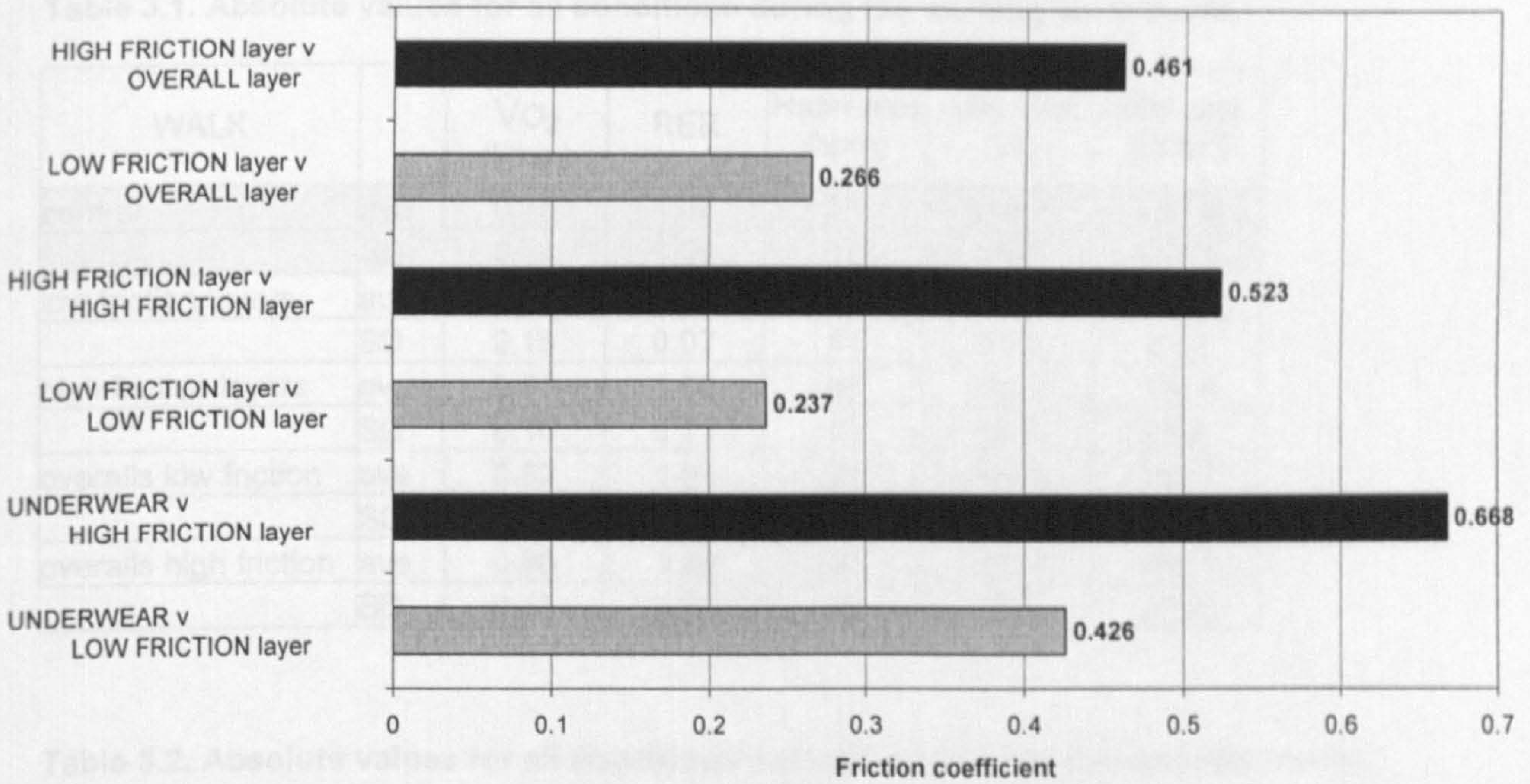


Figure 3.1. Friction coefficient values for the materials used in the present study.

When considering the friction results in relation to the conditions tested in the present study, the measured friction coefficient of 2 layers of the high friction material on top of each other was higher than using it with an overall layer, 0.523 and 0.461 respectively. But 2 layers of the low friction material had a slightly lower friction coefficient than the low friction layer and an overall layer, 0.237 and 0.266 respectively.

3.3 Absolute results

The absolute values for the 4 conditions and the control are included in Table 3.1 for walking and Table 3.2 for the obstacle course data. The values in the tables are not the same as those that will be seen in the graphs that follow. The values in Tables 3.1 and 3.2 are an average of, for example, the metabolic rate of all participants when walking or completing the obstacle course when wearing the low friction layers. However the values in the graphs, also given in Table 3.3 take account of the control conditions, and are based on an average of each participants % increase data (which is derived from comparing the layers or overalls to the same session control).

Table 3.1. Absolute values for all conditions during the walking work mode.

WALK		$\dot{V}O_2$ (l/min)	RER	Heart rate (bpm)	Met rate (W)	Met rate (W/m^2)
control	ave	0.78	1.10	95	279.8	149.6
	SD	0.14	0.09	14	48.2	22.0
low friction layers	ave	0.82	1.02	96	288.3	153.9
	SD	0.15	0.07	17	52.5	23.2
high friction layers	ave	0.81	1.06	96	286.2	152.8
	SD	0.16	0.11	15	55.5	25.6
overalls low friction	ave	0.82	1.06	91	292.3	156.7
	SD	0.12	0.09	11	44.6	21.6
overalls high friction	ave	0.85	1.06	96	300.4	161.1
	SD	0.13	0.08	12	45.6	22.4

Table 3.2. Absolute values for all conditions during the obstacle course work mode.

OBSTACLE COURSE		$\dot{V}O_2$ (l/min)	RER	Heart rate (bpm)	Met rate (W)	Met rate (W/m^2)
control	ave	1.14	1.07	114	404.8	216.4
	SD	0.21	0.08	12	74.0	32.7
low friction layers	ave	1.21	1.04	117	427.3	228.3
	SD	0.24	0.11	15	83.4	36.5
high friction layers	ave	1.20	1.07	117	424.9	227.4
	SD	0.22	0.11	11	73.2	32.7
overalls low friction	ave	1.20	1.05	112	425.4	227.5
	SD	0.19	0.07	8	70.6	30.2
overalls high friction	ave	1.22	1.06	116	432.1	231.1
	SD	0.22	0.08	11	80.5	36.2

Table 3.3. Average percentage increase in metabolic rate for each condition and each work mode, based on % increase from control in each session for each participant.

	WALK	OBSTACLE COURSE	AVERAGE
low friction layers	5.6	6.9	6.2
high friction layers	4.5	6.8	5.6
overalls low friction	5.1	6.1	5.6
overalls high friction	7.9	7.4	7.7

The average value for $\dot{V}O_2$ recorded when walking in the control condition was 0.78 l/min with increases of 0.03 to 0.07 l/min with the additional layers. The values recorded during the obstacle course were higher, 1.14 l/min in the control and increased by 0.06 – 0.08 l/min with additional layers. The heart rate is also higher in the obstacle course 114 beats per min (bpm) in the control condition up to 117 bpm with extra layers compared to 95 bpm rising to 96 bpm when walking. The respiratory exchange ratio (RER) values were very similar across work modes with a metabolic rate of 149.6 W/m^2 walking and 216.4 W/m^2 during the obstacle course. The average increases in metabolic rate seen in Tables 3.1 and 3.2 above when wearing extra layers during walking were 3.2–11.5 W/m^2 (approx 2.1–7.7 %) and 11–14.7 W/m^2 (approx 5.1–6.8 %) during the obstacle course.

3.4 Metabolic rate results

The percentage increases in metabolic rate relative to session controls have been plotted in Figures 3.2 and 3.3. Figure 3.2 is a summary of the layers conditions where participants wore underwear and then 4 low or high friction layers on top of each other all corrected for weight. Figure 3.3 is a summary of the overalls condition where participants wore underwear and then 4 layers made up of a high or low friction layer, an overall, another high or low friction layer and another overall, with the low friction condition corrected for weight. The average columns are of the walking and obstacle course data together. The significant differences highlighted in Figures 3.2 and 3.3 by * are significant increases from the control condition, there were no significant differences between the low and high friction conditions.

For the low and high friction layers (Figure 3.2) the percentage increases when walking were 5.6 and 4.5 % respectively, 6.9 and 6.8 % for the obstacle course, with the average of the work modes being 6.2 and 5.6 %. All results were significantly higher than the control condition except walking in the high friction layers. The differences in the obstacle course between the layers was only 0.1 % but during the walking the increases in the low friction layers were 1 % higher than in the high friction layers which has also caused the average in the low friction layers to be higher.

The data for the overalls and low or high friction layers graphed in Figure 3.3 shows increases of 5.1 and 7.9 % when walking, 6.1 and 7.4 % during the obstacle course and 5.6 and 7.7 % on average, with the low and high friction layers respectively. All results are significantly higher than the control. Although the differences between the conditions were greater with the high friction layers by 2.8 % for walking, 1.3 % during the obstacle course and 1.9 % for the average, these were not statistically significant.

Comparing the layers to the overalls conditions, with the low friction fabric there were not large differences between the observed values when wearing 4 layers of the same material or 4 layers with the 2 low friction layers in between 2 overalls, 5.6 and 5.1 % (layers and overalls respectively) when walking, 6.9 and 6.1 % during the obstacle course and 6.2 and 5.6 % on average. The differences in the observed values for the high friction conditions were greatest during walking, as the increase in metabolic rate was 4.5 and 7.9 % (layers and overalls respectively), 6.8 and 7.4 % during the obstacle course and 5.6 and 7.7 % for the average (values in Table 3.3).

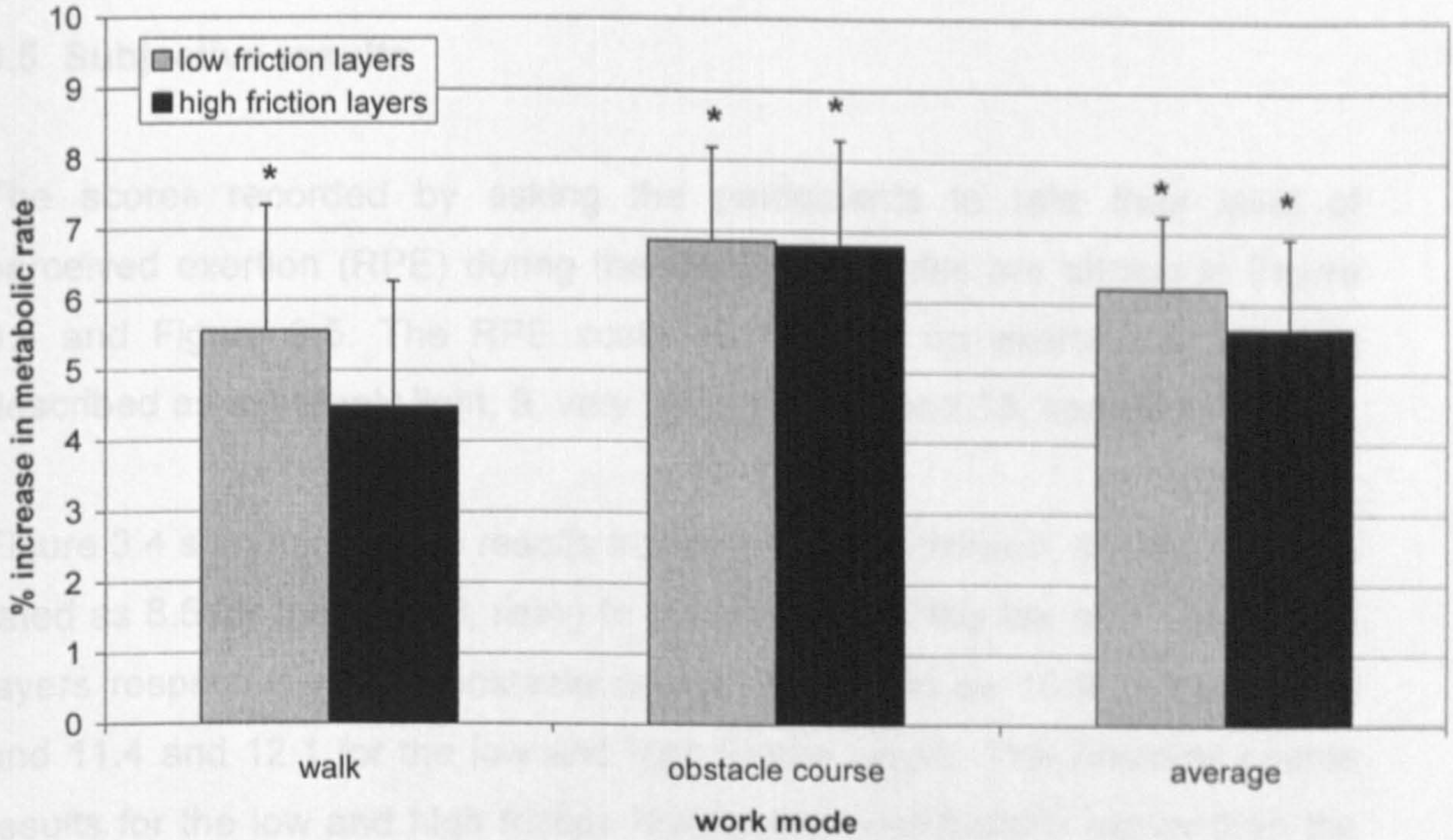


Figure 3.2. Percentage increases in metabolic rate relative to the control condition when wearing high (black bars) and low friction (grey bars) layers walking and completing an obstacle course (n=8). Significance compared to control, $p<0.05$ indicated by *. All conditions had the same weight.

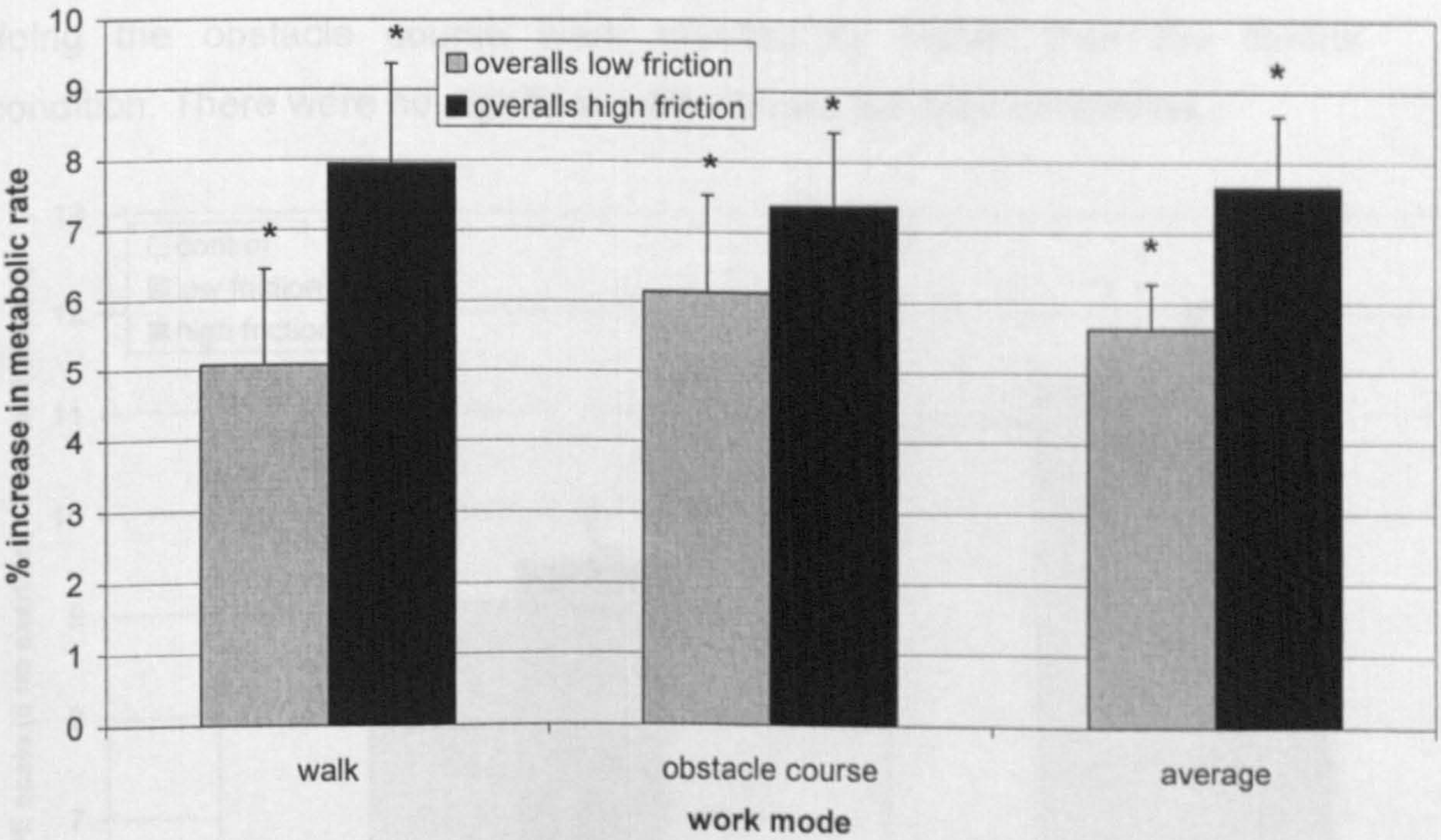


Figure 3.3. Percentage increases in metabolic rate relative to the control condition when wearing overalls with high friction layers (black bars) or low friction layers (grey bars) in between overalls when walking and completing an obstacle course (n=8). Significance compared to control, $p<0.05$ indicated by *. All conditions had the same weight.

3.5 Subjective results

The scores recorded by asking the participants to rate their level of perceived exertion (RPE) during the two work modes are shown in Figure 3.4 and Figure 3.5. The RPE scale starts at 6, no exertion at all, 7 is described as extremely light, 9, very light, 11, light and 13, somewhat hard.

Figure 3.4 summarises the results from the layers condition, the walking was rated as 8.5 for the control, rising to 9.1 and 9.5 for the low and high friction layers respectively. The obstacle course was rated as 10.9 in the control and 11.4 and 12.1 for the low and high friction layers. The obstacle course results for the low and high friction layers were significantly higher than the control. For the overall condition results, in Figure 3.5 the walking was rated as 8.3, 9.4, 9.4 and the obstacle course 10.9, 11.5 and 12 for the control, overalls low friction, overalls high friction respectively. The increase in RPE votes in the overalls low friction walking, overalls high friction walking and doing the obstacle course were significantly higher than the control condition. There were no significant differences between conditions.

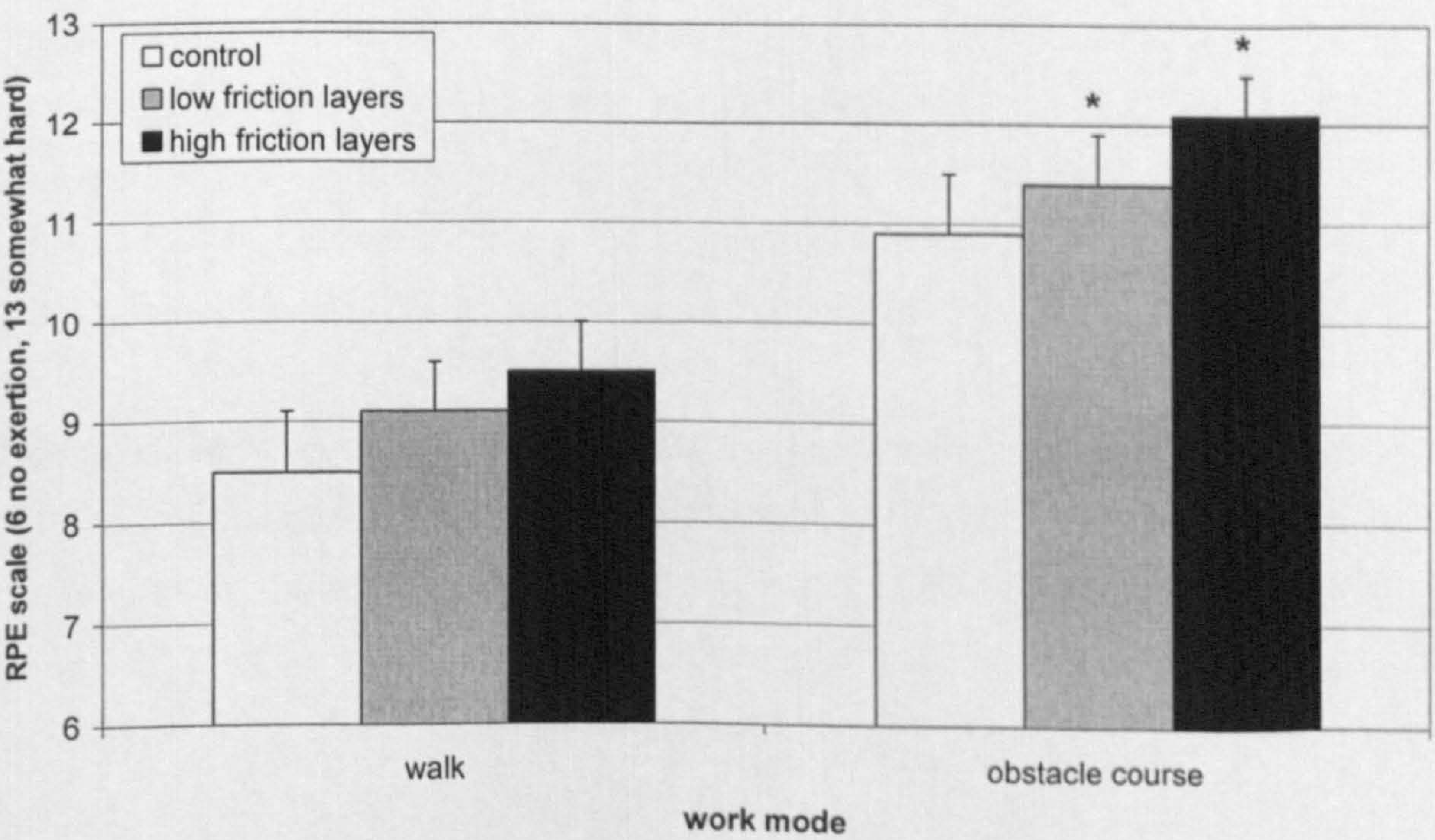


Figure 3.4. Rate of Perceived Exertion scores (n=8) for walking and completing the obstacle course in the control (white bars), low friction layers (grey bars) and high friction layers (black bars). Significance of p<0.05 compared to control indicated by *.

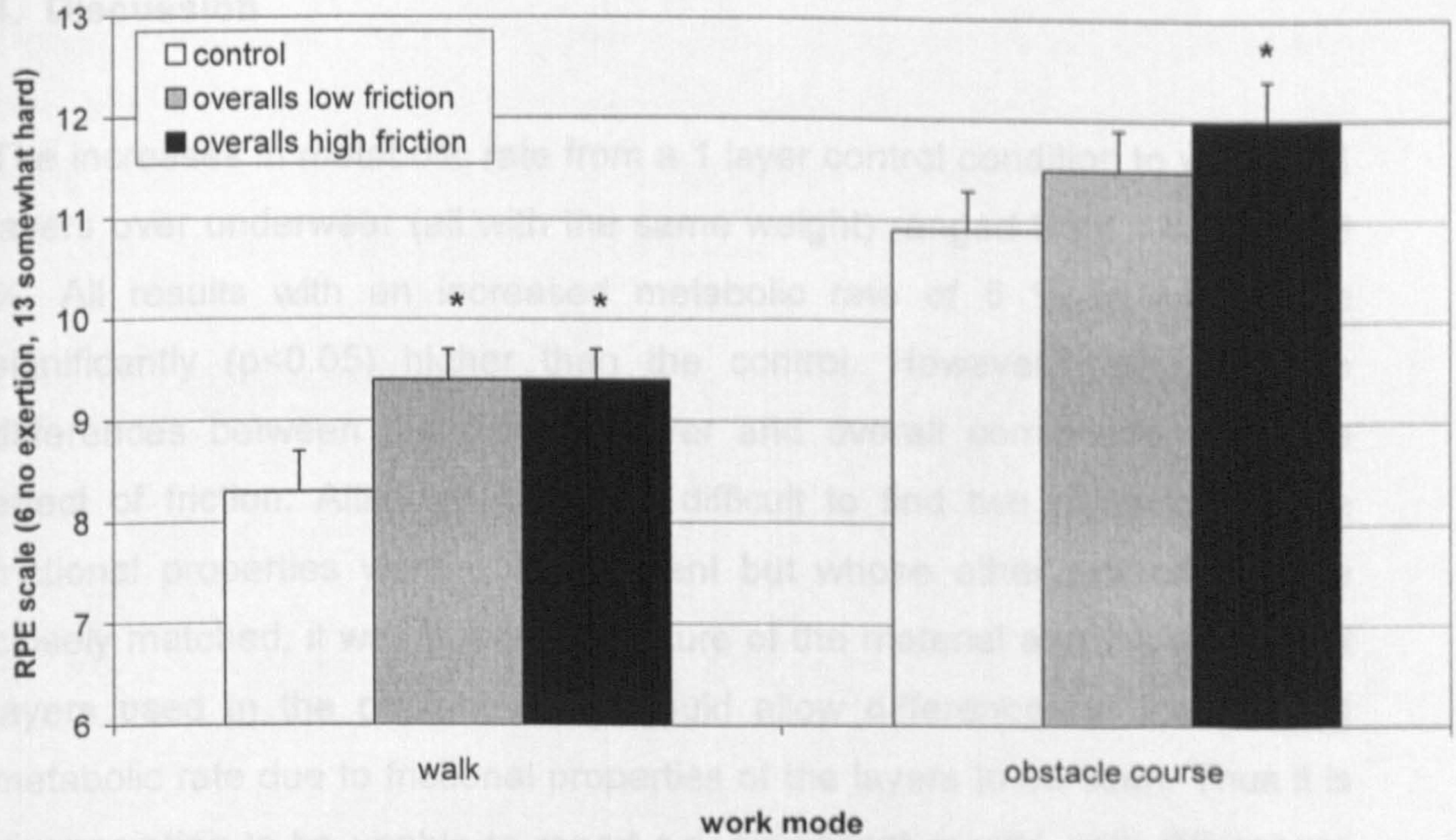


Figure 3.5. Rate of Perceived Exertion scores (n=8) for walking and completing the obstacle course in the control (white bars), overalls low friction (grey bars) and overalls high friction (black bars). Significance of $p<0.05$ compared to control indicated by *.

4. Discussion

The increases in metabolic rate from a 1 layer control condition to wearing 4 layers over underwear (all with the same weight) ranged from 4.5 % to 7.9 %. All results with an increased metabolic rate of 5 % or more were significantly ($p<0.05$) higher than the control. However there were no differences between the different layer and overall combinations for the effect of friction. Although it proved difficult to find two materials whose frictional properties were quite different but whose other properties were closely matched, it was hoped the nature of the material and the number of layers used in the present study would allow differences in the working metabolic rate due to frictional properties of the layers to be seen. Thus it is disappointing to be unable to report any significant results, with differences of less than 3 % and overlapping standard deviations between the high and low friction conditions.

It was surprising that the low friction layers caused minimally higher increases in metabolic rate (relative to control condition) than the high friction layers. Whereas, as expected, in the overalls condition, the increased metabolic rates in the high friction layers were 1.3 to 2.8 % higher in all work modes than the low friction layers. The material tests showed the reduced friction between the low friction layers and the underwear, overalls and other low friction layers, compared to the high friction conditions.

Comparing across the conditions, for example low friction layers and overalls low friction, shows that the metabolic rate when wearing 4 layers of the low friction material was similar to wearing 2 layers and 2 overall layers for all work modes. For the high friction material conditions, the differences between wearing alternate layers of the overalls and 4 layers of high friction fabric were also not significantly different.

The results of the material tests have been ranked from lowest to highest in Table 4.1. The friction coefficients for the low friction material measured against itself, the overall and the underwear were all lower than the high friction measurements. The highest values for the low friction material and high friction material were both recorded with the underwear. The lowest value recorded with the low friction material was with itself (layers), however the lowest value for the high friction material was with the overall.

Table 4.1. Friction coefficients values for all material and layer combinations, ranked from lowest to highest.

clothing	friction value
low friction layers	0.237
low friction + overall	0.266
low friction + underwear	0.426
high friction + overall	0.461
high friction layers	0.523
high friction + underwear	0.668

The friction coefficients of the materials used in this study are in the same ranges as those recorded by Anttonen *et al.* (2001) which have been summarised in Table 4.2. Anttonen *et al.* (2001) were researching optimal low-friction clothing for defence forces. By developing underwear, quilted fabric in the middle layers and satin linings in the overgarment, they managed to decrease friction and measure performance improvements of 5 to 7 % during stair running and uphill walking tasks due to the overall lower friction ensemble.

The low friction values for the present study, 0.237 to 0.426, compare to the new garments of Anttonen *et al.* (2001) in Table 4.2, with friction coefficients of 0.33 to 0.44. The friction values for the standard garments they report are also in a similar range 0.50 – 0.59 to the high friction values 0.461 – 0.668 in the present study.

Table 4.2. Summary of friction coefficient values based on an average of the length/length and cross/cross friction values of Anttonen *et al.* (2001).

layers	new garments	standard garments
underwear + intermediate	0.35	0.59
intermediates	0.44	0.50
intermediate + outer	0.33	0.56

The measurement of fabric friction was the only formal test made on the fabrics used in the present study, however the fabrics were initially selected on their subjective hand. The feel of the fabric surface and a subjective estimate of friction when samples were pulled across each other were the main deciding factors on the fabric purchased. The polyester fabric selected with a satin finish for the low friction layers is best described as having a very smooth surface. By contrast the crepe finished polyester selected for the high friction layers had a rougher feel and uneven surface. These observations fit with literature descriptions, any fabric that offers little frictional resistance to motion and possesses a low coefficient of friction is likely to be described as a smooth fabric (Ajayi 1992b). In contrast high friction usually equals a harsh feel as friction depends on the characteristics of surfaces in mutual contact (Chattopadhyay and Banerjee 1996).

The crepe finished polyester also has a much greater texture to the touch than the satin finished material. The yarns are also visible to the eye with the crepe finish compared to the satin finish which fits with Ajayi (1992a) who suggests structurally protruding yarn crowns and fibre tufts from the fabric surface also influence fabric smoothness and friction.

Calculating the increased energy cost per clothing layer in this study results in values of 1.13 – 1.98 % per layer which is rather lower than the 3 – 4 % quoted by Lotens (1982) when summarising the work of Teitlebaum and Goldman (1972) and Amor *et al.* (1973). However in both of these studies (Teitlebaum and Goldman 1972, Amor *et al.* 1973) the layers worn were arctic and although the controls were corrected for weight, it is easy to assume from the total weight of the ensembles, 11.2 kg and 9 kg respectively that the layers were substantially heavier and most probably thicker than those used in the present study for which the heaviest ensemble weighed 3.4 kg. The layers used by Teitlebaum and Goldman (1972) are described as woollen pants and shirt, field pants and jacket with mohair liner, and arctic parka and pants with mohair liner, and range in weight from 1.61 kg for the woollen pants/shirt to 2.76 kg for the arctic parka/pants. These thicker layers, were probably constructed from bulkier and stiffer materials, which would have been less flexible. In contrast, the layers worn in the present study were designed to be thin and made of lightweight and very flexible material, this would have allowed them to move easily over each other and not impinge on movements where a high degree of flexion was required, e.g. at the elbows and knees during the obstacle course. In hindsight this may be part of the reason the effects seen in the present study were smaller than found in other studies. Future work is needed to look at thicker, more functional layers, or layers within more realistic ensembles.

Teitlebaum and Goldman (1972) give energy costs of 435 W in their control and up to 514 W in the arctic layers when walking at 5.6 km/hr, by contrast the energy cost of the participants in the present study during the walking (5 km/hr) was in the range of 280–300 W although for the obstacle course this average was raised to 430 W. The much higher work rate in the Teitlebaum and Goldman study is another indicator of a higher work load.

It should be noted that in the study of Amor *et al.* (1973) participants also wore loose fitting (mukluk) arctic boots, in the present study participants wore trainers and in the study of Teitlebaum and Goldman (1972) participants wore standard military combat boots. Although Amor *et al.* (1973) do not provide a weight for the footwear they do suggest the increased effort required to walk in the loose fitting boots may in part explain some of the increased energy cost in the arctic clothing condition. The authors also cite Soule and Goldman (1969) who showed an increased energy cost if a load is carried on the feet. The studies of Patton *et al.* (1995) and Murphy *et al.* (2001) comparing battle dress uniform (BDU) to chemical protective (CP) clothing are also affected by adding extra weight to the feet during the CP condition with rubber boots worn over the standard combat boots. Murphy *et al.* (2001) acknowledge that the increase in energy cost above that accounted for by clothing weight can best be explained by a hobbling effect but also the disproportionate energy cost incurred by overboots and gloves. The overboots are reported to weigh 2 kg in the study of Patton *et al.* (1995). Therefore the use of different or heavier footwear is another factor that may be adding to the increased energy costs in these studies. The exact contribution of the boot weight cannot be accurately identified but results from the weight distribution study in the previous chapter suggest carrying 2 kg on the ankles could increase metabolic rate by up to 7 % which would account for most of the 6-11 % increase reported by Patton *et al.* (1995) and the 8-10 % observed by Murphy *et al.* (2001). In the present study lightweight trainers were worn in all conditions.

Statistically significant differences in the recorded RPE results, particularly in the obstacle course confirm that participants felt they were having to work harder in the multilayered conditions than in the control. However on average the walking promoted only very light exertion, 8.3-8.5 in the control, 9.1–9.5 in the layers and overalls. Completing the obstacle course in the extra layers increased participants subjective ratings to 11.4–12.1 in the layers, compared to 10.9 for the control, with 13 described as somewhat hard on the scale. The results indicate that the participants were working harder in the obstacle course than when walking but the effect of the extra layers was similar in both work modes, adding up to 1 vote to their control score.

5. Chapter summary

Wearing 4 layers increased the metabolic cost of walking and completing an obstacle course by 4.5 to 7.9 % compared to a single layer control condition of the same weight. Two layering conditions were investigated, 4 layers of the same material (low and high friction) and layering 2 low or high friction layers between 2 overalls (with long underwear as the first layer for all). Larger differences were recorded in the overall conditions. Metabolic rate increases of 5 % or more above the control condition were found in all but one of the conditions and these findings were statistically significant ($p<0.05$). This finding proved the hypothesis put forward in the introduction that working in a number of layers will result in a higher energy cost than a single layered control weighing the same due to friction between layers. Significantly higher RPE ratings in a number of layered conditions compared to the single layer control were also recorded.

However the differences between the metabolic rate increases in the high and low friction layers were not significant, despite higher friction coefficient values measured in all high friction configurations (with underwear, another high friction layer and an overall), compared to the low friction material. Thus in the present study the hypothesis that increased energy costs measured when wearing high friction clothing layers would be due to the increased friction generated by the material layers moving across each other could not be proven. Given the scale of the increased metabolic rate effect, 2.4 – 20.9 %, found in the initial study of this thesis (Chapter 3) and the fact that the friction between the layers is one of a number of factors that contribute to the gross metabolic rate increase it is perhaps understandable that it was not possible to confirm the effect of the layers friction on metabolic rate in this study. However the results of this study have added weight to the existing data on the issue and provided insight into further work that could be undertaken to try and understand this topic further

There is no doubt the number of layers and their frictional properties is an important contributing factor to the potential energy cost of the wearer. However the ability to be able to isolate purely the influence of friction is very hard and considerable skill and investment would be required to try and promote further investigation.

CHAPTER 6

STUDY 4

INVESTIGATING THE EFFECT OF WET LAYERS AND THEIR FRICTIONAL PROPERTIES ON METABOLIC RATE

1. Introduction

The previous chapter introduced the concept of a possible friction drag effect between clothing layers. Many authors who found increases in energy costs when working in multilayered protective clothing ensembles speculated that this effect may have been responsible for some of the increase recorded.

However, although this friction drag had been put forward by many, a review of the ergonomics, clothing and textile literature revealed a lack of detailed investigation into the issue.

Results from the previous chapter found wearing four layers did increase the metabolic costs of walking and completing an obstacle course by 4.5 to 7.4% compared to a single layered control condition of the same weight, with the increases statistically significant ($p<0.05$) in all but one condition. Layers were made up of high and low friction fabrics and worn in different combinations but the differences in metabolic cost between the high and low friction ensembles tested (up to 2.8 %) did not prove statistically significant.

1.1 Previous research

As reported in the previous chapter, a number of authors (Teitlebaum and Goldman 1972, Amor *et al.* 1973, Lotens 1982, Duggan 1988, Patton *et al.* 1995, Murphy *et al.* 2001, Rintamaki 2005) have suggested a possible link between increased energy costs and friction of multiple clothing layers. However despite an awareness of its possible contribution, only one study, Anttonen *et al.* (2001) attempted to investigate the issue. Anttonen *et al.* (2001) summarise some of the factors that influence friction; pressure, contact surface area, contact points, direction of motion, duration of contact, velocity, fibre, construction of yarn and fabric, finishing of fabric and wetness of fabric.

The previous chapter looked at the friction between a number of layers and also investigated the effect of the fabric finish by using 100 % polyester fabric with a crepe finish and a satin finish to make up a number of high and low friction suits respectively.

No studies have been found which looked at the effects of friction in wet garments, although in a Report to the Scientific Board of National Defence (2000) written in Finnish, Anttonen *et al.* detail some measurements of friction between different fabrics when dry and wet. The increases in wet friction coefficient values between the materials they tested were 7.7 to 102.6 % higher compared to the same material measured dry (Anttonen *et al.* 2000).

1.2 Aims

The previous study looked at the effects of friction on metabolic rate using multiple layers made of high and low friction material. This study will look at the same layer ensemble with overalls, as used in one condition of the previous study (underwear, material layer, overall, material layer, overall) and the same materials (high friction and low friction), with a number of layers wetted. Therefore the aims of this study are;

- To investigate if friction caused by wearing a number of wetted layers has an effect on the metabolic cost of activity with the hypothesis that wet layers will increase the friction between layers and result in a higher energy cost than a single layered control of the same weight.

Extra wet layers will increase the friction further and therefore result in a higher metabolic rate.

- To investigate if the effects of wearing a number of wetted layers are different with high and low friction material layers. The hypothesis being that the resultant energy costs when completing activities wearing the high and low friction layers will be higher with wet layers than dry and that the increases with the wet high friction layers will be greater than with the wet low friction layers due to greater material friction in the high friction layers.

2. Methods

2.1 Participants

Eight male participants took part in the study. They were all volunteers drawn from the student population at Loughborough University. Their physical characteristics are summarised in Table 2.1.

Table 2.1. Participant details.

Gender	Age (yrs)	Height (cms)	Weight (kg)
M	29.4	187	79
M	25.4	180	67
M	24.7	180	72
M	28.6	178	70
M	25.9	178	75
M	23.8	177	60
M	27.8	171	62
M	23.2	180	71
ave	**26.1**	**178.9**	**69.5**
SD	**2.3**	**4.4**	**6.3**

2.2 Clothing

The background to the selection of the high and low friction material and design of the suits is provided in the previous chapter. The layers used in this study were the same as those in the low and high friction layer conditions in the previous study. For the present study participants were required to complete two sessions. One session consisted of wearing 2 low friction layers in between 2 overalls (with underwear as the first layer), the other session consisted of wearing the same ensemble with high friction layers. Within the sessions, participants completed 4 conditions, a control (wearing sweatshirt and tracksuit trousers), all layers dry, inner layers wet, inner and outer layers wet, the details of which are included in Table 2.2.

Table 2.2. Breakdown of layers worn (underwear, layers, overalls) and their status (dry or wet) for each condition within a session, all dry, inner wet, inner and outer wet (control not included in table, tracksuit trousers and sweatshirt).

	ALL DRY	INNER WET	INNER / OUTER WET
underwear	dry	wet	wet
low / high friction layer	dry	wet	wet
overall	dry	dry	dry
low / high friction layer	dry	dry	wet
overall	dry	dry	wet

A number of methods were piloted for wetting the layers including spraying the garments with water to try and achieve an even covering of moisture, another method involved leaving garments overnight in a bag with a known volume of water. An appropriate degree of wetness also had to be judged. The garment needed to be wetted as evenly as possible but excess water dripping from the garment needed to be avoided as this would alter the weight. Various degrees of wetness were assessed by wearing the garments while performing the tasks and visually inspecting the distribution of wetness on the garment. The friction of garments of varying wetness were estimated subjectively by laying them on a table and easing layers across each other. Garments were also wetted, weighed and placed in bags and left to sit for varying time periods and then weighed again. The garments could be left for up to 60 minutes with very little weight change (up to a few grams).

The method chosen for wetting the garments in this study commenced sixty minutes before the participant was due to arrive when the garments to be wetted (underwear, low or high friction layers and overalls) were immersed in water (from the cold tap) by placing them in a 10 litre bucket (a in Figure 2.1) filled to 75 % of its capacity for 60 seconds. The garments were then removed from the bucket and wrung by hand to expel most of the water and then placed on a 100 % cotton towel on a table and covered with another towel (b and c in Figure 2.1). The garment was then rolled down the table as shown in d in Figure 2.1, using the hands to press and roll the towels, moving the hands across the width of the towel after each half turn. This process was used to remove excess water from the garment and evenly distribute the water and therefore weight across the garment. After rolling, the garment was weighed. If the weight was too high, the process was repeated. If the weight was too low, extra water was added to the garment using a spray bottle. Each garment was placed in a plastic bag when its target weight was achieved, the air was pushed out of the bag by hand, it was then tied and placed in the testing lab at room temperature (e in Figure 2.1).

Figure 2.1. Process of wetting garments a. soaking of garment by immersing in bucket of water, b. laying of garment on towel, c. covering garment with second towel, d. rolling of excess water from garment and e. storage of wet garment in plastic bag.

2.3 Weight corrections

In order to make comparisons between the conditions as accurately as possible, all ensembles, wet, dry, low friction and high friction were brought up to the same weight. The explanation for adding weight to bring the weight of clothing up to the heaviest condition can be found in the previous chapter, where the weight correction section details the method used for calculating, correcting and distributing the weight, and how it was placed on participants. The layers for the present study were weighed wet and their weights are provided in Table 2.3.

2.4 Experimental design

The study was a within-subjects design with each participant acting as their own control. Participants attended the lab on two occasions. One session was made up of the low friction conditions; all layers dry, inner 2 layers wet, inner and outer 2 layers wet and a control condition. The other session was made up of the high friction condition; all layers dry, inner 2 layers wet, inner and outer 2 layers wet and a control condition. The session and garment orders were fully balanced.

Table 2.3. Weight details for each layer and weight corrections to be applied.

High friction layers

inner and outer layers wet wet underwear (1.169kg) wet layer (1.29kg) dry overall (0.642kg) wet layer (1.357kg) wet overall (1.084kg)	5.542kg	Heaviest condition, No correction required		
inner layers wet wet underwear (1.169kg) wet layer (1.212kg) dry overall (0.642kg) dry layer (0.697kg) dry overall (0.666kg)	4.386kg	correction 1.156kg	waist ankles wrists	0.721kg 0.094kg 0.05kg
all dry dry underwear (0.572kg) dry layer (0.606kg) dry overall (0.642kg) dry layer (0.697kg) dry overall (0.666kg)	3.183kg	correction 2.359kg	waist ankles wrists	1.472kg 0.194kg 0.102kg
control top and bottoms	0.846kg	correction 4.696kg	waist ankles wrists	2.93kg 0.386kg 0.203kg

Low friction layers

inner and outer layers wet wet underwear (1.169kg) wet layer (0.342kg) dry overall (0.642kg) wet layer (0.36kg) wet overall (1.084kg)	3.597kg	correction 1.945kg waist ankles wrists	 1.214kg 0.160kg 0.084kg
inner layers wet wet underwear (1.169kg) wet layer (0.321kg) dry overall (0.642kg) dry layer (0.286kg) dry overall (0.666kg)	3.084kg	correction 2.458kg waist ankles wrists	 1.534kg 0.202kg 0.106kg
all dry dry underwear (0.572kg) dry layer (0.244kg) dry overall (0.642kg) dry layer (0.286kg) dry overall (0.666kg)	2.41kg	correction 3.132kg waist ankles wrists	 1.954kg 0.286kg 0.136kg
control top and bottoms	0.846kg	correction 4.696kg waist ankles wrists	 2.93kg 0.386kg 0.203kg

2.5 Procedure

The general health and fitness of participants was assessed as they were required to fill out a Health Screen Questionnaire and consent form when they arrived at the laboratory prior to the first session. Participants were shown the obstacle course with the route and timing described and demonstrated to them, they also had a chance to practice before they started.

They were provided with the first set of clothing and given time to dress and put on the heart rate monitor. Weights were attached around the waist, wrists and ankles if necessary in that condition, sweatbands were worn in all conditions.

Subsequently they were instrumented with the MetaMax and instructed to sit at rest while data collection was started. Following a 5 minute seated rest, participants completed the first work mode (walking on a treadmill at 5 km/hr) which lasted 4 minutes, followed by 6 minutes of the obstacle course, moving crates, and going over and under hurdles (all work modes are described in detail in the methodology chapter, as is the floor plan for the obstacle course). They were always asked for their Rate of Perceived Exertion (RPE) score in the final minute of the work periods. Participants then rested and got changed for the next condition. Three layers conditions and a control were completed in each session.

2.6 Analysis

A univariate analysis of variance was used for the metabolic rate data, to establish possible significant differences from the control condition and between the wetted conditions and high and low friction material. Tukey post-hoc tests were carried out to establish where the significance lay.

For the Rate of Perceived Exertion data Wilcoxon Signed Ranks tests were used to establish if the subjective data recorded in the different material and wetted conditions were significant.

2.7 Material testing

The dry material testing was carried out as described in the previous chapter. For the wet material testing, the fabric samples were treated as follows; weigh the dry specimen, submerge in water bath, remove extra water with roller, weigh wet specimen, repeat water removal if necessary until approximately wetting of 100 % on dry fabric weight is achieved. A new specimen was prepared for each measurement.

3. Results

3.1 Participants and environment

Eight male participants (age 26.1±2.3 years, height 178.9±4.4 cm, weight 69.5±6.3 kg) completed both sessions in the low and high friction layers. The average environmental conditions for the room were 16.3±0.4^{0}C and 53±3% relative humidity.

3.2 Material results

The results for the material tests are shown in Figure 3.1 for the low (grey bars) and high (black bars) friction layers respectively. For the inner layers wet condition participants were required to wear wet underwear and a wet low or high friction material layer followed by dry layers and in the inner and outer layers wet condition, participants wore the wet underwear and first layer as just described, followed by a dry layer and then 2 further wet layers. Therefore the material friction coefficient values between the wet underwear and wet material layer, and wet material layer and wet overall layer were measured. The friction coefficients between the overalls and the friction layers when wet and dry were also measured.

The highest values measured were for the wet underwear and wet material layer samples for both the high friction material, 1.449 and the low friction material, 0.533. The other all wet measurement (wet overall layer v wet friction layer samples) produced the next highest friction coefficient values, 0.960 for the high friction layer and 0.525 for the low friction layer. The lowest values were recorded with only one wet sample and the other dry, with very little difference between the wet overall and dry material layer or dry overall and wet material layer, 0.831 and 0.880, 0.493 and 0.479 for the high friction and low friction materials respectively.

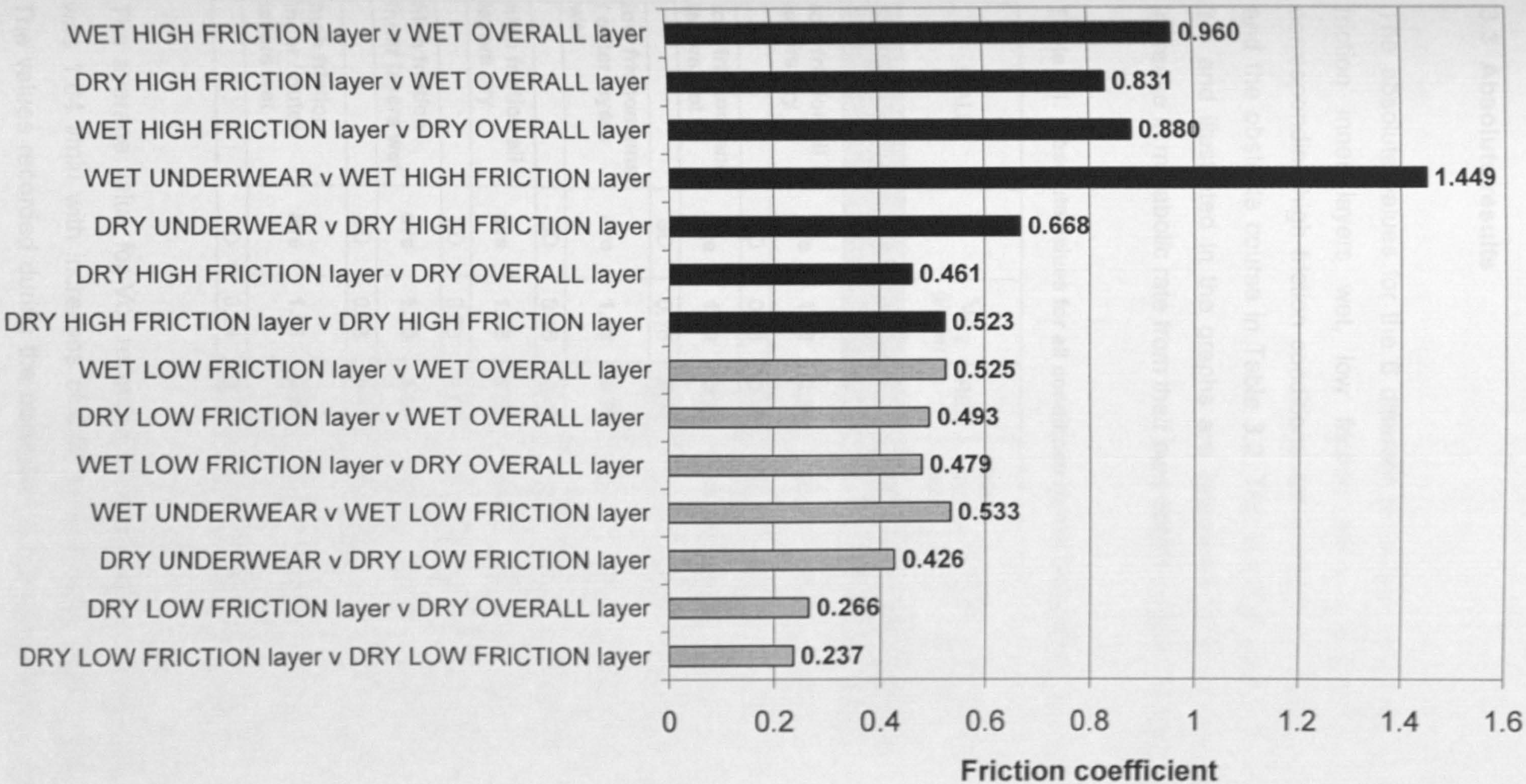


Figure 3.1. Friction coefficient values for the different wet and dry layer combinations, based on material measurements with the Kawabata Evaluation System KES – FB4.

3.3 Absolute results

The absolute values for the 6 different conditions; low friction all dry, low friction inner layers wet, low friction inner / outer layers wet and corresponding high friction conditions are included for walking in Table 3.1 and the obstacle course in Table 3.2. The average values shown in Table 3.3 and illustrated in the graphs are calculated from each participants % increase in metabolic rate from their own control within the same session.

Table 3.1. Absolute values for all conditions during the walking work mode.

WALK		$\dot{V}O_2$ (l/min)	RER	Heart rate (bpm)	Met rate (W)	Met rate (W/m^2)
control	**ave**	**1.04**	**0.83**	**90**	**350.3**	**187.1**
	SD	0.17	0.11	12	53.4	22.5
low friction all layers dry	**ave**	**1.06**	**0.78**	**92**	**353.9**	**189.3**
	SD	0.18	0.12	13	55.0	25.0
low friction inner layers wet	**ave**	**1.09**	**0.79**	**89**	**364.5**	**194.9**
	SD	0.18	0.11	13	56.3	24.7
low friction inner / outer layers wet	**ave**	**1.08**	**0.79**	**89**	**361.4**	**193.1**
	SD	0.16	0.10	12	51.6	20.2
high friction all layers dry	**ave**	**1.08**	**0.85**	**91**	**365.0**	**194.5**
	SD	0.23	0.09	14	75.0	32.5
high friction inner layers wet	**ave**	**1.10**	**0.84**	**90**	**371.8**	**198.3**
	SD	0.23	0.11	14	71.6	31.1
high friction inner / outer layers wet	**ave**	**1.13**	**0.86**	**90**	**382.1**	**203.8**
	SD	0.24	0.12	15	76.4	34.0

The average value for $\dot{V}O_2$ recorded when walking in the control condition was 1.04 l/min with increases of 0.02 to 0.09 l/min with additional layers. The values recorded during the obstacle course were higher, 1.45 l/min in the control and increases of 0.04 to 0.11 l/min with additional layers. The heart rate is also higher in the obstacle course control 104 bpm rising to 108 bpm with extra layers compared to 90 bpm rising to 92 bpm in the control and layers conditions respectively. The respiratory exchange ratio (RER) values were very similar across work modes with a metabolic rate in the control condition of 187.1 W/m^2 walking and 260.4 W/m^2 for the obstacle course. The increases in metabolic rate, based on the data in Table 3.1 and Table 3.2, walking with extra layers was 2.2 – 16.7 W/m^2 (1.2 – 8.9 %) and for the obstacle course, 5.6 – 21 W/m^2 (2.2 – 8.1 %).

Table 3.2. Absolute values for all conditions during the obstacle course work mode.

OBSTACLE COURSE		$\dot{V}O_2$ (l/min)	RER	Heart rate (bpm)	Met rate (W)	Met rate (W/m^2)
control	**ave**	**1.45**	**0.81**	**104**	**486.4**	**260.4**
	SD	0.24	0.10	14	80.3	40.5
low friction all layers dry	**ave**	**1.49**	**0.78**	**108**	**496.7**	**266.0**
	SD	0.22	0.10	13	70.8	35.6
low friction inner layers wet	**ave**	**1.50**	**0.80**	**104**	**502.2**	**269.1**
	SD	0.17	0.09	12	55.8	28.4
low friction inner / outer layers wet	**ave**	**1.52**	**0.79**	**104**	**506.8**	**271.0**
	SD	0.2	0.1	11	73.3	31.9
high friction all layers dry	**ave**	**1.56**	**0.84**	**108**	**525.9**	**281.4**
	SD	0.28	0.09	18	87.8	43.1
high friction inner layers wet	**ave**	**1.55**	**0.86**	**105**	**524.3**	**280.9**
	SD	0.25	0.13	16	79.3	41.1
high friction inner / outer layers wet	**ave**	**1.55**	**0.86**	**105**	**525.2**	**280.8**
	SD	0.33	0.11	15	111.4	54.7

Table 3.3. Average percentage increase in metabolic rate for each condition and each work mode, based on % increase from control in each session for each participant.

	WALK	OBSTACLE COURSE	AVERAGE
low friction all layers dry	3.2	5.4	4.3
low friction inner layers wet	8.4	9.4	8.9
low friction inner / outer layers wet	5.4	9.2	7.4
high friction all layers dry	4.4	8.6	6.2
high friction inner layers wet	6.6	9.2	7.9
high friction inner / outer layers wet	9.3	7.2	8.3

3.4 Metabolic rate results

The percentage increases in metabolic rate relative to session controls have been plotted in Figure 3.2 and Figure 3.3. Figure 3.2 is a summary of the sessions where the low friction layers were worn, with the high friction results illustrated in Figure 3.3. The heaviest layer ensemble was the high friction inner and outer layers wet, the corrections for weight applied to the other ensembles and method for calculating the additional weight and its distribution have been explained previously. The overall results are an average of the walking and obstacle course. The significant differences highlighted (*) are significant increases from the control condition.

For the low friction layer results, presented in Figure 3.2 the smallest increases in metabolic rate when walking, during the obstacle course and overall were seen when all the layers were dry, 3.2, 5.4 and 4.3 % respectively. The largest increases were recorded during the wet inner layers condition, 8.4 % higher than the control when walking, 9.4 % during the obstacle course and 8.9 % overall. The 9.4 % and 8.9 % increases were significantly ($p<0.05$) higher than the control. When both the inner and outer layers were wet the increases in metabolic rate were 5.4 % walking, 9.2 % for the obstacle course and 7.4 % overall, which was also significantly higher than the control ($p<0.05$). The 8.4 % increase recorded for the walking with the inner layers wet, was close to significance with a p value of 0.063.

The data collected during the high friction layer sessions is summarised in Figure 3.3. For the walking work mode the lowest % increase in metabolic rate can be seen in the all dry condition, 4.4 % from the control, rising to 6.6 % when the inner layers were wet and 9.3 % when the inner and outer layers were wet. The overall data (an average of the walking and obstacle course data) also follows this pattern, with increases of 6.2, 7.9 and 8.3 % from the control with increasing numbers of wet layers. However the obstacle course data does not follow this trend, the increases in the dry and inner wet layers conditions were 8.6 and 9.2 % from the control respectively, however the increase when both inner and outer layers were worn wet was only 7.2 %. None of the results reached significance compared to the control values but two of them were close, walking all layers wet (p 0.072) and inner layers wet obstacle course (p 0.078).

Comparing the low and high friction layers, the relationship between the dry and wet inner layers conditions are similar, with greater increases in metabolic rate walking and completing the obstacle course when the inner layers are wetted, as seen in Figure 3.4 and Figure 3.5. The wetting of the inner layers had a larger effect on the metabolic rate increase with the low friction fabric. But the range in values recorded during the work modes were similar with the different fabrics, the range in increases across the work modes wearing the low friction layers was 3.2 to 9.4 % and with the high friction layers, 4.4 to 9.2 %, with the lowest values seen when walking and highest values during the obstacle course irrespective of material.

However, there is not a clear pattern for the results of the wettest conditions (inner and outer layers wet). For the walking work mode the increase in metabolic rate compared to control was higher for the high friction layers than the low friction ones, but in the obstacle course completed with all the layers wet, the low friction layers caused a greater increase in the metabolic rate than the high friction layers, as seen in Figures 3.4 and 3.5. For the low friction layers, the highest increase in metabolic rate was 9.2 % for the obstacle course, and for the high friction layers, 9.3 % when walking.

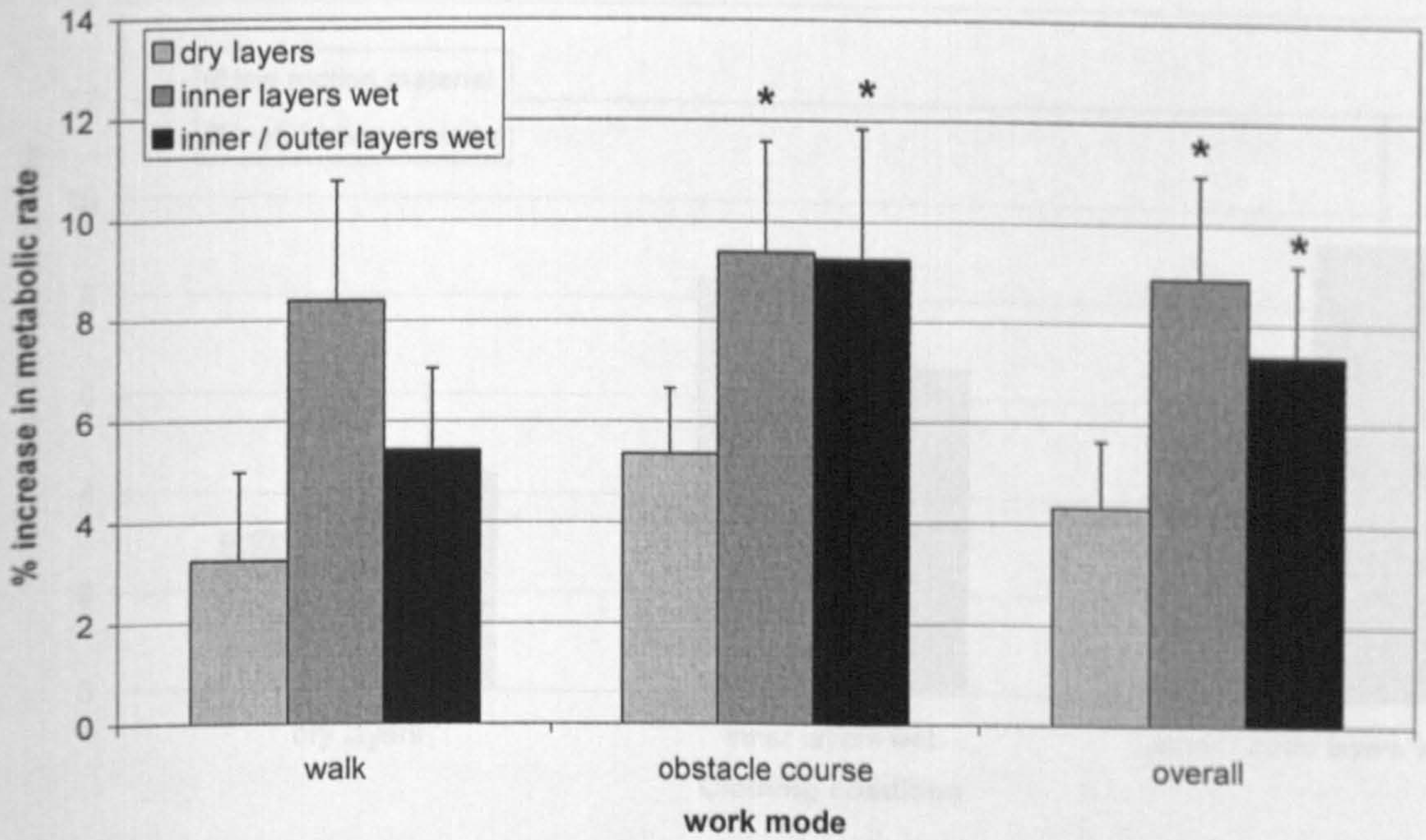


Figure 3.2. Percentage increases in metabolic rate relative to a control for low friction layers, all layers dry (light grey), inner layers wet (grey), inner and outer layers wet (black) (n=8). Sig p<0.05 versus control marked with *.

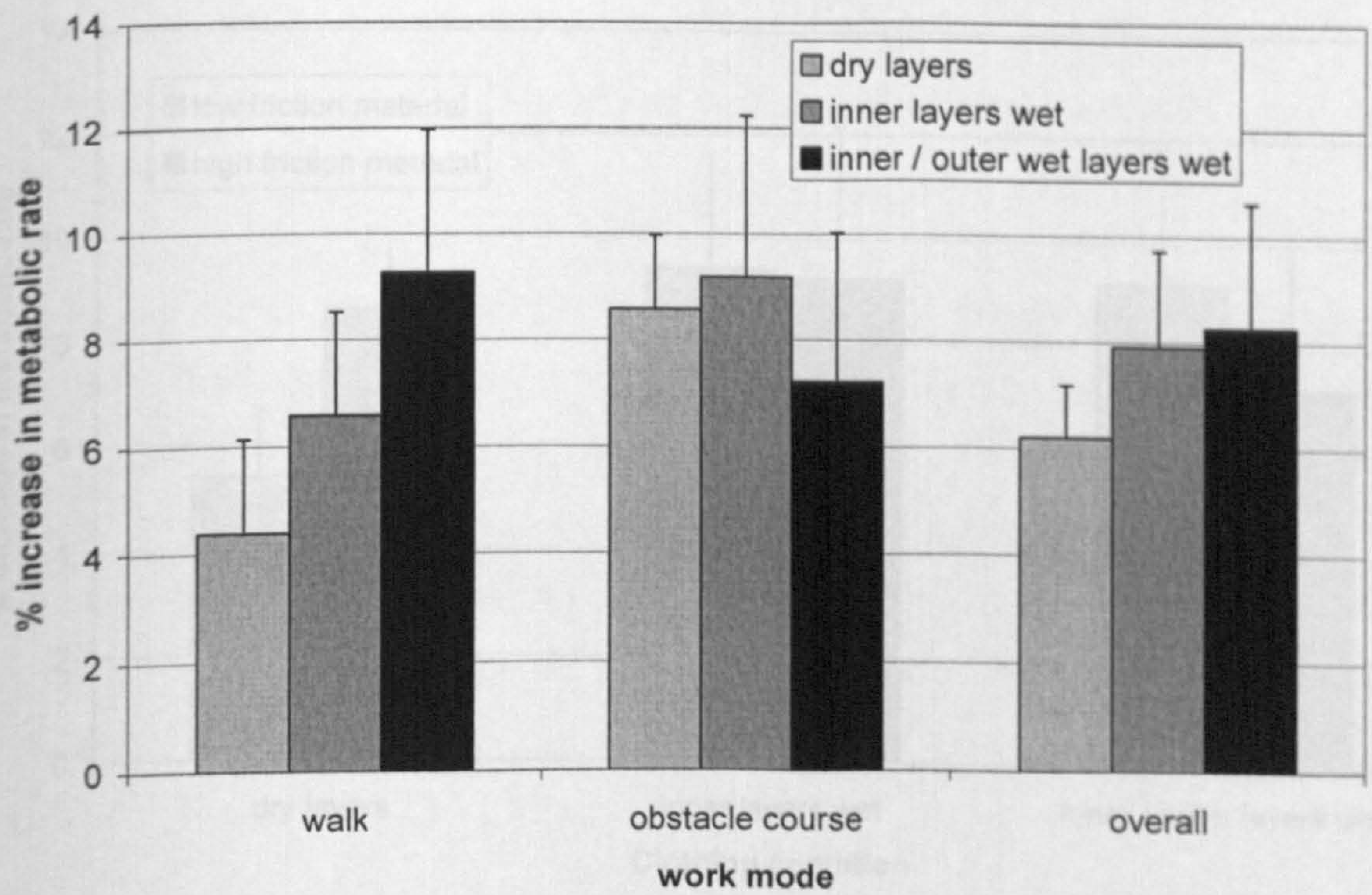


Figure 3.3. Percentage increases in metabolic rate relative to a control for high friction layers, all layers dry (light grey), inner layers wet (grey), inner and outer layers wet (black) (n=8). Sig p<0.05 versus control marked with *.

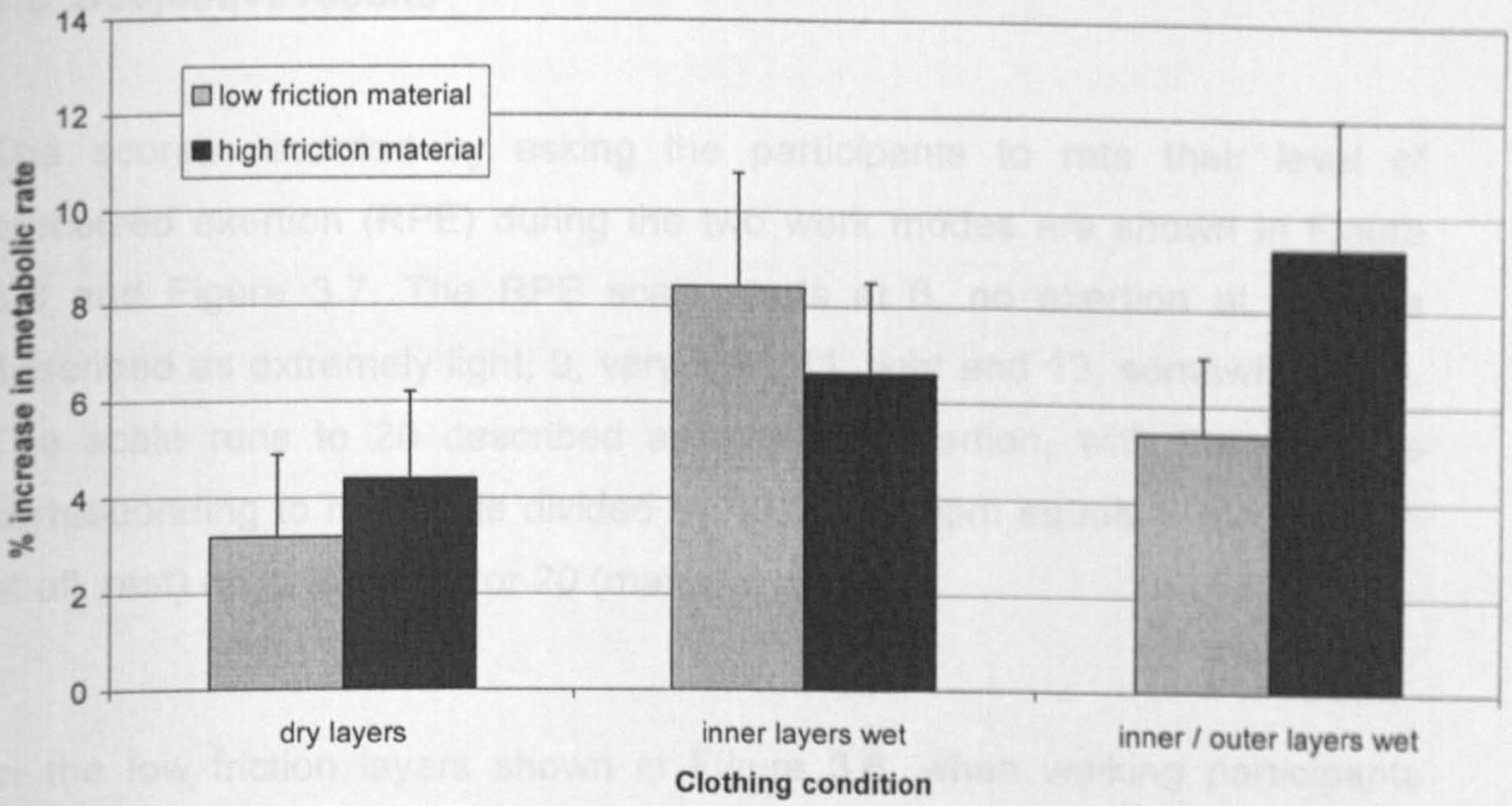


Figure 3.4. Comparison of the % increase in metabolic rate when walking for the low (grey bars) and high (black bars) friction materials in the different conditions.

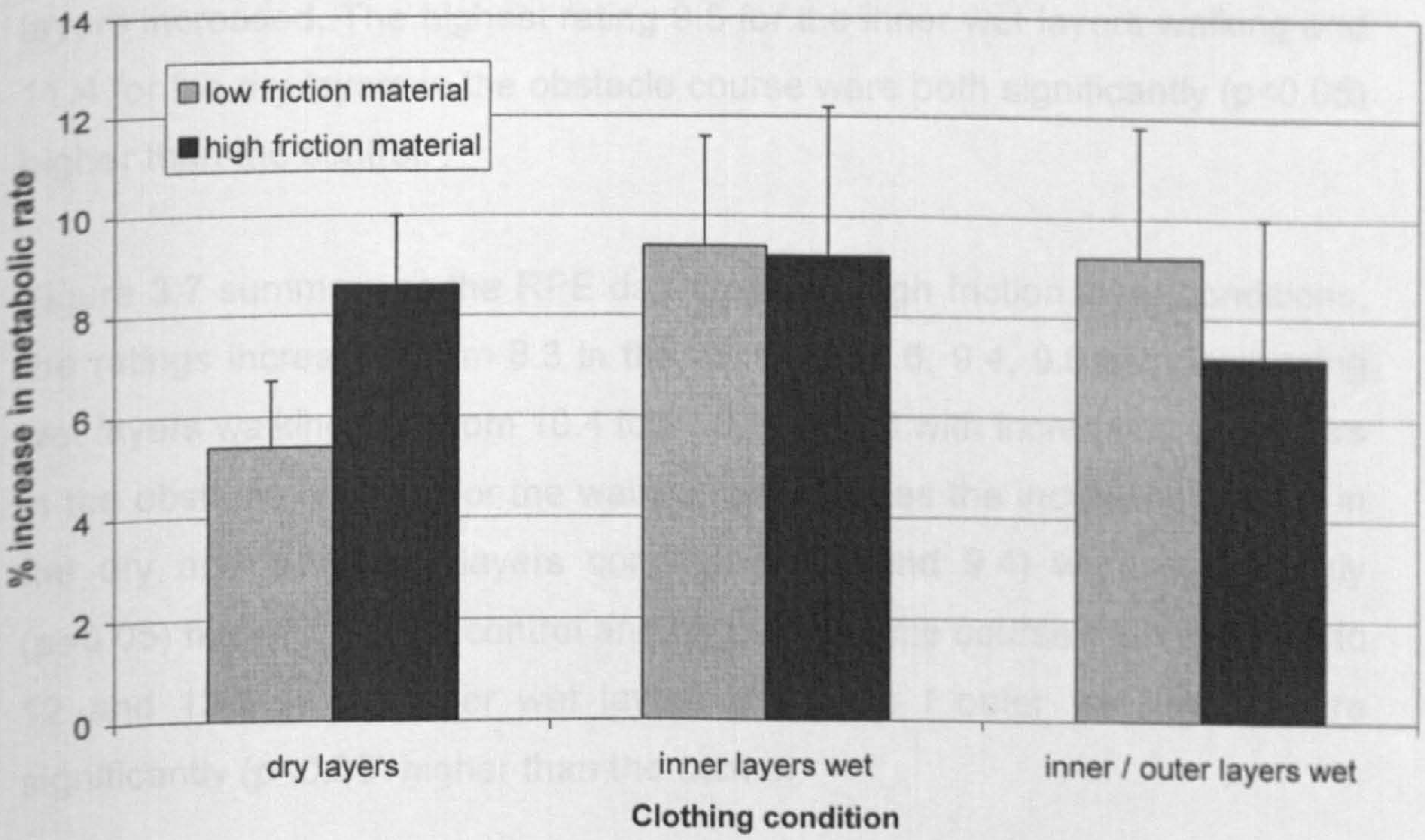


Figure 3.5. Comparison of the % increase in metabolic rate when completing the obstacle course for the low (grey bars) and high (black bars) friction materials in the different conditions.

3.5 Subjective results

The scores recorded by asking the participants to rate their level of perceived exertion (RPE) during the two work modes are shown in Figure 3.6 and Figure 3.7. The RPE scale starts at 6, no exertion at all, 7 is described as extremely light, 9, very light, 11, light and 13, somewhat hard. The scale runs to 20 described as maximal exertion, with the numbers corresponding to heart rate divided by 10, so 60 bpm equals 6 (no exertion at all, rest) up to 200 bpm or 20 (maximal exertion).

In the low friction layers shown in Figure 3.6, when walking participants rated their level of exertion as 9, 9.5, 9.4 for the dry layers, wet inner layers and wet inner and outer layers compared to 8.5 when in the control clothing. When completing the obstacle course in the control clothing participants rated their exertion as 10.4 and this rose to 11.4, 11.1 and 11.4 as the wet layers increased. The highest rating 9.5 for the inner wet layers walking and 11.4 for the dry layers in the obstacle course were both significantly ($p<0.05$) higher than the control.

Figure 3.7 summarises the RPE data from the high friction layer conditions, the ratings increased from 8.3 in the control to 9.6, 9.4, 9.6 with increasing wet layers walking and from 10.4 to 11.8, 12, 12.3 with increasing wet layers in the obstacle course. For the walking work modes the increases in RPE in the dry and inner wet layers conditions (9.6 and 9.4) were significantly ($p<0.05$) higher than the control and for the obstacle course the increases to 12 and 12.3 in the inner wet layers and inner / outer wet layers were significantly ($p<0.05$) higher than the control.

The results from the control conditions were very similar, 8.5 and 8.3 walking in low and high friction sessions and 10.4 and 10.4 in the obstacle course respectively. However with increasing numbers of wet layers, the increases in RPE were greater for the high friction layers, 9.4 to 9.6 walking and 11.8 to 12.3 for the obstacle course, compared to 9 to 9.5 and 11.1 to

11.4 for the same work modes in the low friction layers, but the differences between the low and high friction conditions were not significant.

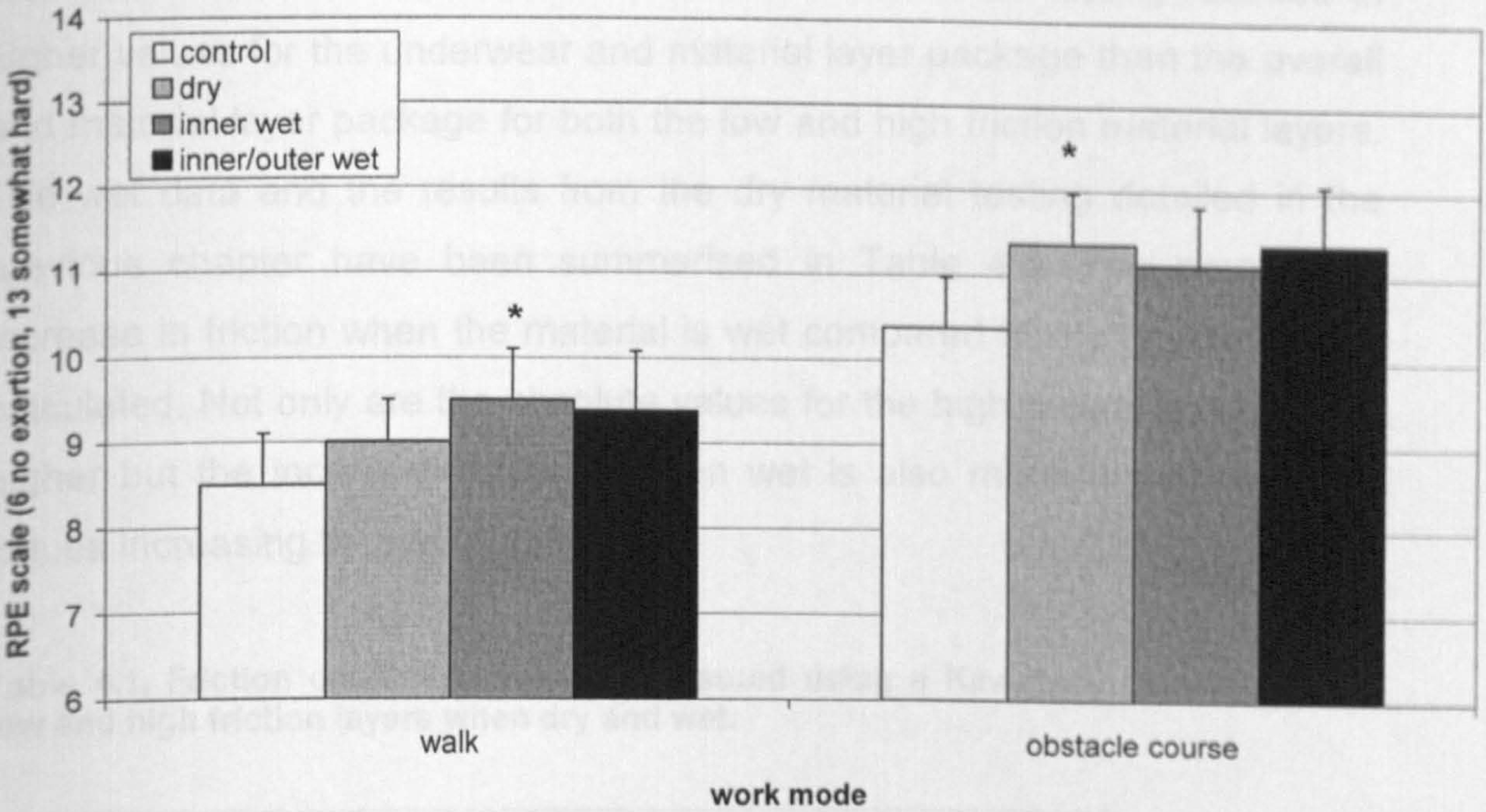


Figure 3.6. Rate of Perceived Exertion scores given by participants (n=8) for the low friction layers in the control (white), dry layers (light grey), wet inner layers (grey) and wet inner and outer layers (black) conditions. Sig of p<0.05 marked by *.

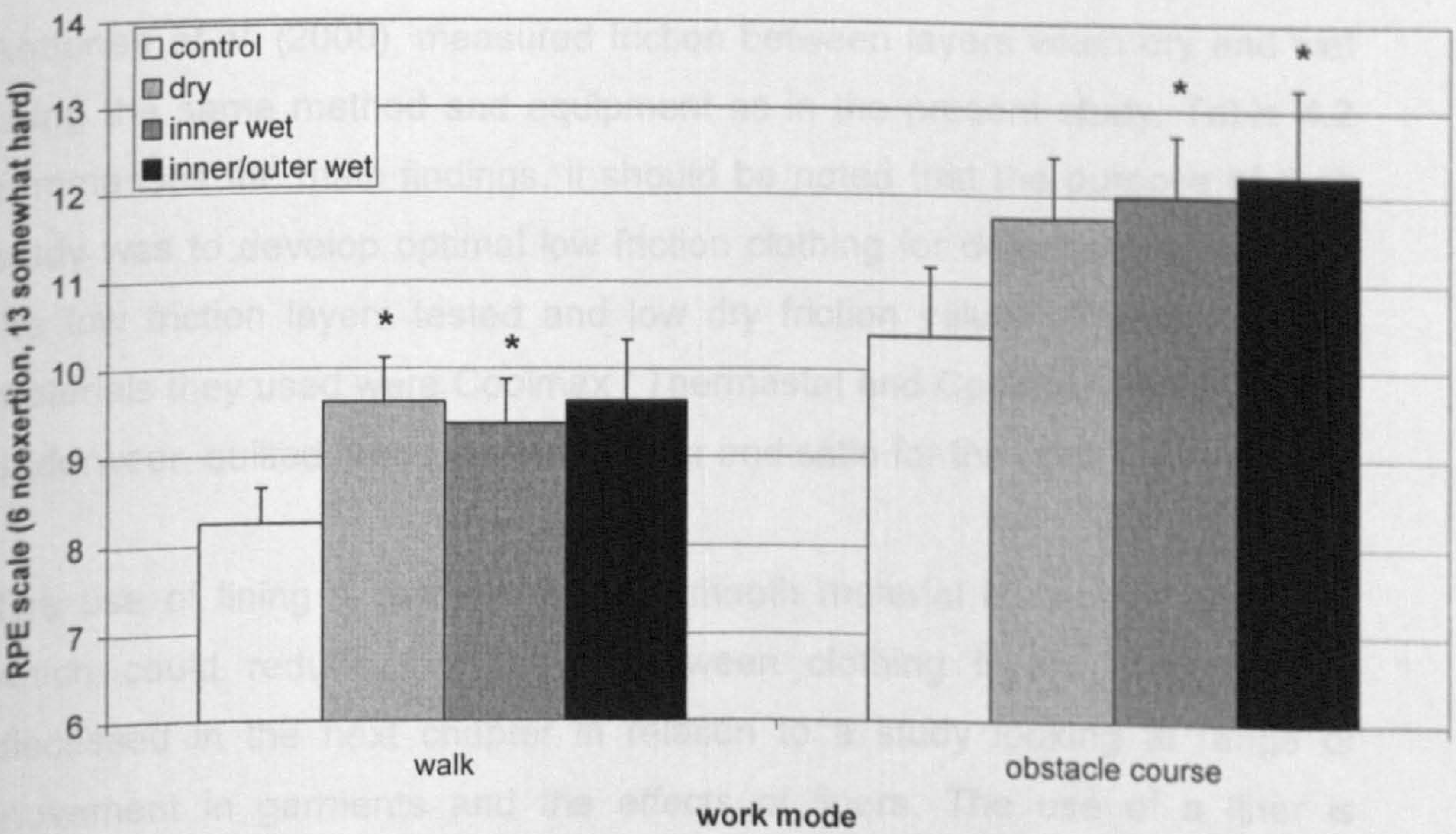


Figure 3.7. Rate of Perceived Exertion scores given by participants (n=8) for the high friction layers in the control (white), dry layers (light grey), wet inner layers (grey) and wet inner and outer layers (black) conditions. Sig of p<0.05 marked by *.

4. Discussion

The friction coefficients obtained from the wet material testing resulted in higher values for the underwear and material layer package than the overall and material layer package for both the low and high friction material layers. The wet data and the results from the dry material testing detailed in the previous chapter have been summarised in Table 4.1. The percentage increase in friction when the material is wet compared to dry has also been calculated. Not only are the absolute values for the high friction layers much higher but the increase in friction when wet is also much higher, with the values increasing by over 100 %.

Table 4.1. Friction coefficient values (measured using a Kawabata system) for the low and high friction layers when dry and wet.

	dry	wet	increase (%)
underwear + low friction layer	0.426	0.533	25.1
low friction layer + overall	0.266	0.525	97.4
underwear + high friction layer	0.668	1.449	116.9
high friction layer + overall	0.461	0.96	108.2

Anttonen *et al.* (2000). measured friction between layers when dry and wet using the same method and equipment as in the present study. Table 4.2 summarises the main findings, it should be noted that the purpose of their study was to develop optimal low friction clothing for defence forces hence the low friction layers tested and low dry friction values. The low friction materials they used were Coolmax / Thermastat and Coolmax / Polyester for underwear, quilted fabric for middlewear and satin for the coat.

The use of lining a garment with a smooth material is another approach which could reduce the friction between clothing layers. This will be discussed in the next chapter in relation to a study looking at range of movement in garments and the effects of liners. The use of a liner is definitely an approach that could be further investigated, particularly for middle and outer layers, for example, jackets. However, it is perhaps not such a feasible approach on a thinner underwear or base layer.

A number of different underwear garments and two outer layers with a low friction middle layer were tested by Anttonen *et al.* (2000). The 5 underwear samples, detailed in Table 4.2 are described below;

1. Plated knit (smooth) 53% cotton / 47% viscose
2. Interlocked knit cotton and polyamide
3. Plated knit (flexible) 50% cotton / 50% viscose
4. Plated knit (smooth) 28% Coolmax / 72% polyester
5. Plated knit (smooth) 55% cotton / 45% viscose

Note. Plated knit; two different threads used for making the textile; resulting in one (e.g. cotton) being towards the skin and one (e.g. viscose) towards the outer layers. (Personal communication, Rintamaki 2006)

Table 4.2. Friction coefficient values (measured using a Kawabata system) for different materials when dry and wet from Anttonen *et al.* (2000).

	dry	wet	increase (%)
underwear 1 + low friction layer	0.325	0.556	71.1
underwear 2 + low friction layer	0.309	0.397	28.5
underwear 3 + low friction layer	0.336	0.598	78.0
underwear 4 + low friction layer	0.365	0.393	7.7
underwear 5 + low friction layer	0.306	0.596	94.8
low friction layer + military outer layer	0.343	0.403	17.5
low friction layer + cotton outerwear	0.34	0.689	102.6

The dry measurements for the different underwear layers are fairly consistent, ranging from 0.306 to 0.365, but once wet the values ranged from 0.393 to 0.596, equating to increases of 7.7 to 94.8 % in friction from dry. These differences are most probably due to the different materials or finish of the underwear.

The friction coefficient values for low friction layer and overall (100 % cotton) in the present study are comparable to the low friction layer and cotton underwear in the Anttonen *et al.* (2000) study, 0.266 dry and 0.525 wet (97.4 % increase as shown in Table 4.1), 0.34 dry and 0.689 wet (102.6 % increase, see Table 4.2) respectively.

El Mogahzy and Gupta (1993) suggest that the results of wetting on friction are interesting because synthetic fibres are considered hydrophobic and absorb little water. They also recorded higher friction in wet tests indicating that the liquid water did not act as an effective boundary lubricating agent.

One possible cause for higher friction in wet media is an increase in yarn surface area as a result of water penetration through interstitial spaces between fibres in the yarn increasing the contact area. The shear of the water surface in wet sliding yarns may also contribute to increased friction (El Mogahzy and Gupta 1993).

The absolute values for all participants walking and for the obstacle course seen in Table 3.1 and 3.2 respectively indicate that the size of the effect of adding wet layers is approximately the same across work modes. The increase in $\dot{V}O_2$ from the control when walking ranged from 0.02 – 0.09 l/min across the wetted conditions, for the obstacle course the increase was 0.04 – 0.11 l/min. The control $\dot{V}O_2$ averaged 1.04 l/min when walking, rising to 1.45 l/min for the obstacle course as participants were required to use their upper body moving crates and greater lower body ranges of movement for the stepping and hurdles.

In the high friction conditions, there is a stepped increase in metabolic rate in the all dry, inner layers wet, inner and outer layers wet ensembles when walking but the increase in metabolic rate is much lower for the obstacle course task when the inner and outer wet layers are worn. None of the results in the high friction ensembles were significantly higher than the control. One possible explanation is that when so many layers are wet, 4 in this scenario, the layers clump together as one. Therefore there is no longer movement between the layers and the corresponding friction so movement actually becomes a little easier and thus the expected increase in metabolic rate is not as high. So the results did not fit the first hypothesis suggested in this chapter, that for garments that have the same weight and number of layers, increasing the number of wet layers will increase the metabolic rate.

The second hypothesis was that the metabolic rate increases would be higher in the high friction layers than in the low friction layers. Figures 3.4 and 3.5 have been plotted to compare the metabolic rate increases in the low (grey bars) and high (black bars) friction materials across the conditions for the walking and obstacle course work modes respectively. The graphs show the results as expected for the dry layers both walking and in the obstacle course. But the trends cannot be applied to all conditions for the obstacle course data.

The subjective data, Ratings of Perceived Exertion obtained at the end of each work mode (shown in Figure 3.6 and 3.7), showed a general trend of stepped increases from the control with increasing numbers of wet layers. In both the low and high friction material conditions there were significantly higher ratings when wearing wet layers compared to the control but no significant difference between the number of wet layers worn.

Although the present study focused on material friction and comfort was not measured, a major source of fabric – evoked discomfort is the sensation of fabric clinging to the skin, moisture has a large effect on friction, due mainly to liquid water on the skin (Kenins 1994). Kenins (1994) describes how not only does heavier weighted fabric create a larger frictional force but wetting the skin doubled the frictional force for coarse wool and cashmere, regardless of the degree of hairiness. Keeping the skin dry is more effective in reducing the fabric to skin friction than the sort of fibre the fabric is made from, the yarn diameter, fabric weight and changes in surface properties. Measurements of fabric to skin friction have shown that hairy skin behaves differently when wet (Kenins 1994). If skin wettedness is so important it could be used to explain the trend shown in Figures 3.4 and 3.5 where the difference between the fabrics is reduced or even reversed as the low friction material may have a stronger cling effect than the higher friction material due to its smoother surface. The issue of static and dynamic friction has not been touched upon here.

Gwosdow *et al.* (1986) also looked at the interaction of skin and material by pulling various kinds of cloth including cotton, linen and silk, across the forearms of participants. They recorded the force required to pull the fabric across the skin, the skin wettedness and subjective measures of pleasantness and fabric coarseness. The coefficient of friction was determined from the contact angle and recorded forces. Measurements were made under a number of thermal environments; neutral, hot and humid, hot and dry. Silk produced the most pleasant sensations but these were reduced in the hot, humid conditions. There was an abrupt increase in friction at the higher skin wettedness levels, ratings of material coarseness also rose. So, friction between skin and clothing may contribute to overall discomfort and partly explain the contribution of skin wettedness to sensations of unpleasantness (Gwosdow *et al.* 1986), although it is difficult to link these observations to the present study findings.

5. Chapter summary

In an extension to the study in Chapter 5, the present study showed that wetting different layers increased the friction coefficient values for all combinations, with the largest increases occurring with the high friction layers. However when participants wore the wetted layers, the high friction conditions did not produce a significantly higher increase in metabolic rate, compared to the low friction layers. The percentage increase in metabolic rate due to wetting was actually higher for the low friction layers when walking in the inner layers wet and during the obstacle course in inner layers wet and inner / outer layers wet conditions. This may be due to the number of wet layers binding together and moving as one, particularly in the obstacle course, reducing the effects of friction and thus the metabolic rate. The participants did subjectively rate their level of perceived exertion higher when wearing wet layers and in the high friction layers, though not significantly. The results of this study have proved inconclusive and deserve further attention.

CHAPTER 7

STUDY 5

EXAMINING THE IMPACT OF PROTECTIVE CLOTHING ON RANGE OF MOVEMENT

1. Introduction

This chapter will address another of the possible contributors to the increased metabolic rate observed when wearing protective clothing. The nature of the protection required in industries where workers are exposed to extreme cold, heat and fire often means garments are constructed of thick, heavy, insulative material. The impact of these garments on ease of movement, range of motion and work efficiency has been referred to in the literature using various terms; clothing bulk, movement restriction and hobbling effect. But the effects have been hard to measure and quantify and so the possible involvement of clothing bulk in increasing energy cost in the wearer is still not clear.

1.1 Previous research

It is well documented that Personal Protective Clothing (PPC) can negatively affect worker performance (Nunneley 1989; Adams *et al.* 1994; Rintamaki 2005). The previous chapters have investigated the effects of clothing weight and number of layers worn, but the additional bulkiness of PPC can also contribute to performance degradation (Patton *et al.* 1995; Murphy *et al.* 2001). Ideally clothing must have sufficient ease. If a garment binds or restricts the wearer, or is too large, wearer mobility and the level of protection it provides can be adversely affected (Huck *et al.* 1997). Bulky clothing compromises movement, requiring added movement or force to complete tasks thereby increasing the metabolic cost of work (Nunneley

1989). Performance degradation can also be measured as decreased range of movement, impaired dexterity, reduced speed and decreased accuracy (Nunneley 1989; Adams *et al.* 1994; Murphy *et al.* 2001; Rintamaki 2005).

Teitlebaum and Goldman (1972) cite Belding *et al.* (1945) who observed that as bulk of clothing increased, the increase in caloric expenditure was much greater than could be accounted for by the increased weight of clothing. Belding *et al.* concluded that the extra caloric output was due to the hobbling effect of clothing. Also cited by Teitlebaum and Goldman (1972) is the work of Gray, Consolazio and Kark (1951) who suggested a binding or hobbling effect of heavier clothing worn in the cold which increased the required work output, thus increasing the caloric demand. Teitlebaum and Goldman (1972) found a significant 16 % increase in metabolic rate walking in arctic clothing and discuss a possible hobbling effect due to interference with movement at the body's joints, produced by clothing bulk.

These observations and comments are backed up more recently by others who have also detailed higher energy costs in a variety of protective clothing ensembles. The bulk and stiffness of the chemical protective clothing (CPC) used by Patton *et al.* (1995) was reported to have contributed to a hobbling / binding effect by interfering with joint movements. The same authors using the same clothing later showed that the CPC had little impact on tasks of a stationary / intermittent nature but a marked impact on tasks requiring whole body mobility (Murphy *et al.* 2001). The continuous tasks (31 Army physical tasks categorised by the degree of whole body mobility. Stationary tasks included; lifting, assembling/disassembling a rifle, intermittent tasks included; lifting and carrying, continuous tasks included; load carriage tasks, obstacle course) required more mobility and demonstrated a greater increase in absolute $\dot{V}O_2$ compared to the stationary and intermittent tasks. Murphy *et al.* (2001) also cite White *et al.* (1989) who reported that tolerance times in their study attenuated rapidly as garments became more cumbersome and work intensity increased.

The literature discussed so far has covered the physiological implications of bulky clothing, where higher $\dot{V}O_2$ and increased energy costs have been attributed to extra movement and effort required to overcome garment bulk, particularly at the joints. However, in a number of studies the authors have been unable to conclude the exact contribution clothing bulk makes to the wearer performance, due to the clothing also having extra weight, a loose fit and an increase in discomfort (Duggan 1988; Rissanen and Rintamaki 1997). Lotens (1982) identifies the difficulty of quantifying the energetic effects of motion restriction experimentally. As he explains, in the laboratory, treadmills and bikes are not well suited for measuring motion restriction movements. In reviewing the data available, he concludes that the effect of bulkiness of clothing cannot be analysed as it is often confounded by other impeding effects (Lotens 1982).

Havenith and Heus (2004) explain that specialised protective clothing is usually tested only to standards which give requirements for the materials used, consequently the effects of the manufacturing process on the material and the effects of clothing design, sizing and fit are overlooked. They therefore suggest the use of a battery of tests which cover the ergonomics of the clothing including 'freedom of movement'.

Ideally PPC and personal protective equipment (PPE) should not restrict movement or otherwise impede job performance, however PPC ensembles often incorporate multiple fabric layers leading to bulky, heavy and inflexible garments (Huck 1988). Range of movement (ROM) can be affected by garment bulk and although anecdotal evidence from workers wearing bulky winter clothing suggest stiffness and bulk may restrict mobility, quantitative evidence is lacking (Adams and Keyserling 1995). If workers are required to wear PPC that limits mobility, worker productivity is likely to drop and in extreme cases contributes to injury (Huck 1988). One needs to consider to what extent is protective clothing an advantage and what degree of mobility loss should be permitted before the clothing becomes a greater danger than the threat the clothing protects against (Lotens 1982).

Adams and Keyserling (1995) evaluated the effects of garment size and fabric weight on range of movement using undersized, appropriately sized and oversized overalls and three different weights of polyester/cotton fabric. The measured variable in the study was the ROM during 12 gross body movements measured with a 2-arm manual goniometer. The ROM, defined as the maximum angular change available at a joint was measured in degrees from a reference / neutral position. The results indicated that the effect of garment size was greater than the garment weight, although increased garment weight decreased the ROM slightly. Compared to nude the undersized garments reduced mean ROM by up to 24 % (hip flexion) with all movements significantly reduced except shoulder extension and trunk lateral flexion. The differences in ROM between undersized and correctly sized garments were also significant, the differences between correct sized and oversized garments were not significant (Adams and Keyserling 1995).

Huck (1988) cites some of the earlier studies that looked at movement restriction, Saul and Jaffe (1955) tested the effects of clothing on gross motor performance, with results indicating performance decreased as the amount of clothing worn increased. An arm and shoulder harness was developed by Nicoloff (1957) (cited in Huck 1988) to simulate body movement restriction in upper body segments and wearing the harness produced significant decrements in movement. The final study cited by Huck (1988) is that of Bachrach *et al.* (1975) who were able to discriminate between diving ensembles using goniometer type apparatus to quantify the restriction to movement of deep sea divers wearing 2 different designs of diving gear.

Various tools and techniques have been devised for measuring joint angles and ROM, the simplest of which is the goniometer (Huck 1988). Using a Leighton flexometer (a gravity goniometer developed by Leighton (1955), for more detail see Huck 1988) and 8 joint movements based on firefighting requirements, Huck (1988) compared 3 different firefighter clothing designs, 2 different moisture barrier materials and wearing / not wearing self contained breathing apparatus (SCBA). The Leighton flexometer was strapped over the clothing and for each of the static movements participants were given the command "move to the fullest extent possible without straining". The effect of the moisture barrier configurations were not significant and the clothing designs were only significant for 2 movements, shoulder adduction / abduction and trunk lateral flexion. The SCBA imposed the greatest restriction to movement, with the upper body, arms and torso movements being significantly affected (Huck 1988).

Bensel *et al.* (1987) examined the effects of standard army chemical protective (CP) clothing and the highest level of chemical warfare protection (known as MOPP IV) on a number of aspects of soldiers performance including body mobility. The impact of the CP clothing on body mobility (measured with a goniometer) varied as a function of the task being performed and items worn. The CP overgarment restricted simple movements of the leg in the sagittal plane and of the arm in the body's frontal plane compared to t-shirt and shorts. A number of gross mobility tasks were also studied along with a questionnaire. The gross movements were only minimally affected by the CP clothing compared to standard battledress uniform (BDU), however superior performance was evident in the BDU compared to the MOPP IV ensemble in all mobility tasks except standing trunk flexion and upper arm forward extension. Subjectively higher ratings were also recorded for the MOPP IV ensemble showing participants were subjectively aware of the restriction imposed by the protection (Bensel *et al.* 1987).

Fit and design issues can also impinge upon movement and performance, Graveling and Hanson (2000) showed that there was scope for improvement in the wearability and fit of firefighter clothing. In their study, inadequate allowance for arm extension, particularly in sleeves with thumb loops, restricted arm movements and bending movements were limited by insufficient body length in garments. Trousers with insufficient provision for expansion in thigh diameter when squatting or kneeling also limited movements (Graveling and Hanson 2000).

Adams and Keyserling (1995) discuss three possible mechanisms by which garments act to constrain movement;

i) garments interfere with movement by preventing body from changing volume or shape, e.g. garment lacks volume or the volume is not distributed as needed if a key dimension is too short.

ii) anchoring or tying of a garment can prevent displacement, e.g. a tight sleeve cannot slide up the arm, garments can pull at the crotch and thighs when the hip is flexed.

iii) multiple constraint mechanisms can act together to impede movement, however these may not be apparent when looking at simple movements e.g. no problem identified with a deep squat or arm abduction but inability to effectively abduct arms when in a deep squat.

When considering the results discussed above, particularly those looking at ROM (Huck 1988; Adams and Keyserling 1995; Huck *et al.* 1997) it is important to note that the movements are static and participants are given verbal instructions, for example "move to the fullest extent possible without straining" (Huck 1988). These static movements may give an accurate picture of what is happening at the extreme joint ranges, e.g. shoulder adduction / abduction and hip flexion / extension, but are these isolated and somewhat simple movements representative of the demands on a firefighter during a shift?

Additionally the goniometer measurements are often stated to have been taken over the top of the protective garments or suits being tested but PPC can complicate angle measurements by hiding body landmarks and joint centres (Adams and Keyserling 1993). The accuracy of this method also needs to be considered as Huck (1988) admits measurements of joint motion taken over large, bulky protective clothing present a greater challenge in obtaining accurate, reproducible measurements.

In summary, the literature reviewed has reported that;

- PPC can negatively affect worker performance and the additional bulkiness of many PPC garments is a likely contributor to performance degradation.

There are two main groups of papers;

- Papers that have suggested that bulky clothing can compromise movement which then requires added effort, increasing the metabolic cost, to complete the task. This theory is normally put forward in the discussion or conclusion of the article.
- Papers that have used goniometers to measure the maximum angular change available at a joint from a reference / neutral position, with the goniometers normally attached over the clothing, and in a static situation.

Therefore the present study will attempt to measure the joint angles on the skin during continuous movements such as walking and stepping in a number of garments that have already been to shown to induce an increase in metabolic rate when worn during work.

1.2 Aims

The aims of this study are;

- To investigate if wearing protective clothing affects the wearers range of movement during walking, stepping and crawling activities.
- To measure hip and knee angles whilst walking, stepping and crawling in a range of protective clothing garments.
- To test the hypothesis that protective clothing restricts movement, requiring extra effort to complete the same task compared to a lightly clothed control.

2. Materials and Methods

2.1 Participants

Six participants took part in the study. They were all volunteers drawn from the student population at Loughborough University. Their physical characteristics are summarised in Table 2.1.

Table 2.1. Participant details.

Gender	Age (yrs)	Height (cms)	Weight (kg)
F	22.1	173	65
M	22.2	173	85
M	29.3	176	91
M	28.6	177	75
M	24.8	185	85
F	25.0	172	70
ave	**25.3**	**176.0**	**78.5**
SD	**3.1**	**4.8**	**10.1**

2.2 Clothing

The clothing used in this study was a sample drawn from the original 14 garments tested in the first study in this thesis. The garments were selected on the basis of their high clothing bulk and previously recorded significant increase in metabolic rate. The Chainsaw (J) protection suit, two coldstore suits (Coldsuit black (H) an all-in-one design, Coldsuit green (I) separate jacket and trousers design) and two firefighters suits, Grey fire (B) and Gold fire (D) were selected. It was also decided to test the firefighter trousers without the jacket. For more information and photographs of the garments, see Methodology (Chapter 2). Participants attended the lab for one session and were supplied with a pair of shorts and a t-shirt to wear, which were worn throughout, for the control and under the protective clothing. Participants wore their own trainers.

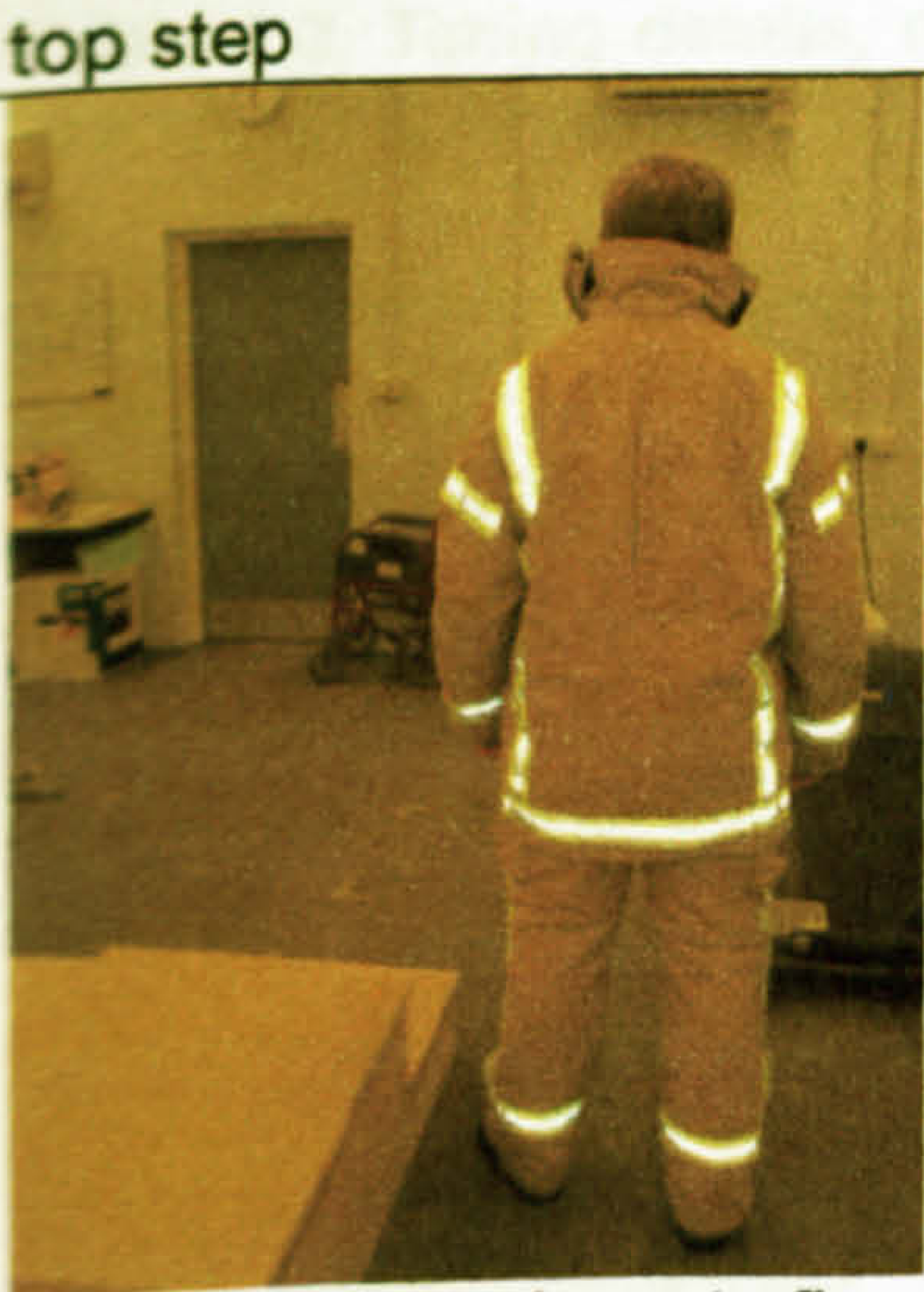
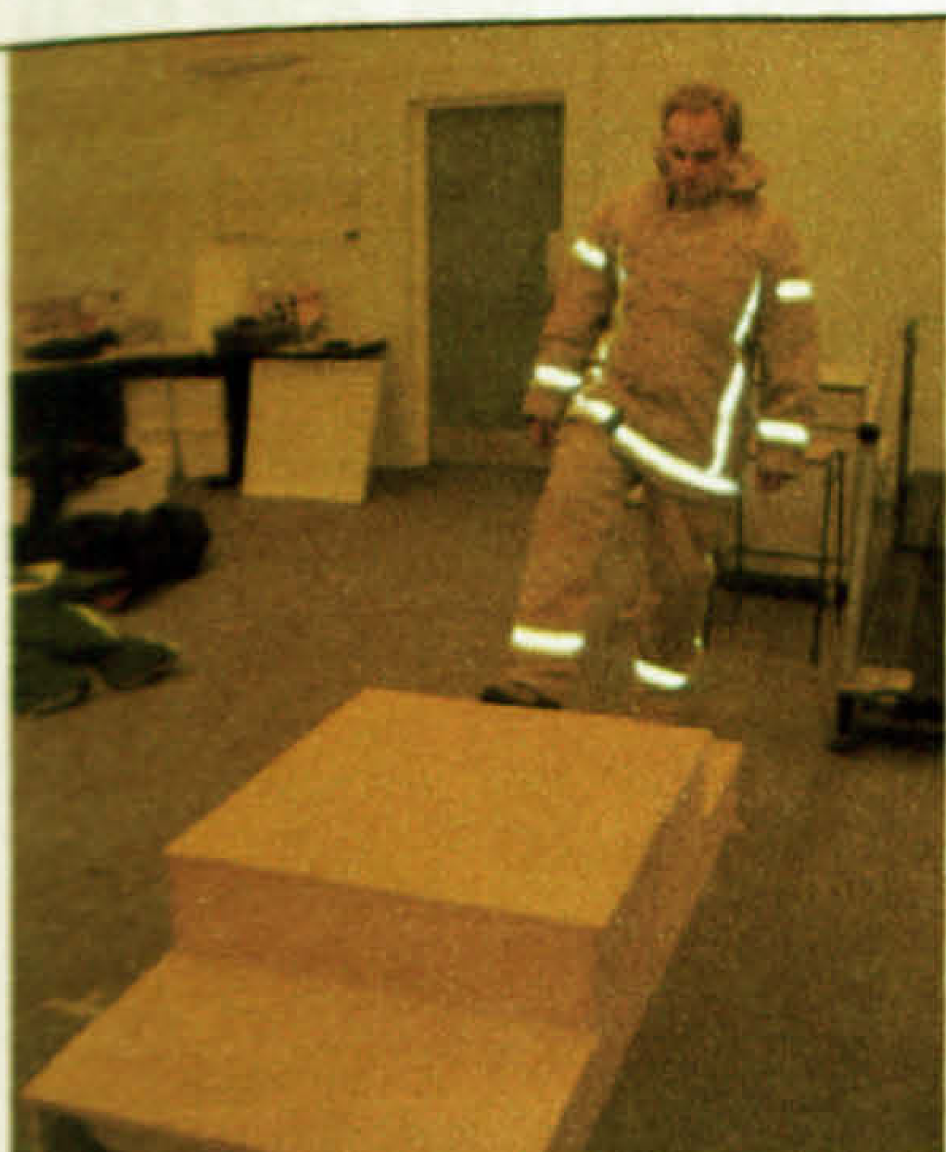
2.3 Work modes

Walking was the most obvious work mode to study due to the fact that the metabolic effects of the clothing had been studied whilst walking previously and to allow comparison with existing literature. Participants walked on a treadmill for a minute at 5 km/hr, as shown in Figure 2.1.

Figure 2.1. Photograph of participant walking on the treadmill.

Stepping and completing an obstacle course were the other work modes for which the metabolic effects were measured previously. These activities were broken down to enable more accurate data collection and analysis. The metronome with verbal counting was used as previously described, but for this study the rate was quicker, set at 72 beeps per minute, or 1 beep every 0.83 seconds. Participants were instructed to move one foot on each beep, this method of a movement per beep was used because it was easier to repeat consistently and accurately. Participants were given a chance to practice the movements and timing so they were smooth during the testing. The stepping and crawling sequences are documented fully in Table 2.2 and 2.3, including photographs and details of timing. Participants repeated the stepping sequence and the crawling sequence six times in each garment.

Table 2.2. Timing details, descriptions of movements and photographs to illustrate the stepping sequence.

 0.83 secs; Right foot onto top step	 1.66 secs; Left foot onto top step	 2.49 secs; Right foot down to floor
 3.32; Left foot down to floor	 4.15; Right foot to base of steps	 4.98; Left foot to base of steps
 5.81; Right foot up to 1st step	 6.64; Left foot up to 2nd step	 7.47; Right foot down to 3rd step

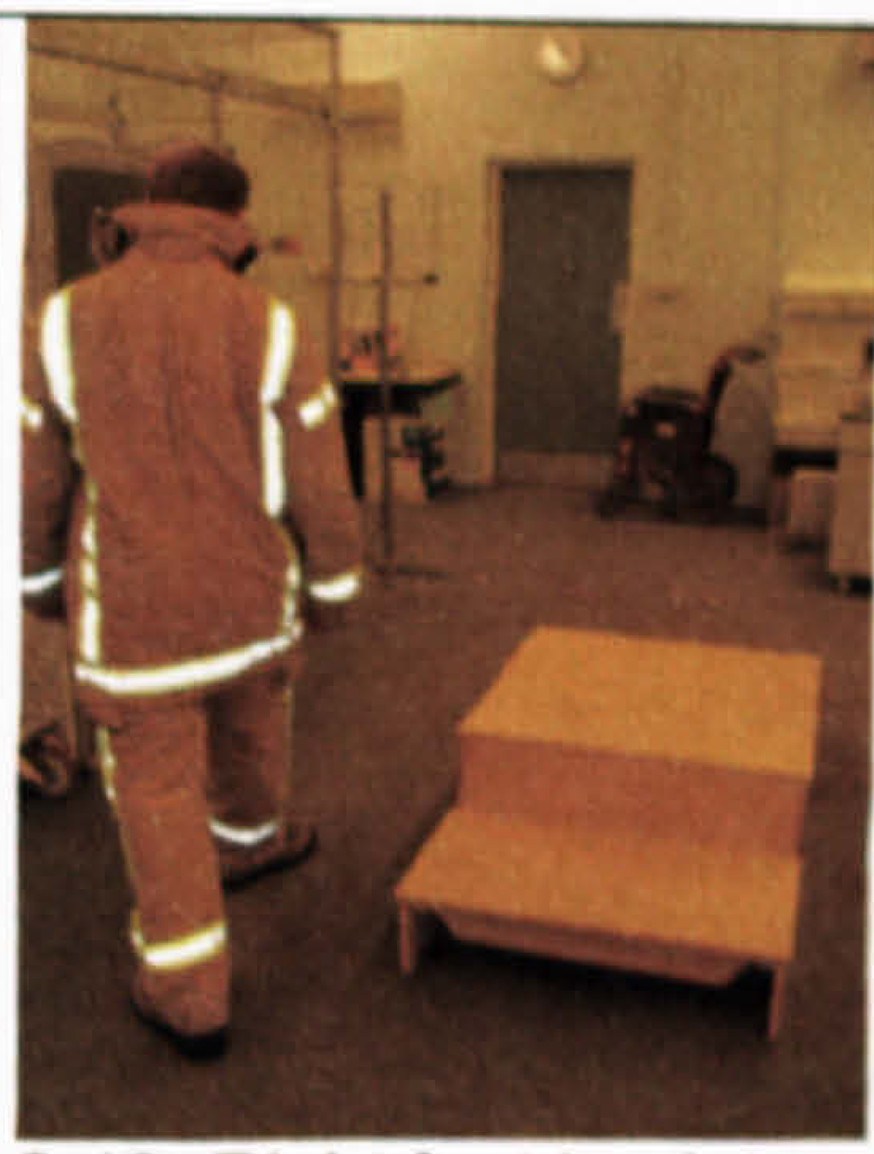
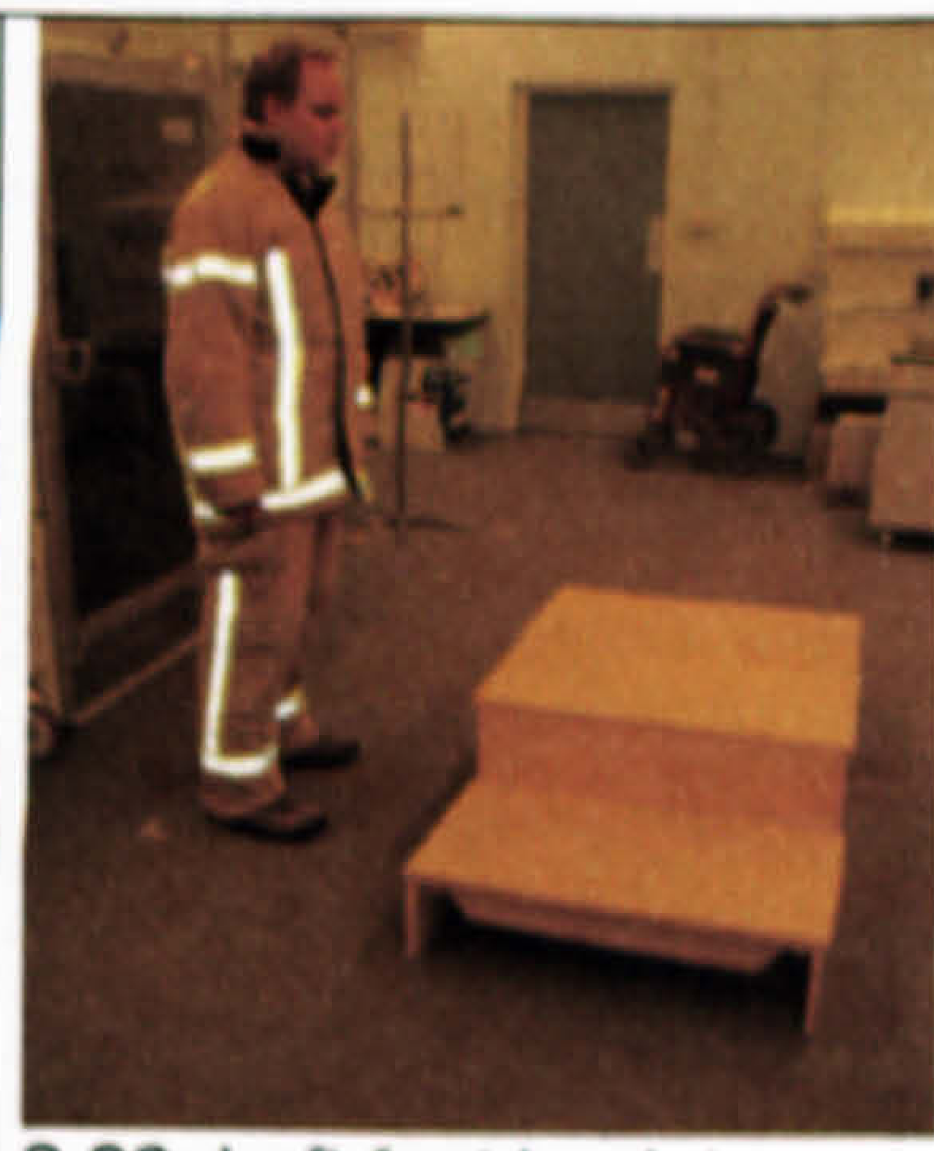
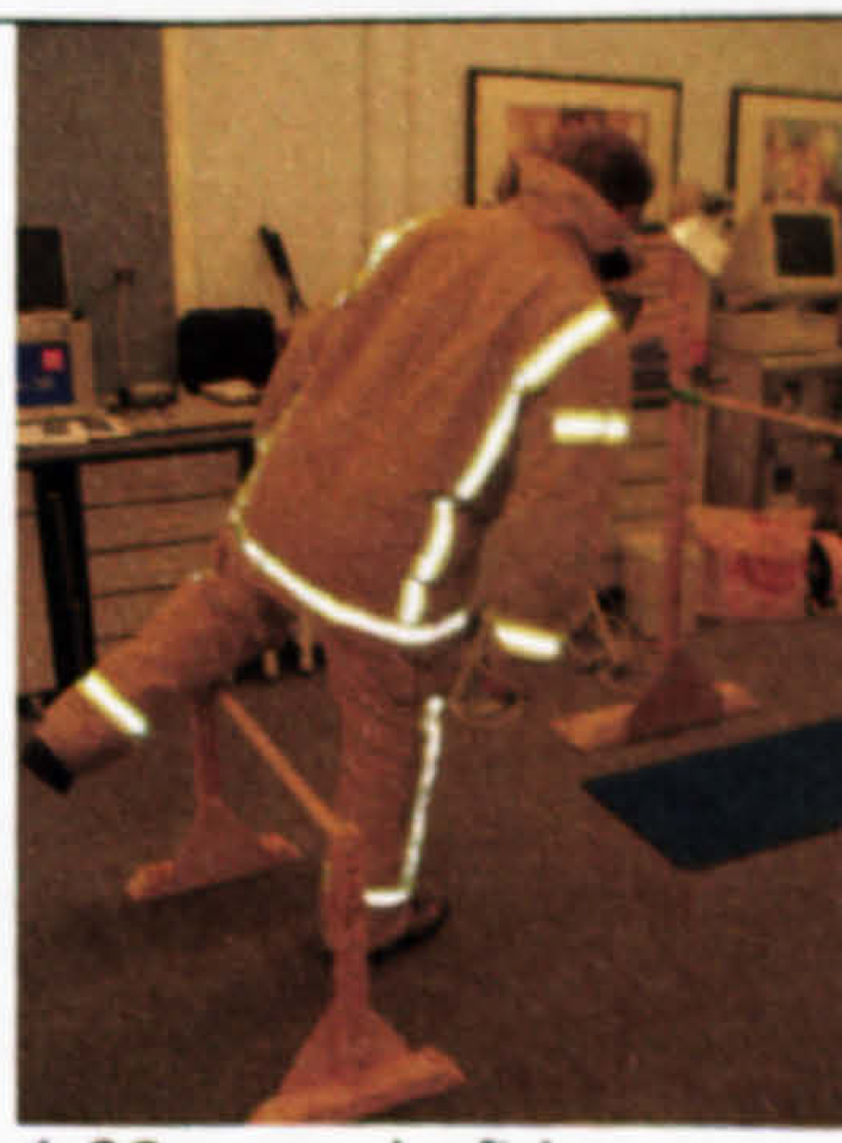
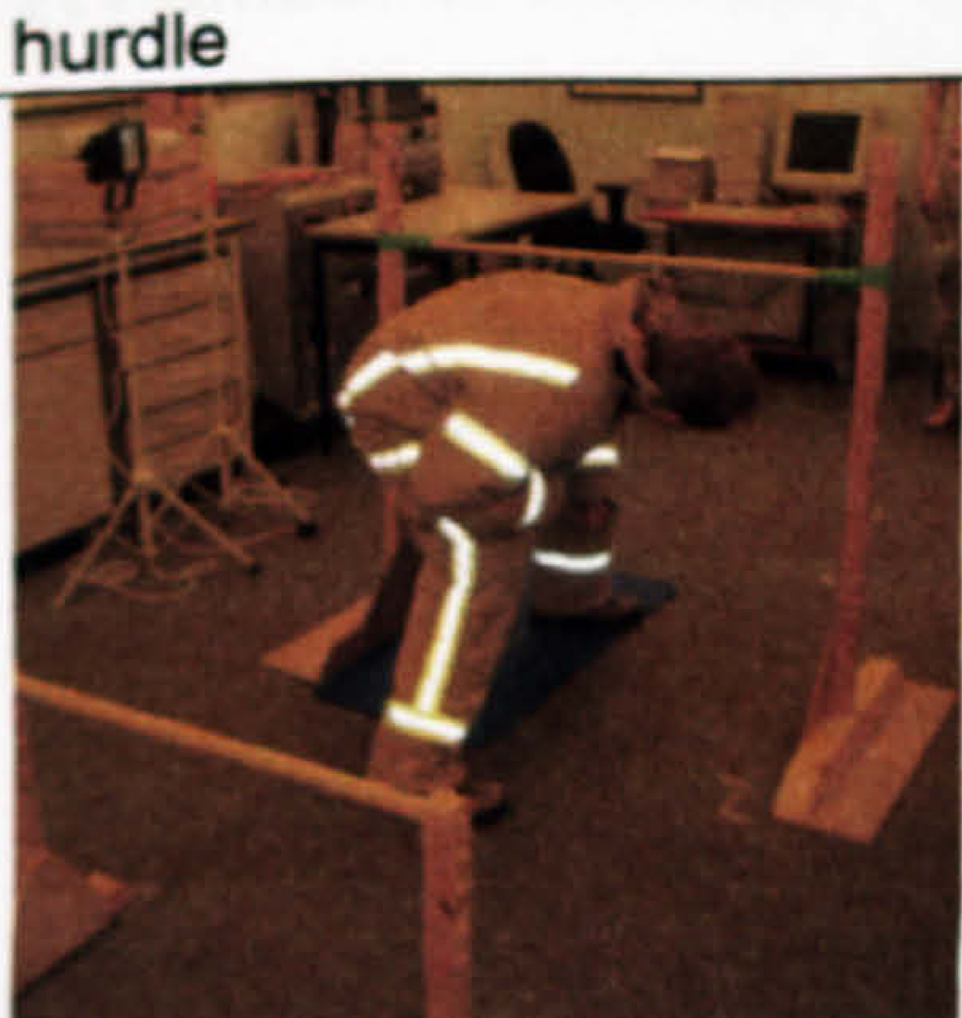
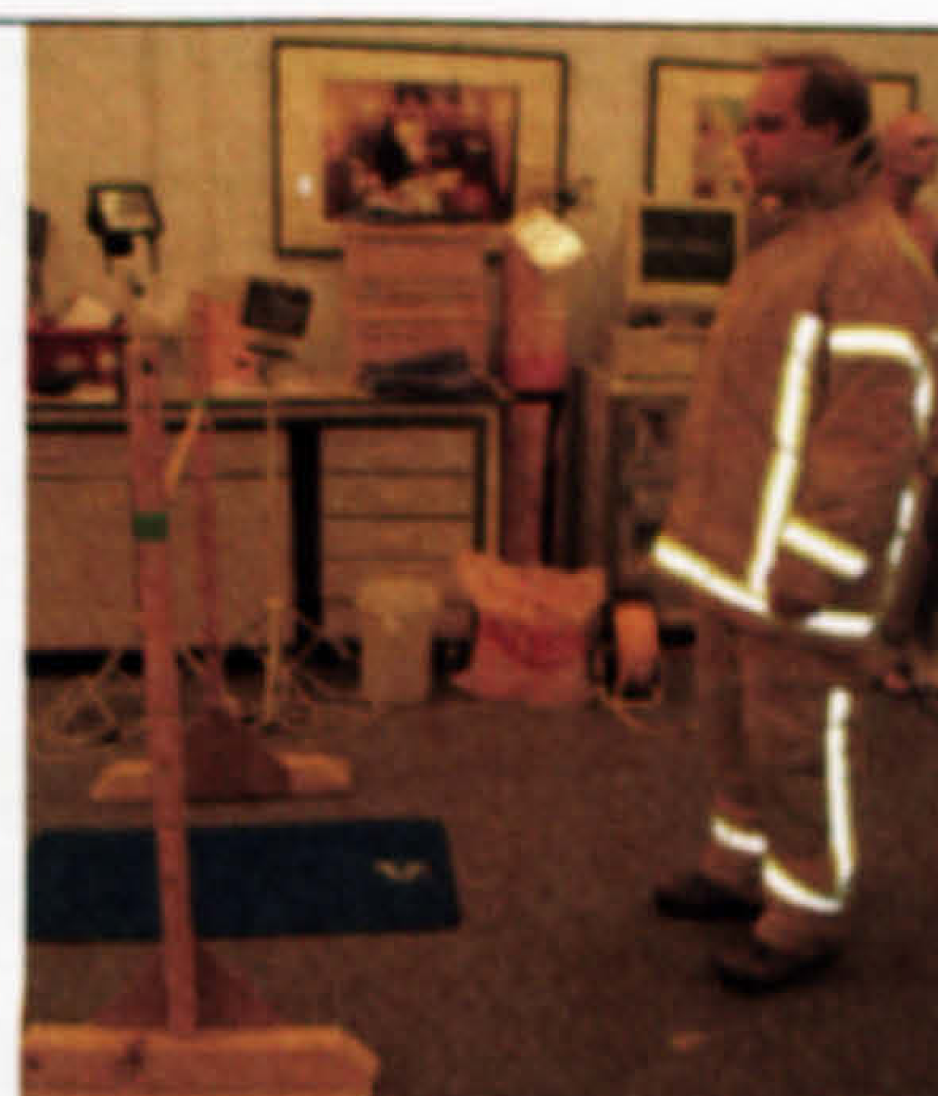
 8.30; Left foot down to floor	 9.13; Right foot back to beginning	 9.96; Left foot back to beginning

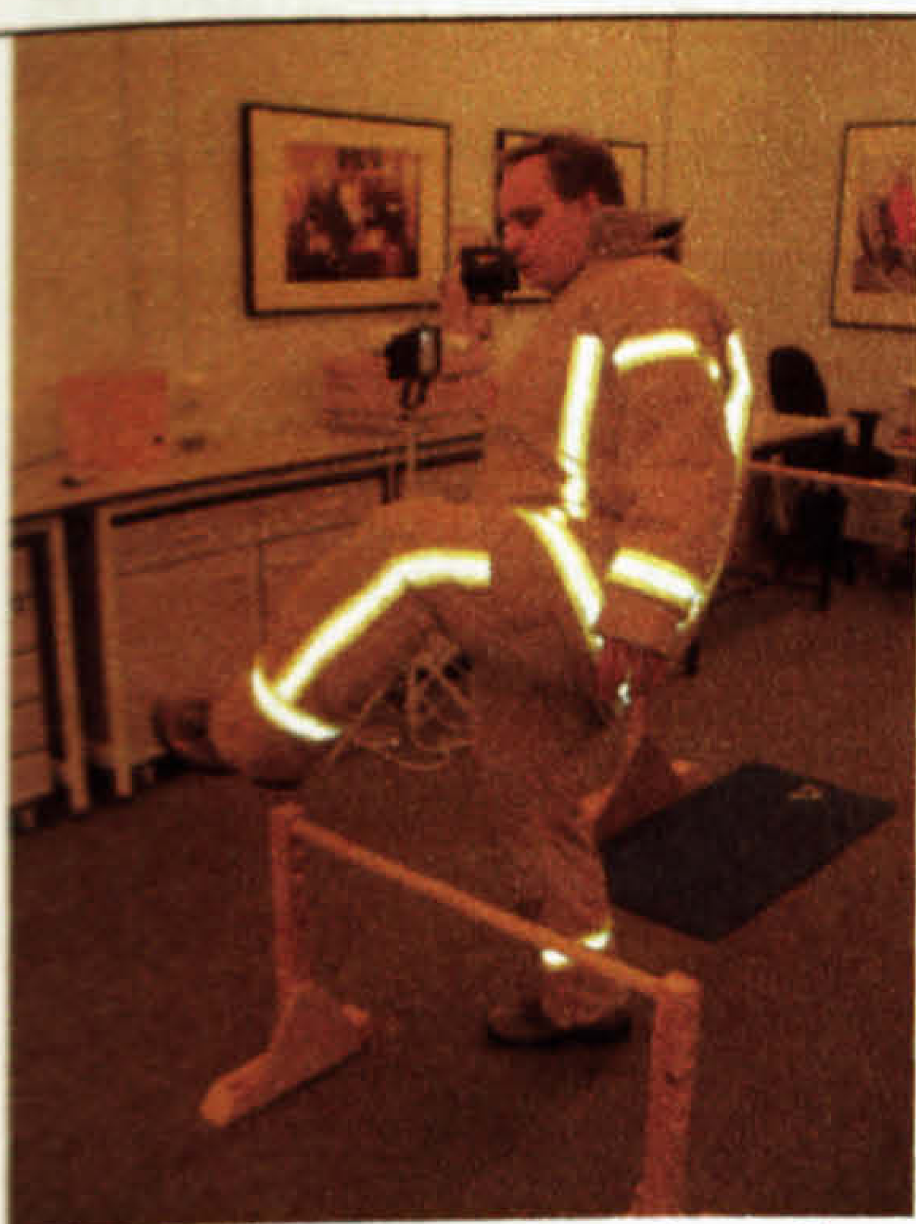
Table 2.3. Timing details, descriptions of movements and photographs to illustrate the crawling sequence.

 0.83 secs; Right leg over hurdle	 1.66 secs; Left leg over hurdle	 2.49 secs; Right leg bends to duck under hurdle
 3.32; Left leg bends to duck under hurdle	 4.15; Right leg turns around to face hurdle	 4.98; Left leg turns around to face hurdle

5.81; Right leg steps forward

6.64; Left leg steps forward, right knee bends to floor

7.47; Right foot steps forward



8.30; Left leg over hurdle

9.13; Right leg over hurdle

9.96; Turn around

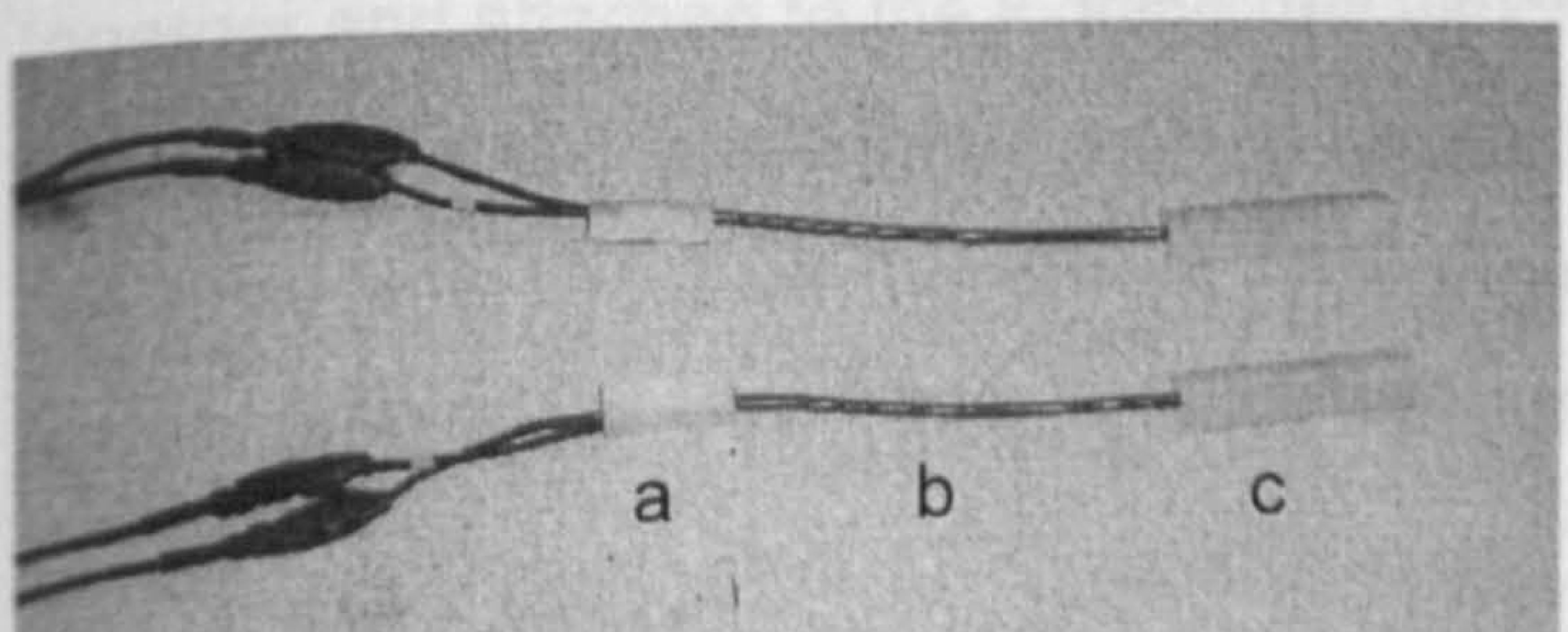
2.4 Measurements and calibration

A number of methods have been used to evaluate restriction to movement, the paper by Huck *et al.* (1997) mentions five (see paper for more detail);

1. movement analysis; involves measurement of ROM for various body joints using goniometers or other similar instrumentation
2. seam stress analysis; evaluation of the strain exerted on a garment due to wearer movement
3. garment slash analysis; also looks at strain on the garment
4. visual analysis; trained observers can provide additional insight into the problems associated with movement while wearing protective clothing
5. subjective preferences; using wearer acceptability scales.

In the Human Sciences Department there were 2 systems available for the present study; electrical goniometers and a CODA motion analysis system. The CODA system is a real-time 3D motion capture and analysis system with sensor units independently capable of measuring the 3-D coordinates of markers in real-time. The automatic intrinsic identification of markers combined with processing of all 3-D co-ordinates in real-time means that graphs and stick figures of the motion and many types of calculated data can be displayed on a computer screen during and immediately after the movement occurs (http://www.charndyn.com/index.html). The CODA system is predominantly used for gait analysis in the department. The markers are normally attached to the skin at anatomical landmarks, if they are to be used with clothing, the markers would need to be secured by straps over the top of the clothing to prevent them moving around. However placing straps around the clothing (above and below the joint) will additionally affect the clothing bulk and range of movement, therefore this method was deemed unacceptable.

A goniometer is a special name given to an electrical potentiometer that can be attached to measure a joint angle. One arm of the goniometer is attached to one limb segment, the other to the adjacent limb segment, and the axis of the goniometer aligned to the joint axis (Winter 1990). A Biometrics Ltd. (Gwent, Wales) package was used in this study. The two endblocks (on each arm of the goniometer), shown in Figure 2.2, are connected by a composite wire (with a protective spring around it) which has a series of strain gauges mounted around the circumference. As the angle between the two ends changes, the change in strain along the length of the wire is measured and this is equated to angle (http://www.biometricsltd.com).



a. fixed endblock
b. protective spring and composite wire
c. telescopic endblock

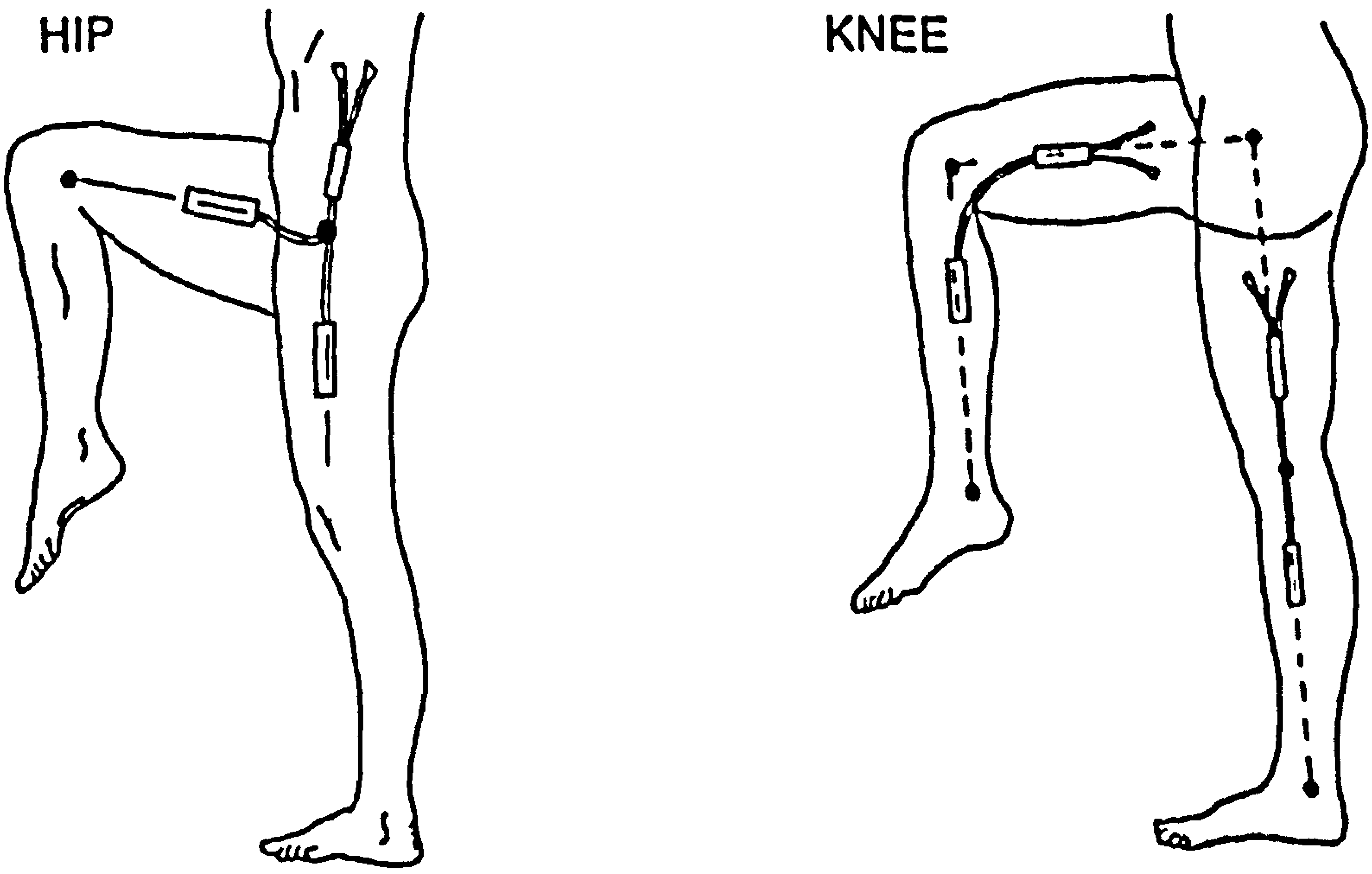
Figure 2.2. Photograph showing 2 goniometers

Electrical goniometers can be used to record movements, not just static positions. The goniometers can be secured on the skin (the endblocks taped above and below the joint to be studied) and the clothing worn over the top, this ensures the goniometers are in the same position for all clothing ensembles as they do not need to be removed to change the clothing. By contrast, the CODA system places markers over the top of the clothing, which would make it very difficult to repeatedly place the markers accurately and consistently in the same place. The goniometers also have the advantage of not affecting or influencing joint movement due to their small size and fact that they are taped to the skin. Based on these advantages of using the goniometers over the CODA system it was decided to use the goniometer system in this experiment.

The number of joints to be studied was limited by the channel capacity of the system. It was decided to focus on the lower limbs initially, as a possible effect was likely to be greater than in the upper body. The shoulder joint, as a ball and socket joint is also more complex to study. In the lower limbs, movement of the ankle joint can be affected by footwear, so the hip and knee joints were selected. The goniometers were attached across these two joints as illustrated in Figure 2.3. The goniometers were calibrated by checking their recorded angles when they were placed at set angles e.g. 45°, 90° with a manual goniometer.

The goniometers were attached to the skin with medical tape on the right side of the body. A mark was made on the skin of the exact location of the endblocks, to allow them to be accurately replaced if displaced during the dressing / undressing. The cables from each goniometer were taped together and attached to the logging unit which was carried around the waist on a belt, the unit was lightweight and positioned in the curve of the back to minimise any effect on movement. The logging unit was connected to a laptop, running the Biometrics Datalink software via a cable.

Once the participants had changed into the shorts and t-shirt provided, the goniometers were attached and the range of movement checked. With the participants then standing in a neutral reference posture (standing upright) the goniometers were set to zero.



Attach the fixed endblock to the side of the trunk in the pelvic region (as shown above). With the limb in the position of reference, attach the telescopic endblock to the thigh so that the axes of the thigh and endblock coincide (when viewed in the sagittal plane, as above). The hip may now be flexed or extended.	Mount the telescopic endblock laterally on the leg so the axes of the leg and endblock coincide, when viewed in the sagittal plane (as shown above) with the leg fully extended in the position of reference, and attach the fixed endblock to the thigh so the axes of the thigh and endblock coincide. The knee may be fully extended or flexed.

Figure 2.3. Illustrations of the sites and positions where the goniometers were attached (notes included for positioning of the goniometers as provided in the Biometrics manual).

2.5 Experimental design

The study was a within-subjects design with each participant acting as their own control. They completed all the protective garments and a control condition (shorts and t-shirt) in one session. The shorts and t-shirt were worn throughout, with the protective garments over the top, trainers (their own) were also worn for all conditions by participants. The garment order was balanced. For each condition participants walked first, stepped, then completed the crawling. Each work mode was repeated six times and recorded as a separate file, before moving onto the next work mode.

2.6 Procedure

On arrival at the lab, the format of the session was explained to the participants and they were given a chance to ask questions before completing a consent form and health screen questionnaire. The work modes and timing was demonstrated to the participants and they were given a chance to practice before changing into the shorts and t-shirt provided. The goniometers were attached to the right leg of the participants with medical tape and marks drawn on the skin of the position of the goniometers in case they were displaced, as described above. With the participant standing in a neutral posture the zero was set on the goniometers.

Participants donned the first set of clothing and the goniometers were connected to the logging unit on a belt which was fastened around the participants waist with the logging unit sitting in the curve of the back. Participants walked for 1 minute on the treadmill, followed by 6 repeats of the stepping cycle and then 6 repeats of the crawling cycle. After all the work modes had been completed for each garment participants were asked to comment generally on the garment; comfort, fit, restriction to movement etc.

2.7 Analysis

The data was exported from the data link software into Microsoft Excel spreadsheets and converted into joint angles. Graphs were plotted for each participant for each condition (7 garments and control) and each workmode (walking, stepping, crawling). Examples of the traces plotted are shown in Figures 2.4, 2.5 and 2.6 for knee and hip angles.

For the walking data, 5 gait cycles were analysed and the maximum and minimum values for knee and hip angles were recorded, the arrows and labels in Figure 2.4 illustrate the points that were recorded from one gait cycle.

The stepping sequence was made up of 6 main movements, described in Table 2.2, these have been highlighted again in Table 2.4. The maximum and minimum angles for these 6 movements were recorded and 5 cycles of the stepping sequence were analysed. The arrows and labels in Figure 2.5 have been provided to illustrate the points recorded for one sequence.

The crawling sequence, previously illustrated in Table 2.3 was made up of 4 main movements, highlighted again in Table 2.5. The maximum and minimum angles for these 4 movements over 5 cycles of the crawling sequence were analysed. Figure 2.6 indicates the points taken for the knee and hip angles for one sequence.

The analysis described above resulted in summary graphs of the control and garments for each participant, for each work mode. As the differences between garments were small a clothing average for all the garments was then calculated, this was analysed with the control average (based on the 6 participants). Paired t-tests were carried out on the control and clothing average values for the maximum knee angle, minimum knee angle, knee angle range (range of movement), maximum hip angle, minimum hip angle, hip angle range (range of movement).

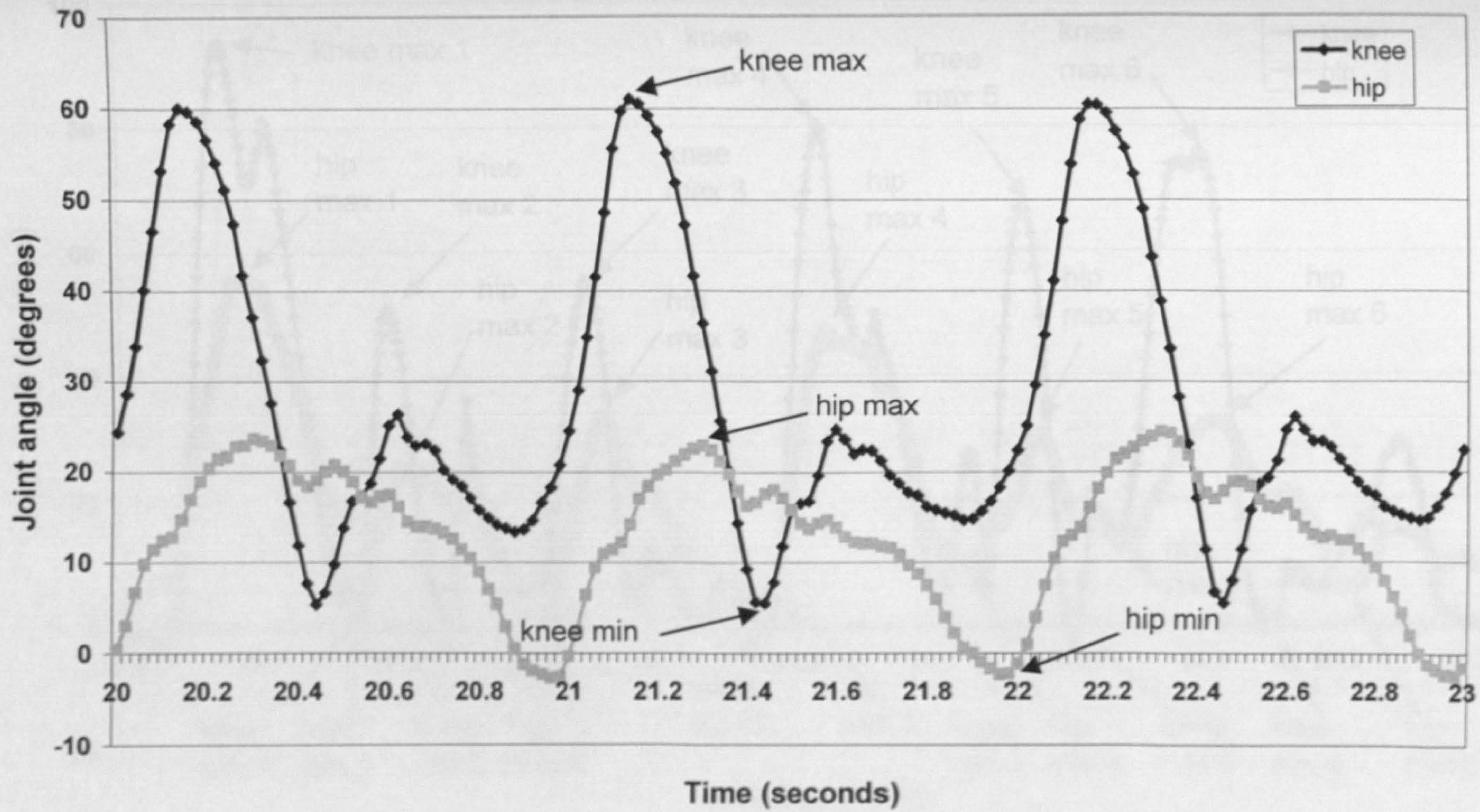


Figure 2.4. Plot of walking data for one participant in one garment.

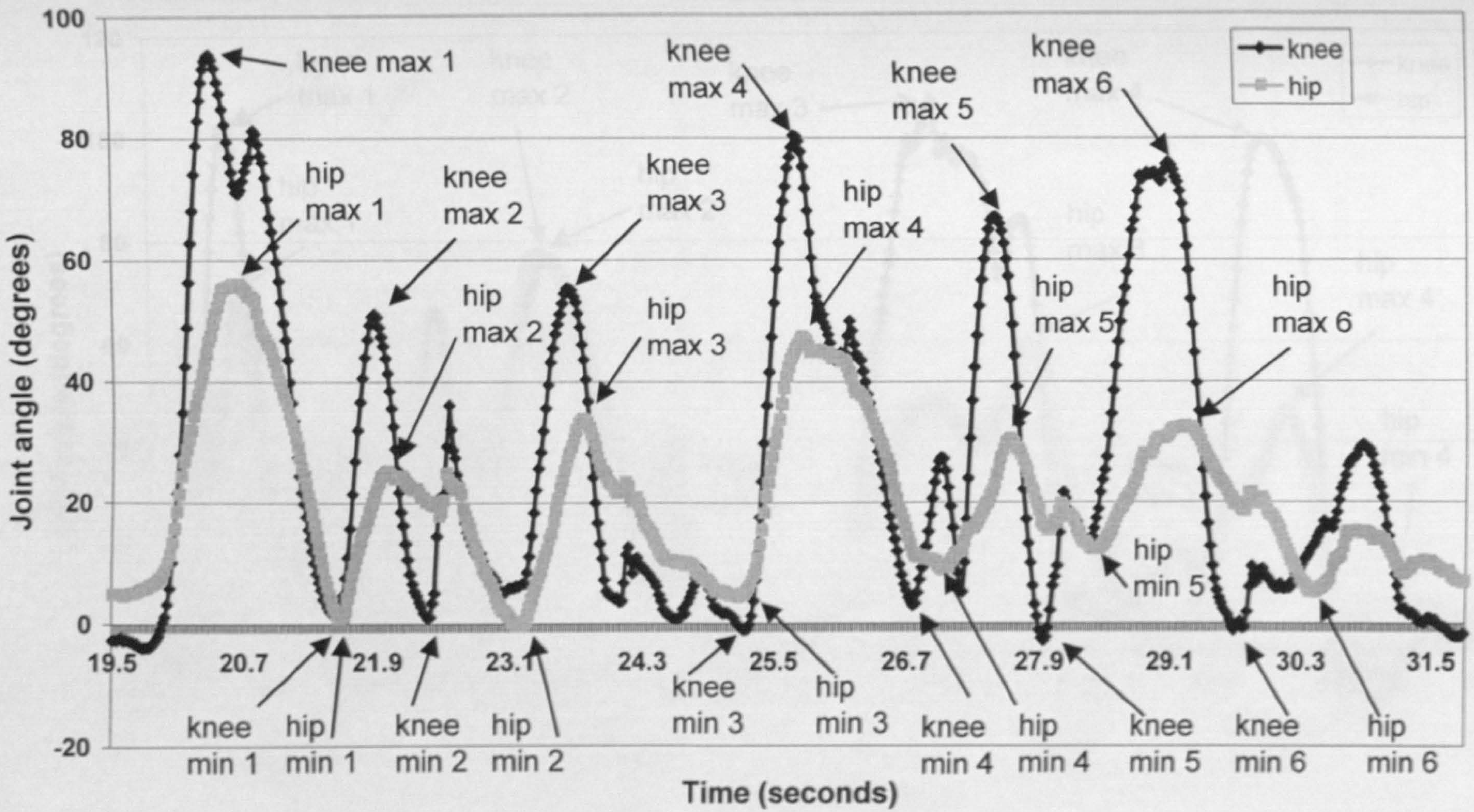


Figure 2.5. Plot of stepping data for one participant in one garment.

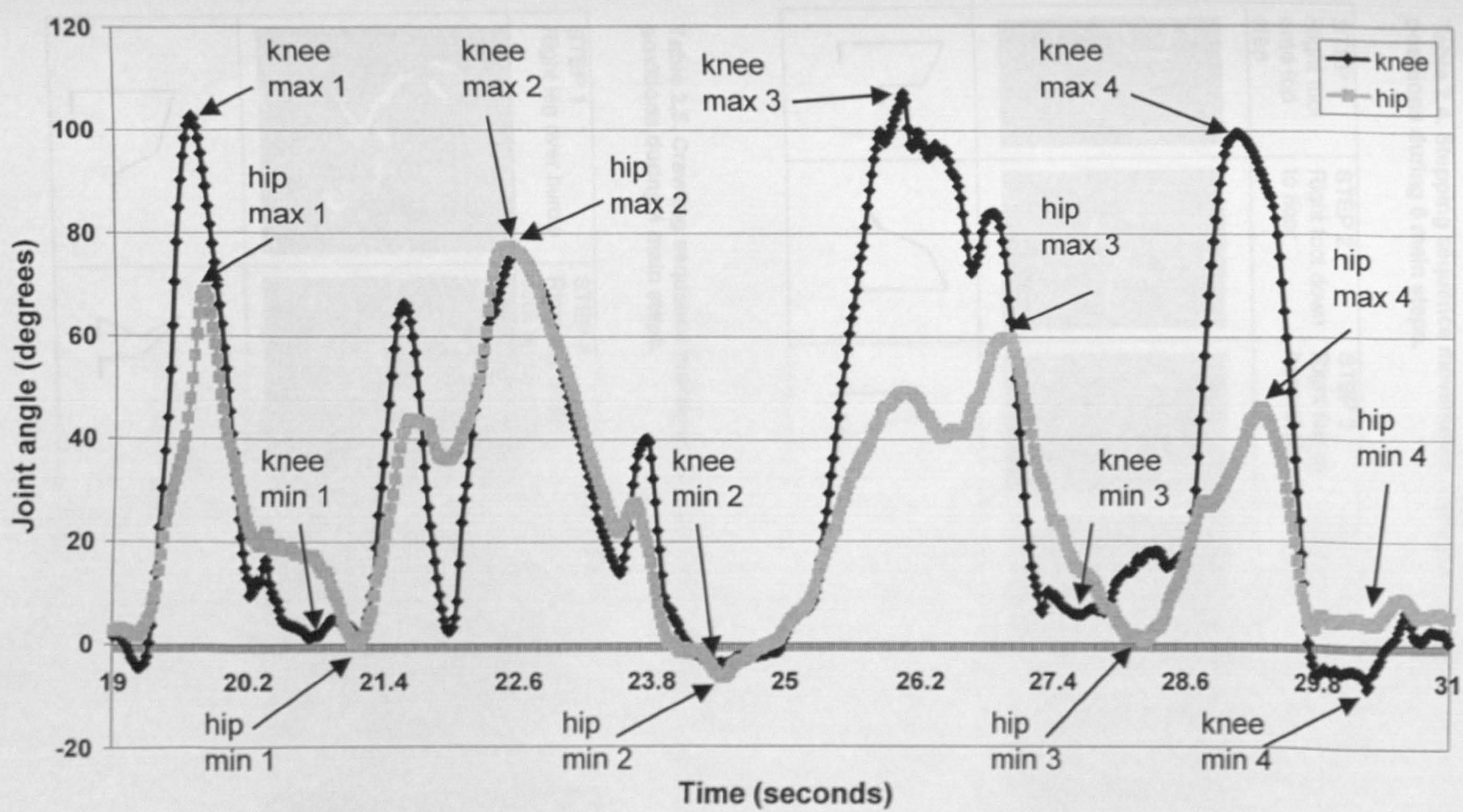


Figure 2.6. Plot of crawling data for one participant in one garment.

Table 2.4. Stepping sequence movements, photographs and illustration of leg positions during 6 main steps.

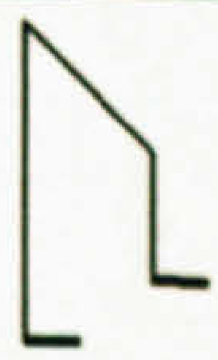
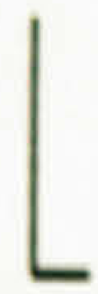
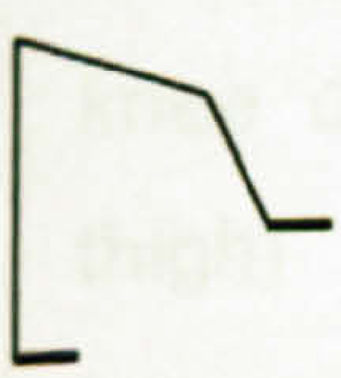
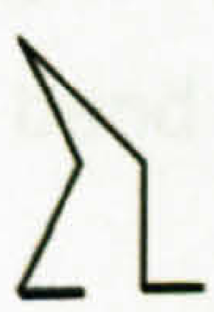
STEP 1 Right foot onto top step	STEP 2 Right foot down to floor	STEP 3 Right foot to base of steps	STEP 4 Right foot onto 1st step	STEP 5 Right foot down to 3rd step	STEP 6 Back to starting position
					
					

Table 2.5. Crawling sequence movements, photographs and illustration of leg positions during 4 main steps.

STEP 1 Right leg over hurdle	STEP 2 Right leg bends to duck under hurdle	STEP 3 Right knee down to crouch under hurdle	STEP 4 Right leg over hurdle
			
			

3. Results

3.1 Walking results

In order to check that the goniometer data measured in the present study was accurate and the joint angles representative, the hip and knee angles during the walking gait were looked at in detail. Figure 3.1 illustrates the angles during one gait cycle, for one participant, with the stance phase and swing phase identified.

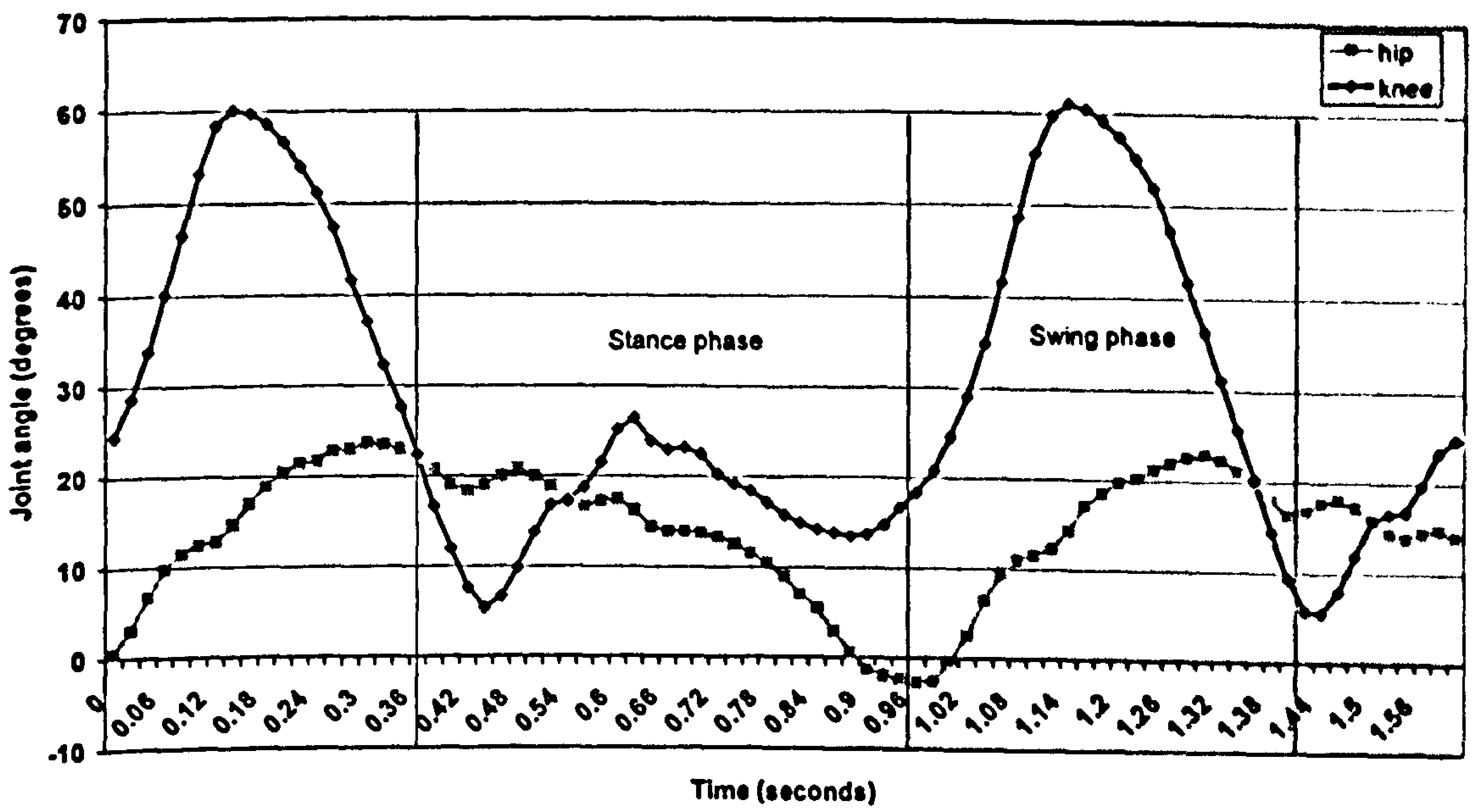


Figure 3.1. Hip and knee angles during walking gait.

The graphs of individual data plotted for the walking work mode tended to show one of three trends;

- very little change in joint angles when clothing was worn compared to control
- reduced joint angles when clothing was worn compared to control (so knee does not bend as much, less forward/upward movement of thigh)
- increased joint angles when clothing was worn compared to control (so greater knee bend and higher thigh lift)

The later two trends are illustrated in Figure 3.2 and 3.3.

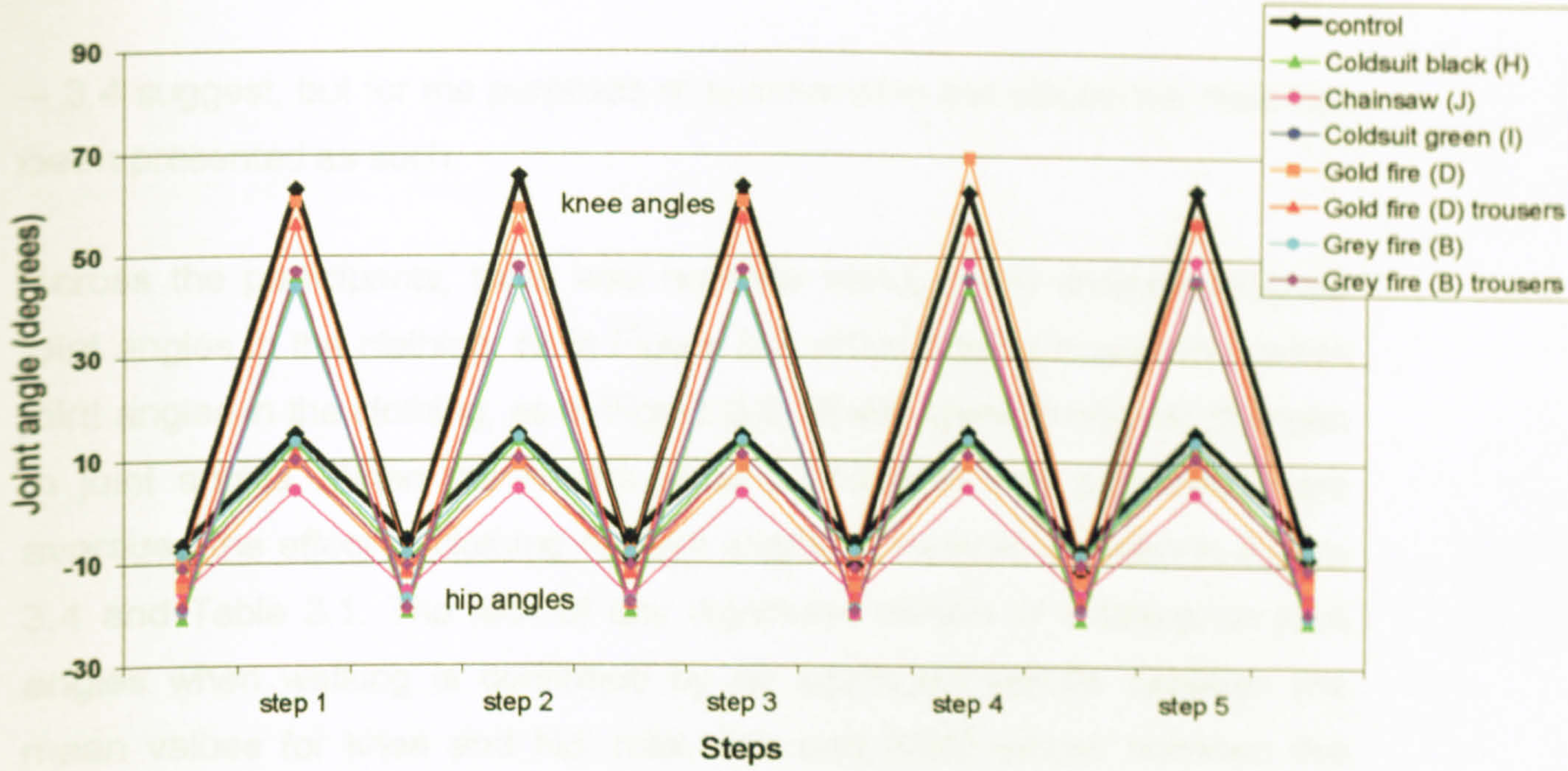


Figure 3.2. Summary graph of joint angles for Participant #2 when walking showing reduced knee and hip angles in clothing compared to control (hips data time shifted to allow maximum / minimum to coincide).

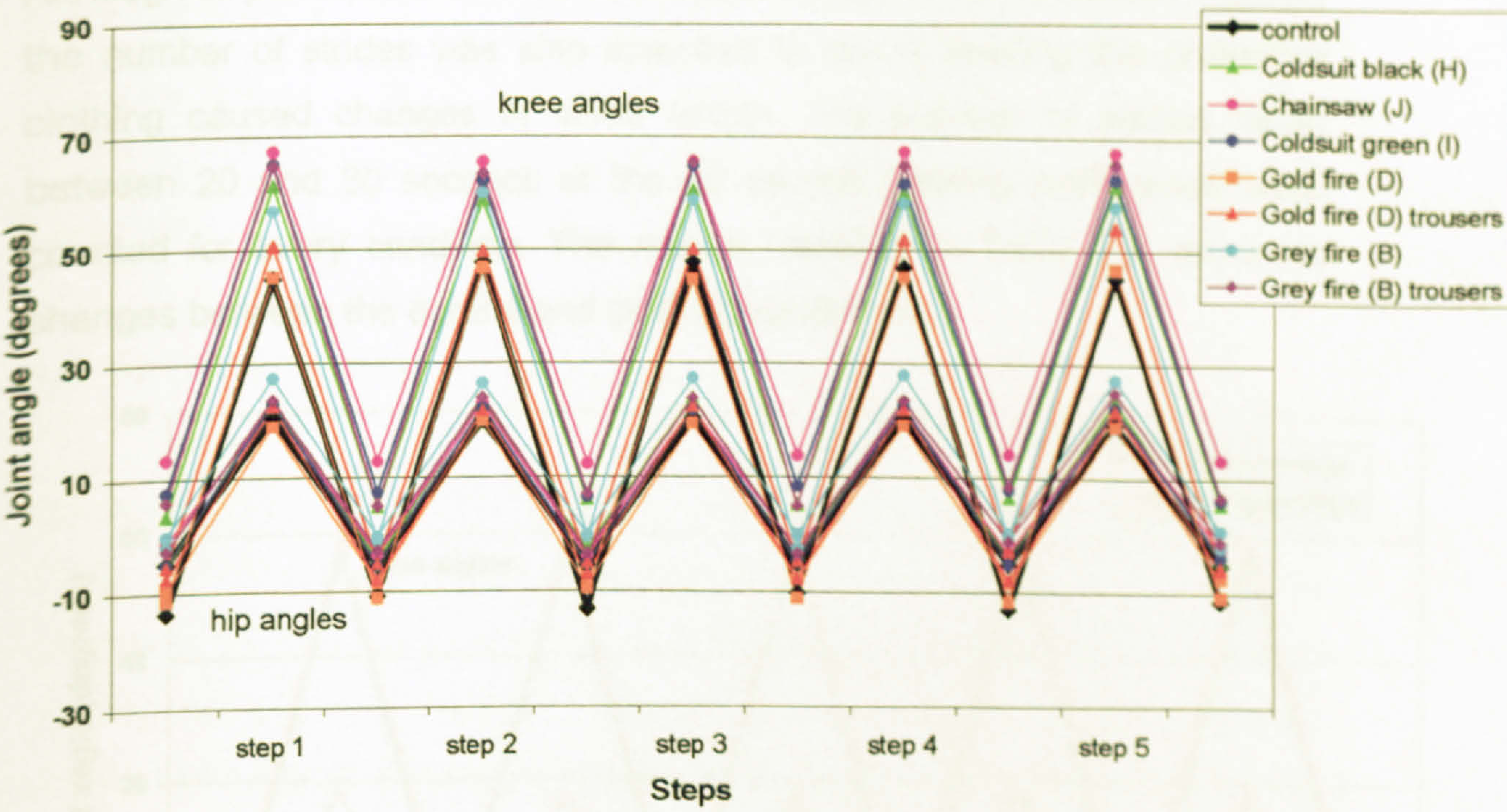


Figure 3.3. Summary graph of joint angles for Participant #4 when walking showing increased knee and hip angles in clothing compared to control (hips data time shifted to allow maximum / minimum to coincide).

As can be seen in the plots of the raw data, Figures 2.4, 2.5 and 2.6, the maximum and minimum knee and hip angles did not coincide as Figures 3.2

– 3.4 suggest, but for the purposes of summarising the values the data has been presented as such.

Across the participants, there was no clear trend, some showed reduced joint angles in the clothing, as in Figure 3.2, whilst some showed increased joint angles in the clothing, as in Figure 3.3, others showed no real changes in joint angles. When the results of all participants and all clothing are averaged the effect of clothing on joint angles is minimal as seen in Figure 3.4 and Table 3.1. The lack of any significant effects of clothing on joint angles when walking is confirmed by no significant results between the mean values for knee and hip, max, min and ROM values between the control and clothing averages as shown in Table 3.1.

Although all participants walked at the same speed on the treadmill, 5 km/hr, the number of strides was also analysed to see if wearing the protective clothing caused changes in stride length. The number of strides taken between 20 and 30 seconds of the 60 second walking work mode were counted for every condition. The results, detailed in Table 3.2, show no changes between the control and clothing conditions.

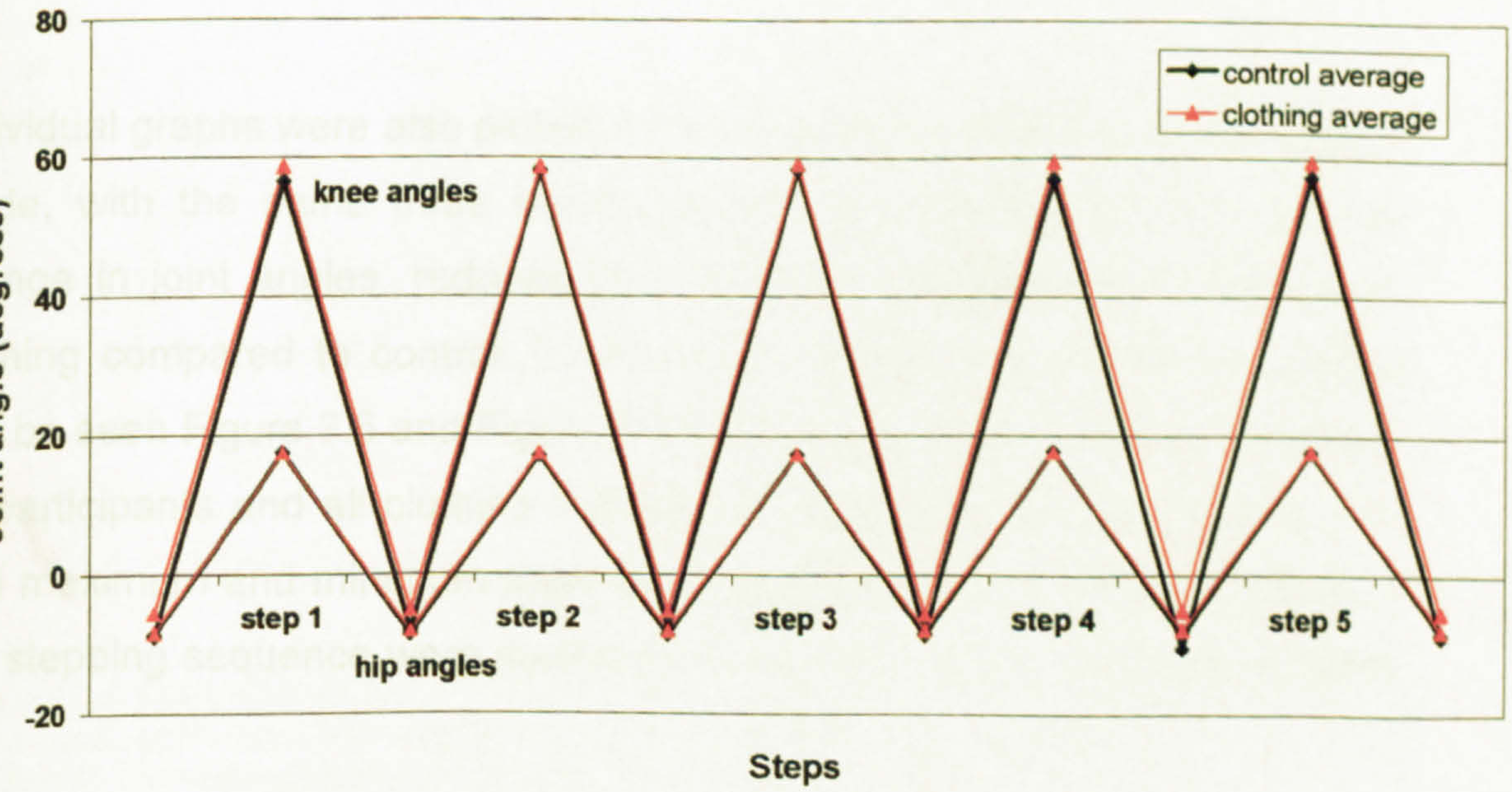


Figure 3.4. Graph of joint angles for control average and clothing average (7 garments) when walking (n=6) (hips data time shifted to allow maximum / minimum to coincide).

Table 3.1. Mean and standard deviations for knee and hip max, min and ROM values for control and clothing conditions when walking. None of the values were significantly different between the control and clothing.

	CONTROL		CLOTHING	
	mean	SD	mean	SD
knee max	56.7	8.7	58.6	8.1
knee min	-8.1	2.9	-5.8	7.5
knee ROM	64.7	8.9	64.5	4.2
hip max	17.5	3.4	17.5	5.3
hip min	-8.7	3.2	-8.2	3.6
hip ROM	26.2	4.2	25.7	3.6

Table 3.2. Number of strides in 10 secs (during 20-30 seconds of the 60 second duration) of walking for each participant in all clothing conditions.

PARTICIPANT NO.	1	2	3	4	5	6
control	10	10.5	10	10	9	10
B Grey fire	10	10.5	10	10	9	10
B Grey fire trousers	10	10	10	10	9	10
D Gold fire	10	10.5	10	10	9	10
D Gold fire trousers	10	10	10	10	9	10
H Coldsuit black	10	10.5	10	10	9	10
I Coldsuit green	10	10	10	10	9	10
J Chainsaw	10	10.5	10	10	9	10

3.2 Stepping results

Individual graphs were also plotted for each participant for the stepping work mode, with the same three trends seen in the walking evident; no real change in joint angles, reduced joint angles or increased joint angles, in clothing compared to control. Examples of reduced and increased angles can be seen Figure 3.5 and Figure 3.6 respectively. The individual data from all participants and all clothing has been combined to produce Figure 3.7. The maximum and minimum knee and hip angles for the 6 main phases of the stepping sequence were summarised and illustrated previously in Table 2.4.

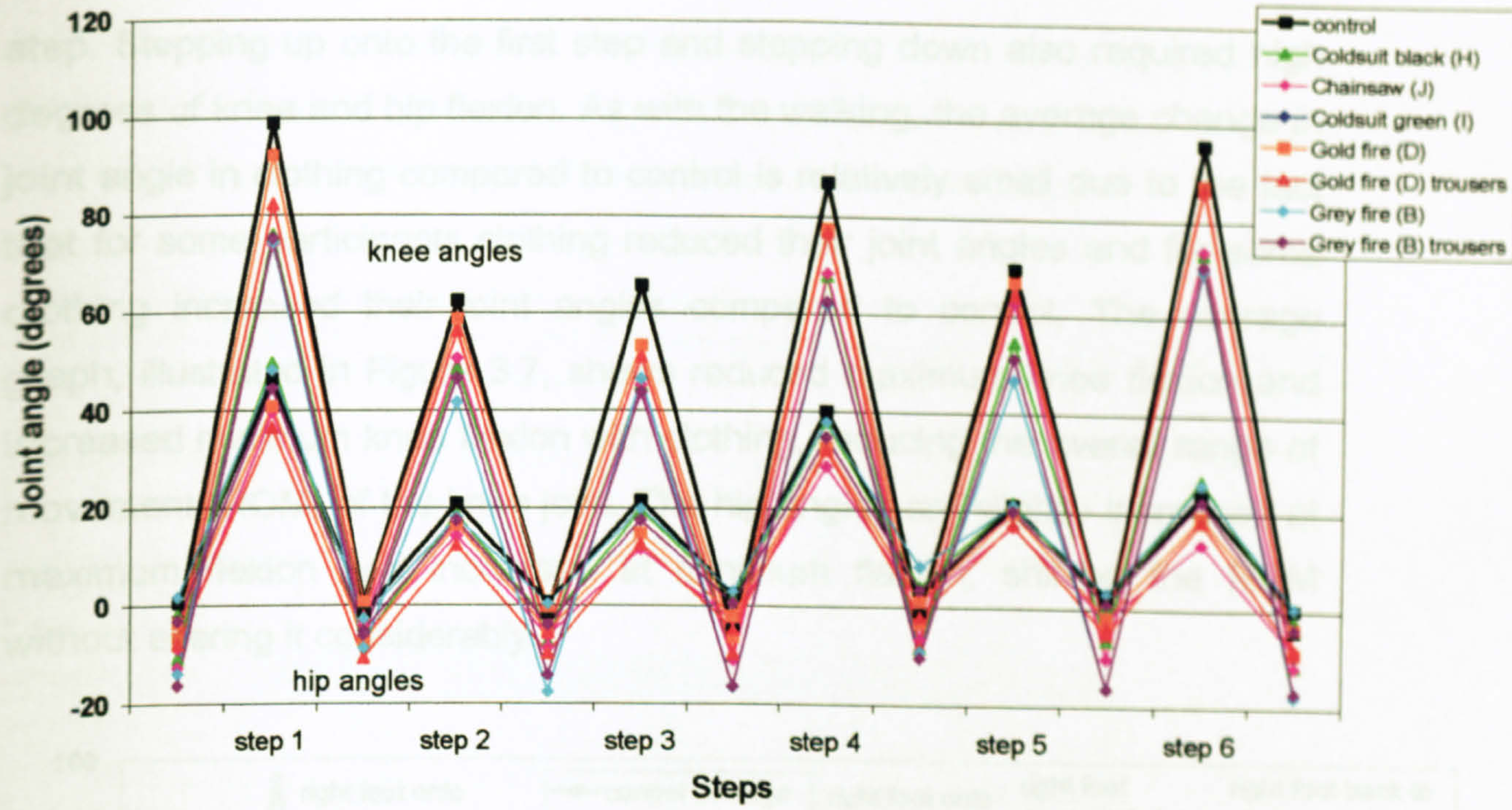


Figure 3.5. Summary graph of joint angles for Participant #2 when stepping showing reduced knee and hip angles in clothing compared to control (hips data time shifted to allow maximum / minimum to coincide).

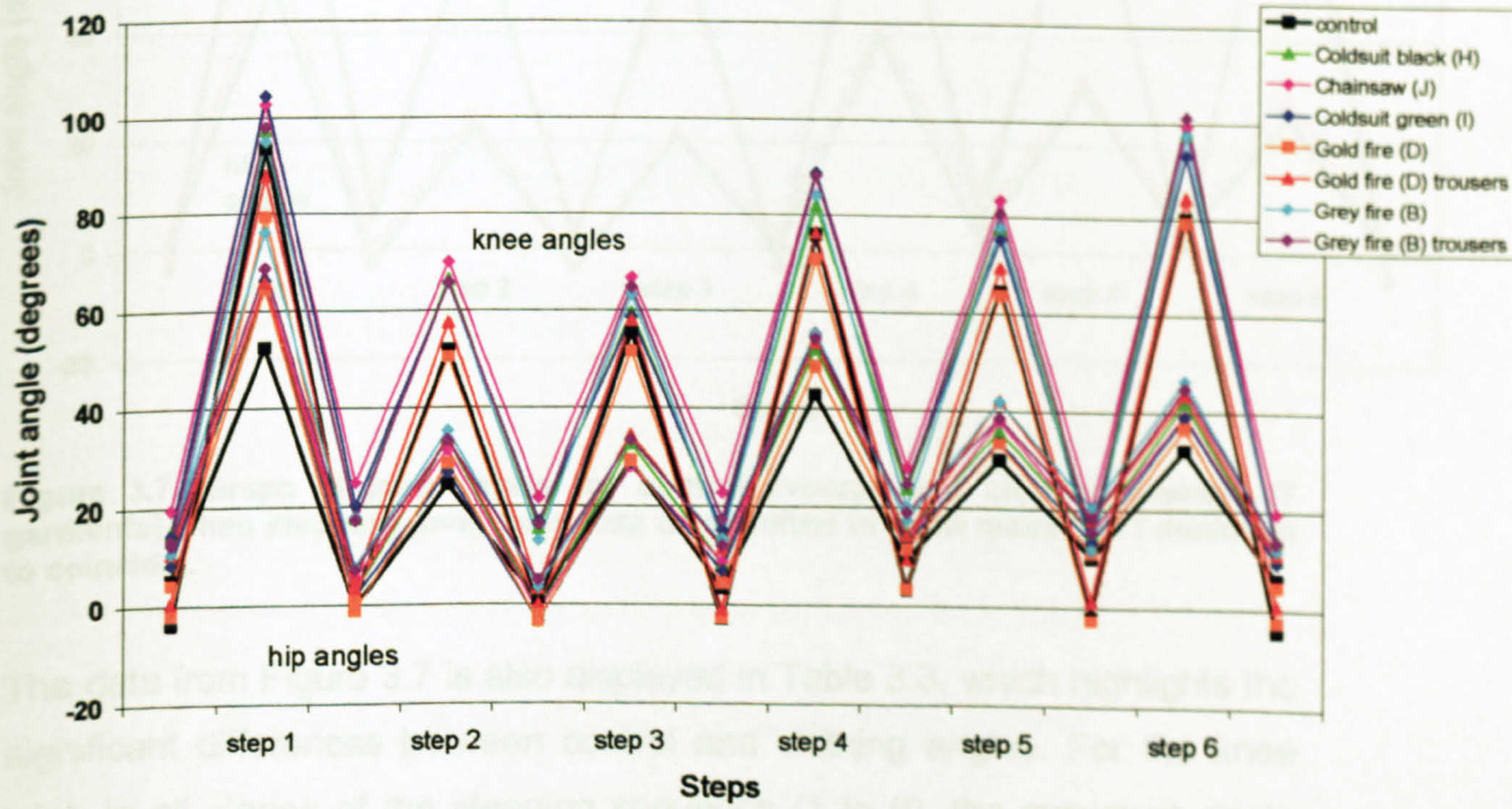


Figure 3.6. Summary graph of joint angles for Participant #4 when stepping showing increased knee and hip angles in clothing compared to control (hips data time shifted to allow maximum / minimum to coincide).

The greatest degree of knee and hip flexion was required for the first stage of the stepping sequence when participants had to step up onto the highest step. Stepping up onto the first step and stepping down also required high degrees of knee and hip flexion. As with the walking, the average change in joint angle in clothing compared to control is relatively small due to the fact that for some participants clothing reduced their joint angles and for some clothing increased their joint angles compared to control. The average graph, illustrated in Figure 3.7, shows reduced maximum knee flexion and increased minimum knee flexion with clothing, reducing the overall range of movement (ROM) of the knee joint. The hip angles are slightly increased at maximum flexion and increased at minimum flexion, shifting the ROM without altering it considerably.

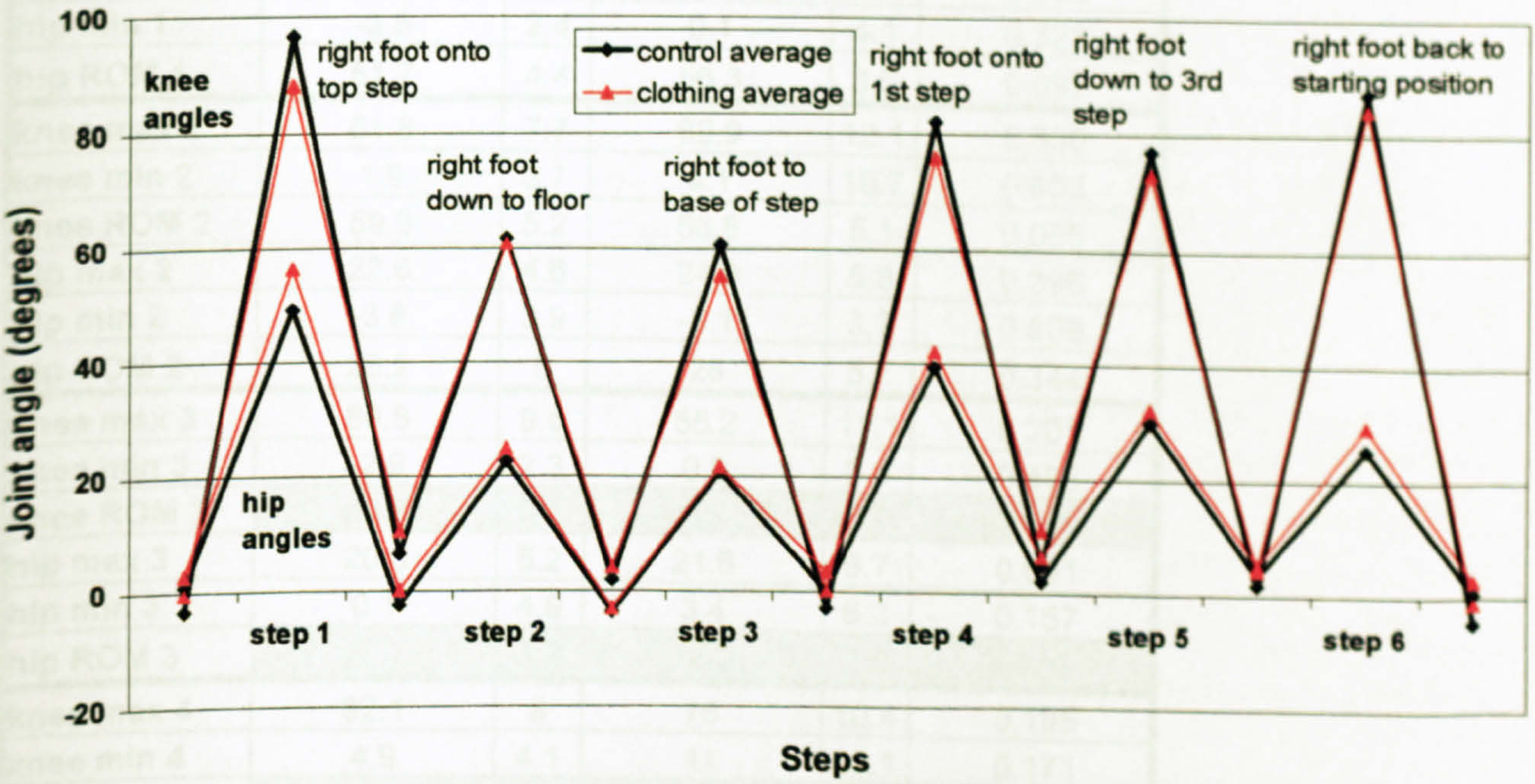


Figure 3.7. Graph of joint angles for control average and clothing average (7 garments) when stepping (n=6) (hips data time shifted to allow maximum / minimum to coincide).

The data from Figure 3.7 is also displayed in Table 3.3, which highlights the significant differences between control and clothing angles. For the knee joint, in all stages of the stepping sequence (1 to 6), the maximum angle recorded was reduced, the minimum angle was increased and the ROM reduced. The reduction in ROM was significant for all the movements apart from the second (right foot down to the floor). For the hip joint, the maximum angle was increased and minimum angle increased in all movements (the minimum angle during step 4, right foot onto 1st step was significantly p<0.041 increased compared to the control). The ROM was greater in stages 1, 2, 5 and 6 of the stepping and reduced in stages 3 and 4 (in stage 3 the ROM was significantly, p<0.003, lower than in the control).

Table 3.3. Mean, standard deviation and significant differences for knee and hip max, min and ROM values for control and clothing conditions when stepping (1 to 6 refers to the 6 parts of the stepping sequence).

	CONTROL		CLOTHING		DIFFERENCE
	mean	SD	mean	SD	significance
knee max 1	96.7	9	88.1	14	0.091
knee min 1	6.6	5.4	10.5	8.9	0.342
knee ROM 1	90.1	11.7	77.6	10.9	0.0005
hip max 1	49.2	5.6	56.4	10.4	0.084
hip min 1	-2.5	2.4	0.1	4.1	0.323
hip ROM 1	51.7	4.4	56.3	8.6	0.097
knee max 2	61.8	7.7	60.9	12.1	0.860
knee min 2	1.9	3.7	4.1	10.7	0.603
knee ROM 2	59.8	5.2	56.8	5.1	0.055
hip max 2	22.6	4.6	24.9	5.8	0.396
hip min 2	-3.6	3.9	-3.1	3.2	0.809
hip ROM 2	26.2	6	28	5.7	0.344
knee max 3	60.8	9.5	55.2	11.1	0.201
knee min 3	-2.9	2.3	0.2	9.5	0.436
knee ROM 3	63.7	8.4	55	6.9	0.001
hip max 3	20.8	5.2	21.6	6.7	0.691
hip min 3	0.1	4.9	3.4	6.3	0.157
hip ROM 3	20.7	3.6	18.2	2.9	0.003
knee max 4	82.1	9	76	10.4	0.195
knee min 4	4.9	4.1	11	11.1	0.171
knee ROM 4	77.3	9.7	65	9.1	0.0005
hip max 4	39.3	5.6	42.1	7.6	0.413
hip min 4	2.1	4.5	6.3	4.9	0.041
hip ROM 4	37.3	4.6	35.8	4.3	0.519
knee max 5	77.1	10.3	73.3	11.7	0.402
knee min 5	1.9	5.1	4.3	10.3	0.508
knee ROM 5	75.3	6.2	69	3.4	0.009
hip max 5	30	7.6	32.2	7.6	0.445
hip min 5	3.3	5.4	5.3	6.5	0.366
hip ROM 5	26.7	7.2	26.9	5.6	0.853
knee max 6	87.3	8.6	84.5	11.2	0.615
knee min 6	-4.6	2.4	-1.1	8.7	0.394
knee ROM 6	91.9	6.9	85.6	7.0	0.024
hip max 6	25.5	4.5	29.6	8.2	0.117
hip min 6	0.7	4.1	2.8	6.5	0.333
hip ROM 6	24.7	4.6	26.8	6.5	0.264

The changes in maximum joint angles compared to control have been plotted in Figure 3.8. The changes in hip angles (black bars) with clothing compared to control were all positive, with the largest increase in flexion, 7.2 degrees for the initial step up onto the top step. This initial movement also caused the greatest change in knee angle (grey bars), a reduction of 8.6 degrees of flexion in the clothing compared to the control. The clothing also had an effect on the hip and knee angles for the other main stepping movements, with increased flexion in the hip and reduced flexion in the knee.

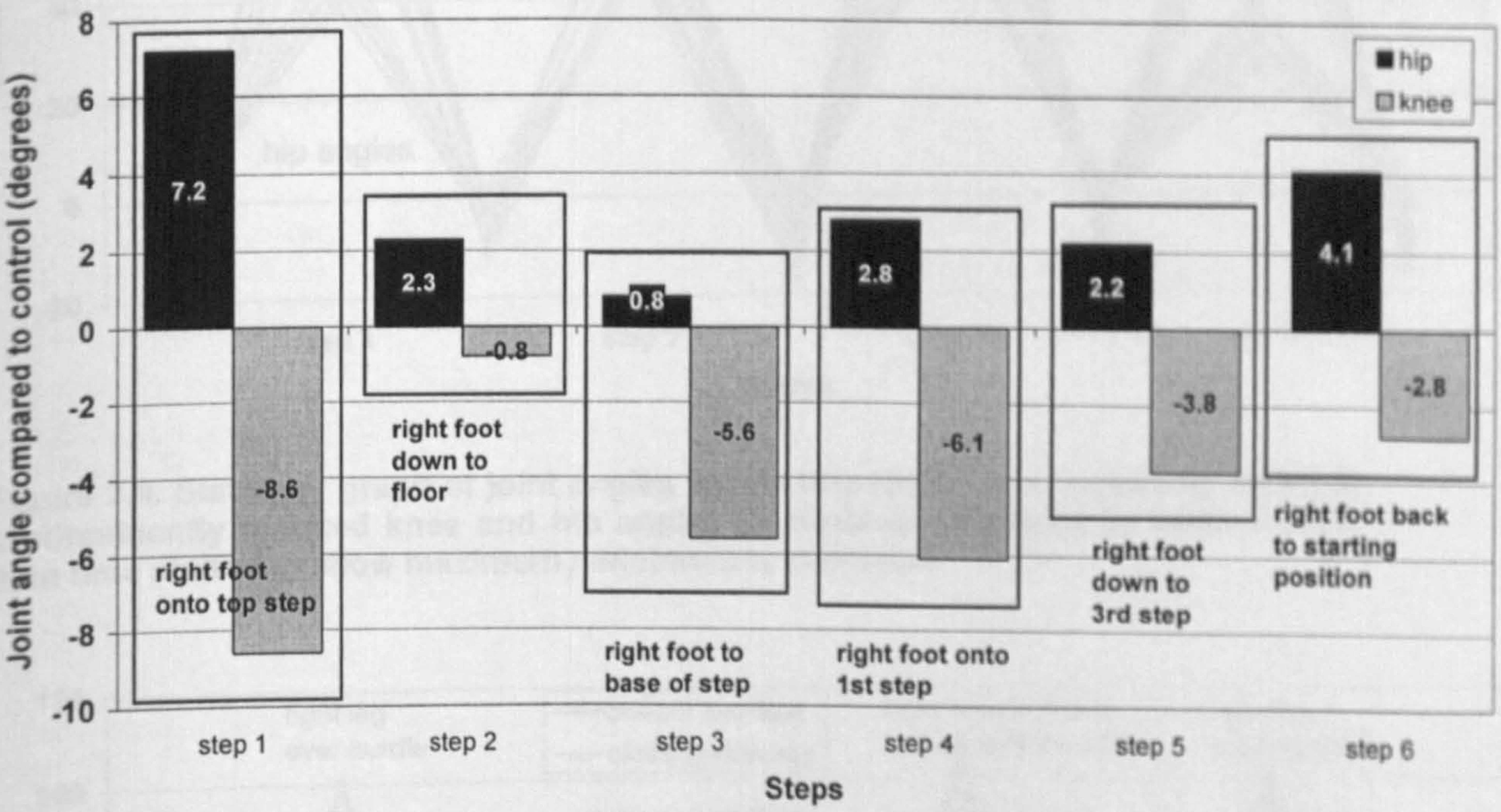


Figure 3.8. Difference in maximum joint angles compared to control for the hip and knee during all phases of the stepping sequence.

3.3 Crawling results

Individual graphs were again plotted for each participant for the crawling work mode, with the trends for no angle change, reduced angles and increased angles with clothing, seen in the walking and stepping. An individual plot illustrating predominantly reduced knee and hip angles when clothing is worn compared to the control is included in Figure 3.9. The individual data from all participants and all clothing has been combined to produce Figure 3.10. The graphs illustrate the maximum and minimum knee and hip angles for the 4 main phases of the crawling sequence as described and illustrated previously in Table 2.5.

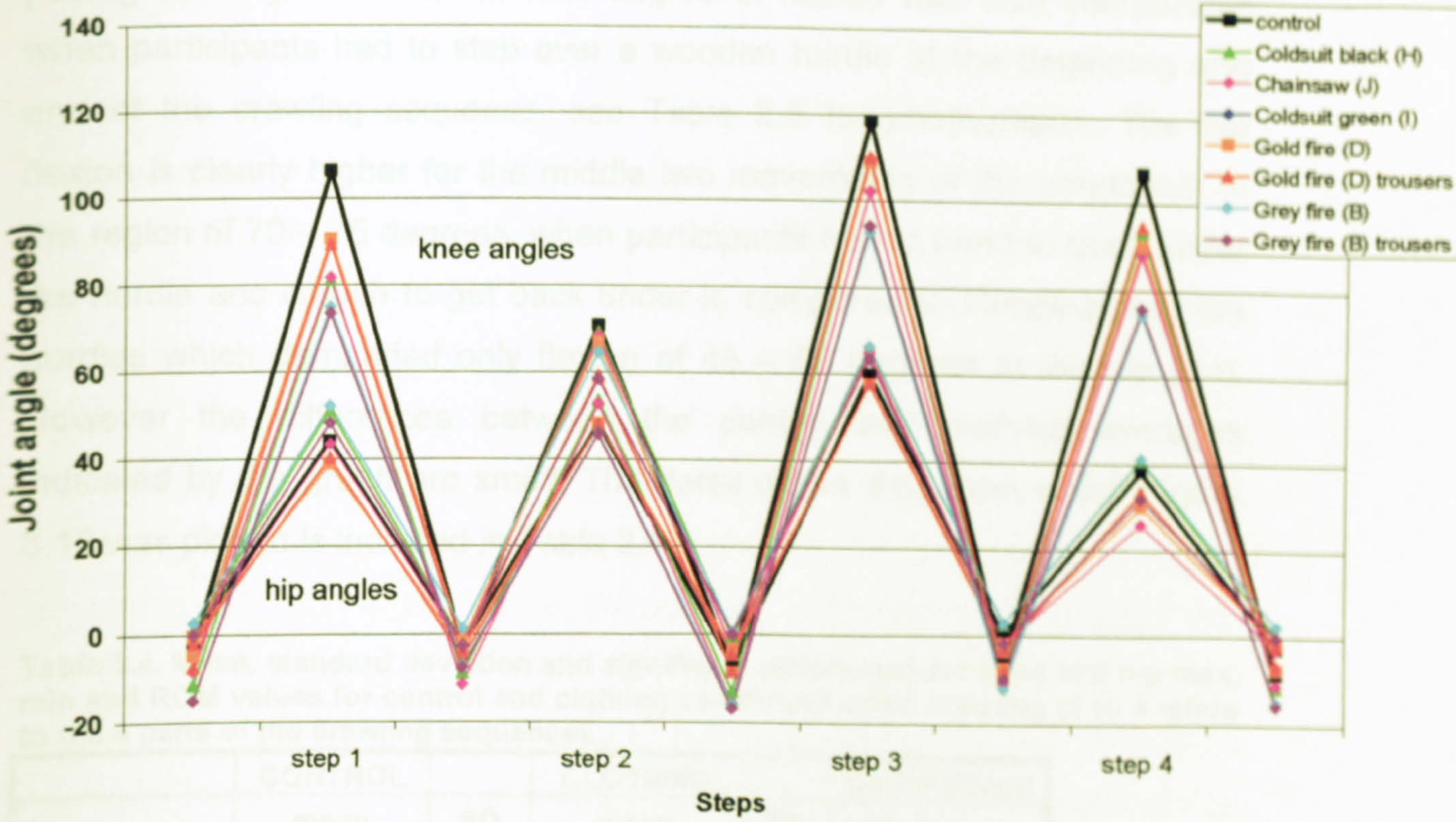


Figure 3.9. Summary graph of joint angles for Participant #2 when crawling showing predominantly reduced knee and hip angles in clothing compared to control (hips data time shifted to allow maximum / minimum to coincide).

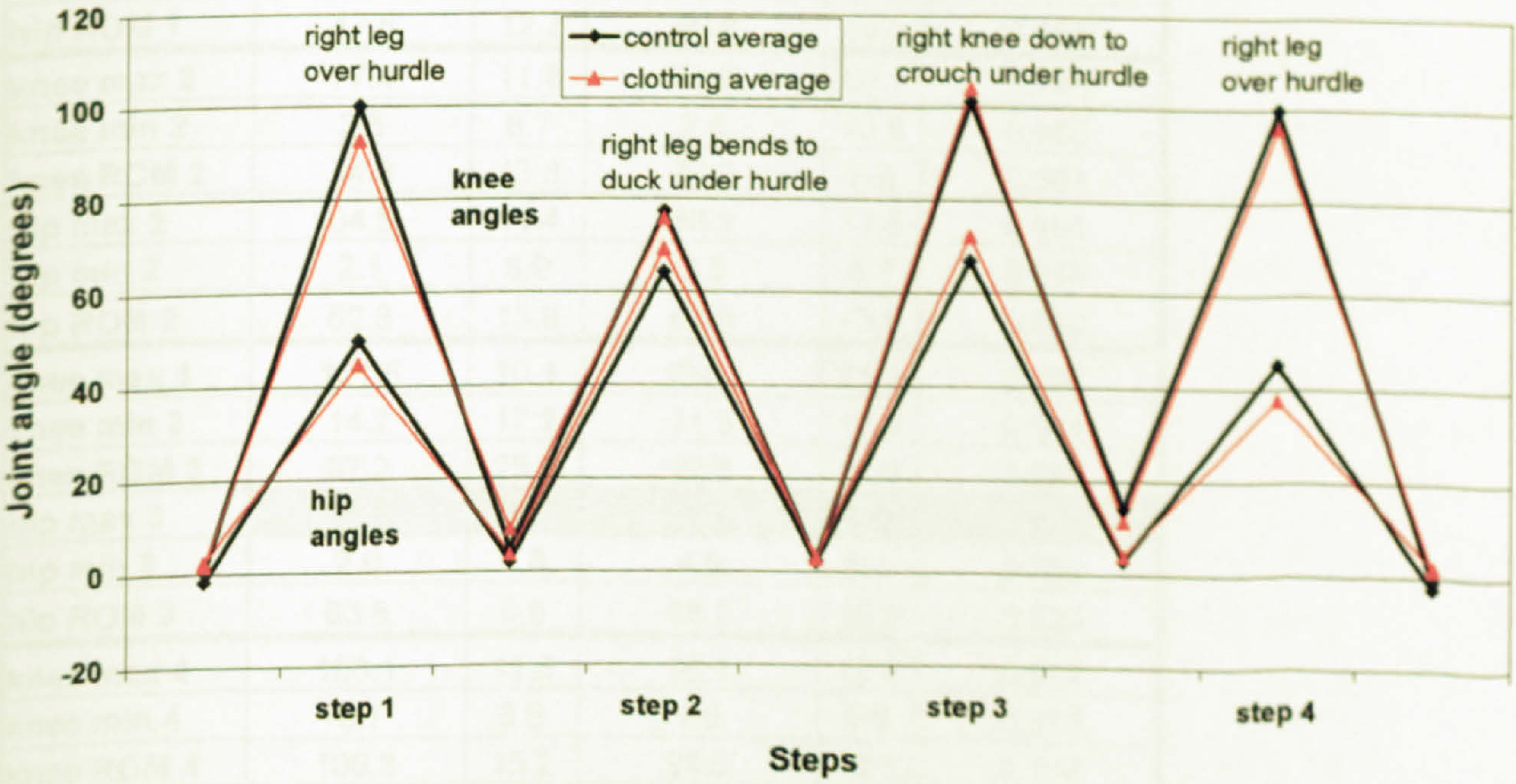


Figure 3.10. Graph of joint angles for control average and clothing average (7 garments) when crawling (n=6) (hips data time shifted to allow maximum / minimum to coincide).

For the knee angles the highest flexion recorded, up to 100 degrees, was during the movement that required participants to crouch under a hurdle, putting their right knee down. The degree of flexion was also comparable when participants had to step over a wooden hurdle at the beginning and end of the crawling sequence, see Table 2.5 for photographs. The hip flexion is clearly higher for the middle two movements of the sequence, in the region of 70 – 75 degrees, when participants had to bend to duck under the hurdle and crouch to get back under it, compared to stepping over the hurdles which demanded only flexion of 45 – 50 degrees in the hip joint. However the differences between the control and clothing averages indicated by the graph are small. The detail of the data from which Figure 3.10 was plotted is included in Table 3.4.

Table 3.4. Mean, standard deviation and significant differences for knee and hip max, min and ROM values for control and clothing conditions when crawling (1 to 4 refers to the 4 parts of the crawling sequence).

	CONTROL		CLOTHING		DIFFERENCE
	mean	SD	mean	SD	significance
knee max 1	100.2	10.8	92.6	21.0	0.307
knee min 1	4.8	6.7	8.9	11.8	0.360
knee ROM 1	95.4	11.8	83.7	14.4	0.031
hip max 1	49.8	12.1	44.5	9.2	0.174
hip min 1	2.0	2.7	3.7	6.8	0.573
hip ROM 1	47.8	12.2	40.8	13.0	0.155
knee max 2	77.4	11.8	75.9	18.1	0.745
knee min 2	2.5	8.7	2.6	10.9	0.985
knee ROM 2	74.8	13.8	73.2	8.9	0.693
hip max 2	64.5	14.4	68.2	11.9	0.081
hip min 2	2.1	8.9	3.3	6.1	0.816
hip ROM 2	62.3	13.9	64.9	13.6	0.630
knee max 3	101.5	10.4	104.1	21.2	0.797
knee min 3	14.2	17.2	11.3	15.0	0.691
knee ROM 3	87.2	25.7	92.8	17.8	0.657
hip max 3	66.8	8.3	72.0	8.8	0.029
hip min 3	2.9	1.8	4.0	8.7	0.766
hip ROM 3	63.8	8.6	68.0	15.3	0.339
knee max 4	100.1	11.8	96.1	19.3	0.512
knee min 4	-0.7	6.6	1.6	9.8	0.612
knee ROM 4	100.8	15.2	94.5	13.1	0.116
hip max 4	45.3	6.7	37.6	7.4	0.226
hip min 4	-2.3	3.5	2.1	3.9	0.015
hip ROM 4	47.7	8.8	35.4	4.2	0.084

The data concerning the changes in knee angle when clothing is worn compared to control show that in 3 of the 4 stages of the crawling work mode the maximum flexion of the knee is reduced, the minimal flexion is increased and the overall range of movement (ROM) reduced, significantly in the first stage, stepping over the hurdle ($p<0.031$). The trends in the third movement in the sequence, crouching down to crawl under the obstacle, are reversed, with a greater maximal knee flexion and lower minimal knee flexion, thus greater ROM. For the hip data the minimal angles achieved were higher for all movements in the clothing, for the last movement, stepping over the hurdle at the end the difference was significant ($p<0.015$). For the maximal hip flexion and hip ROM results, there was a split between the movements, for the hurdle obstacle which had to be stepped over at the beginning and end of each repeat, the maximal hip angle reached was lower and the ROM was lower. For the middle two obstacles, bending under a hurdle and crouching down to come back under it, the maximal angle recorded in the hip was increased (significantly so in the crouching, $p<0.029$), increasing the overall ROM.

These patterns of change are illustrated graphically in Figure 3.11. The reductions in knee angles in the clothing compared to the control, maximally reduced by 7.6 degrees stepping over the first hurdle and the increase, 2.6 degrees in the third movement are evident. The two different trends seen in the hip angles when clothing is worn are also made clearer, reduced flexion when stepping over the hurdle (greater at the end of the sequence) and increased flexion when bending down.

3.4 Subjective results

The participants' comments on the clothing are summarised in Table 3.5. The comments are predominantly about the trousers, and how the participants felt they restricted their movement in the legs, by making it harder to lift and spread the legs and creating resistance in the thighs. A low crotch was also cited as a problem in many of the garments, although this can be linked to fit. The impact of the jackets were felt when having to crouch and crawl under the hurdle due to the bulk of the material around the torso and loss of flexibility in the trunk region.

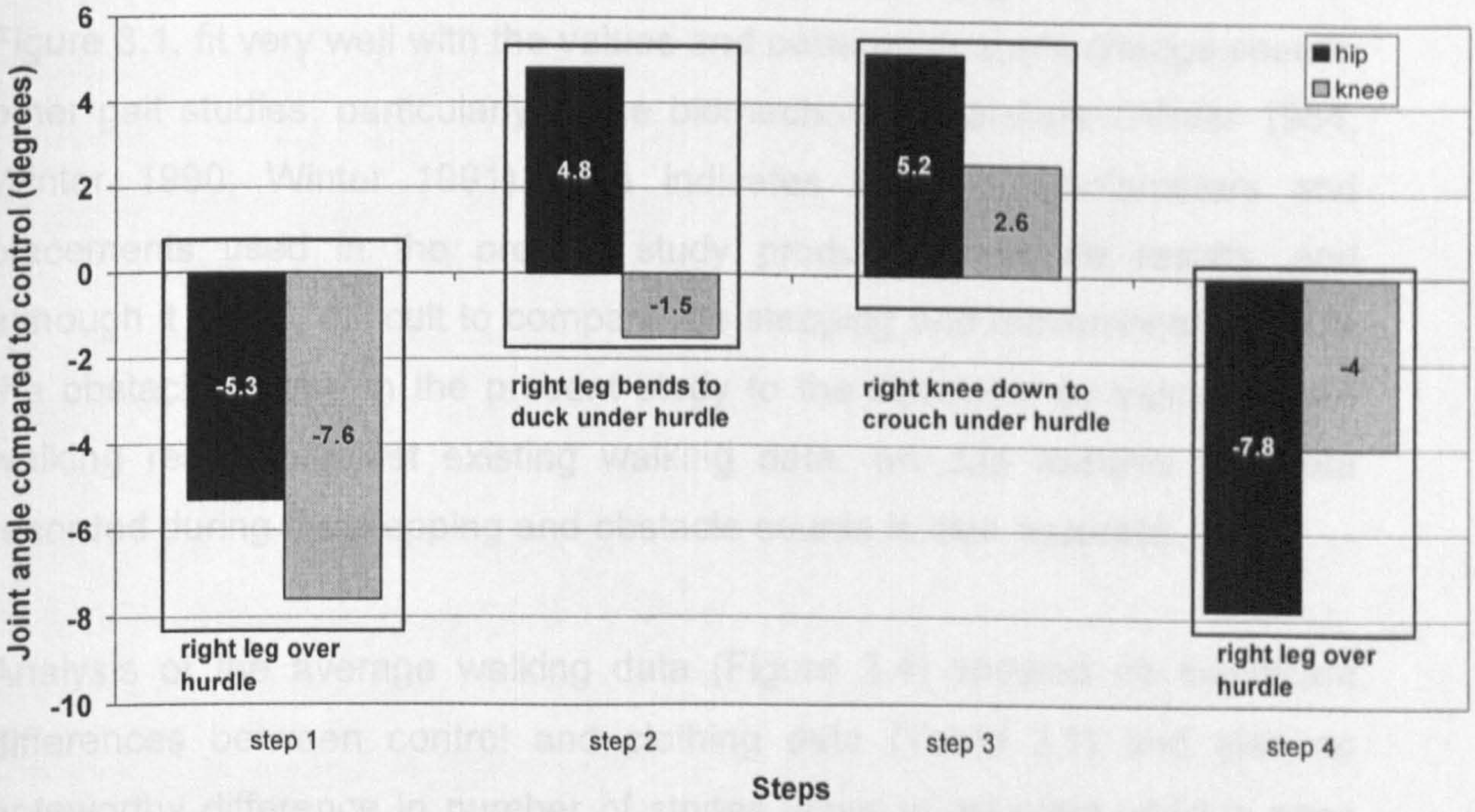


Figure 3.11. Difference in maximum joint angles compared to control for the hip and knee angles during all phases of the crawling sequence.

Table 3.5. Summary of comments from participants on clothing worn.

Clothing	Summary of comments
Grey fire (B)	low crotch lifting leg up at hip very hard, stepping hardest tight fit inside leg, resistance on inner thigh harder to crouch under hurdle due to bulky torso
Grey fire (B) trousers	low crotch tight fit inside leg most restrictive during stepping
Gold fire (D)	restricted at hip during hurdles lose flexibility around trunk, bulky torso jacket covers buttocks restricting movement at waist, hips tighter when crouching hot
Gold fire (D) trousers	easier hip movement than with jacket easier to crouch without jacket cooler felt much lighter
Coldsuit black (H)	low crotch harder to lift legs high pulls on knee, thigh, bum
Coldsuit green (I)	tight fit in the legs
Chainsaw (J)	low crotch restricted in the legs, hard to spread and lift legs heavy trousers

4. Discussion

Analysis of the hip and knee angles during walking gait as illustrated in Figure 3.1, fit very well with the values and patterns of angle change seen in other gait studies, particularly in the biomechanics literature (Winter 1984; Winter 1990; Winter 1991). This indicates that the goniometers and placements used in the present study produced accurate results, and although it is very difficult to compare the stepping and movements made in the obstacle course in the present study to the literature, by validating the walking results against existing walking data, we can assume the data recorded during the stepping and obstacle course is also accurate.

Analysis of the average walking data (Figure 3.4) showed no significant differences between control and clothing data (Table 3.1) and also no noteworthy difference in number of strides taken to maintain walking pace (Table 3.2). The lack of significance during walking is not surprising because of the limited leg swing required as 5km/hr is a comfortable walking pace for most. At a higher walking speed, the differences may have been greater for the clothing compared to the control. When compared to the stepping and crawling movements, walking required the least amount of knee and hip movement as can be seen in Table 4.1. The max knee angle, knee ROM, max hip angle and hip ROM are all considerably lower for walking compared to the other work modes.

Table 4.1. Summary of the maximum angles and ROM in the knee and hip during walking, stepping and crawling.

	walking	stepping	crawling
max knee angle	58.6	88.1	104.1
knee ROM	64.5	85.6	94.5
max hip angle	17.5	56.4	72
hip ROM	25.7	56.3	68

The effects on soldiers movements and walking gait of adding layers of clothing to the body was studied extensively by O'Hearn *et al.* (2005) with

US Army cold weather clothing. Using a video based motion analysis system to capture gait kinematics and kinetics they compared performance in temperate duty uniform with cold weather clothing layers. Previous studies of the mobility effects of army 'extended cold weather clothing systems' (ECWCS) had been largely based on subjective ratings. The work of O'Hearn *et al.* (2005) showed that the effects of the increased clothing layer conditions appeared to be a constrained gait manifesting in a forward lean position of the trunk and reduced arm swing. Increasing the number of layers from 2 to 3 or 4 when walking resulted in a significant increase in hip abduction, which the authors suggest is due to the thickness of the layers at the crotch and thighs. An increase in hip abduction was also evident in some of the data in the present study as a greater max hip angle. The gait patterns are described by O'Hearn *et al.* (2005) as more laboured and the movement, a "somewhat waddling gait". O'Hearn *et al.* (2005) also present evidence that this is a less efficient gait (decreased propelling force and sharper initial vertical amplitude spike) and so is likely to increase the energy cost of working in these garments as shown in the studies of this thesis. The most extreme clothing conditions contrasted in their study were the regular army uniform and 4 layers of cold weather clothing. In the later clothing, participants were reported to have walked and moved differently, leaning forwards, holding the arms forward and down, with less movement at the shoulder. However this forward lean posture with restrained arm movement may have been an adjustment that allowed the gait to remain similar to when the body was unencumbered by clothing as there were no significant differences in temporal and kinetic gait variables (O'Hearn *et al.* 2005) this may also have been the case for some participants in the present study.

In conclusion, O'Hearn *et al.* (2005) note that bulky clothing can induce altered gait patterns, which are adaptive and not necessarily inefficient. But similar levels of clothing protection may differ in mobility restrictions, resulting in a trade-off between protection and mobility.

A substantial amount of the work looking at gait and posture changes has been undertaken in relation to carrying load. A number of papers have looked at the energy cost of load carriage (Goldman and Iampietro 1962, Soule and Goldman 1969, Hughes and Goldman 1970) and equations have been designed to predict energy cost based on walking grades, terrains and loads carried (Givoni and Goldman 1971, Pandolf *et al.* 1977). Others have looked at the most efficient mode of carrying the load, including weight, dimensions and placement of load (Datta and Ramanathan 1971, Legg and Mahanty 1986, Haisman 1988). As has been described in previous chapters the weights of the PPC garments do add extra load to the participant, with the extra load, particularly of the heavier garments such as the firefighter ensembles likely to have an impact on posture and gait. However there is scant consideration of the effects of clothing weight as load in the literature, with many papers comparing load carriage systems and much greater weights.

Using 5 loads of 9-36 kg and high speed cinematography Martin and Nelson (1986) report significantly different gait patterns under all load conditions. Increasing the load, decreased the stride length and increased the stride rate as well as causing an increased forward lean of the trunk for the 2 heaviest loads, stressing the importance of the magnitude and positioning of the load. More detail can be found on postural adjustments in the studies of Bloom and Woodhull-McNeal (1987), Fiolkowski *et al.* (2006) and Kinoshita (1985).

Fiolkowski *et al.* (2006) and Kinoshita (1985) compared a backpack and a front pack or double pack (weight spread over front and back packs). Fiolkowski *et al.* (2006) concluded that use of a front pack results in a more upright posture in gait compared to a backpack carrying the same load. Wearing a backpack, participants walked with a greater forward lean and greater forward flexion at the hip compared to the front pack and control. Kinoshita's (1985) results also conclude that the body posture and gait pattern for a double pack are much nearer to those for normal walking, revealing that loads substantially modified a normal walking gait pattern, but a double pack system was biomechanically more effective than the backpack (which increased the thigh orientation and knee angle in addition to the increased trunk inclination and leg orientation seen with the double pack) (Kinoshita 1985).

In the current study, the total weight of the protective clothing ensembles is much lower (maximum 7 kg) than many of the loads carried (up to 40-50 kg) in the military studies. However a recent study by Attwells *et al.* (2006) has shown that adding loads of 8kg in the form of webbing, increased the ROM at the knee, and the increases in the femur angle (same as hip angle measured in the present study) they observed were significantly ($p<0.001$) higher than the control.

The lower weights of the clothing and the distribution of the clothing weight across the body is also much more uniform than when carrying load, for example, in a rucksack. Therefore it is understandable that the changes in posture described in this study are not as great as reported in other studies.

When wearing the clothing in the present study participants were not given any additional instructions. The individual plots for the stepping, examples of which can be seen in Figure 3.5 and 3.6, seem to show two different behavioural responses. The joint angles and range of movements (ROM) of some participants were reduced in the clothing (compared to the control) as hypothesised. However in others the joint angles and ROM were increased, it seems that some participants exaggerated the movements required, most notably lifting the thigh higher (producing a greater hip angle) when stepping up onto the highest step (height 40 cm). Although this goes against the hypothesis of reduced movement, increasing the ROM to overcome the restriction of the clothing would also be expected to raise the energy cost of the activity.

In summary, for stepping, the maximum knee angle was reduced (the knee was not bending as far due to the clothing) and the minimum knee angle was increased (the knee was not straightening out at the end of the movements) which resulted in a significantly reduced range of movement in 4 of the 6 stepping stages. In the hip, the maximum angle was increased (thigh raised higher) and the minimum angle increased (not straightening out at the hip/waist), on average this meant the hip angle was shifted slightly rather than the ROM being significantly increased or reduced.

When the two joints are considered together, a reduced ability to bend the knee due to the bulk around the knee can seem to be compensated for by exaggerating lifting of the thigh especially when stepping up onto the steps. The clothing also seems to affect the standing posture, with a slight bend in the knee and slight inclination in the thigh, possibly caused by the size and weight of the jackets. O'Hearn *et al.* (2005) also observed that bulky clothing not only constrained movement but also affected the resting posture.

The highest maximum knee and hip angles and greatest knee and hip ROMs across the work modes were recorded during the crawling (Table 4.1). Stepping over a 55 cm high hurdle, required lifting the leg (hip flexion of 37.6 to 49.8°) and bending the knee (knee flexion of 92.6 to 100.2°). Both hip flexion and knee flexion were reduced when clothing was worn compared to the control, as hypothesised. The range of movement in the knee joint was significantly lower ($p<0.031$) in the clothing for the first step over the hurdle at the beginning of the crawling sequence.

The first of the two middle movements of the crawling sequence (bending to duck under a hurdle) prompted a maximum knee flexion of 77.4° in the control and 75.9° in the clothing and hip flexion of 64.5° in the control and 68.2° in the clothing. Having to put the right knee down to crouch when coming back under the hurdle (participants were instructed to do so and a mat was placed on the floor for cushioning), saw similar hip flexion values 66.8 – 72° (although the clothing value was significantly higher than the control ($p<0.029$)), but much higher knee flexion values, 101.5 to 104.1° due to the fact that participants were actually putting a fully bent knee down on the floor.

In Figure 3.11, the plot of hip and knee joint angles compared to the control for the four main movements, the middle two boxes show that when the right leg bends to duck under the hurdle there is an increase of 4.8° in hip flexion and a reduction in knee flexion of 1.5° when the clothing is worn compared to the control, indicating a change in posture. Participants may have felt a degree of restriction at the knee and to compensate leant further forward with the upper thigh. However when crouching they were forced to put the knee down so there was an increase of 2.6° in knee flexion but also still an increase in hip flexion of 5.2° in the clothing. Differences can also be seen in the approach to the hurdles, for the first hurdle, hip and knee angles were reduced compared to the control but the greatest reduction was in the knee (-7.6° flexion than control) compared to the hip (-5.3° flexion than control). However when approaching the hurdle at the end, the greater reduction in flexion is seen in the hip (-7.8°) than in the knee (-4°). So the greatest constraint to movement is in the knee at the beginning and the hip by the end of the sequence.

The comments about the clothing recorded during the study are mainly concerned with the trousers and restrictions to movement in the legs through for example, a low crotch or tight fit on the inside leg pulling on the thigh. These comments suggest there was a subjective awareness of the restrictions imposed by the clothing which was measured as altered joint angles. In the study by Bensel *et al.* (1987) questionnaire responses reflected subjects awareness of the restriction of the full protection MOPP IV suit compared to the battledress uniform (BDU). Subjects also generally rated the BDU positively and the MOPP IV negatively on a number of bipolar dimensions that were selected to describe characteristics of clothing (Bensel *et al.* 1987).

A low crotch may also have been a fit issue and it is likely that this reduced the hip flexion because it would have been much harder to raise the thigh because of the extra material. This was backed up by specific comments about the difficulty of lifting the legs and suggestion that the stepping was the hardest activity particularly in the Grey fire (B) garment. Other comments hinting at the restriction in the legs were; pulls on knee, thigh and bum, tight fit inside leg and resistance on inner thigh.

Although the goniometers focused on the lower limbs, the bulky torso of some garments, particularly the firefighters clothing impeded movements. Specific comments included; harder to crouch under hurdle due to bulky torso, loss of flexibility around trunk, easier to crouch without jacket, these issues were also observed by O'Hearn *et al.* (2005) who attributed a decrease in the extent of standing trunk flexion to the additional bulk of garments as the number of layers increased. When bending at the waist, the garments were compressed but occupied space that could not be displaced, so the ability to bend was therefore impeded because the compressed garments got in the way.

5. Chapter summary

A review of the literature included at the beginning of this chapter showed a widespread awareness of clothing affecting performance, for example, interfering with joint movements (Teitlebaum and Goldman 1972, Patton *et al.* 1995). Some authors reported clothing requiring added movement by the wearer (Nunneley 1989), others a decreased ROM in the clothing (Adams *et al.* 1994, Rintamaki 2005). Whether the required movement is increased or decreased the constraint is clearly due to the external agent, in this situation the clothing (Adams and Keyserling 1995). A number of constraint mechanisms are discussed by Adams and Keyserling (1995) and were described earlier. The literature also seemed to suggest a greater impact on tasks requiring whole body mobility (Murphy *et al.* 2001) although much of the data on range of movement has been collected on static gross body movements and the maximum range of motion with and without the clothing (Huck 1988, Adams and Keyserling 1995).

When the data for all participants was averaged there was no significant difference when walking in clothing compared to a control condition. For the stepping work mode there were statistically significant reductions in the knee ROM in five of the six stages in the clothing compared to the control. The crawling work mode produced fewer significant results, the knee ROM was significantly reduced for the first movement, stepping over a hurdle. The maximum hip angle in the third (crouching under a hurdle) movement and minimum hip angle in the fourth (stepping over a hurdle) movement were significantly higher in the clothing. Comments recorded from the participants also suggest they were aware of the restrictions imposed by the clothing with the area around the crotch the most problematic due to its influence on movements of the thigh and hip.

The present study has investigated the effect of protective clothing on range of movement during walking, stepping and crawling activities, including measuring hip and knee angles. The hypothesis that the protective clothing

(PPC) garments would restrict movement and therefore range of motion was not proven conclusively as although some participants showed a reduced ROM in the clothing, others demonstrated an increased ROM. The increased ROM can be best explained by the somewhat exaggerated movements of some participants to overcome the constraint of the PPC, for example, lifting the upper leg (increasing the ROM in the hip) higher when stepping up to accommodate the bulk and restriction to movement around the crotch.

CHAPTER 8

MODELLING THE EFFECTS OF PPC PROPERTIES ON THE INCREASED METABOLIC RATE

1. Introduction

Many of the PPC garments studied in this thesis are heavy, bulky and made up of multiple layers and stiff fabric as evident from the previous chapters. However it has proved hard to isolate completely the effect of a single garment property on the overall increased energy cost when wearing the actual PPC. An alternative approach to studying the individual contributors to metabolic effects of PPC is by studying them combined.

In this chapter, data on a number of PPC properties will be collected and analysed using Pearson's r and multiple regression, to determine the relative importance of these properties on recorded metabolic rate increases. This technique has been used to study other complex interactions before (Havenith *et al.* 1995). For this purpose, relevant predictive parameters of the clothing tested in Chapter 3 will be determined (weight distribution, insulation, bulk, stiffness) and the previously observed increases in metabolic rate analysed in relation to these predictors.

Attempts will be made to use simple and non-destructive methods to determine the parameters, in order that tests could be repeated by others and would be usable in the workplace.

2. Parameters

2.1 Clothing weight

2.1.1 Introduction

The issue of energy expenditure in relation to weight carried has been reviewed and studied in Chapter 4. The weights of the protective garments and other clothing worn have also been documented in Chapter 3. However a more detailed analysis was completed including a comprehensive breakdown of how the clothing weight is distributed across the garment, given the relevance of weight distribution described in Chapter 4, and this is now presented. The details of the methodology used can be found in Appendix 4.

2.1.2 Results

The total garment weight is plotted in Figure 2.1 and garment section weights given in Table 2.1. There is a range in total garment weight from the heaviest, the Grey fire (B) ensemble at 4.65 kg to the ArmyH2O (L) ensemble at 1.14 kg, the lightest. The breakdown of the weights across the sections of the garments as described in Table 2.1 is shown graphically in Figure 2.2.

2.1.3 Discussion

There is a degree of variance in the proportions of weight seen in the different sections of the garments, as shown in Figure 2.2. Much of this variance can be explained by the design and / or function of the garment. The ArmyVEST (L) comprises of a heavy protective body armour (accounting for 88.3 % of the total clothing weight), which covers the torso only, not the arms. The Welding (G) ensemble is made up of an apron which fastens around the waist with velcro straps around the legs, and gaiters worn over the shoes and ankles, up to the knee, hence the greater percentage of weight supported around the crotch. The Chainsaw (J) garment is designed to prevent injuries to the limbs from the chainsaw blade, so the arms and legs of the garment contain an inner protective material. Figure 2.2 shows that almost 60 % of the total clothing weight is in the legs, this is higher than in any other garment. However the main body of the jacket (torso), does not contain any of the protective fibres and is therefore very light, at just 24 % of the total clothing weight, much lower than all of the other garments.

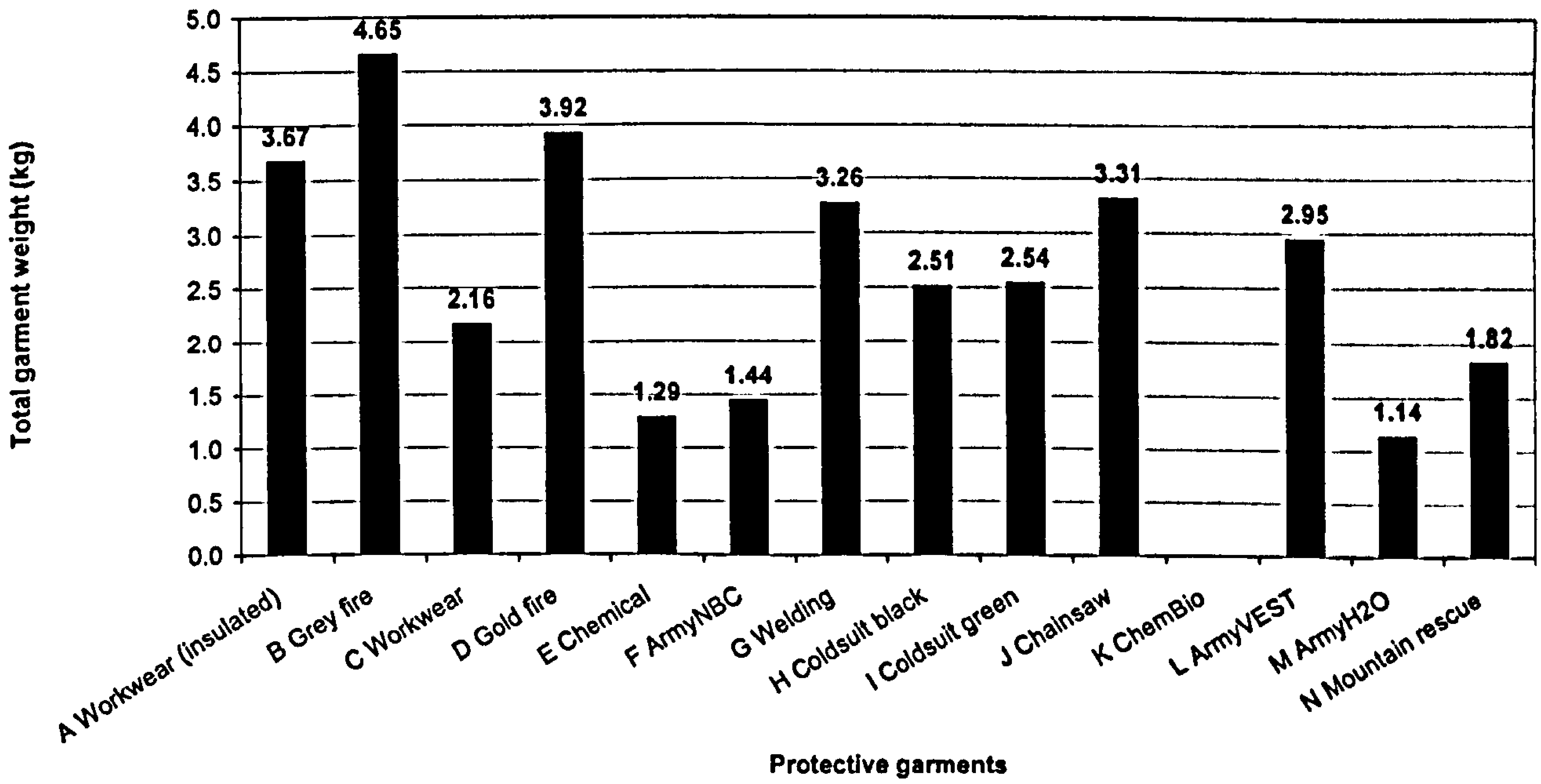


Figure 2.1. Protective garments and their total weight (ChemBio not available).

The 2 firefighter ensembles, Grey fire (B) and Gold fire (D), had the highest total clothing weight. The percentage of this weight in the lower arms was also high compared to the other garments, being 10.5 and 9.2 % respectively. This has important implications for the energy cost of working in these garments as Study 2 (Chapter 4) showed that weight carried at the wrists can be up to 2.7 times more expensive than when it is positionned around the body core (torso). The Workwear (insulated) (A) garment had the highest percentage of total clothing weight in the lower arms at 14 %. For this garment, the total percentage of the clothing weight in the upper body was also the highest of all the garments, over 60 %. This finding can be explained by the fact that the insulation in this garment is provided by a fleece layer that is zipped into the outer jacket.

Table 2.1. Total and garment section weights excluding any footwear (ChemBio not available).

weight in kg	total weight	legs 1	legs 2	legs 3	total legs	arms 1	arms 2	arms 3	total arms
CLOTHING		crotch	upper legs	lower legs		torso	upper arms	lower arms	
A Workwear (insulated)	3.671	0.714	0.200	0.420	1.334	1.595	0.228	0.514	2.337
B Grey fire	4.652	1.014	0.460	0.632	2.106	1.706	0.410	0.430	2.546
C Workwear	2.162	0.513	0.242	0.244	0.999	0.919	0.100	0.144	1.163
D Gold fire	3.920	0.706	0.398	0.546	1.650	1.632	0.228	0.410	2.270
E Chemical	1.287	0.249	0.146	0.200	0.595	0.506	0.110	0.076	0.692
F ArmyNBC	1.443	0.255	0.150	0.212	0.617	0.622	0.116	0.088	0.826
G Welding	3.264	0.238	0.360	0.848	1.446	1.422	0.180	0.216	1.818
H Coldsuit black	2.510	0.248	0.290	0.476	1.014	1.136	0.124	0.236	1.496
I Coldsuit green	2.540	0.532	0.364	0.328	1.224	0.848	0.320	0.148	1.316
J Chainsaw	3.310	0.584	0.626	0.740	1.950	0.796	0.260	0.304	1.360
K ChemBio	---	---	---	---	---	---	---	---	---
L ArmyVEST	2.946	0.261	0.100	0.130	0.491	2.455	---	---	2.455
M ArmyH2O	1.138	0.261	0.100	0.130	0.491	0.487	0.080	0.080	0.647
N Mountain rescue	1.820	0.258	0.134	0.344	0.736	0.852	0.120	0.112	1.084

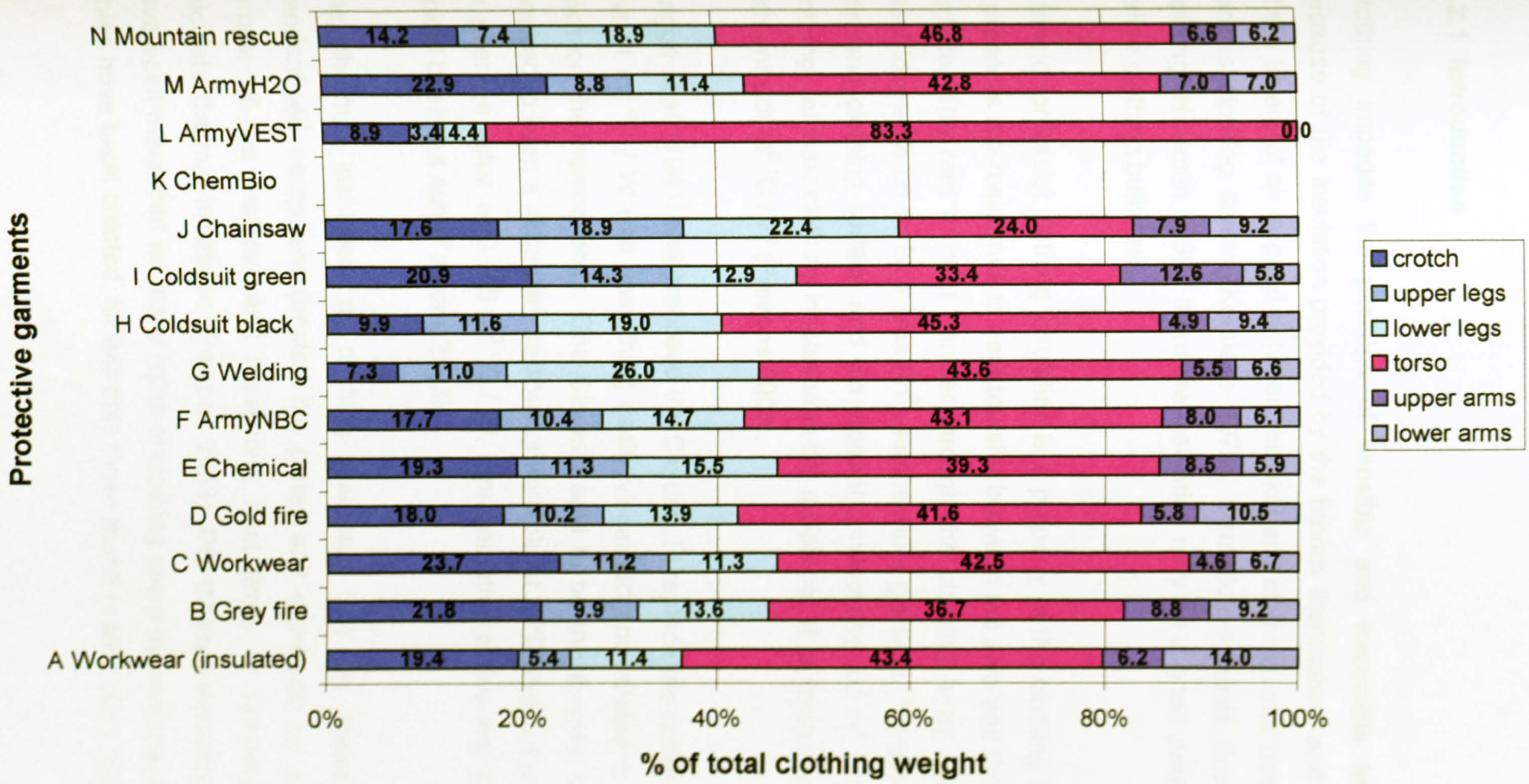


Figure 2.2. Garment section weights as a % of total clothing weight for all protective garments (ChemBio not available).

PAGE NUMBERING AS ORIGINAL

2.2 Clothing insulation

2.2.1 Introduction

Clothing impedes the passage of sensible and insensible heat, both because of the insulation provided by the fabrics themselves and because of the layers of air trapped between the skin and clothing, and between the various clothing layers (Kerslake 1972). Insulation requires thickness of clothing (Havenith 1999), therefore insulation may be a good parameter to define clothing bulkiness.

Intrinsic (or basic) clothing insulation is a property of the clothing itself and represents the resistance to heat transfer between the skin and the clothing surface. The rate of heat transfer through the clothing is by conduction, which depends on surface area (m^2), temperature gradient (°C) between the skin and clothing surface and the thermal conductivity (W m^2 / °C) of the clothing. Intrinsic clothing insulation is the reciprocal of clothing conductivity with units of m^2 °C / W (Parsons 2003).

Gagge *el al.* (1941) first proposed the Clo unit, to replace the rather physical unit of m^2 °C / W with something easily visualised and related to clothing worn on the human body. One Clo was said to be the thermal insulation required to keep a sedentary person comfortable at 21°C and is said to have an average value of 0.155 m^2 °C / W, representative of the insulation of a typical business suit (Parsons 2003).

The thermal insulation of clothing materials can be measured on standardised equipment (heated flat plates and cylinders) by placing a sample of the material and measuring heat flows or temperature, to calculate thermal insulation (Parsons 2003). Dry thermal insulation values have been measured for many types of clothing using thermal manikins and tables have been created, for example those found in ISO 9920 (ISO 2003).

However these tables are not exhaustive, especially in regard of specialist garments, such as PPC.

The insulation of a specific clothing ensemble can be determined in several ways with a varying degree of accuracy and effort (Lotens and Havenith 1991).

a) Measurement while the clothing is worn by subjects.
   This method is laborious and requires sophisticated equipment but gives realistic data.
b) Measurement on a thermal manikin.
   This method has better reproducibility, but requires an expensive manikin.
c) Regression by means of tables of previously determined insulation values.
   The tables are based on manikin measurements.
d) Regression on the physical characteristics of the clothing.
   Best results are obtained with regression on a covered skin area and thickness of the items of clothing.
e) Calculation of heat and mass transfer when the geometry of the clothing is known

The continuing and growing interest in manikins is based on the fact that they:

- represent a realistic and objective method for assessment of clothing thermal functions,
- comprise a quick, accurate and reproducible method for measurement of thermal insulation,
- are cost effective instruments for comparative measurements and for product development;
- provide input values for thermal modelling and prediction of safe and comfortable working conditions (Holmer and Nilsson 1995).

The most common tool used to measure the thermal insulation of a garment or an ensemble, and the method employed here, is the thermal manikin. Thermal manikins are heated to represent the human body and the power required to maintain that temperature is used to estimate the heat transfer between a person and the environment.

2.2.2 Results

The results of the measurements are given in Table 2.2, the ChemBio suit was not available. See Appendix 5 for details of the methodology employed.

Table 2.2. Insulation values for all garments based on 2 separate measurements (1,2). In the calculations for the selected zones values, the data from the head, hands and feet zones were excluded.

Units $m^2 °C / W$	All zones			Selected zones		
	1	2	ave	1	2	ave
A Workwear (insulated)	0.287	0.305	0.296	0.424	0.432	0.428
B Grey fire	0.336	0.331	0.334	0.516	0.493	0.505
C Workwear	0.265	0.278	0.272	0.364	0.383	0.374
D Gold fire	0.337	0.350	0.344	0.528	0.542	0.535
E Chemical	0.215	0.210	0.213	0.264	0.262	0.263
F ArmyNBC	0.244	0.252	0.248	0.327	0.331	0.329
G Welding	0.210	0.202	0.206	0.252	0.240	0.246
H Coldsuit black	0.314	0.313	0.314	0.472	0.470	0.471
I Coldsuit green	0.369	0.358	0.364	0.658	0.650	0.654
J Chainsaw	0.276	0.274	0.275	0.389	0.393	0.391
M Army H20	0.229	0.233	0.231	0.283	0.286	0.285
N Mountain rescue	0.257	0.253	0.255	0.339	0.336	0.338
Control tracksuit	0.200	0.198	0.199	0.244	0.241	0.243

2.2.3 Discussion

The garments with the highest insulation values were the two coldstore garments (Coldsuit black H and Coldsuit green I) and the two firefighter garments (Grey fire B and Gold fire D). These results fit with the nature of the working environment in which these garments would be worn and their main function to insulate the wearer from extreme cold and heat respectively.

2.3 Clothing bulk

2.3.1 Introduction

As has already been illustrated and discussed in earlier chapters, PPC can increase measurably the metabolic (energy) cost of work, with the added weight and restriction of movement caused by the PPC suggested to contribute to the increases recorded. The resultant energy cost of wearing the PPC is therefore dependent on various aspects of the clothing, such as its weight, number of layers and bulk. Some PPC garments, particularly those worn in cold environments can be very bulky, which can restrict movement especially at the joints. As with the issues of clothing weight and friction between layers, clothing bulk has been hypothesised by many authors to be a contributor to the increased metabolic cost of protective garments but has not been fully studied. The literature on this area has been discussed in detail in Chapter 7.

In summary, the bulkiness of clothing, often expressed as the number of clothing layers, has been shown to influence energy expenditure. Lotens (1982) summarized this into a 'Rule of thumb' of a 4 % increase in energy cost for each clothing layer, at a marching speed and a 3 % increase per layer at a slower pace. But he points out that the actual source of this effect is not well understood, with friction between layers and hobbling gait both possible explanations. He concludes, "it seems a logical, although yet unproven hypothesis that motion restriction does raise energy cost considerably" (Lotens 1982). Bulk is a difficult issue to quantify. Lotens (1982) also described military tests looking at performance decrement wearing different types of clothing but concluded that the bulkiness of the clothing could not be analysed separately as it was confounded with motion restriction and other impeding effects.

As mentioned in Section 2.2, insulation may be a representative parameter of bulkiness (Havenith 1999), but often PPC is made of special materials incorporated for durability and protection. These may be relatively heavy for the insulation they provide, therefore it is considered relevant to add other parameters to try and define bulkiness, as well as the insulation method and results already described.

Clothing bulk was measured using 3 different methods, details of methodology are included in Appendix 6. In summary;

- The fit method considered the bulk by measuring the extra material at the three sites by pinching the fabric tight and measuring the excess.
- The circumference method measured the extra thickness of the garment by measuring the circumference of the arm, torso and leg with and without clothing.
- The thickness method measured the depth of the clothing material whilst the garment was laid on the floor.

2.3.2 Fit bulk results

The results of the fit bulk measurements for the three sites measured, arm, torso, leg and overall are shown in Table 2.3 and Figure 2.3.

Table 2.3. Average values for clothing FIT BULK measured on 12 garments at 3 sites (the coverage on the legs for the welding garment was a split apron that was fastened around the legs with velcro, therefore as it did not reach around the back of the leg it was not possible to estimate the bulk).

protective garments	arm bulk (cm)		torso bulk (cm)		leg bulk (cm)		overall bulk (cm)
	ave	SD	ave	SD	ave	SD	
A Workwear (insulated)	8.0	2.1	10.1	1.7	10.5	3.5	28.6
B Grey fire	9.3	1.4	10.4	1.8	9.6	2.6	29.3
C Workwear	9.8	1.8	8.8	1.5	6.7	2.3	25.2
D Gold fire	8.5	1.4	13.8	1.9	10.3	2.3	32.6
E Chemical	8.4	1.6	8.7	2.6	8.1	1.6	25.1
F ArmyNBC	8.4	2.0	7.4	1.2	7.6	2.7	23.4
G Welding	6.4	1.6	7.7	1.2	---	---	14.1
H Coldsuit black	9.8	2.3	12.1	2.5	9.8	2.6	31.6
I Coldsuit green	8.8	1.7	9.5	1.7	5.5	3.2	23.8
J Chainsaw	8.8	1.7	12.3	2.5	6.6	1.4	27.6
M ArmyH2O	10.2	1.6	10.7	1.6	8.1	1.2	28.9
N Mountain rescue	9.4	1.3	11.8	1.6	5.4	4.0	26.5

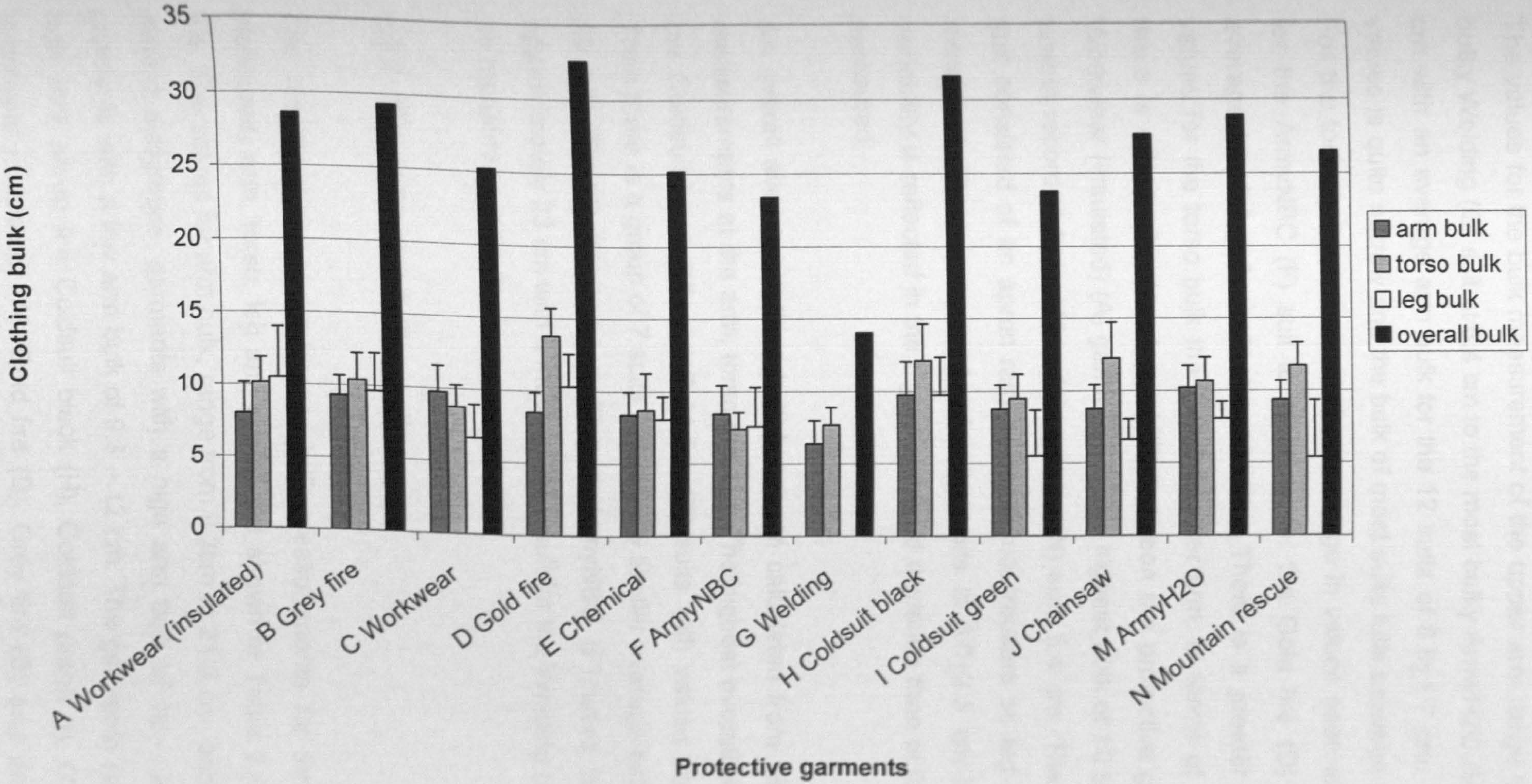


Figure 2.3 Bar chart showing values for arm, torso, leg and overall clothing FIT BULK (measured in cms) for 12 protective garments (the coverage on the legs for the welding garment was made up a split apron that was fastened around the legs with velcro therefore as it did not reach around the back of the leg it was not possible to estimate the bulk).

The values for the bulk measurement of the upper arm range from the least bulky Welding (G) suit at 6.4 cm to the most bulky ArmyH2O (M) suit at 10.2 cm with an average arm bulk for the 12 suits of 8.8±1.7 cm. The range of values is quite narrow and the bulk of most suits falls between 8 and 10 cm. For the torso bulk measurements, the range in values seen is from 7.4 cm for the ArmyNBC (F) suit to 13.8 cm for the Gold fire (D) suit with an average of 10.3±1.8 cm for the 12 suits. There is a greater range in the values for the torso bulk than for the upper arm. In terms of the leg bulk, there is a large degree of variability between the protective garments, the Workwear (insulated) (A) garment had the highest bulk of 10.5 cm, with the lowest recorded in the Mountain rescue (N) suit, 5.4 cm. The Welding (G) suit consisted of an apron rather than actual trousers so leg bulk was not measured. The average value for the suits is 8.0±2.5 cm but the large variability is reflected in the higher standard deviation than at the other sites measured.

An overall average clothing bulk has been calculated from the sum of the measurements at the arm, torso and leg. The highest overall bulk is seen in the Coldsuit black (H) and Gold fire (D) suits with values above 30 cms. Then there is a group of 7 suits with a fairly similar average between 25 and 29 cm. The Coldsuit green (I) and ArmyNBC (F) were both lower at approximately 23 cm with a much lower result for the Welding (G) suit due to no measurement for the legs.

2.3.3 Circumference bulk results

The results of the circumference bulk measurements for the three sites measured, arm, torso, leg and overall are shown in Table 2.4 and Figure 2.4. The values for arm bulk, range from 9.3cm to 21.5 cm. and fall into two distinct subgroups, garments with a high arm bulk of 18 – 21.5 cm and garments with a low arm bulk of 9.3 – 12 cm. The garments falling into the high bulk group are Coldsuit black (H), Coldsuit green (I), Chainsaw (J), Workwear (insulated) (A), Gold fire (D), Grey fire (B) and Workwear (C).

With the Mountain rescue (N), Chemical (E), Welding (G), ArmyH2O (M) and ArmyNBC (F) garments comprising the low bulk group.

The range in values recorded for the torso bulk is greater than for the arm bulk, with the highest values in the Grey fire (B), Gold fire (D) and Workwear (C) garments of 27.1, 26.9 and 26.9 cm respectively. The lowest values are again seen in the Mountain rescue (N) and ArmyH2O (M) garments, at 8.4 and 8.8 cm respectively.

The bulk measurements in the leg, range from 1.4 to 16.8 cm. With a leg bulk of 1.4 cm, the Welding (G) garment, and at 1.9 cm the Mountain rescue (N) garment had the lowest values. The highest values were seen in the two coldstore garments, Coldsuit green (I) (14.4 cm) and Coldsuit black (H) (16.8 cm) with the Chainsaw (J) and Grey fire (B) garments also in this range. The results are lower than those recorded for the arm and torso regions of the protective garments.

Table 2.4. Average values for clothing CIRCUMFERENCE BULK measured on 12 garments at 3 sites.

protective garments	arm bulk (cm)		torso bulk (cm)		leg bulk (cm)		overall bulk (cm)
	ave	SD	ave	SD	ave	SD	
A Workwear (insulated)	18	4.0	24.3	7.2	8.9	4.1	51.2
B Grey fire	21.4	4.4	27.1	7	15.3	4	63.8
C Workwear	18.5	4.0	26.9	2.4	7.1	1.9	52.5
D Gold fire	19.5	3.2	26.9	7	11.9	2.5	58.3
E Chemical	10.5	3.4	14.8	7.6	5.9	4.7	31.2
F ArmyNBC	12	12.0	16	7	7.3	3.6	35.3
G Welding	10.3	4.0	22.2	10.5	1.4	1.1	33.9
H Coldsuit black	21.5	3.5	23.9	4.8	16.8	3.6	62.2
I Coldsuit green	20	3.7	23.3	5.7	14.4	3.4	57.7
J Chainsaw	18.1	4.3	13.3	3.7	15.4	3.7	46.8
M ArmyH2O	9.6	4.0	8.8	6.8	3.5	2.4	21.9
N Mountain rescue	9.3	3.6	8.4	3	1.9	1.9	19.6

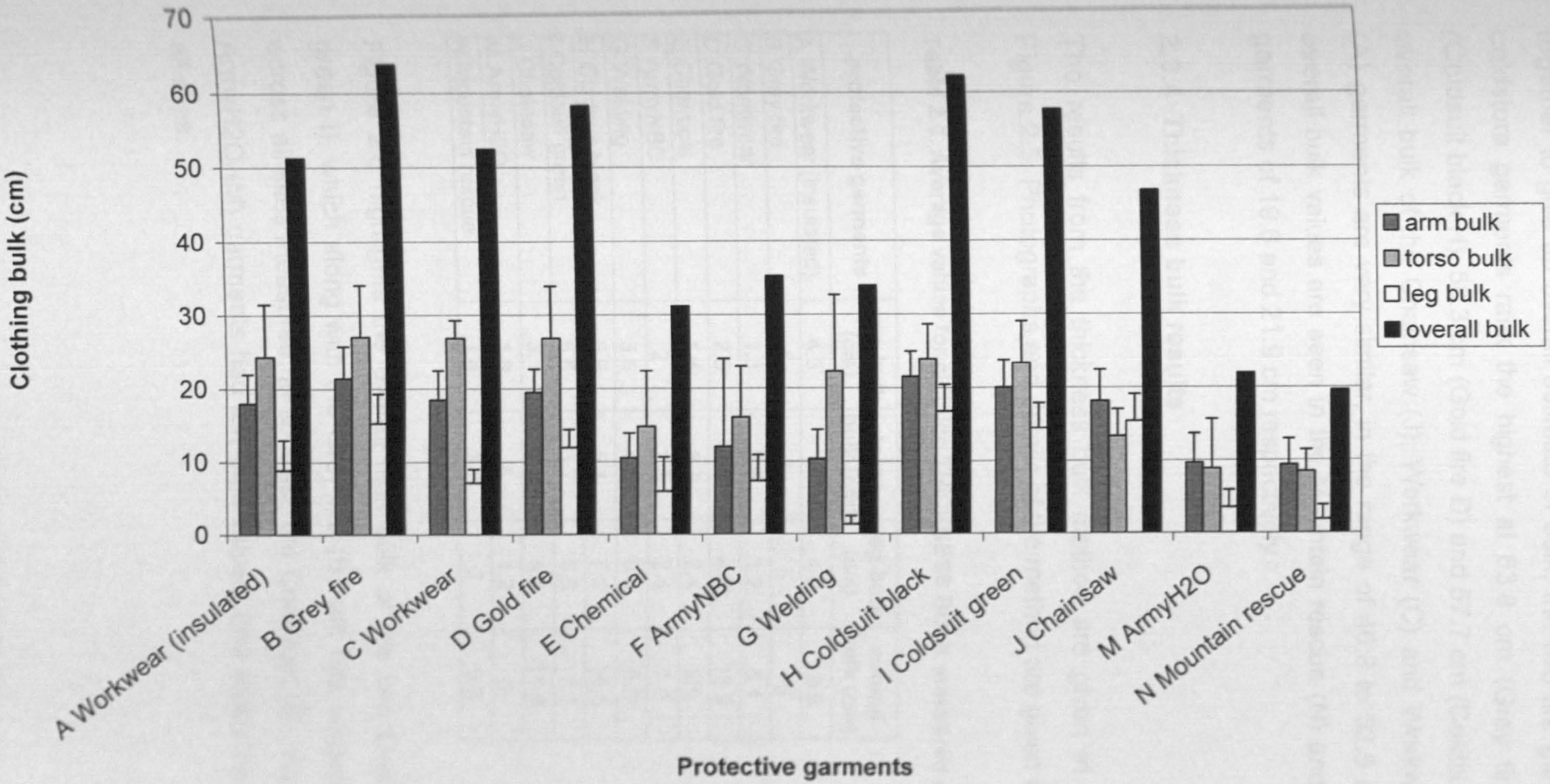


Figure 2.4. Bar chart showing values for arm, torso, leg and overall clothing CIRCUMFERENCE BULK (measured in cms) for 12 protective garments.

When the results of the arm, torso and leg bulk measurements are summed together to give an overall estimate of bulk, the two fire garments and two coldstore garments rank the highest at 63.8 cm (Grey fire B), 62.2 cm (Coldsuit black H), 58.3 cm (Gold fire D) and 57.7 cm (Coldsuit green I). The overall bulk of the Chainsaw (J), Workwear (C) and Workwear (insulated) (A) garments are very similar, in the range of 46.8 to 52.5 cm. The lowest overall bulk values are seen in the Mountain rescue (N) and ArmyH2O (M) garments of 19.6 and 21.9 cm respectively.

2.3.4 Thickness bulk results

The results from the thickness bulk method are given in Table 2.5 and Figure 2.5. Photographs and details of the method are given in Appendix 6.

Table 2.5. Average values for clothing THICKNESS BULK measured on 12 garments.

protective garments	arm bulk (cm)	torso bulk (cm)	leg bulk (cm)	overall bulk (cm)
A Workwear (insulated)	4.3	5	4.6	13.9
B Grey fire	5	5	5	15
C Workwear	1.3	2.6	1.2	5.1
D Gold fire	2.5	4.6	4.8	11.9
E Chemical	1.4	1.7	2.4	5.5
F ArmyNBC	2	2.8	2.4	7.2
G Welding	3.5	4.8	0.5	8.8
H Coldsuit black	5.5	5.4	7.6	18.5
I Coldsuit green	5.5	6.2	5.6	17.3
J Chainsaw	3.1	4.3	4.4	11.8
M ArmyH2O	1.8	2	1.2	5
N Mountain rescue	1.4	3.2	2	6.6

Figure 2.5 highlights the overall high bulk of the two Coldsuits (black H, green I), which along with the Grey fire (B) suit has consistently high bulk across all sites measured. In contrast, the Chemical (E), Workwear (C) and ArmyH2O (M) garments had low bulk values, and again these were across all sites.

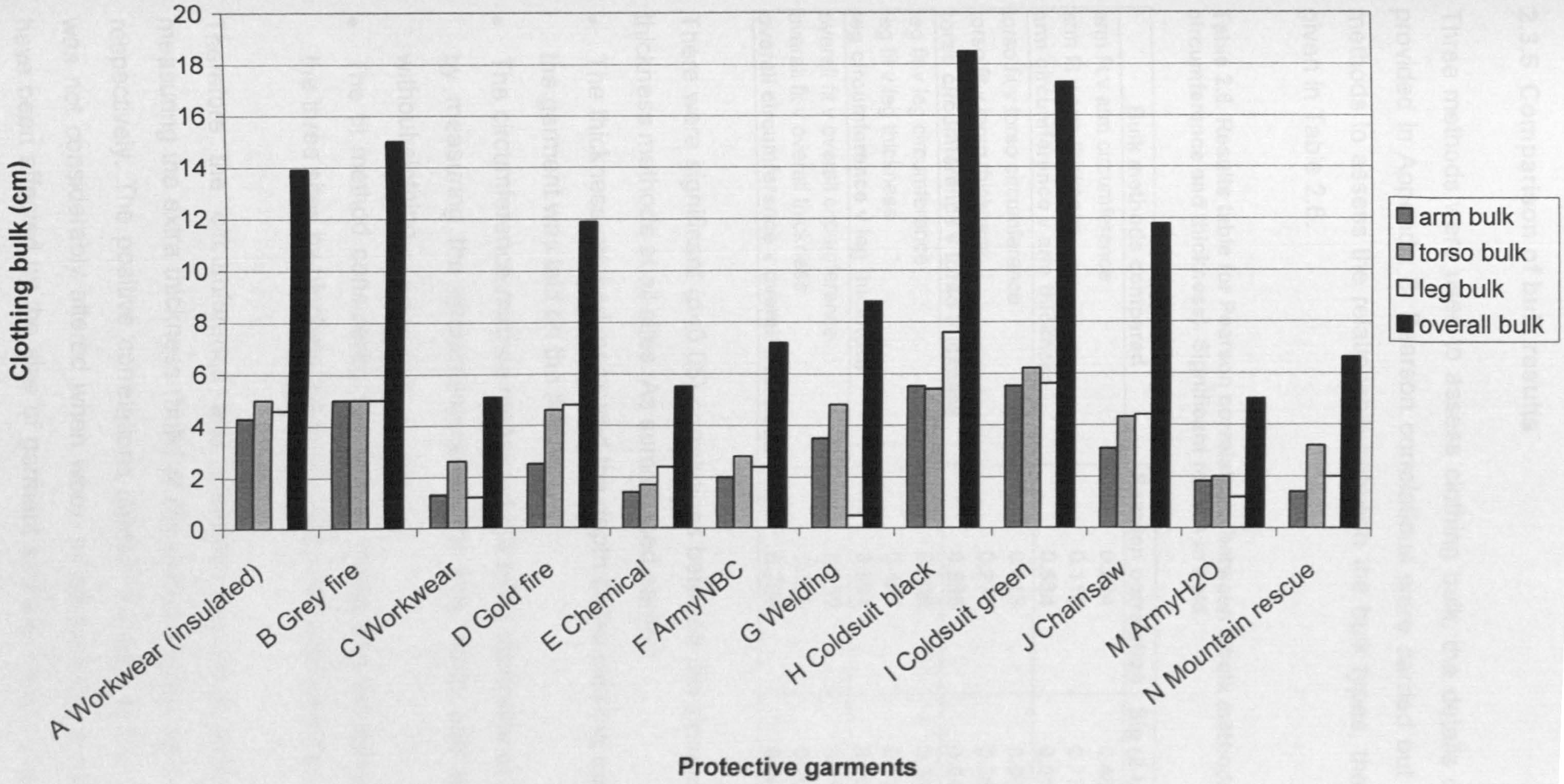


Figure 2.5. Bar chart showing values for arm, torso, leg and overall clothing THICKNESS BULK (measured in cms) for 12 protective garments.

2.3.5 Comparison of bulk results

Three methods were used to assess clothing bulk, the details of which are provided in Appendix 6. Pearson correlations were carried out between all methods to assess the relationship between the bulk types, the results are given in Table 2.6.

Table 2.6. Results table for Pearson correlations between 3 bulk methods used (fit, circumference and thickness). Significant results in bold.

Bulk methods compared	Pearson correlation	Sig (2-tailed)
arm fit v arm circumference	0.224	0.483
arm fit v arm thickness	0.110	0.734
arm circumference v arm thickness	**0.684**	**0.014**
torso fit v torso circumference	0.015	0.964
torso fit v torso thickness	0.277	0.383
torso circumference v torso thickness	**0.595**	**0.041**
leg fit v leg circumference	0.306	0.360
leg fit v leg thickness	0.425	0.192
leg circumference v leg thickness	**0.901**	**0.000**
overall fit v overall circumference	0.389	0.211
overall fit v overall thickness	0.325	0.302
overall circumference v overall thickness	**0.789**	**0.002**

There were significant ($p<0.05$) correlations between the circumference and thickness methods at all sites. As summarised earlier;

- The thickness method measured the depth of the clothing material whilst the garment was laid on the floor.
- The circumference method measured the extra thickness of the garment by measuring the circumference of the arm, torso and leg with and without clothing.
- The fit method considered the bulk by measuring the extra material at the three sites by pinching the fabric tight and measuring the excess.

Therefore the circumference and thickness methods were essentially measuring the extra thickness (bulk) of the material when worn and unworn respectively. The positive correlations confirm the size of the clothing bulk was not considerably altered when worn. In contrast the fit method would have been affected by the size of garment and the wearer, and the lack of any significant correlations with the other two methods show that it is measuring a different aspect of bulk.

2.3.6 Discussion

The garments measured showed a range in bulk values, across the three methods used. In each method measurements were made at the same three sites in order to assess the arm, torso and leg bulk. The highest bulk values were seen at the torso compared to the other sites. When the overall values were calculated for each suit (based on the sum of the 3 sites measured) the two firefighters suits (Grey fire B, Gold fire D) and two coldstore suits (Coldsuit black H, Coldsuit green I) consistently came out with the highest bulk. The insulation for these suits is very important to their primary function, protection from the heat and cold respectively. In contrast some of the suits with lower overall bulk values included the Chemical (E), Workwear (C) and ArmyNBC (F) ensembles. In most instances these garments would be worn over the top of other layers as the outer protective layer when additional protection was required against chemical splash, outdoor weather and a nuclear, biological and chemical threat respectively. It is therefore important for their function that the garments do not add too much additional bulk to the overall clothing ensemble.

If the bulk of the garment impedes the freedom of movement compared to a lightweight tracksuit, used as the control condition in this study, the extra effort required to complete the tasks which were all performed at set speeds (controlled by speed on the treadmill and timing with a metronome for the stepping and obstacle course) would add to the energy cost of the activity. As described in the previous research this has been termed a 'hobbling' effect by many including Teitlebaum and Goldman (1972), Duggan (1988) and Patton *et al.* (1995).

The fit of the garment will also have an influence on bulk, a garment that is too large for the wearer is likely to inflate the bulk measurements. As many of the previous studies have highlighted, the area of clothing bulk, possible hobbling and motion restriction still needs further attention.

2.4 Clothing stiffness

2.4.1 Introduction

Just as bulk has been suggested to interfere with joint movements, forcing the wearer of the protective garment to work harder to complete the same movements, the stiffness of such clothing ensembles can have a similar effect (Duggan 1988). In describing a hobbling or binding effect of clothing, Patton *et al.* (1995) who studied chemical PPC also assert that stiffness as well as bulkiness can interfere with joint movements. Garment stiffness was also cited by Meinander *et al.* (2004) when trying to explain the higher than predicted metabolic rate in human subject trials.

Nunneley (1989) stresses the need to understand more fully the interactions between physical and physiological factors. In discussing the development of computer models that predict human responses to work, clothing and the environment, she concludes that the validity of their output is limited in part by the need to represent more faithfully the interactions. She cites the example of the weight and stiffness of protective outfits increasing the metabolic costs of a task. Holmes *et al.* (1988) also highlight the fact that there is still a great deal to learn regarding the relationship between material stiffness and physiological behaviour. They indicate that there are 2 extremes, with stiff material producing a high level of resistance to bending, resulting in body and limb movements being impeded, especially at the joints. In contrast, materials with a low level of resistance produce a clinging sensation but little has been done to examine the threshold levels of stiffness between these two extremes and in relation to the activities of the wearer. This knowledge would help to prevent the dramatic elevation seen in the physical effort required to combat material stiffness, without falling into the area where lack of stiffness is in itself an undesirable form of behaviour (Holmes *et al.* 1988).

A paper by Peirce in 1930 describes how in judging the 'feel' or handle of a material, use is made of such sensations as stiffness and how it is desirable to devise physical tasks that analyse and reflect the sensation felt, to give numerical values to the measurement. The paper goes on to detail an instrument on which it is possible to measure the angle through which a specimen of cloth droops when a definite length is held over an edge, with the angle converted into 'bending length' by mathematical formulae. The method is strictly a measure of the draping quality of a fabric as stiffer material will have a longer bending length (Pierce 1930).

Most recently Harrabi *et al.* (2006) documented two methods under development for the characterisation of the flexibility of protective gloves. Flexibility is one of the major properties that define how a glove interferes with the worker ability to perform tasks and hence its degree of usefulness. The 'free deforming' technique they use is described, which they adapted from the ASTM D 4032 standard, and is based on the use of a probe to push a film sample through an orifice drilled in a platform (Harrabi *et al.* 2006).

Material testing of fabric stiffness is possible using machines and material samples but in choosing a methodology for measuring the garment stiffness in this trial it was not feasible to cut up the garments so a method of measuring drape was devised, details and photographs are provided in Appendix 7.

2.4.2 Results

The results of the stiffness measurements are detailed in Table 2.7 below. The values for the 3 sites measured are shown in centimetres and a higher number is representative of a stiffer garment. The methodology photos in

Appendix 7 illustrate that the point at which the garment touched the floor after being draped from a platform was measured, with a stiffer garment resulting in a greater value as it reaches the floor further from the platform than a less stiff garment. The results are also shown graphically in Figure 2.6.

Table 2.7. Stiffness measurements taken at 3 sites (arm, torso and leg) and overall for 12 protective garments. Results in cms.

protective garments	arm stiffness (cm)	torso stiffness (cm)	leg stiffness (cm)	overall stiffness (cm)
A Workwear (insulated)	27	21	15.5	63.5
B Grey fire	16	16.5	20.5	53
C Workwear	12.5	14.5	23	50
D Gold fire	20	27.5	21	68.5
E Chemical	22	22	27	71
F ArmyNBC	15	14	26	55
G Welding	25	18	15.5	58.5
H Coldsuit black	33.5	28	48.5	110
I Coldsuit green	39.5	30.5	49.5	119.5
J Chainsaw	30	19	20	69
M ArmyH2O	21.5	33	12	66.5
N Mountain rescue	21	12	34	67

The arm stiffness results show a range in values from 39.5 cm recorded in the Coldsuit green (I) ensemble to 12.5 cm in the Workwear (C) ensemble. The Coldsuit black (H) also had a high stiffness value for the arm as did the Chainsaw (J) and Workwear (insulated) (A) suits. For the torso stiffness, the values range from 33 cm for the ArmyH2O (M) combination to 12 cm for the Mountain rescue (N) garment. Other stiff garments included the two Coldsuits (black H and green I) and the Gold fire (D) ensemble, whilst other garments which had very low values for stiffness include the ArmyNBC (F) and Workwear (C) suits. The values for leg stiffness range from 49.5 cm and 48.5 cm for the Coldsuits, green I and black H respectively to 12 cm for the ArmyH2O (M) combination. The two coldsuits had much higher values (stiffer garments) than the other garments with the next highest being the Mountain rescue (N) garment at 34 cm.

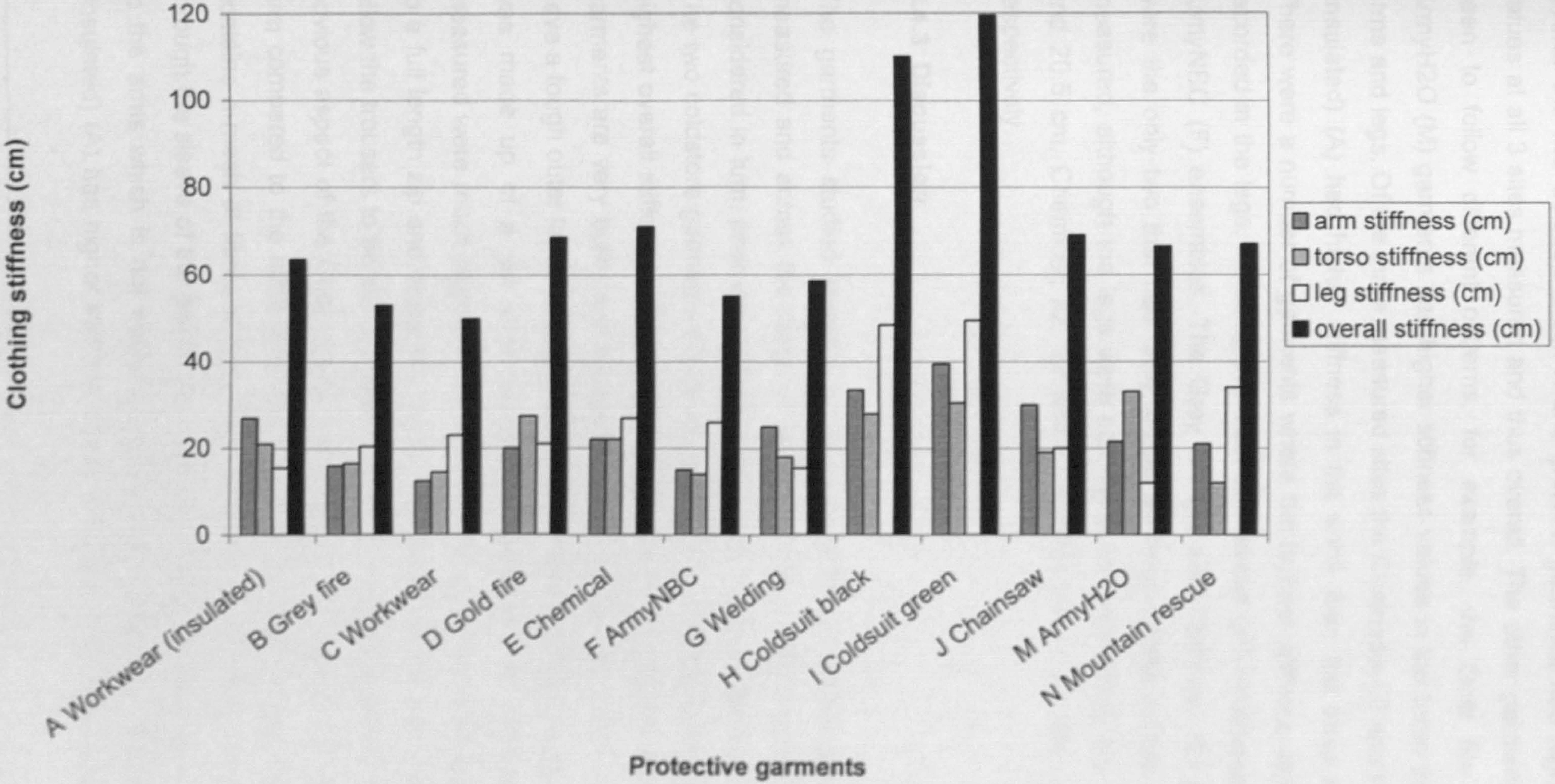


Figure 2.6. Bar chart showing values for arm, torso, leg and overall stiffness (measured in cms) for 12 protective garments. Stiffer garments produce higher values.

Overall the two Coldsuit (black H and green I) garments had high stiffness values at all 3 sites measured and thus overall. The other garments can be seen to follow different patterns, for example, the Gold fire (D) and ArmyH2O (M) garments had higher stiffness values in the torso than in the arms and legs. Of the three measured sites the Chainsaw (J) and Workwear (insulated) (A) had higher stiffness in the arms than the torso and legs. There were a number of garments where the highest stiffness values were recorded in the legs, including the Mountain rescue (N), Workwear (C) and ArmyNBC (F) ensembles. The Grey fire (B) and Chemical (E) garments were the only two that had fairly similar stiffness values across the sites measured, although the legs were still higher for both (Grey fire; 16, 16.5 and 20.5 cm, Chemical; 22, 22 and 27 cm for the arms, torso and legs respectively.

2.4.3 Discussion

The garments studied showed a range of stiffness values across sites measured and across the range of garments tested. Each garment will be considered in turn, photographs of the garments are provided in Chapter 2. The two coldstore garments (Coldsuit black H and Coldsuit green I) had the highest overall stiffness values, this may in part be due to the fact that the garments are very bulky and insulated making them a lot stiffer. They also have a tough outer fabric to prevent wear. The Mountain rescue (N) garment was made up of a ski style jacket and trousers, the stiffness values measured were much higher in the leg which may partly have been related to a full length zip and storm flap down the outside of the leg, designed to allow the trousers to be put on / taken off without removing boots. The most obvious aspect of the Chainsaw (J) ensemble is the higher stiffness in the arm compared to the other sites, due to the design of the jacket, the arm contains a mesh of fibres which would prevent the chainsaw blade cutting through the sleeve of the jacket. This feature adds both weight and stiffness to the arms which is not seen in the body of the jacket. The Workwear (insulated) (A) has higher stiffness in the arms and torso as it is the jacket that is insulated and not the legs which consequently have a lower degree of stiffness.

The two fire garments (Grey fire B, Gold fire D) have similar stiffness values to each other and across the sites measured, apart from the torso of the Gold fire (D) jacket. The stiffness values for the Chemical (E) suit were quite high in relation to the range of the garments, this can be explained by the fact that the suit is made of 100% PVC coated nylon for protection but this is not a very flexible material. The key feature of the Workwear (C) garment is the trousers which have additional fabric on the knees which goes someway to explaining the greater leg stiffness recorded in this garment. The same material is used in all parts of the Welding (G) garment although the design and construction of the jacket probably explains the higher stiffness recorded in the arm. In the ArmyH2O (M) ensemble, a GoreTex waterproof jacket is worn with combat trousers. The waterproof fabric is much stiffer than the cotton mix trousers (unfortunately the waterproof trousers were unavailable for testing), hence the much higher stiffness value recorded for the torso and arm compared to the leg. Finally the ArmyNBC (F) ensemble which showed quite low stiffness values for the arm and torso compared to the leg. Although the same fabric is used throughout the garment, the legs have extra pockets, adding material and stiffness to the garment.

3. Modelling

3.1 Correlations

3.1.1 Methodology

The first study of this thesis (Chapter 3) produced data on the percentage increase in metabolic rate when walking, stepping and completing an obstacle course wearing a range of PPC. The present chapter has described the results from a number of measurements made of the PPC properties (method details included in appendix).

The aim of the modelling is to try and establish the best predictors of the increase in metabolic rate seen when wearing PPC. The variables to be used are listed here;

Criterion (dependent) variables

- % increase in met rate overall
- % increase in met rate walking
- % increase in met rate stepping
- % increase in met rate obstacle course

Predictor (independent) variables

Clothing weight

- total clothing weight
- crotch leg weight
- upper leg weight
- lower leg weight
- total leg weight
- torso body weight
- upper arm weight
- lower arm weight
- total upper body weight

Clothing insulation

- total insulation
- garment insulation (excludes hands, feet, head)

Clothing stiffness

- torso stiffness
- arm stiffness
- leg stiffness

Clothing bulk

- torso fit bulk
- arm fit bulk
- leg fit bulk
- torso circumference bulk
- arm circumference bulk
- leg circumference bulk
- torso thickness bulk
- arm thickness bulk
- leg thickness bulk

Correlations between the predictor and criterion variables were analysed using Pearson's r. The analysis was made using data on 12 cases (protective clothing garments). The ChemBio garment was not available for any of the measurements made in the present chapter. The ArmyVEST garment data was also excluded from the analysis as there was some missing data on bulk and stiffness and the fact that the unusual characteristics of the garment (for example, very concentrated weight distribution) due to its specialised purpose may have affected the overall results of the analysis.

3.1.2 Results

The results of the Pearson's r correlation are provided in Table 3.1.

Torso circumference bulk, a measure of the extra bulk of material from the PPC around the core region (chest, back, stomach), had the strongest significant ($p<0.001$) positive correlation ($r=0.828$) for the overall % increase in metabolic rate. The effect of the torso bulk was evident across all work modes as evidenced by the strong significant correlations with % metabolic rate increase for the walking ($r=0.727$, $p<0.007$), stepping ($r=0.764$, $p<0.04$) and obstacle course ($r=0.620$, $p<0.031$) work modes.

Table 3.1. Pearson's r correlation matrix. Significance (p<0.05) shown with dark shading, results narrowly missing significance shown with light shading.

		% increase overall	% increase walking	% increase stepping	% increase obstacle course
total clothing weight	Pearson Correlation	0.500	0.437	0.464	0.412
	Sig. (2-tailed)	0.082	0.135	0.111	0.162
crotch leg weight	Pearson Correlation	**0.638**	**0.540**	**0.601**	**0.522**
	Sig. (2-tailed)	**0.019**	**0.057**	**0.030**	**0.067**
upper leg weight	Pearson Correlation	0.288	0.385	0.195	0.159
	Sig. (2-tailed)	0.340	0.194	0.523	0.603
lower leg weight	Pearson Correlation	0.282	0.369	0.171	0.192
	Sig. (2-tailed)	0.351	0.214	0.576	0.530
total leg weight	Pearson Correlation	0.496	0.517	0.405	0.367
	Sig. (2-tailed)	0.085	0.070	0.170	0.217
torso body weight	Pearson Correlation	0.183	0.071	0.222	0.204
	Sig. (2-tailed)	0.549	0.818	0.465	0.505
upper arm weight	Pearson Correlation	0.377	0.485	0.349	0.127
	Sig. (2-tailed)	0.227	0.110	0.266	0.693
lower arm weight	Pearson Correlation	**0.655**	0.459	**0.639**	**0.587**
	Sig. (2-tailed)	**0.021**	0.133	**0.025**	**0.045**
total upper body weight	Pearson Correlation	0.399	0.281	0.413	0.361
	Sig. (2-tailed)	0.177	0.353	0.161	0.226
total insulation	Pearson Correlation	0.349	0.241	0.341	0.308
	Sig. (2-tailed)	0.267	0.450	0.278	0.330
garment insulation	Pearson Correlation	0.303	0.239	0.303	0.229
	Sig. (2-tailed)	0.338	0.454	0.339	0.475
torso stiffness	Pearson Correlation	-0.125	-0.010	-0.023	-0.309
	Sig. (2-tailed)	0.700	0.976	0.943	0.328
arm stiffness	Pearson Correlation	-0.173	-0.082	-0.070	-0.300
	Sig. (2-tailed)	0.590	0.799	0.828	0.343
leg stiffness	Pearson Correlation	-0.200	-0.238	-0.155	-0.122
	Sig. (2-tailed)	0.532	0.456	0.631	0.706
torso fit bulk	Pearson Correlation	-0.192	-0.461	-0.178	0.165
	Sig. (2-tailed)	0.550	0.131	0.580	0.609
arm fit bulk	Pearson Correlation	-0.303	-0.376	-0.242	-0.160
	Sig. (2-tailed)	0.338	0.228	0.449	0.619
leg fit bulk	Pearson Correlation	**0.615**	0.487	**0.636**	0.471
	Sig. (2-tailed)	**0.044**	0.129	**0.035**	0.144
torso circum bulk	Pearson Correlation	**0.828**	**0.727**	**0.764**	**0.620**
	Sig. (2-tailed)	**0.001**	**0.007**	**0.004**	**0.031**
arm circum bulk	Pearson Correlation	**0.570**	0.456	**0.564**	0.433
	Sig. (2-tailed)	**0.053**	0.136	**0.056**	0.160
leg circum bulk	Pearson Correlation	0.336	0.322	0.360	0.165
	Sig. (2-tailed)	0.286	0.308	0.251	0.607
torso thickness bulk	Pearson Correlation	0.306	0.369	0.292	0.120
	Sig. (2-tailed)	0.333	0.238	0.357	0.710
arm thickness bulk	Pearson Correlation	0.319	0.479	0.364	-0.041
	Sig. (2-tailed)	0.313	0.115	0.245	0.900
leg thickness bulk	Pearson Correlation	0.311	0.219	0.349	0.224
	Sig. (2-tailed)	0.325	0.494	0.267	0.483

Lower arm weight, a measure of the weight of the garment carried below the elbow had the next highest positive correlation (r=0.655, p<0.021) with % increase in met rate overall and was also significantly correlated with % increase in metabolic rate when stepping (r=0.639, p<0.025) and % increase in metabolic rate for the obstacle course (r=0.587, p<0.045).

Two other clothing parameters, crotch leg weight and leg fit bulk, had significant correlations with the overall % increase in metabolic rate and that recorded during stepping. Crotch leg weight is a measure of the weight of a garment carried in the crotch area, see methodology photographs in Appendix 4 for more detail. Leg fit bulk, positively correlated with an increase in overall working metabolic rate (r=0.615, p<0.044) and stepping metabolic rate (r=0.636, p<0.035), is described in section 2.3.2 above.

3.2 Regression

3.2.1 Methodology

A multiple regression was subsequently carried out using the stepwise method. A number of preliminary models emerged. However it was decided to treat the results with extreme caution as there were a large number of predictors compared to the number of cases and as it is generally accepted that the ratio of cases to predictor variables should be 10:1, with 5:1 as a minimum. The model summaries are included in Table 3.2.

3.2.2 Results

The strongest predictor for the overall percentage increase in metabolic rate is torso circumference bulk (Model 1). The equation for the model is
$y = 3.7 + (0.44*TCB)$
(TCB; torso circumference bulk, R^2 adj=0.66, p<0.01)

In Model 2, the addition of total insulation increases the explained variance (adjusted R^2) to 78%. It must be noted that in Model 2, there is a sign change in the coefficient for insulation, compared to the sign it had in the correlation and the equation for the model is

$y = 11.6 + (0.65*TCB) - (41.6*TI)$

(TI; total insulation, R^2 adj=0.78, $p<0.01$)

Total insulation was shown to have a positive correlation with % increase in metabolic rate in Table 3.1. As the effect of insulation is subtracted from the bulk due to its negative coefficient, this indicates that a garment with a high torso bulk as a result of high insulation is going to have less of an effect on metabolic rate increase than a garment that has a high torso bulk but with a lower total insulation. It has been highlighted earlier that insulation requires thickness and therefore bulk. But bulk can also come from other parameters, such as stiff fabric, which impact on the wearers metabolic rate.

Only 2 predictors are considered due to concerns over the number of cases used for the modelling and this is the case for the modelling data as a whole. In order to be able to undertake further modelling with greater confidence a lot more data points are required as well as a large scale validation.

Table 3.2. Results of the stepwise multiple regression for the dependent variable, % increase in overall metabolic rate.

Coefficients(a)

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	3.708	2.006		1.848	.098
	torso circum bulk	.442	.097	.835	4.551	.001
2	(Constant)	11.616	3.746		3.101	.015
	torso circum bulk	.647	.118	1.222	5.487	.001
	total insulation	-41.569	17.709	-.523	-2.347	.047

a Dependent Variable: % increase overall

Table 3.2. Results of the stepwise multiple regression for the dependent variable, % increase in overall metabolic rate (cont'd).

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.835(a)	.697	.663	2.24685	.697	20.713	1	9	.001
2	.906(b)	.821	.776	1.83387	.124	5.510	1	8	.047
3	.968(c)	.936	.909	1.16903	.116	12.687	1	7	.009
4	.986(d)	.972	.953	.84347	.035	7.446	1	6	.034
5	.998(e)	.996	.992	.35643	.024	28.600	1	5	.003
6	.999(f)	.999	.997	.21824	.003	9.338	1	4	.038
7	1.000(g)	1.000	1.000	.08396	.001	24.028	1	3	.016

a Predictors: (Constant), torso circum bulk
b Predictors: (Constant), torso circum bulk, total insulation
c Predictors: (Constant), torso circum bulk, total insulation, arm fit bulk
d Predictors: (Constant), torso circum bulk, total insulation, arm fit bulk, lower arm weight
e Predictors: (Constant), torso circum bulk, total insulation, arm fit bulk, lower arm weight, torso fit bulk
f Predictors: (Constant), torso circum bulk, total insulation, arm fit bulk, lower arm weight, torso fit bulk, torso stiffness
g Predictors: (Constant), torso circum bulk, total insulation, arm fit bulk, lower arm weight, torso fit bulk, torso stiffness, leg fit bulk

3.3 Discussion

The strongest correlate of an increased metabolic rate when working is the bulk of the garment around the torso. The impact of a high level of bulk around the torso, is likely to be due to a reduction in movement, which then forces the wearer to perform less efficient, exaggerated or extra movements to complete the task to the same level, consequently increasing the level of energy expenditure.

Lower-arm weight was also a good predictor. Weight supported at the extremities, in this case on the arms below the elbow, has to be accelerated and decelerated with each movement. The arm swing involved in the stepping work mode and arm movements required to move the crates in the obstacle course when wearing PPC would therefore significantly increase the metabolic rate. The narrow range of movement and lack of arm swing required during treadmill walking explain the absence of a significant correlation with the metabolic rate % increase during walking.

In the case of the crotch leg weight result, a higher clothing weight in this region is going to make movements around the hip harder, especially lifting the thigh as required when stepping and at the extreme end of the movement ranges, e.g. when crouching and crawling, which would explain the significant positive correlations between crotch leg weight and metabolic rate increase during stepping and overall. In the range of movement study (5) detailed in Chapter 7 participants repeatedly reported problems in the crotch area of garments, for example, finding it hard to lift their thigh. These two findings confirm the impact of the crotch area and the weight / fit of the garment in that area to be especially important both subjectively and physiologically.

The fit of the garments around the thigh was assessed by the fit bulk method (at the site of measurement the extra garment material was pinched and measured). Garments with a higher leg fit bulk, have more 'spare' material in the thigh region, which if impeding ease of movement and reducing range of joint motion could raise the metabolic cost of work.

Although the statistical analysis suggests that torso bulkiness is the main predictor of increased energy costs, the experimental results from the earlier chapters point out the marked role of clothing weight on the arms and legs. As the statistical conclusion may partly be affected by the fact that the model parameters may not be independent (for example, torso bulkiness associated with bulkiness in the sleeves and legs of the garment) a degree of caution should be used when drawing conclusions. There are also some factors which were not considered in the modelling as they were not studied in this thesis, such as the role of increased body temperature, which are known to affect metabolic rate. As cited in Chapter 1, a rise in body temperature of 1°C can raise metabolic rate by 13% (Parsons 2003).

There were some negative correlations also evident in Table 3.1, the highest being the correlations of torso and arm fit bulk of –0.461 and –0.376 respectively with the % increase in metabolic rate when walking. The technique for measuring fit bulk, involved measuring the spare material of the garment at three sites (see Appendix 6 for details). Tight garments, resulting in low values for torso and arm fit bulk, could be assumed to impede and restrict movements, which, as has been previously discussed, increases the metabolic cost of working. In contrast therefore a garment with a higher fit bulk has more spare material which if occurring in the torso and arm region seems to provide more give, allowing for a greater ease of movement and contributing to a reduced increase in metabolic rate. However this spare material does not have the same effect in the legs, as an increased leg fit bulk was seen to be a strong correlate of an increased metabolic rate, so the spare material seems to be hindering lower limb movement especially at the knee and hip joints. There are also weak negative correlations between garment stiffness and % increase in metabolic rate.

In summary, the strongest correlate of an increased metabolic rate when working is the bulk of the garment around the torso. Garment bulk around the thigh is also associated with an increased metabolic rate. PPC garments with a large proportion of weight supported in the lower arm and in the crotch also show significant relationships with increased overall metabolic rates.

CHAPTER 9

OVERALL SUMMARY, CONCLUSIONS AND FUTURE WORK

1. Overall summary

Studies presented in this thesis have considered the overall effects of protective clothing on energy consumption during different activities, followed by investigations into the contribution of a number of relevant clothing parameters, to the overall metabolic effect.

The initial study (Chapter 3) highlighted that protective clothing (PPC) ensembles from a variety of industries significantly increased the metabolic cost of walking, stepping and completing an obstacle course including lifting and moving crates, crawling on hands and knees, and moving under and over obstacles. The garments tested caused metabolic rate increases of 2.4 - 20.9 % compared to a control condition. A simple plot of the % increase in metabolic rate results in relation to total clothing weight highlighted the significance of garment weight.

The study of simulated weight distributions on metabolic rate (Chapter 4) concluded that the equivalent weight of protective garments and the distribution of that weight had a significant effect on the metabolic cost of work. The effect of the load was dependent on the site of the extra weight, being particularly costly when placed on the wrists and ankles, as weight on the limbs has to be accelerated and decelerated with each step. If it was assumed that clothing weight was located totally on the extremities the predicted increase in metabolic rate (2.25 % per kg) comes close to the average increase in metabolic rate for clothing weight (2.7 % per kg) observed in the first study (Chapter 3). This, however, is unrealistic and so further possible contributors were investigated.

The potential effect of multiple layers (Chapter 5) was investigated, fuelled partly by a number of comments in the literature regarding a possible 'friction drag' between clothing layers and a suggested 'rule of thumb' of a 3-4 % increase in energy cost per layer. However there is a real lack of data and information on the interaction of clothing, layers and fabric. The difficulty of the study was in trying to isolate the effect of layers with different frictional properties, from the other parameters of the layers, for example, weight, bulk and stiffness. A number of identically sized layers (suits), made of 100% polyester material with a satin (low friction) finish and crepe (high friction) finish were produced. The study showed that wearing 4 layers increased the metabolic cost of walking and completing an obstacle course by 4.5 to 7.9 % compared to a single layer weight-balanced control condition. However the differences between wearing layers of the 2 different materials (high and low friction), up to 2.8 %, were not statistically significant despite higher friction coefficient values measured in material tests for all high friction configurations, as the effect size remained below the sensitivity of the method.

Wetting one or more of the layers in a 4 layer ensemble increased working metabolic rates above those in a dry single layer weight-balanced control with a number of significant results (7.4 - 9.4 %, $p<0.05$). However the differences between the high and low friction conditions, up to 3.9 %, were not statistically significant (Chapter 6). The use of more extreme fabric layers (for example lycra) or fabrics with a greater diversity of surface structure may have improved the results but would have been far less realistic, producing unusable data. Alternatively off the shelf layers could have been used, but the level of control (for weight, stiffness etc.) would have been much reduced. The 3-4 % increase in energy cost per layer rule, cited in the literature clearly did not work for the test clothing studied in Chapter 6, however the layers used in the studies in this thesis were made up of thin fabrics, as opposed to the arctic layers, reported in the literature on which the rule of thumb was based.

The study on range of movement (ROM) (Chapter 7) did not provide entirely consistent evidence that PPC garments caused a reduced ROM, as suggested by other authors. Though statistically significant reductions in knee ROM due to a range of PPC were observed during stepping in five of the six stages, and for crawling in some of the movements, combined with changes to the hip movement and angle for the latter activity, obtaining significance was made difficult due to the opposite responses in some participants. This could have been caused by different types of behavioural compensation to the hindrance of the PPC.

In the final experimental chapter (Chapter 8), measurement of a number of potential clothing parameters which may have influenced the increased metabolic rate was carried out. The data was subsequently used to try and model the significance of these parameters. Clothing bulk around the torso and thigh, and high concentrations of clothing weight in the lower arms and crotch areas were seen to be significantly correlated with an increased metabolic rate, however a low number of garments limited the power of a regression and a lot more data would be required to produce a reliable predictive model. The model did not include any discussion of the effect of thermal load on metabolic rate as this thesis has focussed on the metabolic effect of clothing and therefore studies have been designed to eliminate any possible thermal influence on the metabolic rates recorded.

The work presented in this thesis has shown that working in PPC garments from a range of industries, across a number of work modes, increases the wearers metabolic rate. This expands the previously limited knowledge of the effect of a few garments, for example, arctic and NBC ensembles when walking and stepping. The thesis has also gone on to investigate a number of the factors, often discussed but not previously studied in this context, that might be contributing to the increased metabolic rate. A number of authors have supported notions of a hobbling effect due to clothing bulk and a friction drag due to multiple clothing layers. However these factors are often compounded as many of the garments are heavy, bulky and made up of multiple layers and stiff fabric, and it has proved very hard to isolate the effect of a single garment property on the overall increased energy cost when wearing the actual PPC.

2. Conclusions

1. Protective clothing ensembles from a variety of industries increased the metabolic cost of walking, stepping and completing an obstacle course by 2.4 - 20.9 % compared to a control (tracksuit) condition.

2. Subjective ratings of perceived exertion (RPE) were significantly higher ($p<0.05$) for all but two garments when walking, stepping and completing an obstacle course compared to a control (tracksuit) condition.

3. On average there was a 2.7 % increase in metabolic rate for every kg increase in clothing weight, with some variation due to the position of the weight and the physical demands of the task. Work requiring greater ranges of movement in all limbs incured a greater increase in energy cost.

4. If the clothing weight would be assumed to be located wholly on the wrists and ankles the energy cost per kg was 2.25 %. Although this value is close to that seen for clothing weight (2.7 %/kg), this assumption is clearly unrealistic.

5. Wearing 4 layers increased the metabolic cost of walking and completing an obstacle course by 4.5 to 7.9 % compared to a single layer control condition of the same weight.

6. The differences between wearing layers of 2 different materials (high and low friction) in a multilayer ensemble, were not significant, despite higher friction coefficient values measured in material tests for all high friction configurations. This could be due to the choice of garments used.

7. Though statistically significant reductions in knee range of movement (ROM) due to the PPC were observed during stepping in five of the

six stages, and for some of the crawling movements (which also prompted changes in the hip angles), obtaining wider significance was made difficult due to opposite responses in some participants.

8. The hypothesis that the protective clothing (PPC) garments would restrict movement and therefore range of motion was not proved conclusively due to different types of behavioural compensation to the hindrance of the PPC.

9. Comments recorded from the participants suggest they were aware of the restrictions imposed by the clothing with the area around the crotch the most problematic due to its influence on movements of the thigh and hip.

10. The strongest correlate of an increased metabolic rate when working was the garment bulk around the torso.

11. Garment bulk around the thigh was also associated with an increased metabolic rate and PPC garments, with a large proportion of weight supported in the lower arm and in the crotch also showing significant relationships with increased overall metabolic rates.

12. The sensitivity of the method has meant that little significance has been found with differences of less than 5 % in metabolic cost. This has been coupled with the small size of the effect when trying to isolate one garment parameter e.g. friction between layers.

13. It has not been possible to develop an extensive model for the effect of protective clothing and its properties on energy consumption. Due to the difficulties of sensitivity and effect sizes, a lot more data would be required.

3. Future work

In 1994, Adams *et al.* published a paper highlighting how PPC can affect worker performance and how the ability to predict performance changes due to PPC attributes would assist with the design and selection of protective clothing. They proposed a conceptual model that could lead to the prediction of these effects based on garment properties, the Garment Impediment Index. They highlighted a number of garment properties including, weight, stiffness and bulk and a number of objective performance measures, including energy expenditure. However the sheer volume of data that would be required to compile this Garment Impediment Index is huge. They acknowledged that garment factors are typically confounded and the challenge is to isolate the properties, however the work undertaken in this thesis and the lack of data available in this area since the paper was published in 1994, highlights the realistic difficulties in achieving this.

There is a huge variety of protective clothing in use designed primarily for function and protection. In hindsight perhaps the most important results to come out of the work presented in this thesis are those that have highlighted the potential size of the effect that working in protective clothing can have on energy consumption. The incorporation of this information into standards for worker safety, e.g. heat stress standard ISO 7933, has the potential to be far more significant for those who work in PPC than the knowledge of the contribution of individual garment parameters to the overall increase.

Further work could be undertaken but a lot of consideration would need to be made, especially if pursuing the route of trying to isolate individual parameters, about the expected size of effect and the sensitivity of any method used.

Future work needs to take a multidisciplinary approach, bringing together the expertise of those in the fields of textile, material and clothing science, as well as ergonomics and engineering. Newer materials are being developed that could have significant implications in protective clothing, for example, materials that can provide insulation without the previous levels of weight or bulk, so future work in this area should be encouraged.

CHAPTER 10

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APPENDICES

GENERIC HEALTH SCREEN FOR STUDY VOLUNTEERS

It is important that volunteers participating *in research* studies are currently in good health and have had no significant medical problems in the past. This is to ensure *(i) their own* continuing well-being and (ii) to avoid the possibility of individual health issues confounding study outcomes.

Please complete the questions in this brief questionnaire to confirm fitness to participate:

If YES to any question, please describe briefly in the spaces provided (eg to confirm problem was/is short-lived, insignificant or well controlled.)

(Please tick as appropriate)

1 **At present,** do you have any health problem for which you are:

(a) on medication, prescribed or otherwise	**Yes**	☐	**No**	☐
(b) attending your general practitioner	**Yes**	☐	**No**	☐
(c) on a hospital waiting list	**Yes**	☐	**No**	☐

2 **In the past two years,** have you had any illness which required you to:

(Please tick as appropriate)

(a) consult your GP	**Yes**	☐	**No**	☐
(b) attend a hospital outpatient department	**Yes**	☐	**No**	☐
(c) be admitted to hospital	**Yes**	☐	**No**	☐

3 **Have you ever** had any of the following: *(Please tick as appropriate)*

(a) Convulsions/epilepsy	**Yes**	☐	**No**	☐
(b) Asthma	**Yes**	☐	**No**	☐
(c) Eczema	**Yes**	☐	**No**	☐
(d) Diabetes	**Yes**	☐	**No**	☐
(e) A blood disorder	**Yes**	☐	**No**	☐
(f) Head injury	**Yes**	☐	**No**	☐
(g) Digestive problems	**Yes**	☐	**No**	☐
(h) Heart problems	**Yes**	☐	**No**	☐
(i) Problems with bones or joints	**Yes**	☐	**No**	☐
(j) Disturbance of balance / co-ordination	**Yes**	☐	**No**	☐
(k) Numbness in hands or feet	**Yes**	☐	**No**	☐
(l) Disturbance of vision	**Yes**	☐	**No**	☐
(m) Ear / hearing problems	**Yes**	☐	**No**	☐
(n) Thyroid problems	**Yes**	☐	**No**	☐
(o) Kidney or liver problems	**Yes**	☐	**No**	☐
(p) Allergy to nuts	**Yes**	☐	**No**	☐
(q) Migraines	**Yes**	☐	**No**	☐

(Please tick as appropriate)

Questions for female participants

(a) are your periods normal/regular?	**Yes**	☐	**No**	☐
(b) are you on "the pill"?	**Yes**	☐	**No**	☐
(c) could you be pregnant?	**Yes**	☐	**No**	☐

Thank you for your co-operation!

Declaration Of Consent

I, ... hereby volunteer to be an experimental participant in a thermal environment experiment during the period of / on ....2007.

My replies to the above questions are correct to the best of my belief and I understand that they will be treated with the strictest confidence by the experimenter. The purpose of the experiment has been explained by the experimenter and I understand what will be required of me.

I understand that I may withdraw from the experiment at any time and that I am under no obligation to give reasons for withdrawal or attend again for experimentation. I also understand that the experimenter is free to withdraw me from experimentation at any time.

I undertake to obey the laboratory regulations and the instructions of the experimenter regarding safety, participant only to my right to withdraw as declared above.

Signature of Participant .... Date ....

Signature of Experimenter .... Date ....

Data for Figures 3.1, 3.2, 3.3 and 3.4 in Chapter 3.

	% increase in metabolic rate from control			
	overall	walking	stepping	obstacle course
A Workwear (insulated)	18.7	19.1	19.8	17.4
B Grey fire	15.7	20.9	14.5	11.8
C Workwear	15.6	16.8	14.0	15.9
D Gold fire	14.5	14.2	12.2	16.9
E Chemical	12.8	13.4	12.6	12.3
F ArmyNBC	12.4	17.5	10.1	9.4
G Welding	12.1	18.3	9.4	8.6
H Coldsuit black	11.8	13.8	11.1	10.5
I Coldsuit green	11.4	16.4	10.2	7.5
J Chainsaw	10.0	13.0	8.0	9.0
K ChemBio	10.0	7.2	5.8	17.1
L ArmyVEST	7.3	8.7	6.7	6.7
M ArmyH2O	6.8	11.9	5.1	3.2
N Mountain rescue	5.6	4.2	2.4	10.3

Data for Figure 3.5 in Chapter 3.

RPE results	walking	stepping	obstacle course
control	8.8	11.0	11.9
A Workwear (insulated)	10.7	12.2	13.8
B Gold fire	11.4	12.8	14.6
C Workwear	10.3	12.5	12.9
D Gold fire	11.6	13.0	14.9
E Chemical	10.1	12.1	13.2
F ArmyNBC	11.3	12.7	13.3
G Welding	10.6	12.4	13.3
H Coldsuit black	11.2	12.3	14.0
I Coldsuit green	11.2	12.8	13.8
J Chainsaw	11.3	13.1	14.2
K ChemBio	10.4	12.0	13.0
L ArmyVEST	10.2	12.2	13.1
M ArmyH2O	10.0	11.6	12.6
N Mountain rescue	9.7	11.5	12.5

Data for Figure 3.6 in Chapter 3.

TS results	walking	stepping	obstacle course
control	3.7	4.5	5.1
A Workwear (insulated)	4.5	5.5	6.2
B Gold fire	4.7	6.0	6.9
C Workwear	4.3	5.4	5.8
D Gold fire	5.3	6.4	6.9
E Chemical	4.3	5.4	6.1
F ArmyNBC	4.7	5.5	6.3
G Welding	4.3	5.1	5.9
H Coldsuit black	5.2	6.1	6.9
I Coldsuit green	5.3	6.3	6.8
J Chainsaw	4.9	5.9	6.6
K ChemBio	4.4	5.5	6.3
L ArmyVEST	4.4	5.3	6.3
M ArmyH2O	4.5	5.4	6.1
N Mountain rescue	4.3	5.0	5.8

Data for Figures 3.1, 3.2 and 3.3 in Chapter 4.

% increase in metabolic rate from control			
	overall	walking	obstacle course
waist 2	6	3	8
waist 4	7	6	4
waist 6	7	8	10
waist 8	11	9	11
waist 10	12	10	13
ankles 2	8	8	10
ankles 4	10	11	9
wrists 2	7	7	4
wrists 4	10	6	10
ankles/wrists 4	10	9	9
ankles/wrists 8	19	17	21

Data for Figure 3.6 in Chapter 4.

RPE results	walking	obstacle course
control	9	12
waist 2	9	13
waist 4	10	13
waist 6	10	13
waist 8	10	13
waist 10	11	14
ankles 2	10	13
ankles 4	10	13
wrists 2	10	13
wrists 4	10	14
ank/wris 4	10	14
ank/wris 8	11	14

Methods for measuring clothing weight and its distribution

The protective garments were weighed on a set of weighing scales (Sartorius Ltd. Epsom, Surrey). In order to be able to weigh sections of the clothing a small platform was used to support the weight of the parts of the garments not being weighed, see Figure 4.1. The top edge of the scales and platform were at the same height.

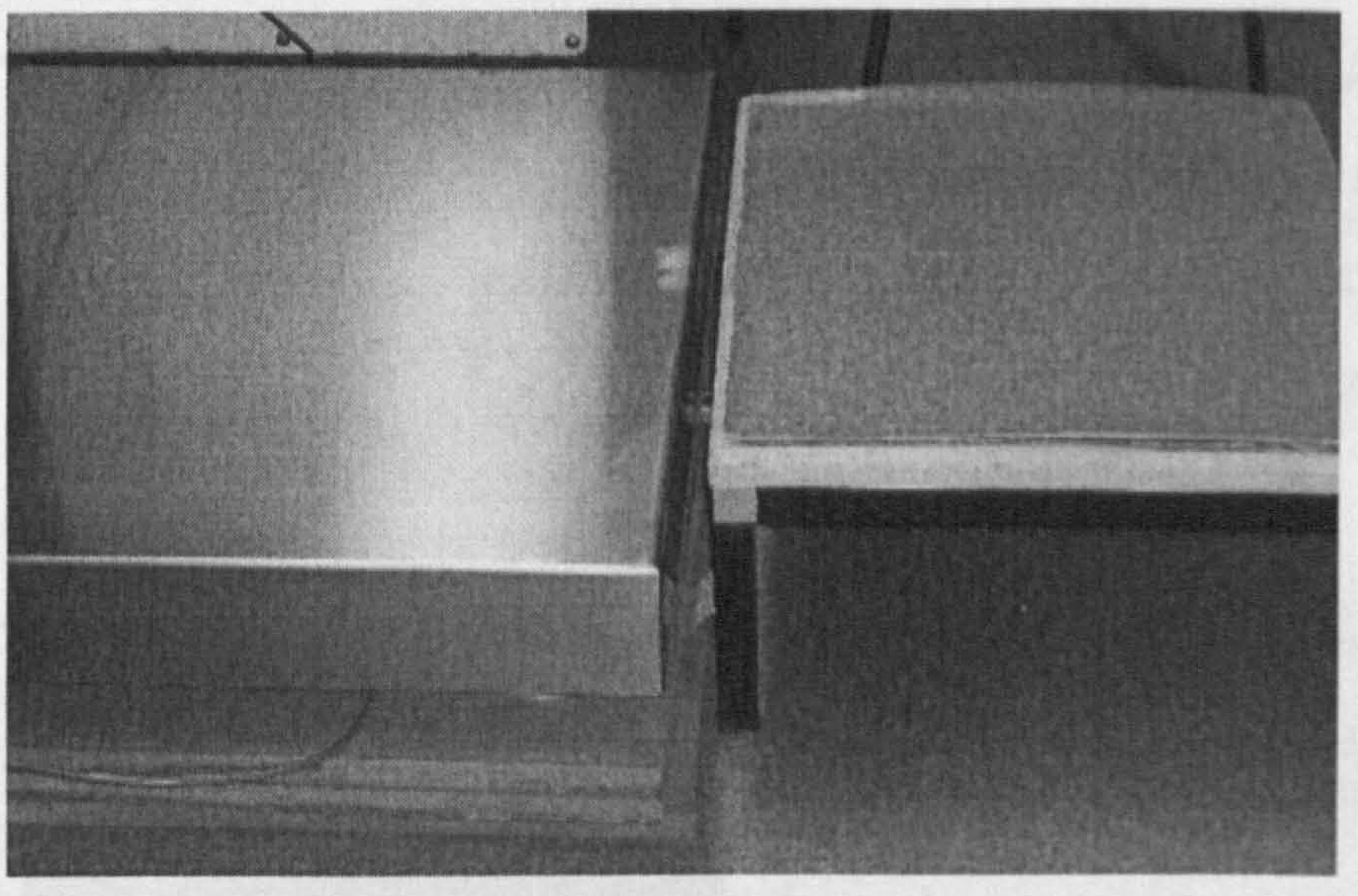
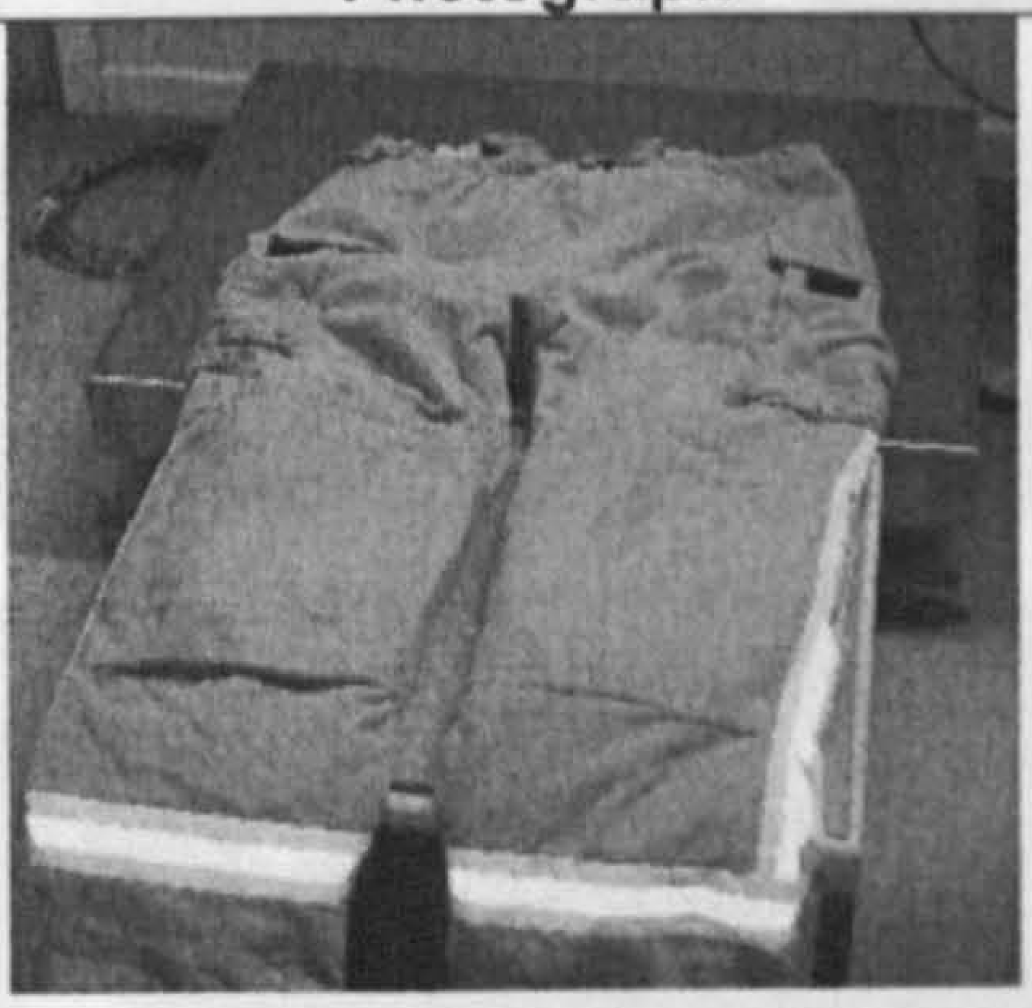
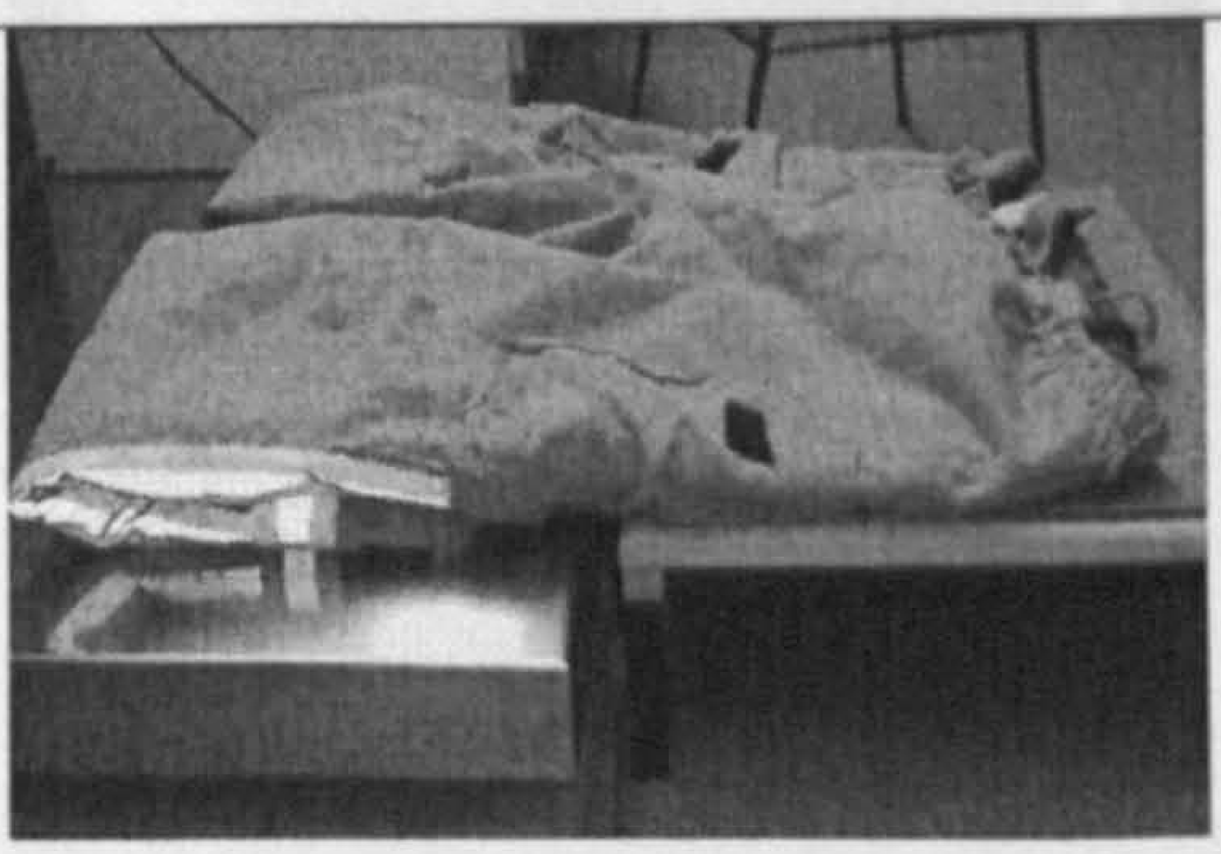
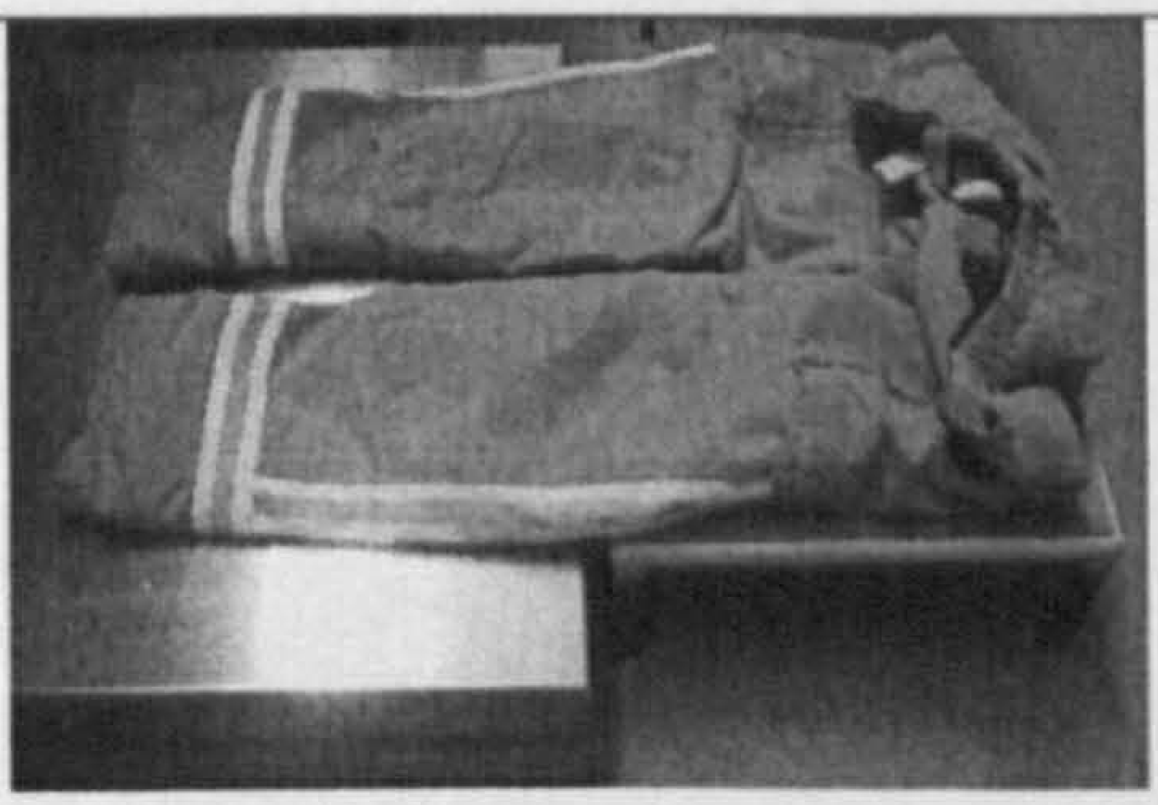
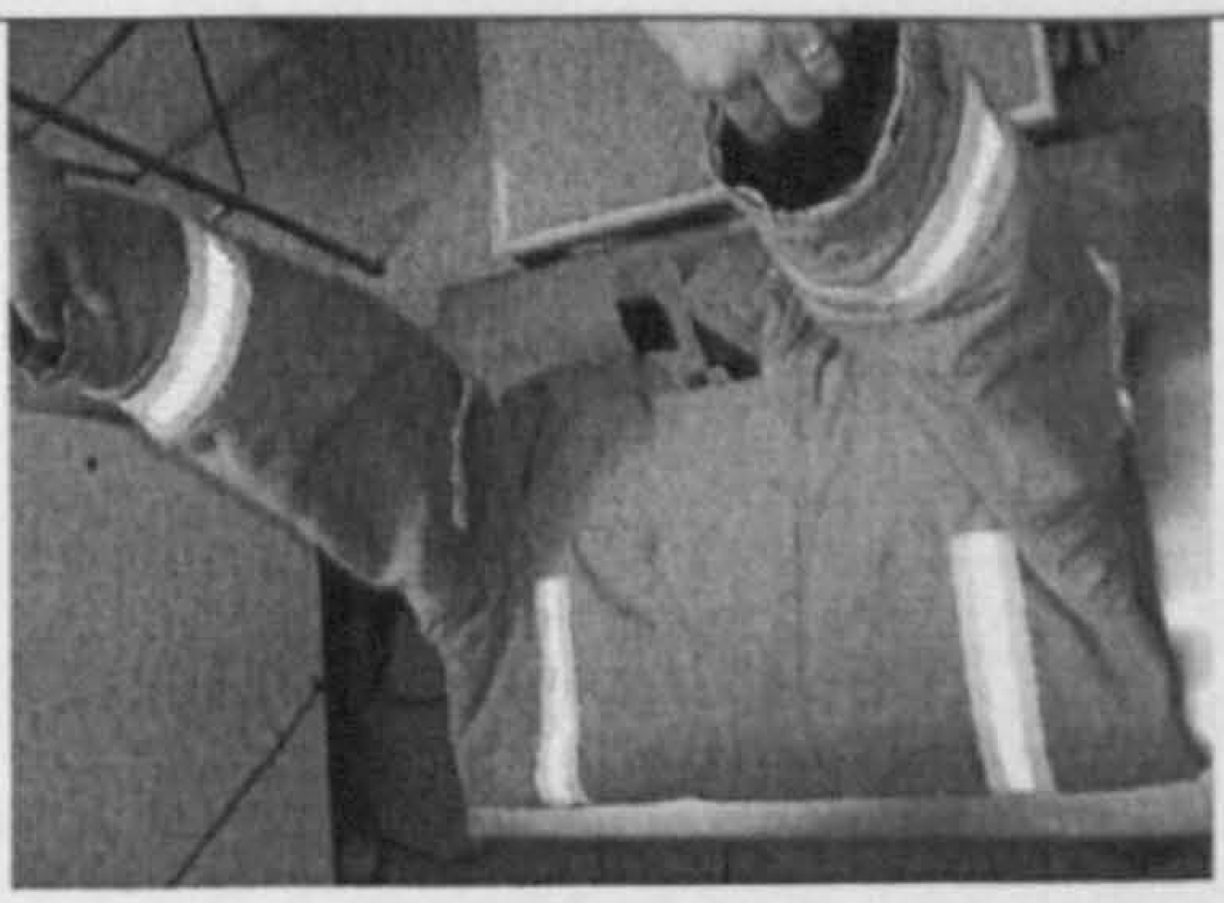
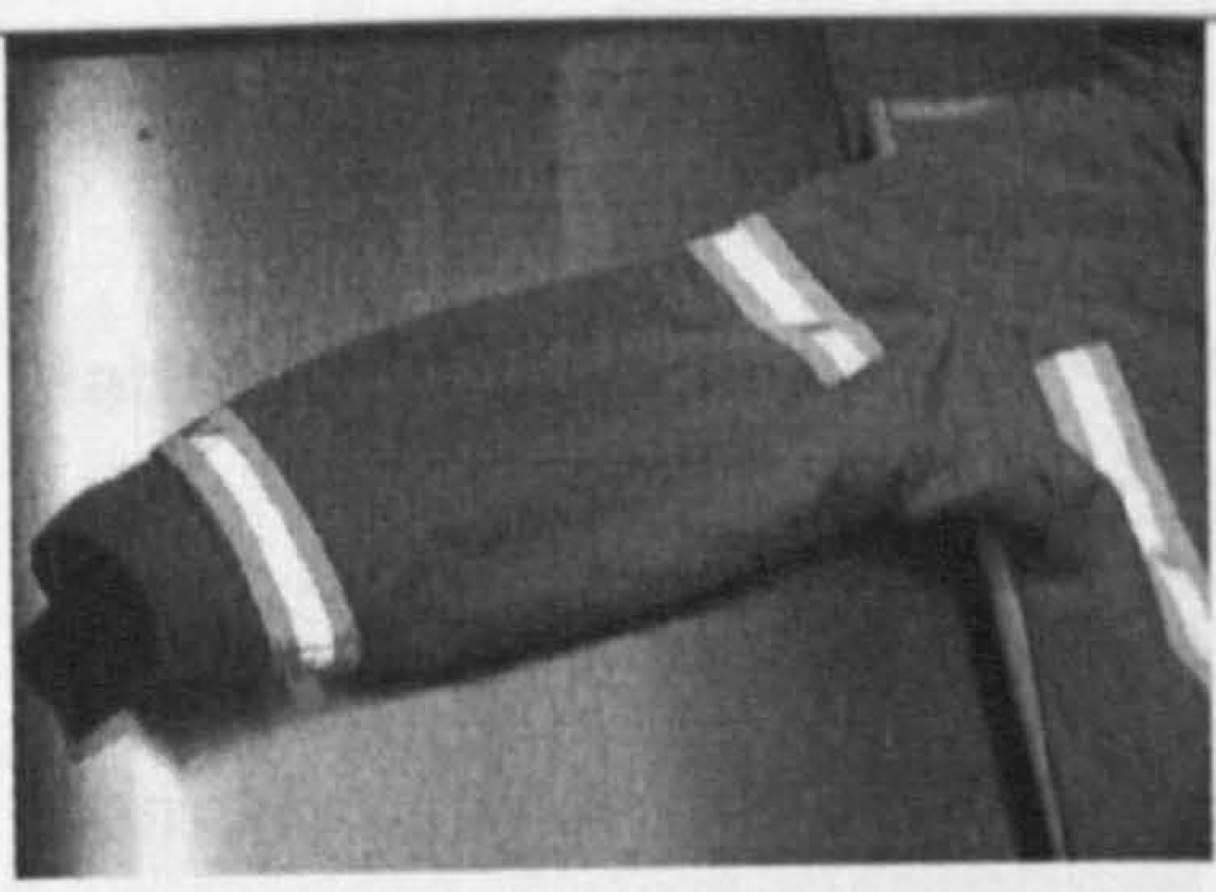


Figure 4.1. Photograph of scales and platform used to weigh garments.

The trouser garments were split into 3 sections to be weighed as shown in Table 4.1, with the weight of the garment to be weighed placed on the scales and the rest of the weight supported by the platform. Three weights were also recorded for the jacket part of the garments. Descriptions of the sections weighed and photographs to illustrate the method are also included in Table 4.1.

Table 4.1. Photographs and descriptions of the weighing of the lower body garment sections.

Photograph	Description
	Legs 1 measurement - Crotch Weight of legs of the garment supported on the platform.
	Legs 2 measurement - Upper legs Weight of crotch of garment supported on platform. Legs of garment folded to fit on scales, weighing from crotch downwards. Upper legs weight calculated from this weight minus lower legs weight.
	Legs 3 measurement - Lower legs Weight of crotch and upper legs supported on platform. Weighing garment from knees down.
	Arms 1 measurement - Torso Weight of torso calculated by subtracting weight of arms from total jacket weight. (Checked by placing garment torso on scales, with weight of garment arms supported.)

	Arms 2 measurement - Upper arms Weight of garment torso supported by platform. Weight of sleeve measured from shoulder seam. Upper arms weight calculated from this weight minus lower arms weight.
	Arms 3 measurement - Lower arms Weight of garment torso and upper arm supported on platform, weight of sleeve from elbow down weighed on scales.

Methods for measuring clothing insulation

For the manikin measurements in this chapter, Newton a 34 zone walking thermal manikin (Measurement Technology Northwest, Seattle, USA) was used. The dimensions of the manikin are designed to match a 50th percentile US / European male (see Figure 5.1 for photographs). The accompanying computer system measures the temperature and power consumption of each of the 34 independently heated thermal zones.

12 garments (plus the control tracksuit) were each measured twice on the thermal manikin, whose skin temperature was set to be maintained at 34°C. The ambient conditions were 17°C, 50% relative humidity.

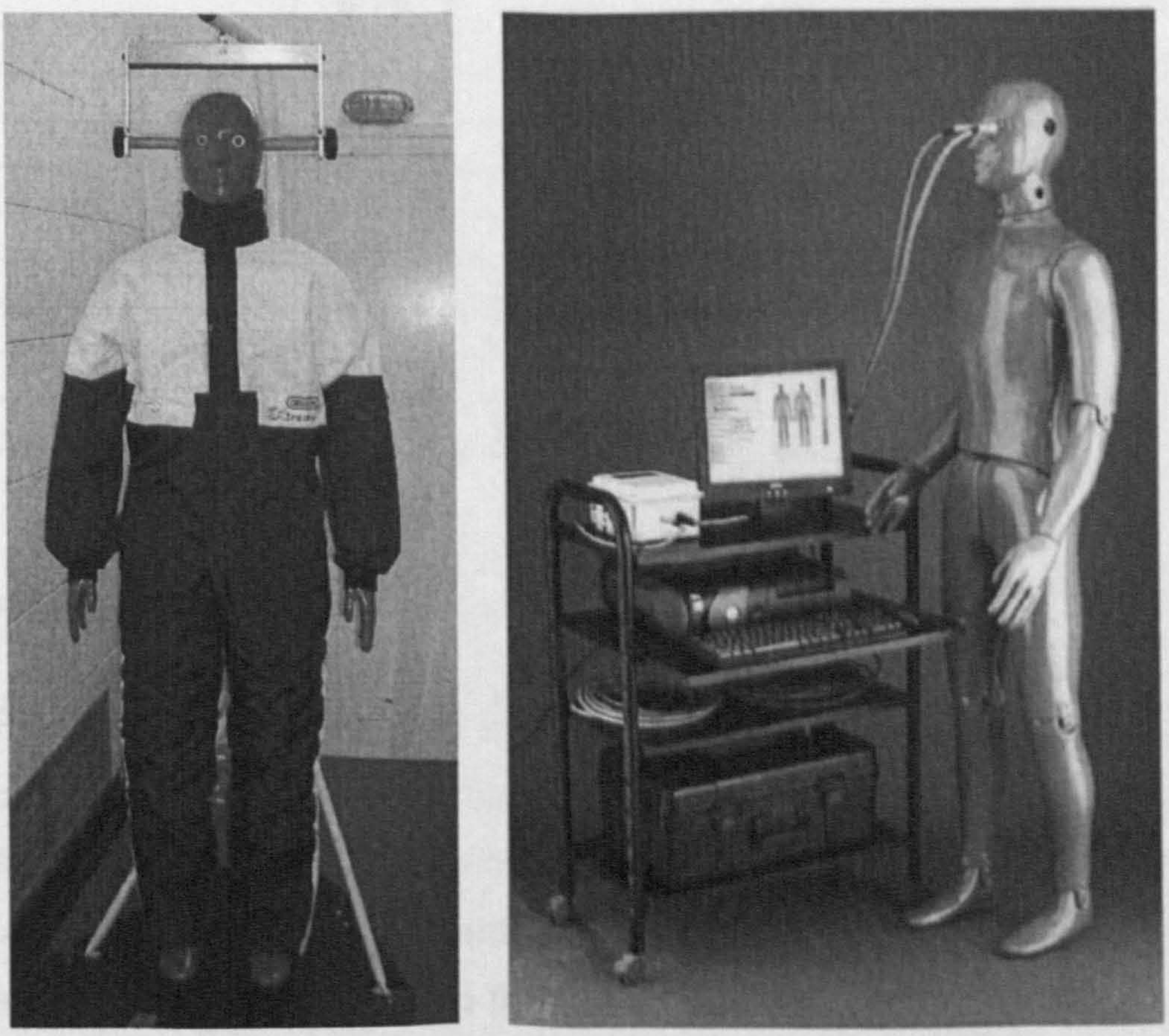


Figure 5.1. Photographs of Newton, clothed in PPC and 'nude' with operating system (Measurement Technology Northwest).

Methods for measuring clothing bulk

Clothing bulk was measured using 3 different methods, fit bulk and circumference bulk involved measuring the bulk of garments whilst worn, with the final method, thickness bulk, based on measuring the material bulk of the garments. 12 PPC garments were measured.

Measurements for the first two methods were made on eight participants (4 male, 4 female). They were all volunteers drawn from the student population at Loughborough University. Their physical characteristics are detailed in Table 6.1 below.

Table 6.1. Participant details.

Participant no.	Gender M / F	Age years	Height cm	Weight kg
1	F	21.4	169	65
2	M	35.8	180	55
3	M	22.2	175	85
4	F	29.8	168	57
5	M	29.3	176	91
6	F	27	150	59
7	F	22.1	171	59
8	M	24.8	183	79
Average ± SD		26.6 ± 5.0	171.5 ± 10.1	68.8 ± 14.1

Fit bulk method

Participants were provided with a pair of work trousers and t-shirt to wear under the protective garments being measured. Measurements of the excess clothing fabric were then made at 3 sites; the upper arm, torso and upper thigh, using a standard tape measure, by pinching the clothing fabric at each site and measuring the excess fold of material as illustrated by the photographs in Figure 6.1 below.

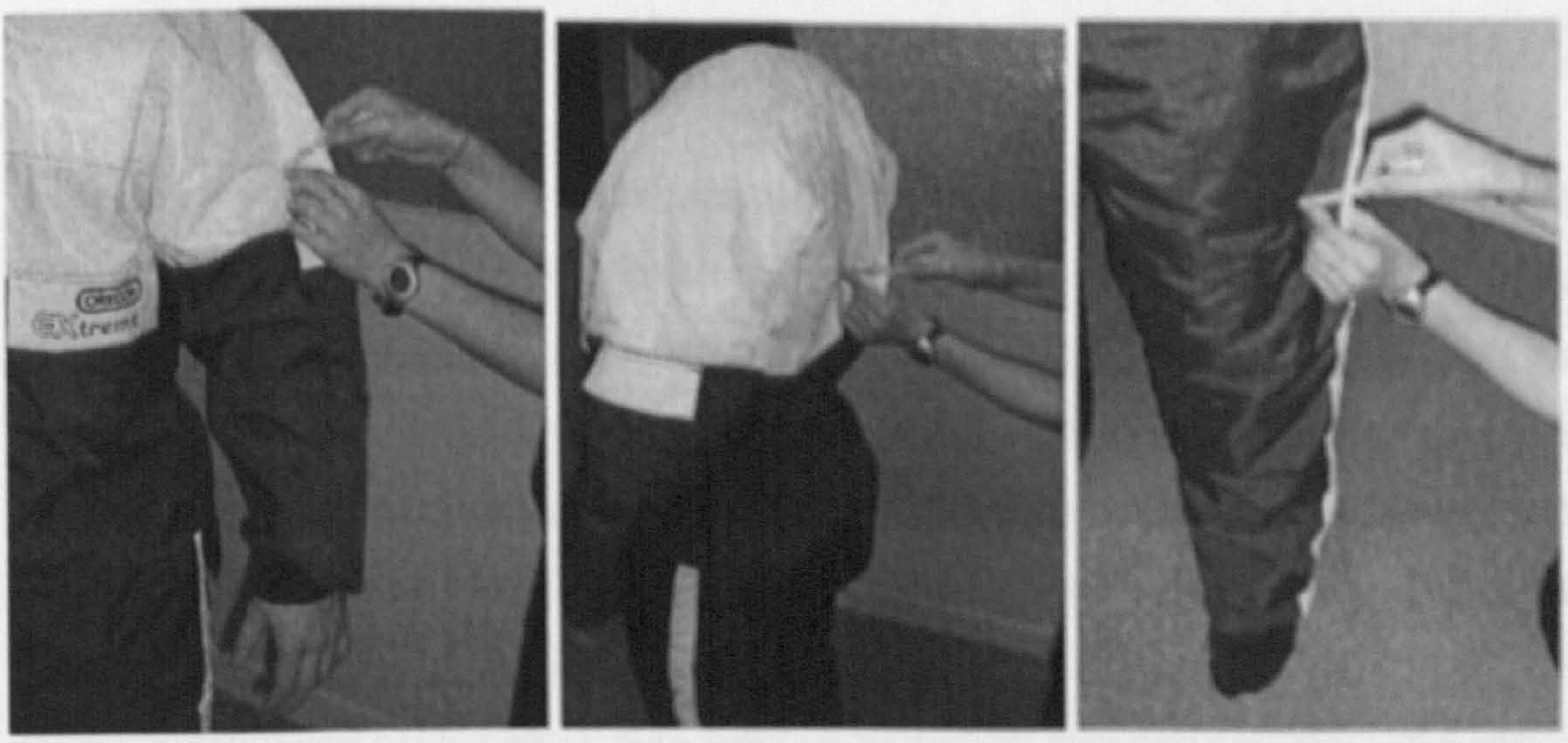


Figure 6.1. Photographs showing site (upper arm, torso and upper thigh) and method of measuring excess clothing bulk by pinching the excess fabric and measuring fold of material.

Circumference bulk method

Participants were provided with a pair of work trousers and t-shirt to wear and the circumference of the upper arm, torso and upper thigh was measured using a tape measure. Participants were then issued with the PPC garments to wear over the work trousers and t-shirt. Measurements of the circumference at the upper arm, torso and upper thigh, over the top of each PPC garment were then made, as illustrated in Figure 6.2. The values for the circumference of the arm, torso and leg in the standard work trousers and t-shirt were subtracted from the values recorded for each PPC garment.

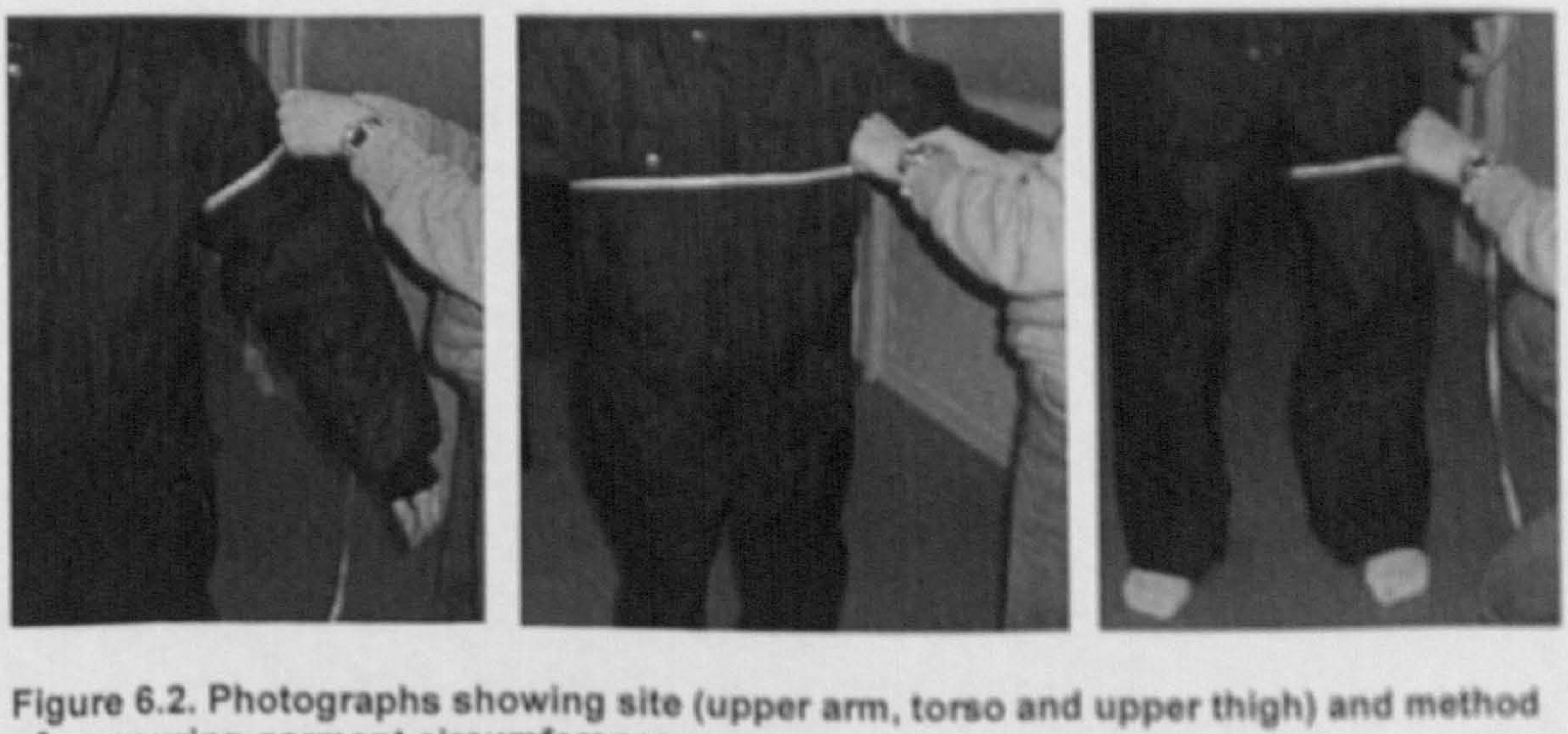


Figure 6.2. Photographs showing site (upper arm, torso and upper thigh) and method of measuring garment circumference.

Thickness bulk method

The final method used to estimate the clothing bulk, involved laying each garment out on the floor with a wooden metre rule placed across the segment to be measured, arm, torso or leg. A smaller metal ruler, placed on the floor at right angles to the metre ruler, allowed the thickness bulk of the clothing to be recorded by reading off the value on the metal ruler, which equated to the thickness of each garment section. Figure 6.3 contains photographs to illustrate the method.

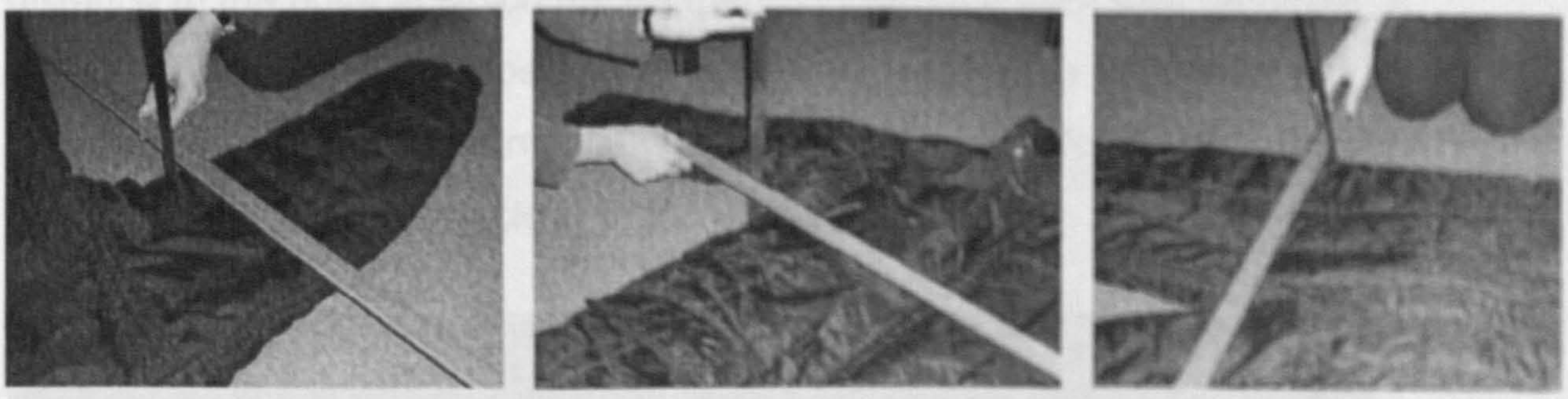


Figure 6.3. Photographs showing site (arm, torso and leg) and method of measuring clothing thickness bulk by measuring the thickness of the material.

Methods for measuring clothing stiffness

Estimates of garment stiffness were made for 3 sites, the arm (sleeve), torso (main body of the garment) and leg (trousers). Measurements were made by supporting the garment on a small platform 20cm above the ground, as illustrated in Figure 7.1 and allowing the section of the garment to be measured to drape over the edge. A tape was in place on the floor and the distance to the point at which the garment touched the floor was recorded. A stiff fabric would not drape easily off the edge of the platform and its recorded value would be much higher than that of a floppy fabric which would touch the floor very close to the platform.

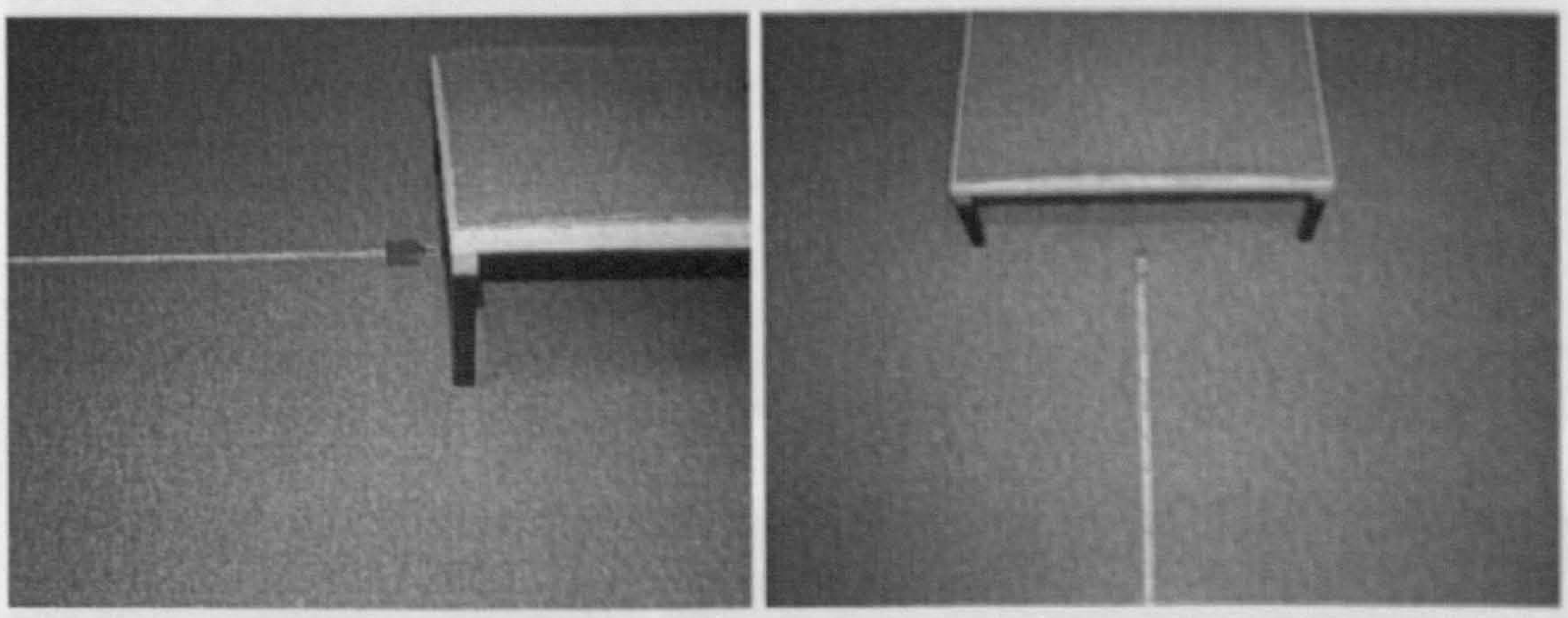


Figure 7.1. Photographs to illustrate platform and tape measure used for stiffness measurements and their positions during measurements.

For the arm measurement the main body of the garment was placed on the platform with the seam of the left sleeve on the edge of the platform allowing the left sleeve of the garment to drape off the platform as in Figure 7.2. For the torso measurement, the main body of the garment was supported on the platform with the armpits of the garment in line with the edge of the platform allowing the torso section of the garment to drape over the edge, this is shown in Figure 7.3. In order to estimate the stiffness of the garment in the leg as accurately as possible the trousers were laid on the platform with the crotch at the edge of the platform and the left leg of the garment draped off the platform as illustrated in Figure 7.4.

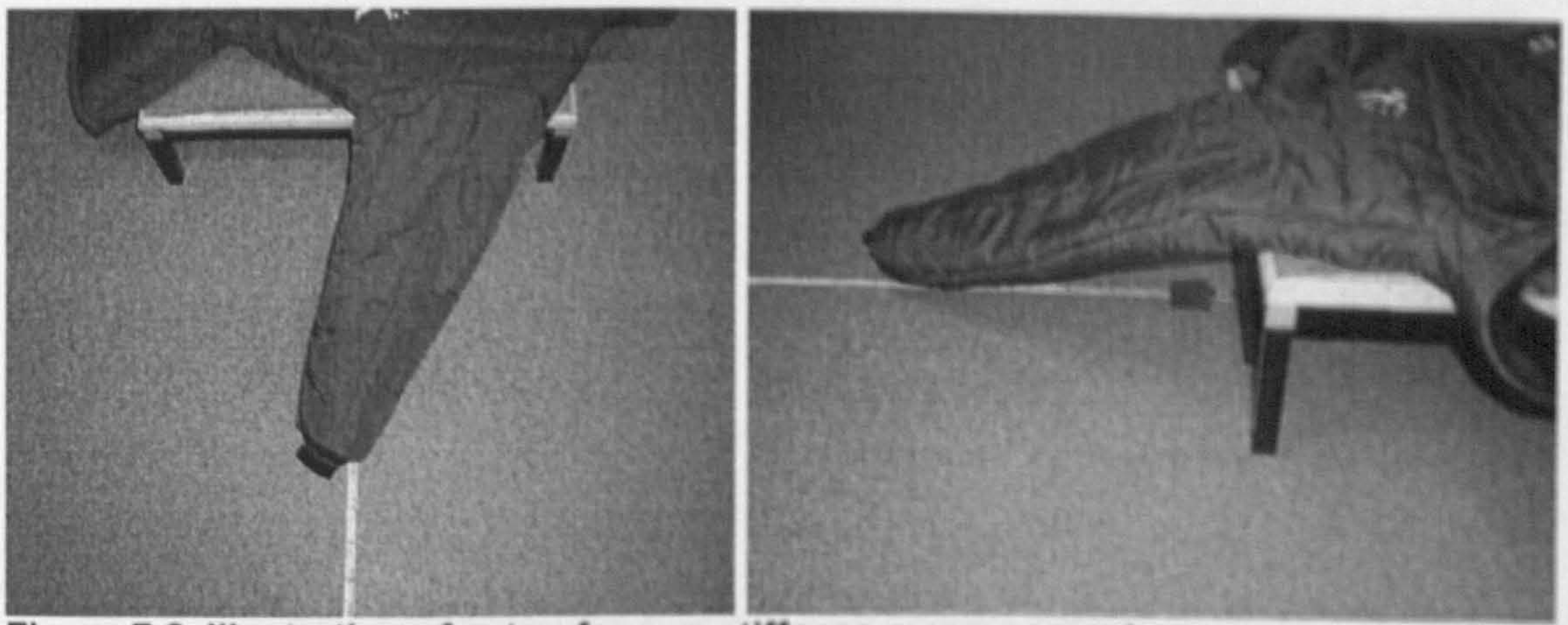


Figure 7.2. Illustration of setup for arm stiffness measurement.

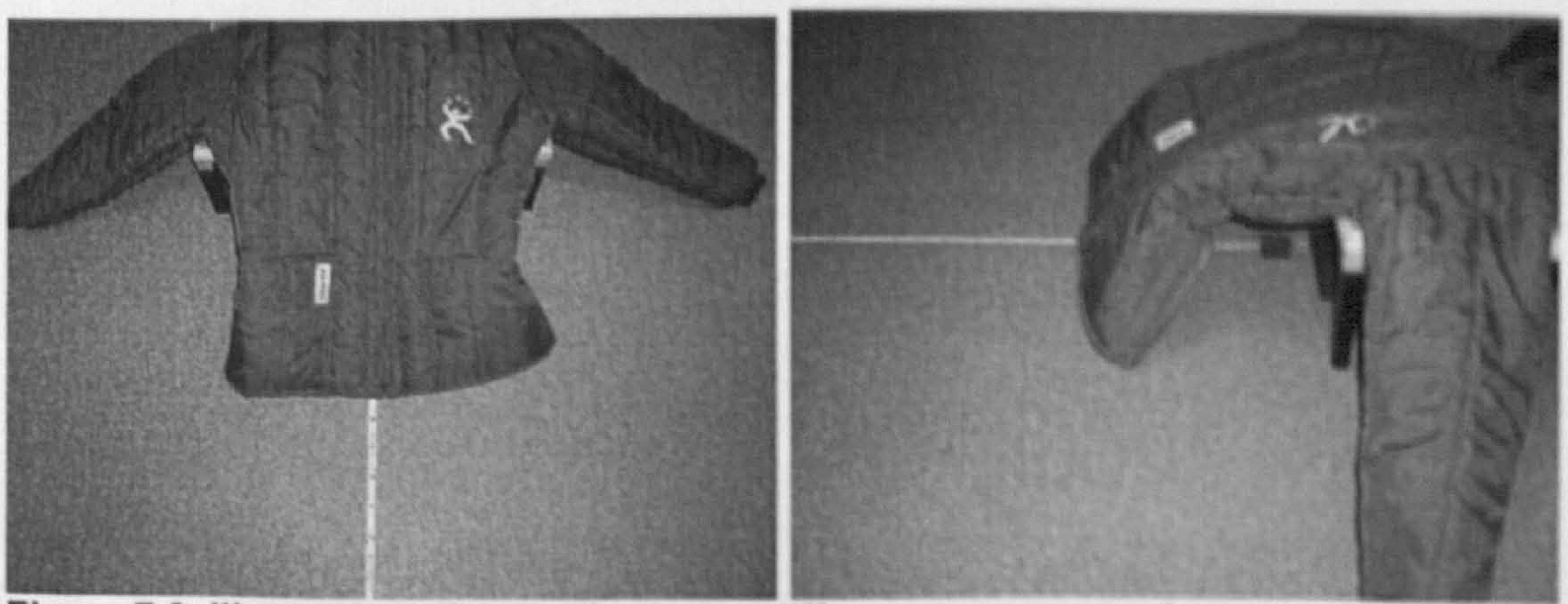


Figure 7.3. Illustration of setup for torso stiffness measurement.

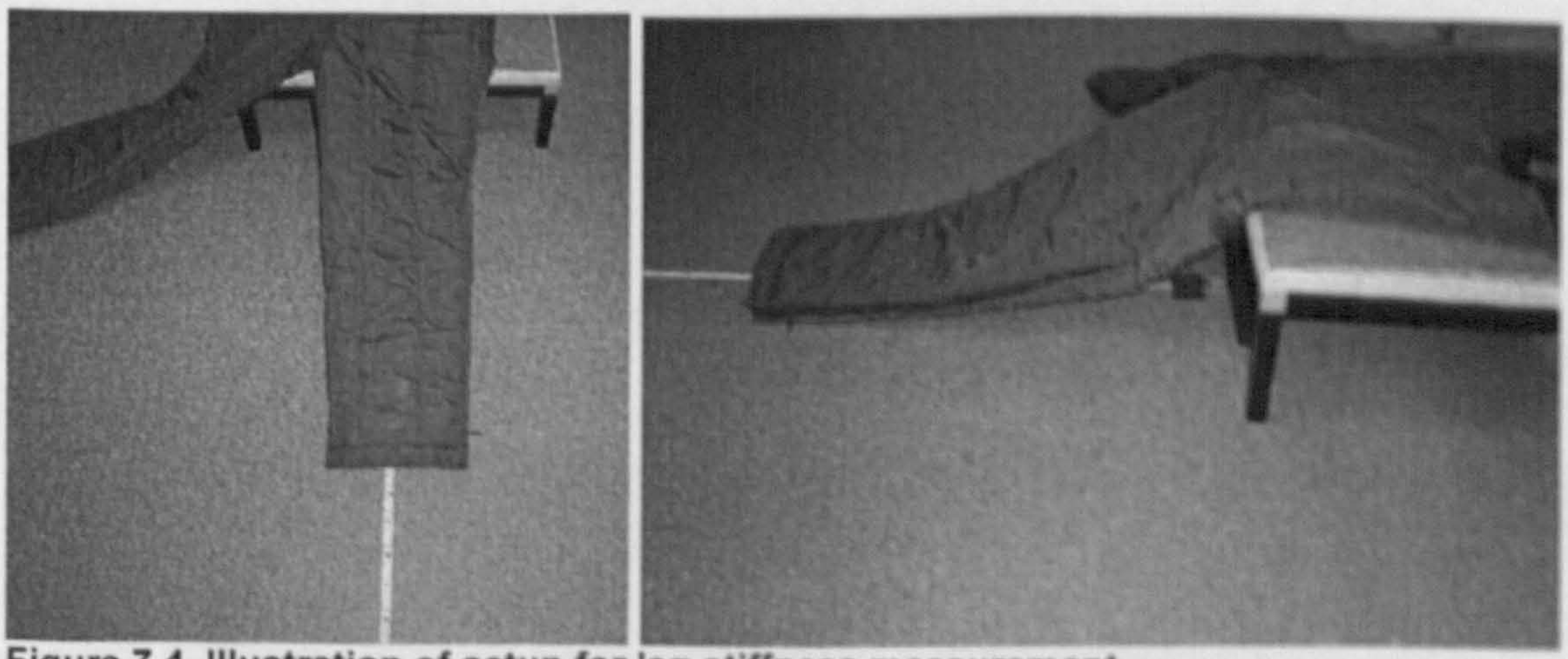


Figure 7.4. Illustration of setup for leg stiffness measurement.