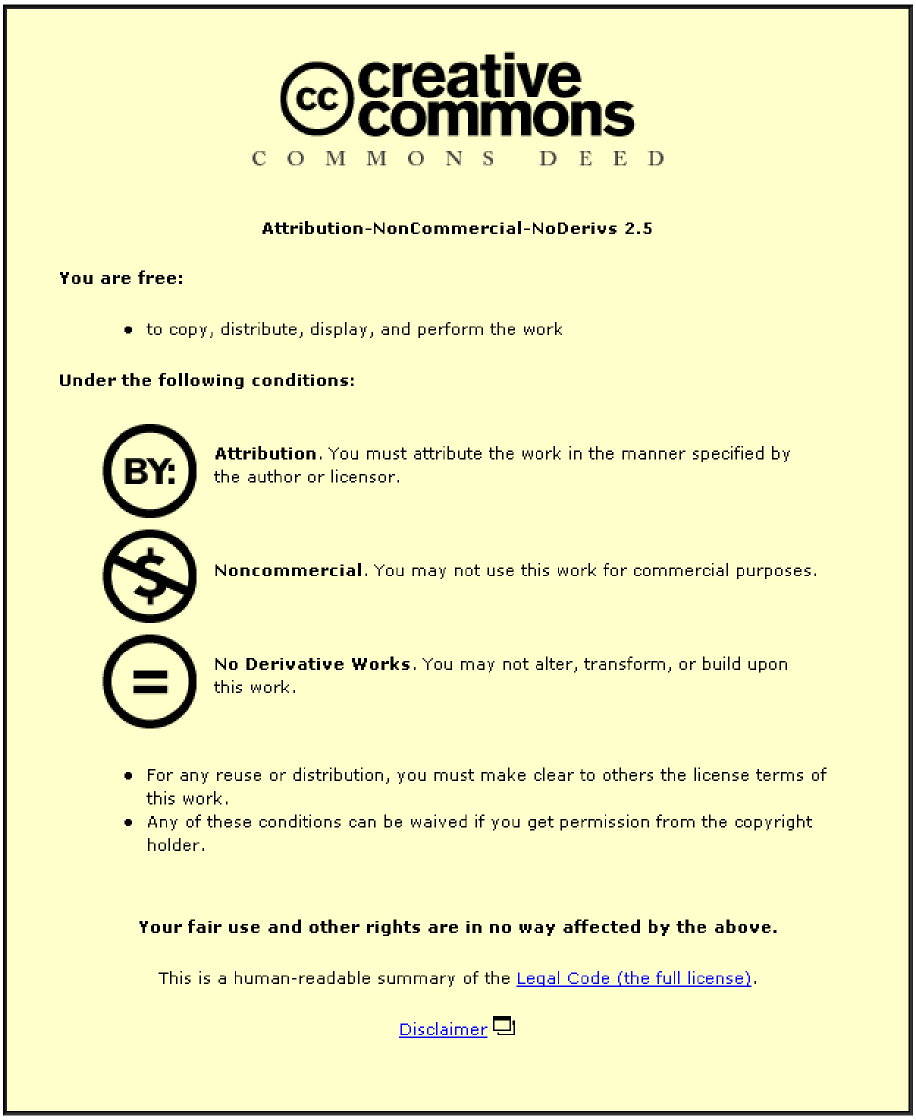

MODELLING THE EFFECTS OF PERSONAL PROTECTIVE CLOTHING PROPERTIES ON THE INCREASE OF METABOLIC RATE

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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.

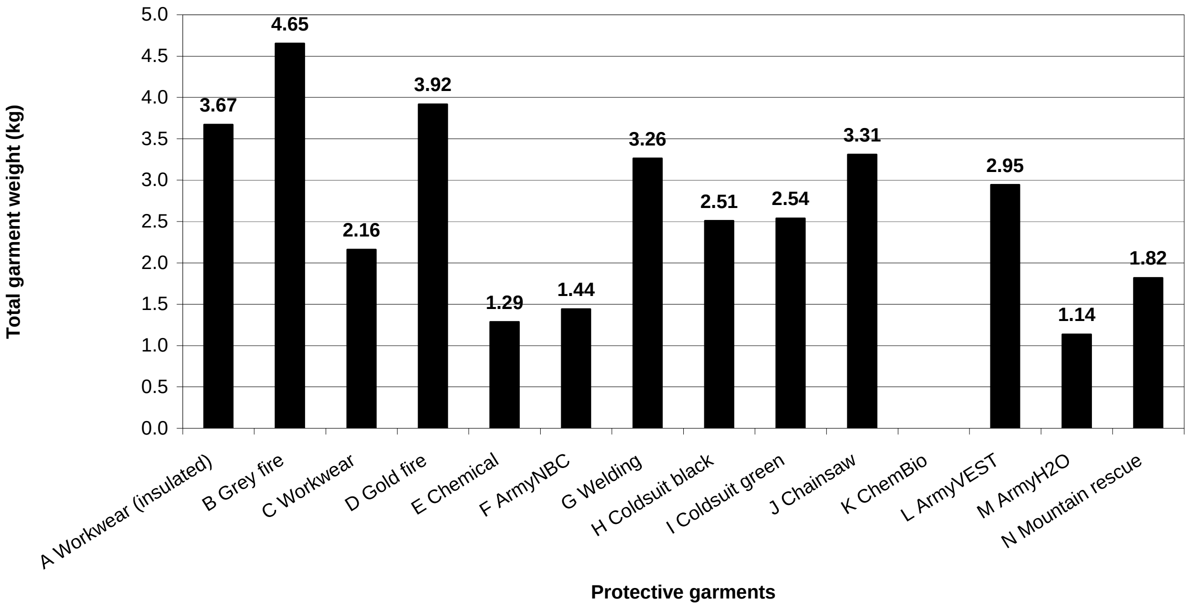

Figure 2.1. Protective garments and their total weight (ChemBio not available).

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

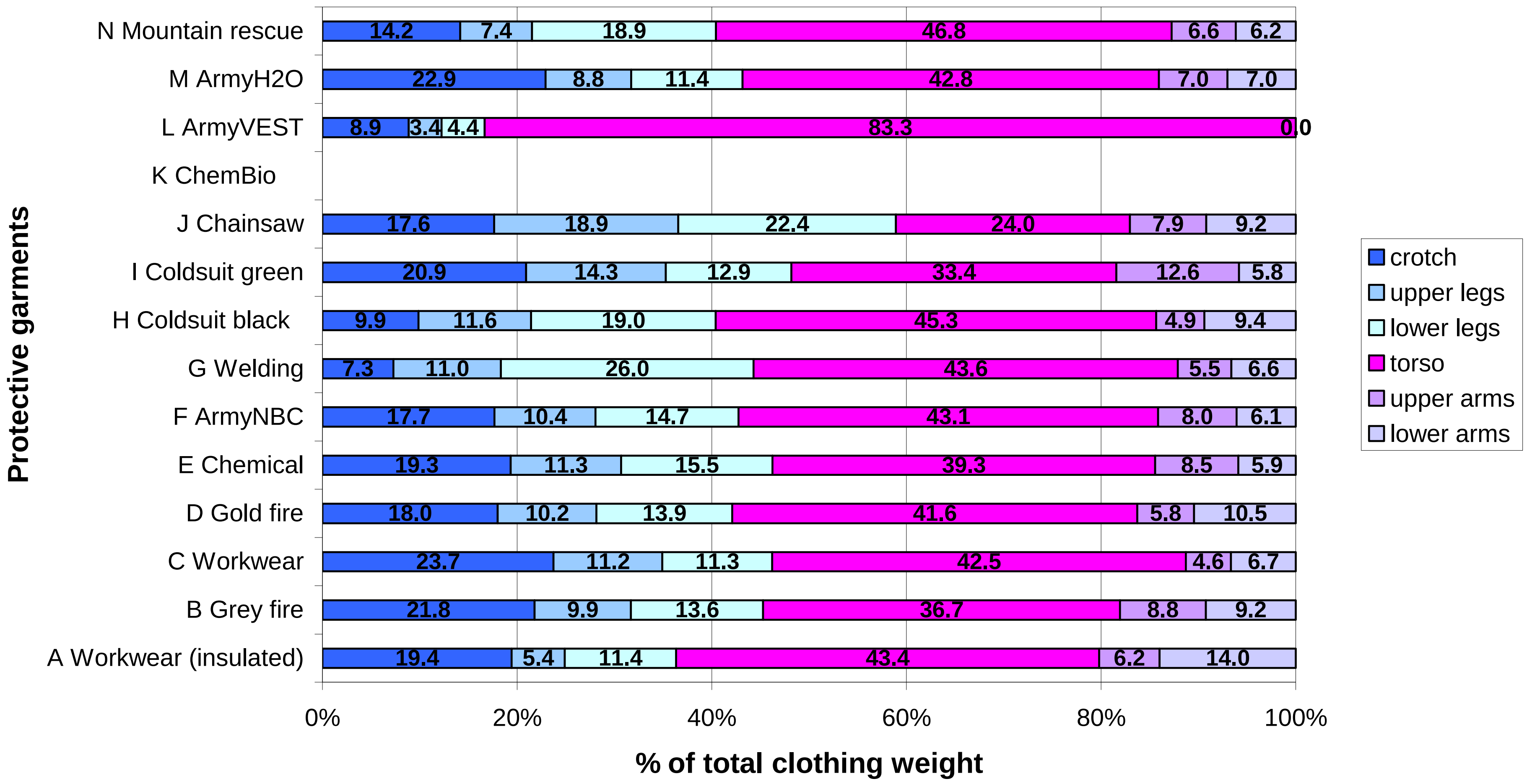

Figure 2.2. Garment section weights as a % of total clothing weight for all protective garments (ChemBio not available).

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 (^oC) between the skin and clothing surface and the thermal conductivity ($W\ m^2\ /\ ^oC$) of the clothing. Intrinsic clothing insulation is the reciprocal of clothing conductivity with units of $m^2\ ^oC\ /\ W$ (Parsons 2003).

Gagge *el al.* (1941) first proposed the Clo unit, to replace the rather physical unit of $m^2\ ^oC\ /\ W$ 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^oC and is said to have an average value of $0.155\ m^2\ ^oC\ /\ W$, 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**

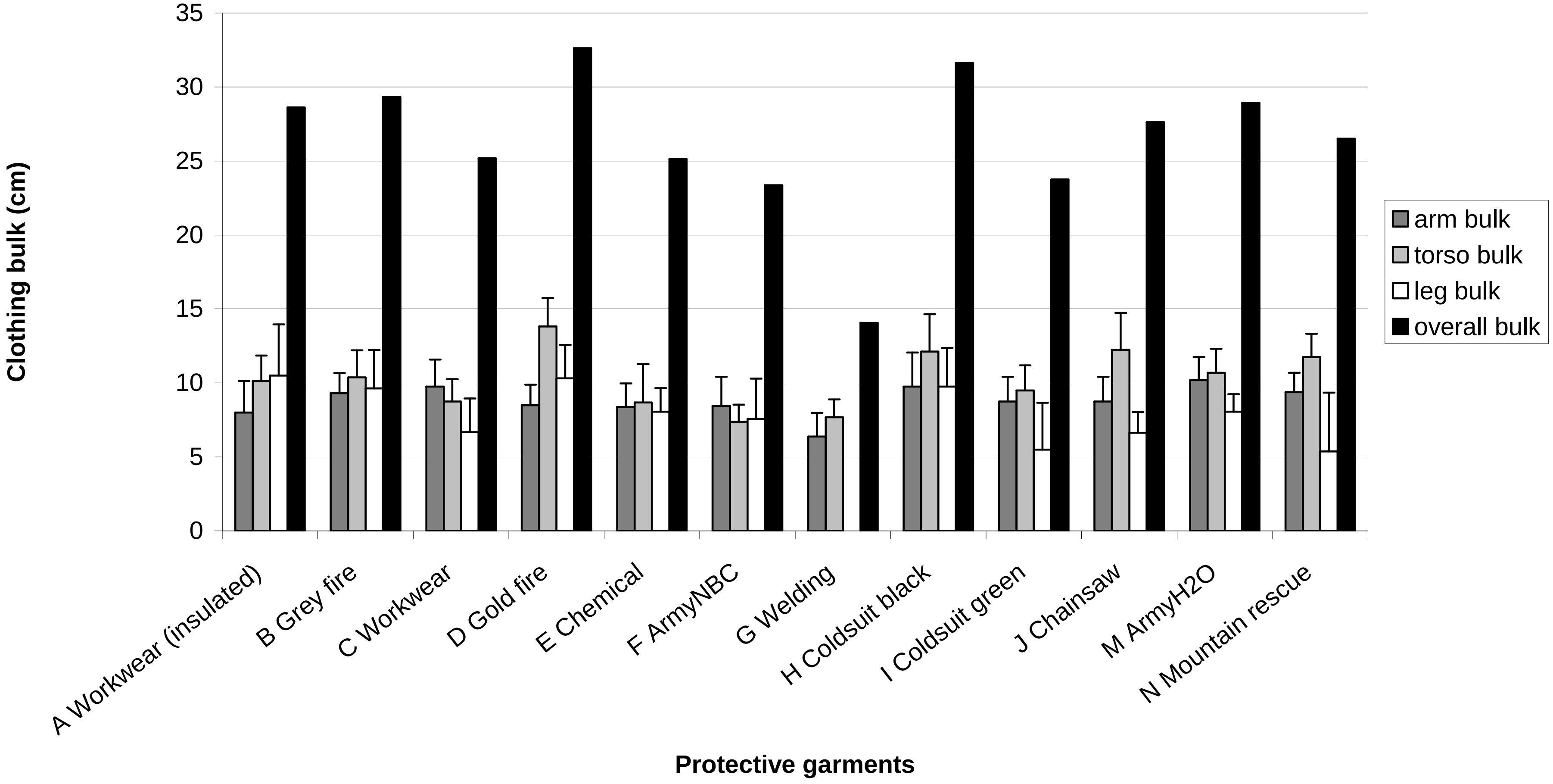

Figure 2.3 Bar chart showing values for arm, torso, leg and overall clothing FIT BULK (measured in cms) for 12 protective garments (the coverage on the legs for the welding garment was made up a split apron that was fastened around the legs with velcro therefore as it did not reach around the back of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

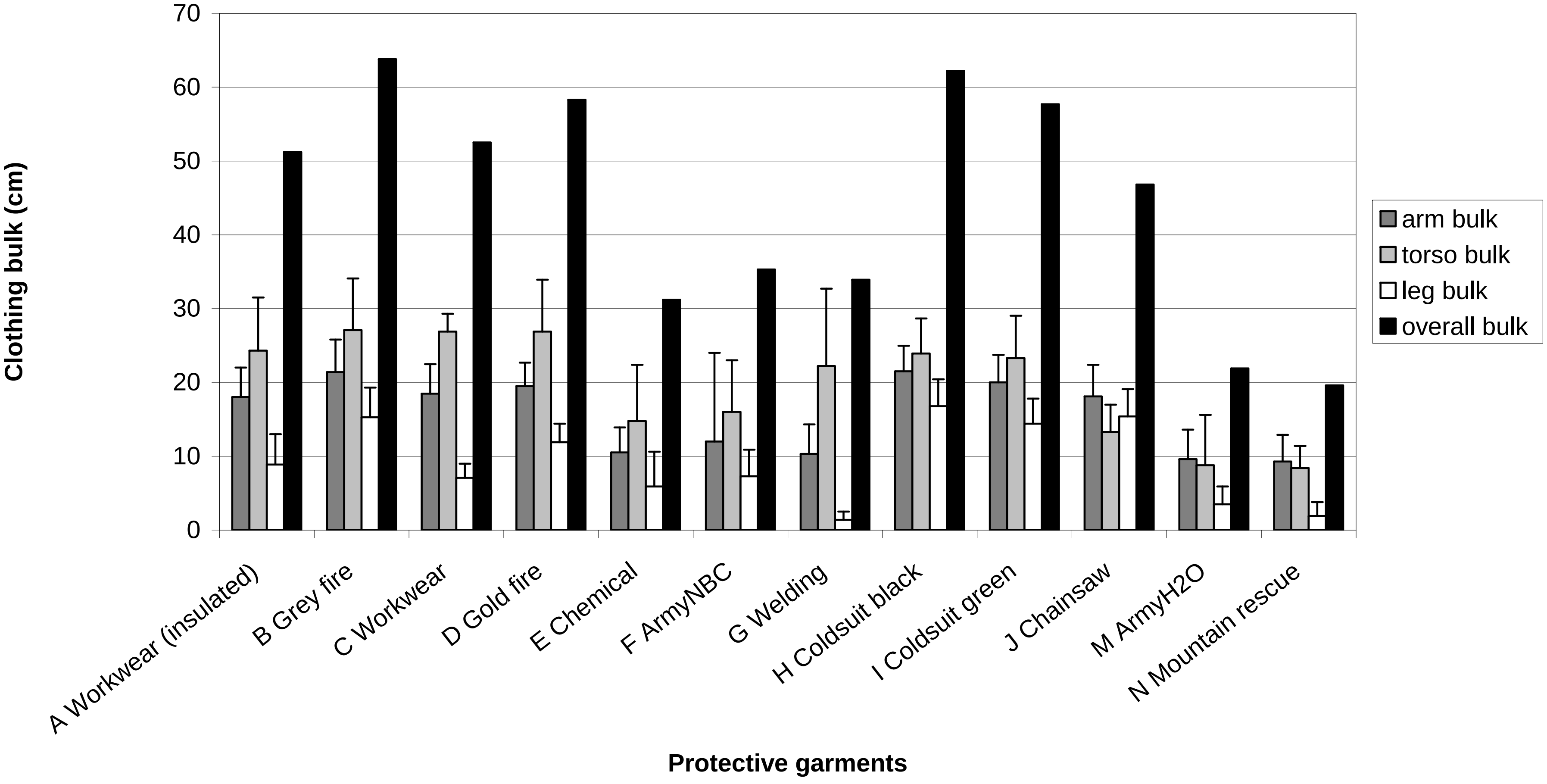

Figure 2.4. Bar chart showing values for arm, torso, leg and overall clothing CIRCUMFERENCE BULK (measured in cms) for 12 protective garments.

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.

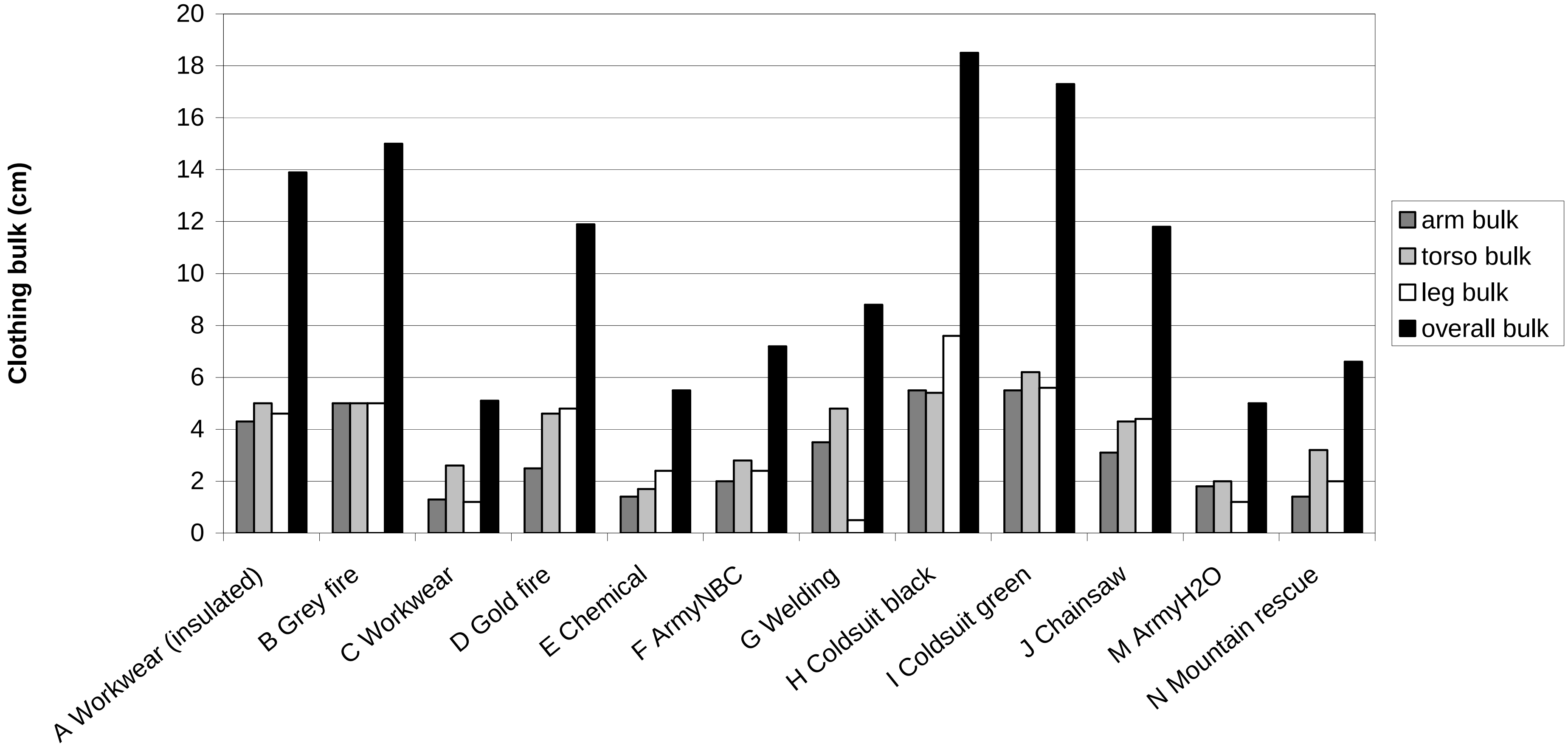

Figure 2.5. Bar chart showing values for arm, torso, leg and overall clothing THICKNESS BULK (measured in cms) for 12 protective garments.

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.

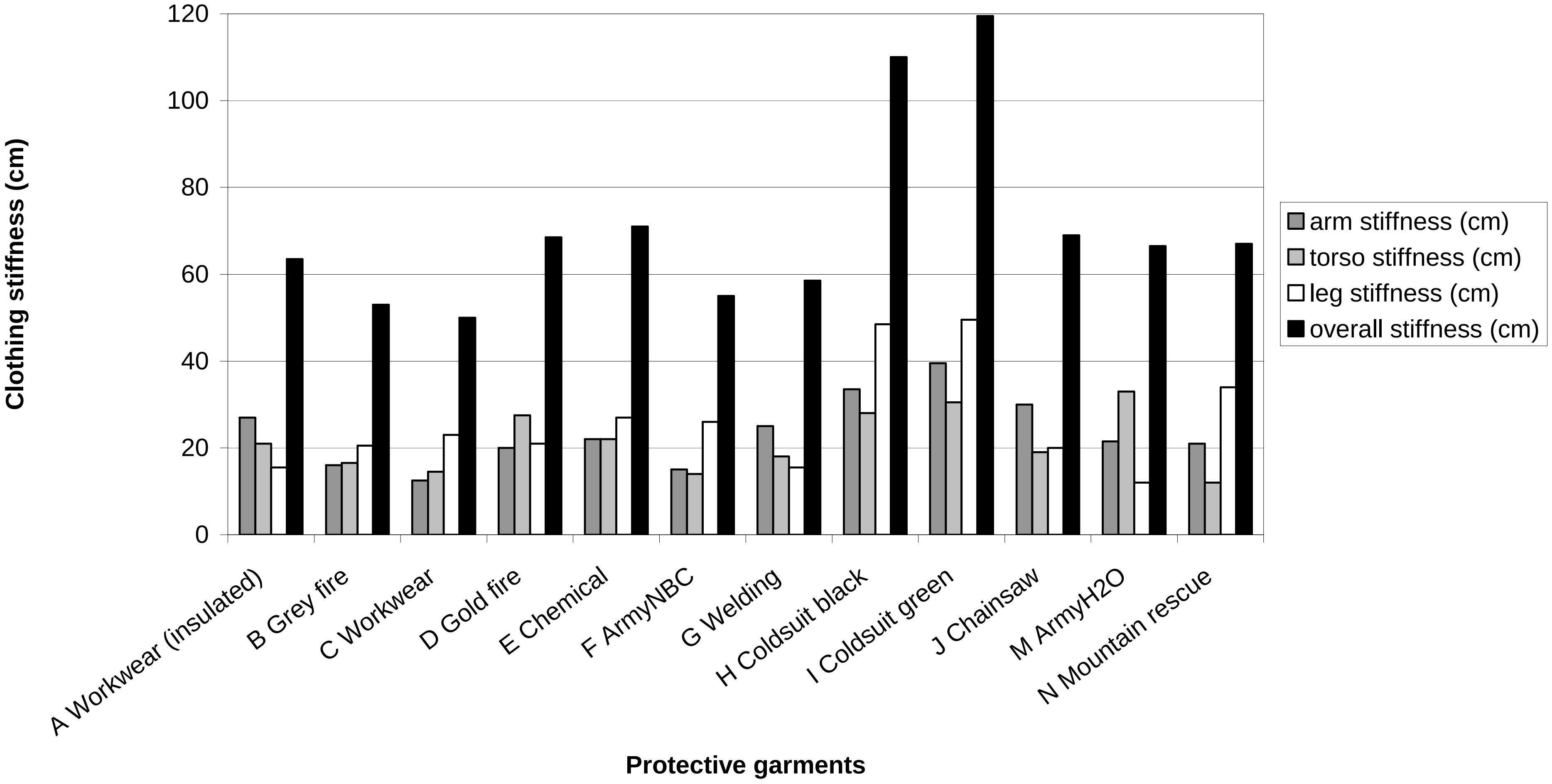

Figure 2.6. Bar chart showing values for arm, torso, leg and overall stiffness (measured in cms) for 12 protective garments. Stiffer garments produce higher values.

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.

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