- EFFECTS OF SIMULATED CLOTHING WEIGHT DISTRIBUTIONS ON METABOLIC RATE-

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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.

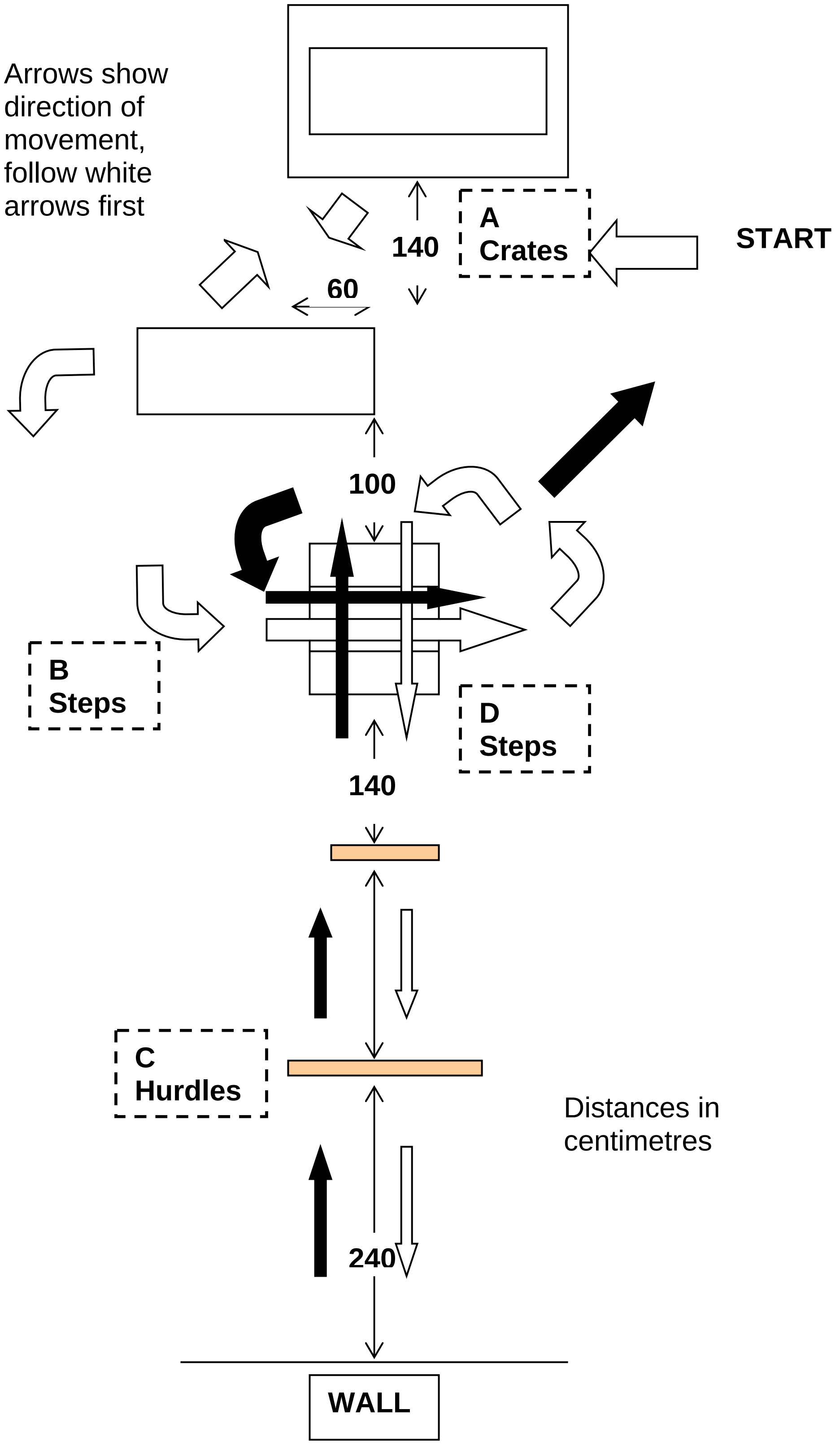

Figure 2.2. Floor plan for the obstacle course completed. A key for the shapes used can be found in Table 2.3, Equipment section, Chapter 2. For extra explanation of boxes with dashed lines, see detailed task descriptions in Table 2.3, Equipment section, Chapter 2, including photographs.

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 ^{o}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		**Heart Rate**	**$\dot{V}O_2$**	**RER**	**Met Rate**	**Met Rate**
COURSE		**[bpm]**	**[l/min]**		**[W]**	**[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.

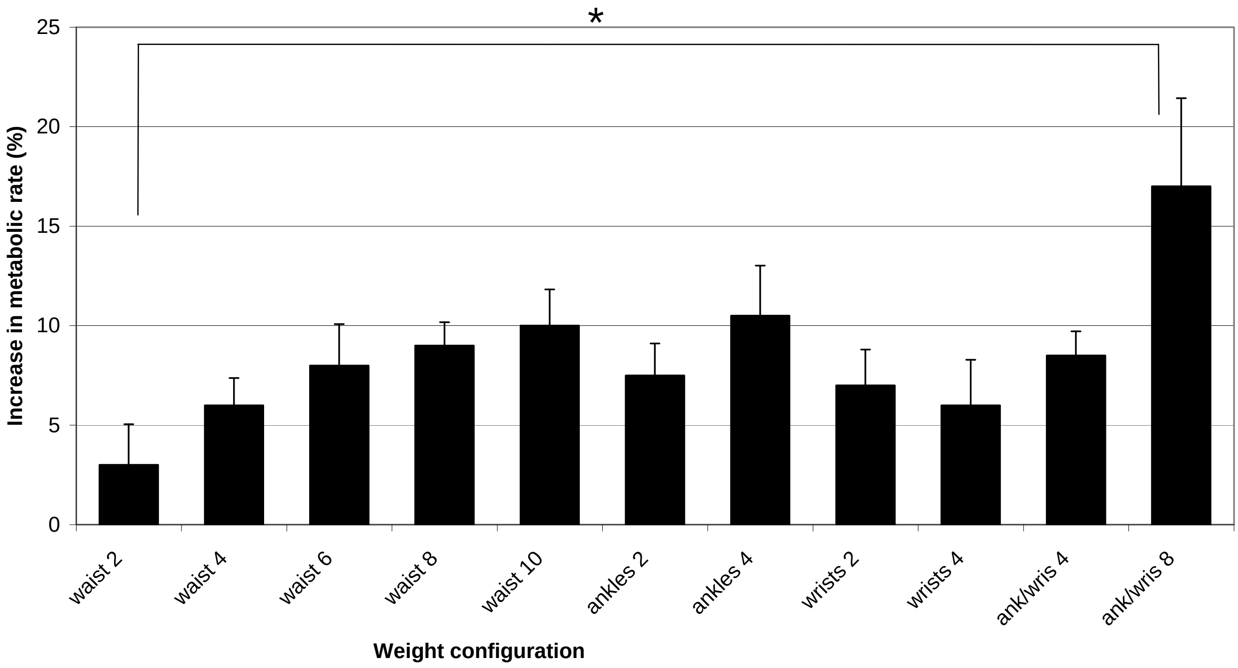

Figure 3.1. Increase in metabolic rate when carrying weight simulations around the waist, ankles and wrists (ank/wris; weight split between sites) when walking at 5 km/hr on a treadmill compared to an unweighted control, significance ($p<0.05$) marked by *. (weights in kgs on x-axis).

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.

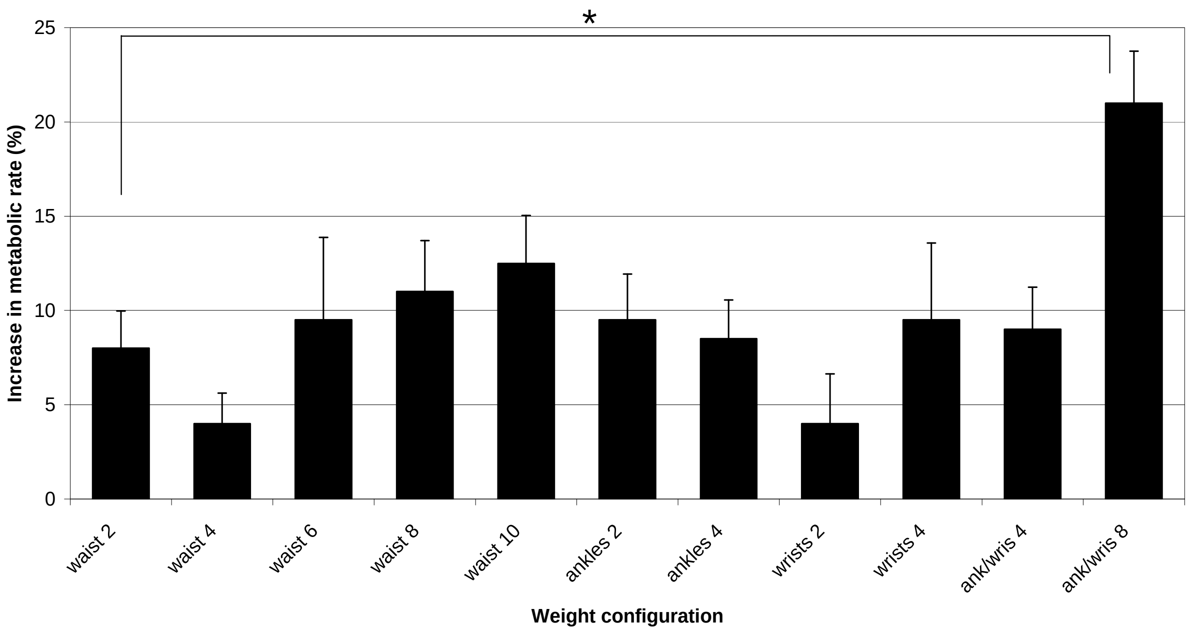

Figure 3.2. Increase in metabolic rate when carrying weight simulations around the waist, ankles and wrists (ank/wris; weight split between sites) when completing the obstacle course, compared to an unweighted control, significance (p<0.05) marked by *. (weights in kgs on x-axis).

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.

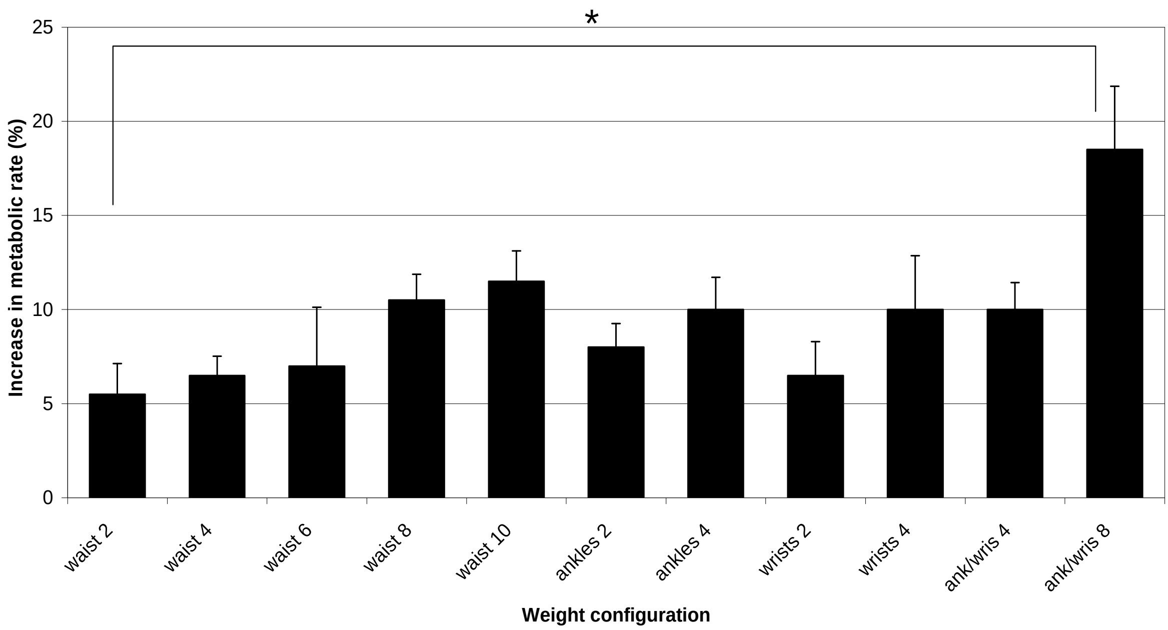

Figure 3.3. Overall increase in metabolic rate when carrying weight simulations around the waist, ankles and wrists (ank/wris; weight split between sites), based on average of data collected when walking and completing an obstacle course, compared to an unweighted control, significance ($p<0.05$) marked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

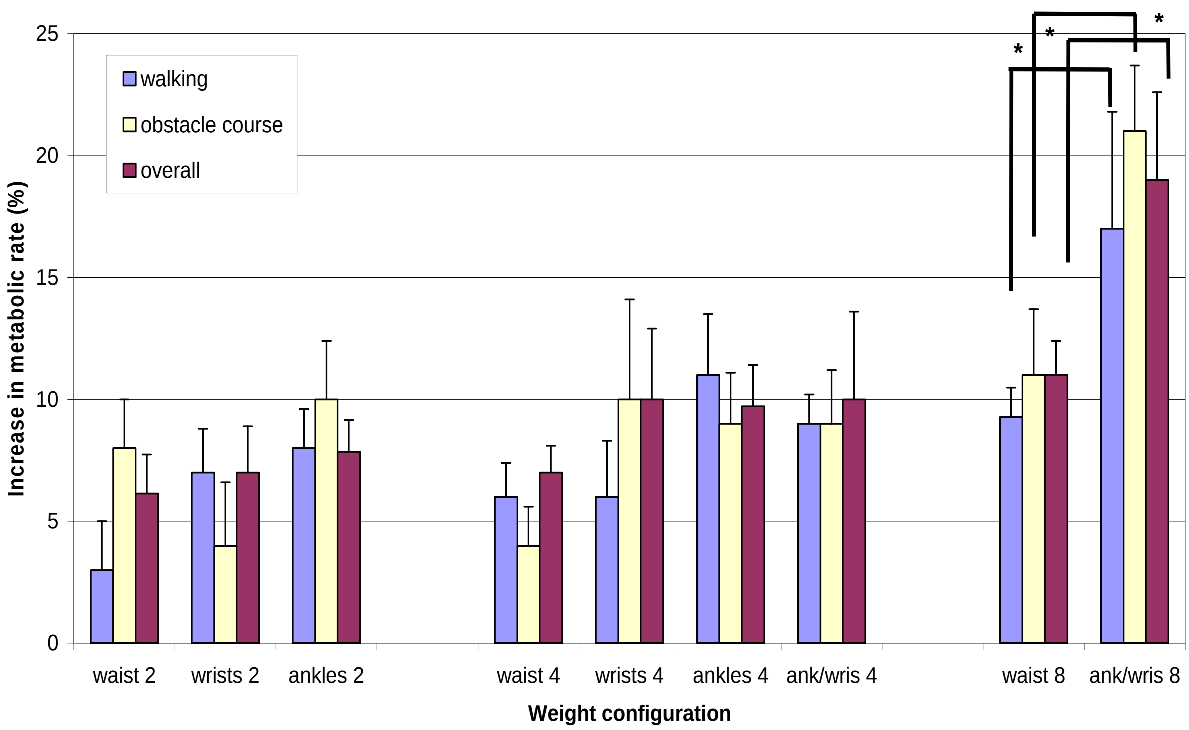

Figure 3.4. Increase in metabolic rate due to carrying weight around the waist, ankles, wrists or ankles and wrists (ank/wris) for two work modes, walking (light grey bars) and obstacle course (white bars) and overall (average of data collected when walking and completing an obstacle course (dark grey 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.

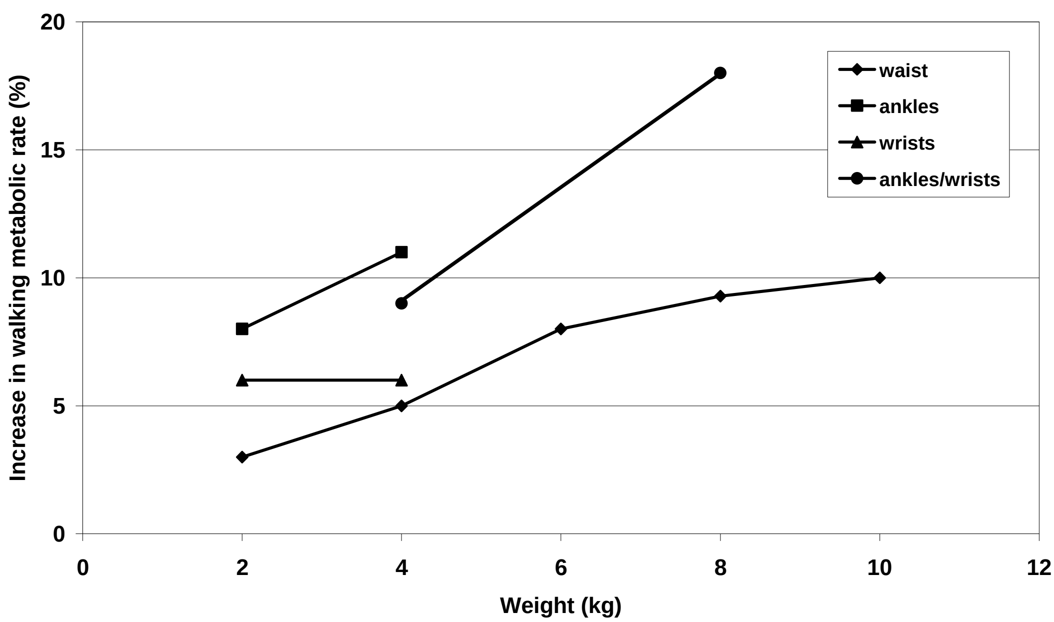

Figure 3.5. Graph of metabolic rate increase in relation to weight carried when walking for the 4 weight distribution sites (waist, ankles, wrists, ankles/wrists).

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.

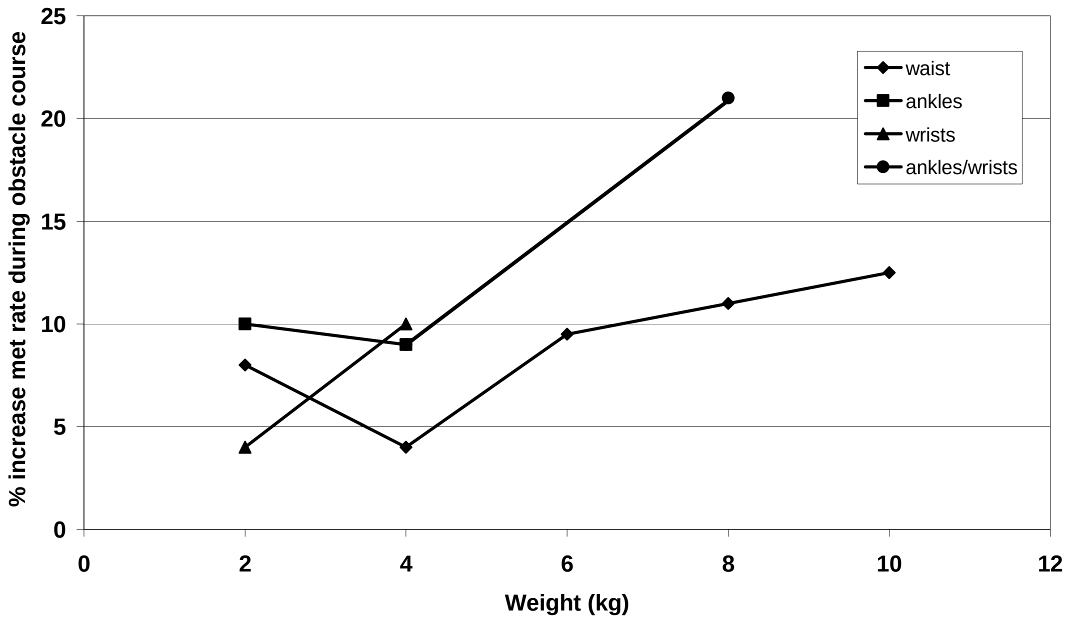

Figure 3.6. Graph of metabolic rate increase in relation to weight carried during the obstacle course for 4 weight distribution sites (waist, ankles, wrists, ankles/wrists).

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.

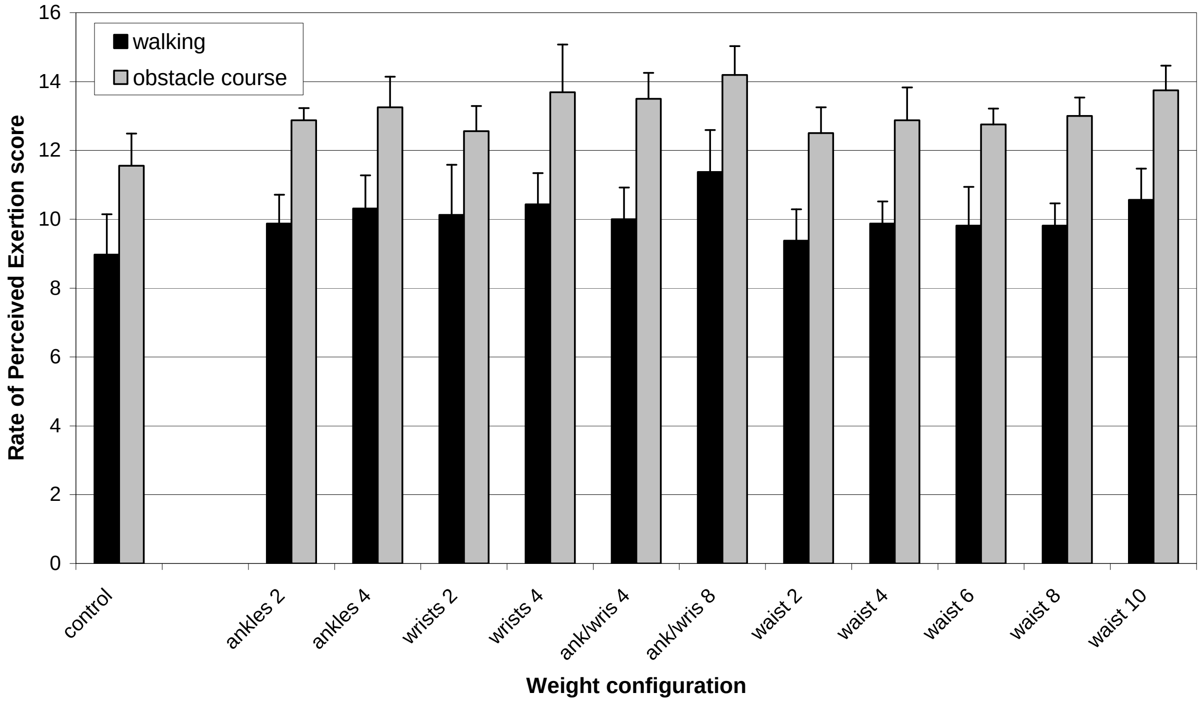

Figure 3.7. Graph of results of 'Rate of Perceived Exertion' responses taken during last minute of walking and obstacle course work modes for all weight simulations and control.

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.

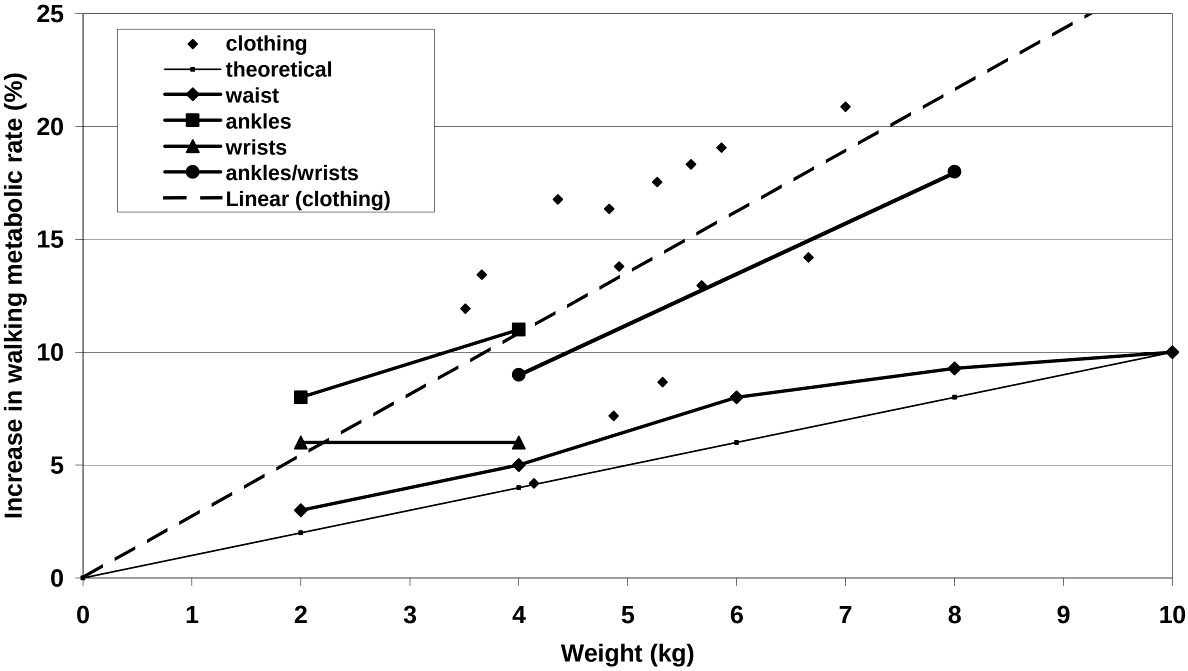

Figure 4.1. Increase in metabolic rate in relation to clothing weight or load carried on the waist, ankles, wrists, ankles/wrists. Theoretical line based on equation of Givoni and Goldman (1971).

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^{o}C, 29.5^{o}C and 30.0^{o}C in the 20^{o}C, 0^{o}C and –15^{o}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.

REFERENCES

Adams, P. H. and Keyserling, W. M. (1993). 'Three methods for measuring range of motion while wearing protective clothing; a comparative study.' *International Journal of Industrial Ergonomics* 12: 177-191.

Adams, P. S. and Keyserling, W. M. (1995). 'The effect of size and fabric weight of protective coveralls on range of gross body motions.' *American Industrial Hygiene Association Journal* 56: 333 -340.

Adams, P. S., Slocum, A. C. and Monroe Keyserling, W. (1994). 'A model for protective clothing effects on performance.' *International Journal of Clothing Science and Technology* 6(4): 6 - 16.

Adriaens, P. E., Schoffelen, P. F. M. and Westerterp, K. R. (2003). 'Intra-individual variation of basal metabolic rate and the influence of daily habitual physical activity before testing.' *British Journal of Nutrition* 90: 419-423.

Ainsworth, B. E., Haskell, W. L., Leon, A. S., Jacobs Jr, D. R., Montoye, H. J., Sallis, J. F. and Paffenbarger Jr, R. S. (1993). 'Compendium of Physical Activities: classification of energy costs of human physical activities.' *Medicine and Science in Sports and Exercise* 25(1): 71 - 80.

Ajayi, J. O. (1992a). 'Effects of fabric structure on frictional properties.' *Textile Research Journal* 62(2): 87-93.

Ajayi, J. O. (1992b). 'Fabric smoothness, friction and handle.' *Textile Research Journal* 62(1): 52-59.

Amor, A. F., Vogel, J. A. and Worsley, D. E. (1973). ‘The energy cost of wearing multilayer clothing.’ Army Personnel Research Establishment, Ministry of Defence. (Farnborough, Hants, UK). Report No. 18/73.

Anttonen, H., Rintamaki, H., Risikko, T., Oksa, J., Lehtonen, M., Meinander, H., Nousiainen, P. and Makinen, M. (2000). ‘Friction and function of clothing’ (in Finnish) Report to Scientific Board of National Defence, Oulu Regional Institute of Occupational Health.

Anttonen, H., Oksa, J., Lehtonen, M., Meinander, H. and Makinen, M. (2001). 'Friction of clothing and it's effect on performance'. *Nordic Military Clothing Seminar*, Helsinki, Finland (20-22 August 2001).

Attwells, R. L., Birrell, S. A., Hooper, R. H. and Mansfield, N. J. (2006). 'Influence of carrying heavy loads on soldiers' posture, movements and gait.' *Ergonomics* 49(14 / 15): 1527 - 1537.

Auble, T. E., Schwartz, L. and Robertson, R. J. (1987). 'Aerobic requirements for moving handweights through various ranges of motion while walking.' *The Physician and Sportsmedicine* 15(6): 133-140.

Baker, S. J., Grice, J., Roby, L. and Matthews, C. (2000). 'Cardiorespiratory and thermoregulatory response of working in fire-fighter protective clothing in a temperate environment.' *Ergonomics* 43(9): 1350 - 1358.

Barker, R. L. (2002). 'From fabric hand to thermal comfort: the evolving role of objective measurements in explaining human comfort response to textiles.' *International Journal of Clothing Science and Technology* 14(3/4): 181-200.

Bennett, B. L., Hagan, D. R., Banta, G. and Williams, F. (1995). 'Physiological responses during shipboard fire fighting.' *Aviation, Space and Environmental Medicine* 65: 225 - 231.

Bensel, C. K., Teixeria, R. A. and Kaplan, D. B. (1987). ‘The Effects of US Army Chemical Protective Clothing on Speech Intelligibility, Visual Field, Body Mobility and Psychomoter Coordination of Men.’ United States Army Natick Research, Development and Engineering Centre, Natick, Massachusetts. Technical Report Natick /TR-87/037.

Bernard, T. E. and Matheen, F. (1999). 'Evaporative resistance and sustainable work under heat stress conditions for two cloth anticontamination ensembles.' *International Journal of Industrial Ergonomics* 23: 557 - 564.

Bernard, T. E., Luecke, C. L., Schwartz, S. W., Kirkland, K. S. and Ashley, C. D. (2005). 'WBGT clothing adjustments for four clothing ensembles under three relative humidity levels.' *Journal of Occupational and Environmental Hygiene* 2: 251 -256.

Bilzon, J. L. J., Scarpello, E. G., Smith, C. V., Ravenhill, N. A. and Rayson, M. P. (2001). 'Characterisation of the metabolic demands of simulated shipboard Royal Navy fire-fighting tasks.' *Ergonomics* 44(8): 766 - 780.
Bishop, P., Gu, D. and Clapp, A. (2000). 'Climate under impermeable protective clothing.' *International Journal of Industrial Ergonomics* 25: 233 - 238.
Bishop, P., Ray, P. and Reneau, P. (1995). 'A review of the ergonomics of work in the US military chemical protective clothing.' *International Journal of Industrial Ergonomics* 15: 271 - 283.
Bishop, P. A., Pieroni, R. E., Smith, J. F. and Constable, S. H. (1991). 'Limitations to heavy work at 21ºC of personnel wearing the US military chemical defense ensemble.' *Aviation, Space and Environmental Medicine* 62: 216 - 220.
Bloom, D. and Woodhull-McNeal, A. P. (1987). 'Postural adjustments while standing with two types of loaded backpack.' *Ergonomics* 30(10): 1425 - 1430.
British Standards (2000). '7963: Ergonomics of the thermal environment - Guide to the assessment of heat strain in workers wearing personal protective equipment.' British Standards Institute.
Budd, G. M. (2001). 'How do wildland fire-fighters cope? Physiological and behavioural temperature regulation in men suppressing Australian summer bushfires with hand tools.' *Journal of Thermal Biology* 26: 381 - 386.
Budd, G. M., Brotherhood, J. R., Hendrie, A. L., Cheney, N. P. and Dawson, M. P. (1997). 'Stress, strain and productivity in men suppressing wildland fires with hand tools.' *International Journal of Wildland Fire* 7(2).
Cadarette, B. S., Levine, L., Staab, J. E., Kolka, M. A., Correa, M., Whipple, M. and Sawka, M. N. (2001). 'Heat strain imposed by toxic agent protective systems.' *Aviation, Space and Environmental Medicine* 72(1): 32 - 37.
Carter, J. and Jeukendrup, A. E. (2002). 'Validity and reliability of three commercially available breath-by-breath respiratory systems.' *European Journal of Applied Physiology* 86: 435 - 441.
Chattopadhyay, R. and Banerjee, S. (1996). 'The frictional behaviour of
ring-, rotor- and friction-spun yarn.' *Journal of the Textile Institute* 87(Part 1, No. 1): 59-67.
Claremont, A. D. and Hall, S. J. (1988). 'Effects of extremity loading upon energy expenditure and running mechanics.' *Medicine and Science in Sports and Exercise* 20(2): 167-171.
Consolazio, C. F., Matoush, L. O., Nelson, R. A., Torres, J. B. and Isaac, G. J. (1963). 'Environmental temperature and energy expenditures.' *Journal of Applied Physiology* 18(1): 65-68.
Crockford, G. W. (1999). 'Protective clothing and heat stress: Introduction.' *Annals of Occupational Hygiene* 43(5): 287 - 288.
Das, A., Kothari, V. K. and Vandana, N. (2005). 'A study on frictional characteristics of woven fabrics.' *AUTEX Research Journal* 5(3): 133-140.
Datta, S. R. and Ramanathan, N. L. (1971). 'Ergonomic comparison of seven modes of carrying loads on the horizontal plane.' *Ergonomics* 14(2): 269-278.
Davis, P. O., Dotson, C. O. and Laine Santa Maria, D. (1982). 'Relationship between simulated fire fighting tasks and physical performance measures.' *Medicine and Science in Sports and Exercise* 14(1): 65 - 71.
Dorman, L. E. and Havenith, G. (2005). 'The effects of protective clothing on metabolic rate'. *Proceedings of the 11th International Conference of Environmental Ergonomics*, Ystad, Sweden. Holmer,I., Kuklane, K. and Gao.C. (eds).
Duggan, A. (1988). 'Energy cost of stepping in protective clothing ensembles.' *Ergonomics* 31(1): 3 - 11.
Duggan, A. and Haisman, M. F. (1992). 'Prediction of the metabolic cost of walking with and without loads.' *Ergonomics* 35(4): 417 - 426.
Duncan, H. W., Gardner, G. W. and Barnard, J. B. (1979). 'Physiological responses of men working in fire fighting equipment in the heat.' *Ergonomics* 22(5): 521 - 527.
Durnin, J. V. G. A. and Passmore, R. (1967). Energy Expenditure in Occupational Activities. Energy, work and leisure. London, Heinemann Educational Books Ltd.: 47 - 82.
El Mogahzy, Y. E. and Gupta, B. S. (1993). 'Friction in fibrous materials. Part II: Experimental study of the effects of structural and morphological factors.' *Textile Research Journal* 63(4): 219-230.

Faerevik, H. and Reinertsen, R. E. (2003). 'Effects of wearing aircrew protective clothing on physiological and cognitive responses under various ambient conditions.' *Ergonomics* 46(8): 780 - 799.
Faff, J. and Tutak, T. (1989). 'Physiological responses to working with fire fighting equipment in the heat in relation to subjective fatigue.' *Ergonomics* 32(6): 629 - 638.
Fine, B. J. (2002). 'Human performance of military tasks while wearing chemical protective clothing.' GlobalSecurity.Org.webpage
http://www.globalsecurity.org/wmd/library/report/2002/mopp-human-performance.htm
Fiolkowski, P., Horodyski, M., Bishop, M., Williams, M. and Stylianou, L. (2006). 'Changes in gait kinematics and posture with the use of a front pack.' *Ergonomics* 49(9): 885 - 894.
Francis, K. and Hoobler, T. (1986). 'Changes in oxygen consumption associated with treadmill walking and running with light hand-carried weights.' *Ergonomics* 29(8): 999-1004.
Fredrix, E. W. H. M., Soeters, P. B., von Meyerfeldt, M. F. and Saris, W. H. M. (1990). 'Measurement of resting energy expenditure in a clinical setting.' *Clinical Nutrition* 9: 299-340.

Frim, J., Heslegrave, R., Bossi, L. and Popplow.J. (1992). 'Thermal strain in F-18 pilots during sustained chemical defence operations'. *Proceedings of the Fifth International Conference on Environmental Ergonomics*, Maastricht, The Netherlands. Lotens, W.A. and Havenith,G. (eds).
Frisancho, A. R. (1993). Chapter 2. Human Adaptation and Accommodation, University of Michigan Press: 25-52.
Ftaiti, F., Duflot, J. C., Nicol, C. and Grelot, L. (2001). 'Tympanic temperature and heart rate changes in fire-fighters during treadmill runs performed with different fireproof jackets.' *Ergonomics* 44(5): 502 - 512.
Gavhed, D. C. E. and Holmer, I. (1989). 'Thermoregulatory responses of firemen to exercise in the heat.' *European Journal of Applied Physiology* 59(115 - 122).
Givoni, B. and Goldman, R. F. (1971). 'Predicting metabolic energy cost.' *Journal of Applied Physiology* 30(3): 429 - 433.
Goldman, R. F. (1963). 'Tolerance time for work in the heat when wearing CBR protective clothing.' *Military Medicine* 128(8): 776-786.
Goldman, R. F. (1965). 'Energy cost of soldiers performing combat type activity.' *Ergonomics* 8: 321 - 327.
Goldman, R. F. (1969). 'Physiological costs of body armor.' *Military Medicine* 134(3): 204-210.
Goldman, R. F. (1988). 'Standards for human exposure to heat.' Environmental Ergonomics: Sustaining Human Performance in Harsh Environments. I. B. Mekjavic, E. W. Banister and J. B. Morrison (eds) London, Taylor and Francis: 99 - 136.
Goldman, R. F. (1990). 'Heat stress in firefighting ; the relationship between work, clothing and environment.' *Fire Engineering*: 47 - 52.
Goldman, R. F. and Iampietro, P. F. (1962). 'Energy cost of load carriage.' *Journal of Applied Physiology* 17(4): 675-676.
Graveling, R. and Hanson, M. (2000). 'Design of UK firefighter clothing.' *Nokobetef 6 and 1st European Conference on Protective Clothing*: 277 - 280.
Graves, J. E., Pollock, M. L., Montain, S. J., Jackson, A. S. and O'Keefe, J. M. (1987). 'The effect of hand-held weights on the physiological responses to walking exercise.' *Medicine and Science in Sports and Exercise* 1987(3): 260-265.

Graves, J. E., Martin, A. D., Miltenberger, L. A. and Pollock, M. L. (1988). 'Physiological responses to walking with hand weights, wrists weights and ankle weights.' *Medicine and Science in Sports and Exercise* 20(3): 265-271.
Gwosdow, A. R., Stevens, J. C., Berglund, L. G. and Stolwijk, J. A. J. (1986). 'Skin friction and fabric sensations in neutral and warm environments.' *Textile Research Journal* 56: 574.
Haisman, M. F. (1988). 'Determinants of load carrying ability.' *Applied Ergonomics* 19(2): 111-121.

Hanson, M. (1999). 'Development of a draft British Standard: the assessment of heat strain for workers wearing personal protective equipment.' *Annals of Occupational Hygiene* 43(5): 309 - 319.
Hanson, M. and Graveling, R. (1999). 'Development of a draft British Standard: the assessment of heat strain for workers wearing personal protective equipment.' *Institute of Occupational Medicine Report* Research Report(TM/99/03).
Harrabi, L., Dolez, P. I., Vu-Khanh, T. and Lara, J. (2006). 'Evaluation of the flexibility of protective gloves'. *3rd European Conference on Protective Clothing (ECPC) and NOKOBETEF 8*, Gydnia, Poland.
Hausswirth, C., Bigard, A. X. and Le Chevalier, J. M. (1997). 'The Cosmed K4 Telemetry System as an accurate device for oxygen uptake measurements during exercise.' *International Journal of Sports Medicine* 18: 449 - 453.
Havenith, G. (1999). 'Heat balance when wearing protective clothing.' *Annals of Occupational Hygiene* 43(5): 289 - 296.
Havenith, G. and Heus, R. (2004). 'A test battery related to ergonomics of protective clothing.' *Applied Ergonomics*: 3 - 20.
Havenith, G., Heus, R. and Lotens, W. A. (1990). 'Clothing ventilation, vapour resistance and permeability index: changes due to posture, movement and wind.' *Ergonomics* 33(8): 989 - 1005.
Havenith, G., Holmer, I. and Parsons, K. C. (2002). 'Personal factors in thermal comfort assessment: clothing properties and metabolic heat production.' *Energy and Buildings* 34: 581 - 591.
Henane, R., Bittel, J., Viret, R. and Morino, S. (1979). 'Thermal strain resulting from protective clothing of an armored vehicle crew in warm conditions.' *Aviation, Space and Environmental Medicine* 50(6): 599 - 603.
Holewijn, M. (1990). 'Physiological strain due to load carrying.' *European Journal of Applied Physiology* 61: 237-245.
Holmer, I. and Nilsson, H. (1995). 'Heated manikins as a tool for evaluating clothing.' *Annals of Occupational Hygiene* 39(6): 809 - 818.
Holmes, G. T., Marsh, P. L., Barnett, R. B. and Scott, R. A. (1988). 'Clothing materials - their required characteristics and their impact on biomedical factors' (Chapter 4). Handbook on clothing. Biomedical effects of military clothing and equipment systems., NATO AC/243 (Panel 8).
Huck, J. (1988). 'Protective clothing systems; a technique for evaluating restriction of wearer mobility.' *Applied Ergonomics* 19(3): 185 - 190.
Huck, J. (1991). 'Restriction to movement in fire-fighter protective clothing; evaluation of alternate sleeves and liners.' *Applied Ergonomics* 22(2): 91-100.
Huck, J., Maganga, O. and Kim, Y. (1997). 'Protective overalls: evaluation of garment design and fit.' *International Journal of Clothing Science and Technology* 9(1): 45 - 61.
Hughes, A. L. and Goldman, R. F. (1970). 'Energy cost of hard work.' *Journal of Applied Physiology* 29(5): 570 - 572.
Ilmarinen, R., Griefahn, B., Makinen, H. and Kunemund, C. (1994). 'Physiological responses to wearing a fire fighters turnout suit with and without a microporous membrane in the heat.' *Proceedings of the Sixth Conference on Environmental Ergonomics.* Montebello, Canada: Frim,J., Ducharme,M.B. and Tikuisis, P. (eds).
Ilmarinen, R. and Makinen, H. (1992). 'Heat strain in fire-fighting drills.' *Proceedings of the Fifth Conference on Environmental Ergonomics* Maastricht, The Netherlands: Lotens, W.A. and Havenith, G. (eds).
ISO (1989). 7243: Hot environments - Estimation of the heat stress on working man, based on the WBGT index (wet bulb globe temperature), Geneva: International Standards Organisation.
ISO (2003). 9920: Ergonomics of the thermal environment - Estimation of the thermal insulation and evaporative resistance of a clothing ensemble, Geneva, International Standards Organisation.
ISO (2004). 7933: Hot environments - Analytical determination and interpretation of thermal stress using calculation of required sweat rate, Geneva: International Standards Organisation.
ISO (2004). 8996: Ergonomics - Determination of metabolic heat production, Geneva: International Standards Organisation.

Jones, B. H., Toner, M. M., Daniels, W. L. and Knapik, J. J. (1984). 'The energy cost and heart rate response of trained and untrained subjects walking and running in shoes and boots.' *Ergonomics* 27(8): 895-902.
Joy, R. J. T. and Goldman, R. F. (1968). 'A method of relating physiology and military performance; A study of some effects of vapor barrier clothing in a hot climate.' *Military Medicine* 133(6): 458 - 470.
Kawabata, S. (1980). The Standardization and Analysis of Hand Evaluation (2nd edition). The Hand Evaluation and Standardization Committee, The Textile Machinery Society of Japan, Osaka Tiger Printing Co., Ltd. Osaka, Japan.
Kawakami, Y., Nozaki, D., Matsuo, A. and Fukunaga, T. (1992). 'Reliability of measurement of oxygen uptake by a portable telemetric system.' *European Journal of Applied Physiology* 65: 409 - 414.
Kenins, P. (1994). 'Influence of fiber type and moisture on measured fabric-to-skin friction.' *Textile Research Journal* 64(12): 722-728.
Kerslake, D. M. (1972). ‘Clothing’ (Chapter 5). The Stress of Hot Environments, Cambridge University Press.
Kinoshita, H. (1985). 'Effects of different loads and carrying systems on selected biomechanical parameters describing walking gait.' *Ergonomics* 28(9): 1347 - 1362.
Knapik, J. J., Harman, E. and Reynolds, K. (1996). 'Load carriage using packs: A review of physiological, biomechanical and medical aspects.' *Applied Ergonomics* 27(3): 207-216.
Larsson, P. U., Wadell, K. M. E., Jakobsson, E. J. I., Burlin, L. U. and Henriksson-Larsen, K. B. (2004). 'Validation of the MetaMax II portable metabolic measurement system.' *International Journal of Sports Medicine* 25: 115-123.
Legg, S. L. and Mahanty, A. (1985). 'Comparison of five modes of carrying a load close to the trunk.' *Ergonomics* 28(12): 1653-1660.
Legg, S. L. and Mahanty, A. (1986). 'Energy cost of backpacking in heavy boots.' *Ergonomics* 29(3): 433-438.
Li, Y. (2001). The Science of Clothing Comfort, The Textile Institute.
Lima, M., Hes, L., Vasconcelos, R. and Martins, J. (2005). 'Frictorq, Accessing fabric friction with a novel fabric surface tester.' *AUTEX Research Journal* 5(4): 194-201.
Lotens, W. A. (1982). Clothing design and its relation to military performance. Soesterberg, The Netherlands, TNO Institute for perception. Report No. IZF 1982-34.
Lotens, W. A. (1986). Loss of performance due to military clothing and equipment. Soesterberg, The Netherlands, TNO Institute for perception. Report No. IZF 1986-13
Lotens, W. A. (1988a). ‘Military performance of clothing’ (Chapter 15). Handbook on clothing. Biomedical effects of military clothing and equipment systems., NATO AC/243 (Panel 8).
Lotens, W. A. (1988b). ‘Optimal design principles for clothing systems’ (Chapter 17). Handbook on clothing. Biomedical effects of military clothing and equipment systems., NATO AC/243 (Panel 8).
Lotens, W. A. and Havenith, G. (1991). 'Calculation of clothing insulation and vapour resistance.' *Ergonomics* 34(2): 233 - 254.
Louhevaara, V., Ilmarinen, R., Griefahn, B., Kunemund, C. and Makinen, H. (1995). 'Maximal physical work performance with European standard based fire-protective clothing system and equipment in relation to individual characteristics.' *European Journal of Applied Physiology* 71: 223 - 229.
MacDougall, J. D., Reddan, W. G., Layton, C. R. and Dempsey, J. A. (1974). 'Effects of metabolic hyperthermia on performance during heavy prolonged exercise.' *Journal of Applied Physiology* 36(5): 538 - 544.
Macfarlane, D. J. (2001). 'Automated Metabolic Gas Analysis Systems: A Review.' *Sports Medicine* 31(12): 841 - 861.
Malcolm, S., Armstrong, R., Michaliades, M. and Green, R. (2000). 'A thermal assessment of army wet weather jackets.' *International Journal of Industrial Ergonomics* 26: 417 - 424.
Marszalek, A., Smolander, J., Soltynski, K. and Sobolewski, A. (1999). 'Physiological strain of wearing aluminized protective clothing at rest in young, middle-aged and older men.' *International Journal of Industrial Ergonomics* 25: 195 - 202.

Martin, P. E. and Nelson, R. C. (1986). 'The effect of carried loads on the walking patterns of men and women.' *Ergonomics* 29(10): 1191 - 1202.
Mayer, A. (2006). 'The need of continuous improvement of the EN standards on PPE and of the information given to consumers'. *3rd European Conference on Protective Clothing (ECPC) and NOKOBETEF 8*, Gydnia, Poland.
McArdle, W. D., Katch, F. I. and Katch, V. L. (2001). Exercise Physiology; Energy, Nutrition and Human Performance. Baltimore, USA, Lippincott Williams and Wilkins.
McLaughlin, J. E., King, G. A., Howley, E. T., Bassett Jr, D. R. and Ainsworth, B. E. (2001). 'Validation of the COSMED K4 b2 portable metabolic system.' *International Journal of Sports Medicine* 22: 208 - 284.
McLellan, T. M. (1996). 'Heat strain while wearing the current Canadian or a new hot-weather French NBC protective clothing ensemble.' *Aviation, Space and Environmental Medicine* 67(11): 1057 - 1062.
McLellan, T. M., Bell, D. G. and Dix, J. K. (1994). 'Heat strain with combat clothing worn over a chemical defence (CD) vapor protective layer.' *Aviation, Space and Environmental Medicine* 65: 757 - 763.
McLellan, T. M., Jacobs, I. and Bain, J. B. (1993). 'Influence of temperature and metabolic rate on work performance with Canadian forces NBC clothing.' *Aviation, Space and Environmental Medicine* 64(7): 587 - 594.
McLellan, T. M., Pope, J. I., Cain, J. B. and Cheung, S. S. (1996). 'Effects of metabolic rate and ambient vapour pressure on heat strain in protective clothing.' *European Journal of Applied Physiology* 74: 518 - 527.
McLellan, T. M. and Selkirk, G. A. (2004). 'Heat stress while wearing long pants or shorts under firefighting protective clothing.' *Ergonomics* 47(1): 75 - 90.
Meinander, H., Anttonen, H., Bartels, V., Holmer, I., Reinertsen, R. E., Soltynski, K. and Varieras, S. (2004). 'Manikin measurements versus wear trials of cold protective clothing (Subzero project).' *European Journal of Applied Physiology* 92: 619-621.
Meyer, T., Davison, R. C. R. and Kinderman, W. (2005). 'Ambulatory Gas Exchange Measurements - Current Status and Future Options.' *International Journal of Sports Medicine* 26: S19 - S27.
Meyer, T., Georg, T., Becker, C. and Kinderman, W. (2001). 'Reliability of gas exchange measurements from two different spiroergometry systems.' *International Journal of Sports Medicine* 22: 593 - 597.
Millard, C. E. (1994). 'Thermoregulation of armoured fighting vehicle crew in hot climates'. *Sixth International Conference on Environmental Ergonomics*, Montebello, Canada. Frim,J., Ducharme,M.B. and Tikuisis, P. (eds).
Millard, C. E., Spilsbury, P. M. and Withey, W. R. (1994). 'The effects of heat acclimation on the heat strain of working in protective clothing'. *Sixth International Conference on Environmental Ergonomics*, Montebello, Canada. Frim,J., Ducharme,M.B. and Tikuisis, P. (eds).
Montain, S. J., Sawka, M. N., Cadarette, B. S., Quigley, M. D. and McKay, J. M. (1994). 'Physiological tolerance to uncompensable heat stress: effects of exercise intensity, protective clothing and climate.' *Journal of Applied Physiology* 77(1): 216 - 222.
Murgatroyd, P. R., Shetty, P. S. and Prentice, A. M. (1993). 'Techniques for the measurement of human energy expenditure: a practical guide.' *International Journal of Obesity* 17: 549 - 568.
Murgatroyd, P. R., Davies, H. L. and Prentice, A. M. (1987). 'Intra-individual variability and measurement noise in estimates of energy expenditure by whole body indirect calorimetry.' *British Journal of Nutrition* 58: 347-356.
Murphy, M. M., Patton, J., Mello, R., Bidwell, T. and Harp, M. (2001). 'Energy cost of physical task performance in men and women wearing chemical protective clothing.' *Aviation, Space and Environmental Medicine* 72(1): 25 - 31.
Nunneley, S. A. (1988). 'Design and evaluation of clothing for protection from heat stress: An overview.' Environmental Ergonomics: Sustaining Human Performance in Harsh Environments. I. B. Mekjavic, E. W. Banister and J. B. Morrison. (eds) London, Taylor and Francis: 87 - 98.
Nunneley, S. A. (1989). 'Heat stress in protective clothing: Interactions among physical and physiological factors.' *Scandinavian Journal of Work and Environmental Health* 15(Suppl 1): 52 - 57.

O'Hearn, B. E., Bensel, C. K. and Fronduti, A. P. (2005). 'Biomechanical analyses of body movement and locomotion as affected by clothing and footwear for cold weather climates.' US Army Research, Development and Engineering Command, Natick Soldier Centre, Natick, MA, USA. Report No. Natick/TR-05/013

Ohnaka, T., Tochihara, Y. and Muramatsu, T. (1993). 'Physiological strains in hot-humid conditions while wearing disposable protective clothing commonly used by the asbestos removal industry.' *Ergonomics* 36(10): 1241 - 1250.

Oksa, J., Kaikkonen, H., Sorvisto, P., Vaapo, M., Martikkala, V. and Rintamaki, H. (2004). 'Changes in submaximal cardiorespiratory capacity and submaximal strain while exercising in the cold.' *Journal of Thermal Biology* 29: 815 - 818.

Pandolf, K. B., Givoni, B. and Goldman, R. F. (1977). 'Predicting energy expenditure with loads while standing or walking very slowly.' *Journal of Applied Physiology* 43(4): 577-581.

Parsons, K. C. (1988). 'Protective clothing: heat exchange and physiological objectives.' *Ergonomics* 31(7): 991 - 1007.

Parsons, K. C. (1994). 'Heat transfer through human body and clothing systems.' Protective clothing systems and materials. M. Raheel. (eds) New York, USA, Marcel Dekker Inc.: 137 - 171.

Parsons, K. C. (1999). 'International Standards for the Assessment of the Risk of Thermal Strain on Clothed Workers in Hot Environments.' *Annals of Occupational Hygiene* 43(5): 297 - 308.

Parsons, K. C. (2000). 'An adaptive approach to the assessment of risk for workers wearing protective clothing in hot environments'. *Nokobetef 6 and 1st European Conference on Protective Clothing*, Stockholm, Sweden May 7-10th 2000.

Parsons, K. C. (2003). Human Thermal Environments: The effects of hot, moderate and cold environments on human health, comfort and performance. London, Taylor and Francis.

Patton, J. F., Bidwell, T. E., Murphy, M. M., Mello, R. P. and Harp, M. E. (1995). 'Energy cost of wearing chemical protective clothing during progressive treadmill walking.' *Aviation, Space and Environmental Medicine* 66: 238 - 242.

Peel, C. and Utsey, C. (1993). 'Oxygen consumption using the K2 telemetry system and a metabolic cart.' *Medicine and Science in Sports and Exercise* 25(3): 396 - 400.

Peirce, F. T. (1930). 'The handle of cloth as a measurable quantity.' *Shirley Institute Memoirs* 9(8): 83 - 122.

Pierrynowski, M. R., Winter, D. A. and Norman, R. W. (1981). 'Metabolic measures to ascertain the optimal load to be carried by man.' *Ergonomics* 24(5): 393-399.

Raheel, M. (1994). 'Protective clothing; An Overview.' Protective clothing systems and materials. M. Raheel (eds) New York, USA, Marcel Dekker Inc.: 1 - 23.

Rietjens, G. J. W. M., Kuipers, H., Kester, A. D. M. and Keizer, H. A. (2001). 'Validation of a computerised metabolic measurement system (Oxycon-Pro) during low and high intensity exercise.' *International Journal of Sports Medicine* 22: 291 - 294.

Rintamaki, H. (2005). 'Protective clothing and performance in cold environments'. *The Third International Conference on Human-Environment System (ICHES) 12 -15 September*, Tokyo, Japan.

Rissanen, S. and Rintamaki, H. (1994). 'Thermal responses and physical strain in men wearing protective clothing in the cold'. *Sixth International Conference on Environmental Ergonomics*, Montebello, Canada. Frim,J., Ducharme,M.B. and Tikuisis, P. (eds).

Rissanen, S. and Rintamaki, H. (1997). 'Thermal responses and physiological strain in men wearing impermeable and semipermeable protective clothing in the cold.' *Ergonomics* 40(2): 141 - 150.

Roecker, K., Prettin, S. and Sorichter, S. (2005). 'Gas Exchange Measurements with High Temporal Resolution: The Breath-by-Breath Approach.' *International Journal of Sports Medicine* 26: S11 - S18.

Romet, T. T. and Frim, J. (1987). 'Physiological responses to fire fighting activities.' *European Journal of Applied Physiology* 56: 633 - 638.

Rossi, R. (2003). 'Fire fighting and its influence on the body.' *Ergonomics* 46(10): 1017 - 1033.

Schulz, H., Helle, S. and Heck, H. (1997). 'The validity of the Telemetric system CORTEX X1 in the ventilatory and gas exchange measurement during exercise.' *International Journal of Sports Medicine* 18: 454 - 457.
Shishoo, R. (2002). 'Recent developments in materials for use in protective clothing.' *International Journal of Clothing Science and Technology* 14(3/4): 201 - 215.
Skoldstrom, B. (1987). 'Physiological responses of fire fighters to workload and thermal stress.' *Ergonomics* 30(11): 1589 - 1597.
Smith, D. L. and Petruzzello, S. J. (1998). 'Selected physiological and psychological responses to live-fire drills in different configurations of fire fighting gear.' *Ergonomics* 41(8): 1141 - 1154.
Smith, D. L., Petruzzello, S. J., Kramer, J. M. and Misner, J. E. (1997). 'The effects of different thermal environments on the physiological and psychological responses of fire-fighters to a training drill.' *Ergonomics* 40(4): 500 - 510.
Soule, R. G. and Goldman, R. F. (1969). 'Energy cost of loads carried on the head, hands or feet.' *Journal of Applied Physiology* 27(5): 687 - 690.
Spitzer, H., Hettinger, T. and Kaminsky, G. (1982). Tafeln fur den Energieumsatz bei korperlicher Arbeit, Beuth Verlag GmbH, Berlin, Koln.
Stirling, M. (2000). 'Aspects of firefighter protective clothing selection.' *Nokobetef 6 and 1st European Conference on Protective Clothing*: 269 - 272.
Taylor, H. L. and Orlansky, J. O. (1993). 'The effects of wearing protective chemical warfare combat clothing on human performance.' *Aviation, Space and Environmental Medicine*(March): A1 - A41.
Taylor, N. A. S., Fogarty, A. and Armstrong, K. (2001). 'Metabolic heat storage in thermal protective clothing; a comparison of fire-fighter personal protective ensembles.' *University of Wollongong and New South Wales Fire Brigades*.
Teitlebaum, A. and Goldman, R. F. (1972). 'Increased energy cost with multiple clothing layers.' *Journal of Applied Physiology* 32(6): 743 - 744.
Thorndike, G. H. and Varley, L. (1961). 'Measurement of the coefficient of friction between samples of the same cloth.' *Journal of the Textile Institute* 52: P255-P266.
White, M. K., Hodous, T. K. and Vercruyssen, M. (1991). 'Effects of thermal environment and chemical protective clothing on work tolerance, physiological responses and subjective ratings.' *Ergonomics* 34(4): 445 - 457.
White, M. K., Vercruyssen, M. and Houdous, T. K. (1989). 'Work tolerance and subjective responses to wearing protective clothing and respirators during physical work.' *Ergonomics* 32(9): 1111 - 1123.
Wideman, L., Stoudemire, N. M., Pass, K. A., McGinnes, C. L., Gaesser, G. A. and Weltman, A. (1996). 'Assessment of the Aerosport TEEM 100 portable metabolic measurement system.' *Medicine and Science in Sports and Exercise* 28(4): 509 - 515.
Williams, N. (1993). 'Working in a hot environment.' *Occupational health* 1993 (August): 275 - 277.
Wilmore, J. H. and Costill, D. L. (1999). Physiology of Sport and Exercise. Champaign, IL, Human Kinetics.
Wilson, D. (1963). 'A study of fabric-on-fabric dynamic friction.' *Journal of the Textile Institute* 54(4): T143-T155.
Winter, D. A. (1984). 'Kinematic and kinetic patterns in human gait; variability and compensating effects.' *Human Movement Science* 3: 51-76.
Winter, D. A. (1990). Biomechanics and Motor Control of Human Movement, John Wiley and Sons Inc.
Winter, D. A. (1991). The Biomechanics and Motor Control of Human Gait: Normal, Elderly and Pathological, University of Waterloo Press.
Young, A. J., O'Brien, C., Sawka, M. N. and Gonzalez, R. R. (2000). 'Physiological problems associated with wearing NBC protective clothing during cold weather.' *Aviation, Space and Environmental Medicine* 71(2): 184 - 189.