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

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1. Introduction

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

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

1.1 Previous research

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

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

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

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

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

greater in the CP clothing across a range of walking speeds. The percentage increase when completing continuous tasks in the study of Murphy *et al.* (2001) was reduced from 13.7 % to 8 % after correction for weight in the CP clothing condition, leaving an 8 % difference in energy cost due to factors other than weight.

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

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

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

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

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

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

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

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

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

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

Although fabric friction has gained much significance, Das *et al.* (2005) explain that there is still no suitable instrument in the textile industry to measure it. Kawabata developed the KES – FB4 for measuring surface friction and surface roughness but this is not available to most due to the high cost. Most researchers use the Instron Tensile Tester with attachments (Das *et al.* 2005). Others, including Das *et al.* (2005) and Lima *et al.* (2005)

have come up with their own equipment, see papers for more detail. The Kawabata System of Evaluation (KES) is still the most well developed system for evaluating the fabric hand. The unique feature of the KES is the ability to measure fabric mechanical properties at small strains with high sensitivity, and a capability to isolate the contribution of individual fabric properties (Barker 2002).

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

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

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

1.2 Aims

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

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

2. Methods

2.1 Participants

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

Table 2.1. Participant details

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

2.2 Clothing

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

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

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

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

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

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

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

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

2.3 Weight corrections

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

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

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

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

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

2. sweatbands

3. sweatbands with weights attached

4. sweatbands

5. sweatbands with weights attached

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

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

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

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

Table 2.2. Weight details for ensembles and layers.

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

2.4 Work modes

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

2.5 Floor plan and details

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

2.6 Experimental design

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

2.7 Procedure

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

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

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

2.8 Analysis

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

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

2.9 Material testing

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

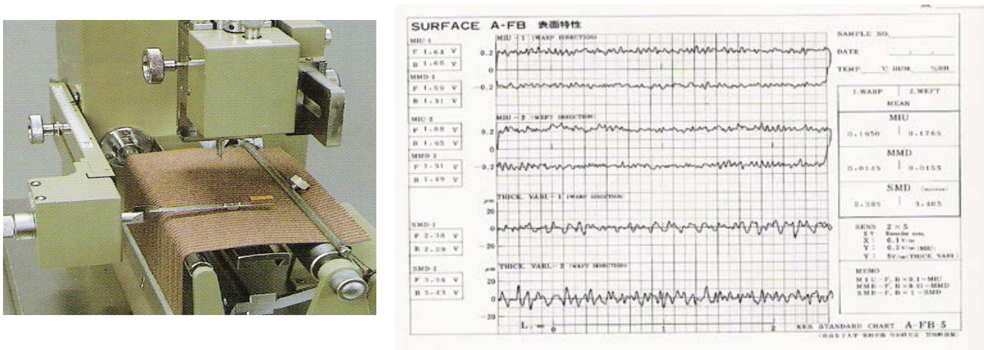

Figure 2.4. Photograph showing Kawabata Evaluation System (KES – FB4), the friction sensor is on the fabric and surface roughness sensor in the air. In the testing carried out for this study the standard friction sensor was replaced by a circular fabric covered sensor. Example of results for illustration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

3. Results

3.1 Participants and environment

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

3.2 Material results

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

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

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

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

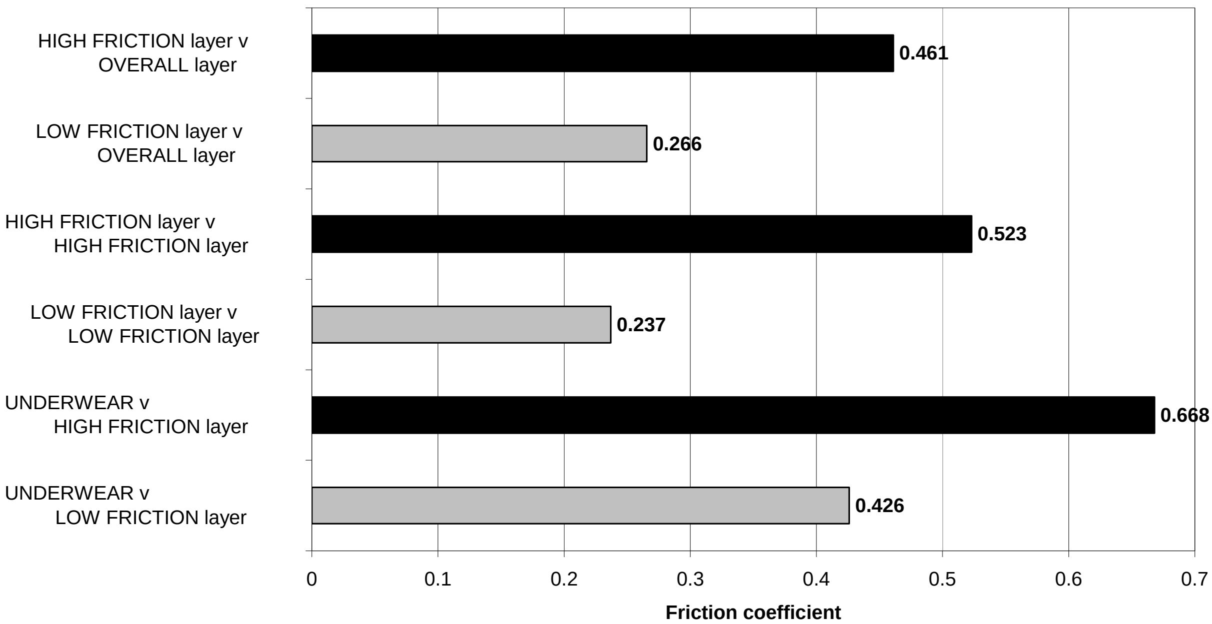

Figure 3.1. Friction coefficient values for the materials used in the present study.

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

3.3 Absolute results

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

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

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

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

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

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

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

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

3.4 Metabolic rate results

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

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

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

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

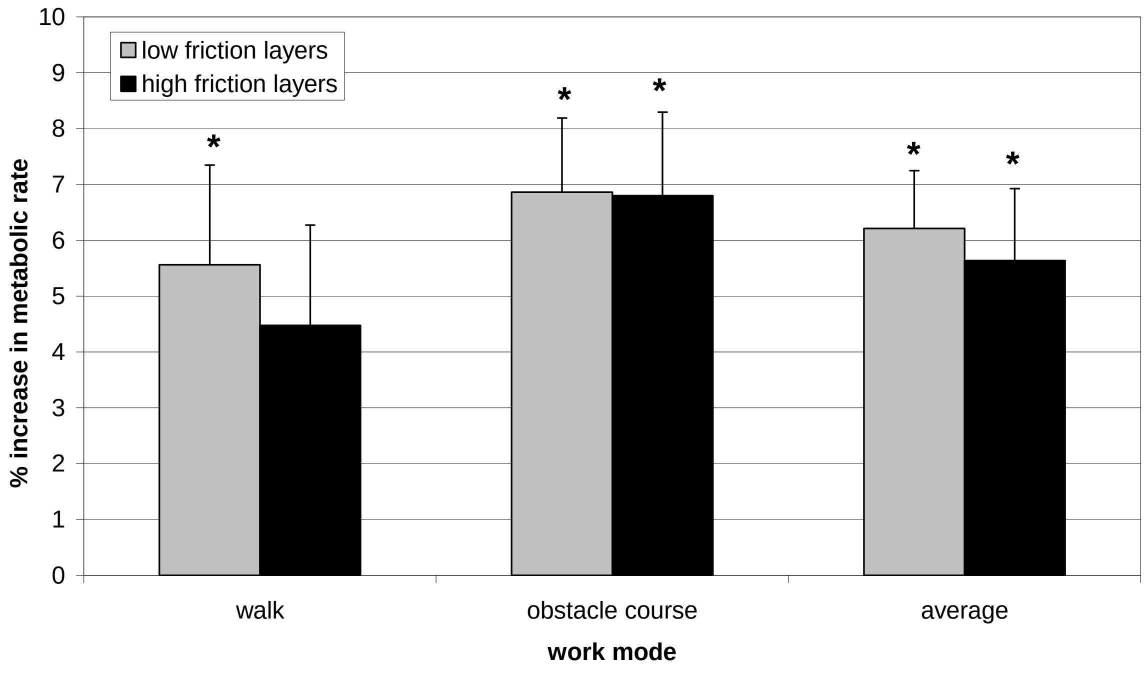

Figure 3.2. Percentage increases in metabolic rate relative to the control condition when wearing high (black bars) and low friction (grey bars) layers walking and completing an obstacle course (n=8). Significance compared to control, p<0.05 indicated by *. All conditions had the same weight.

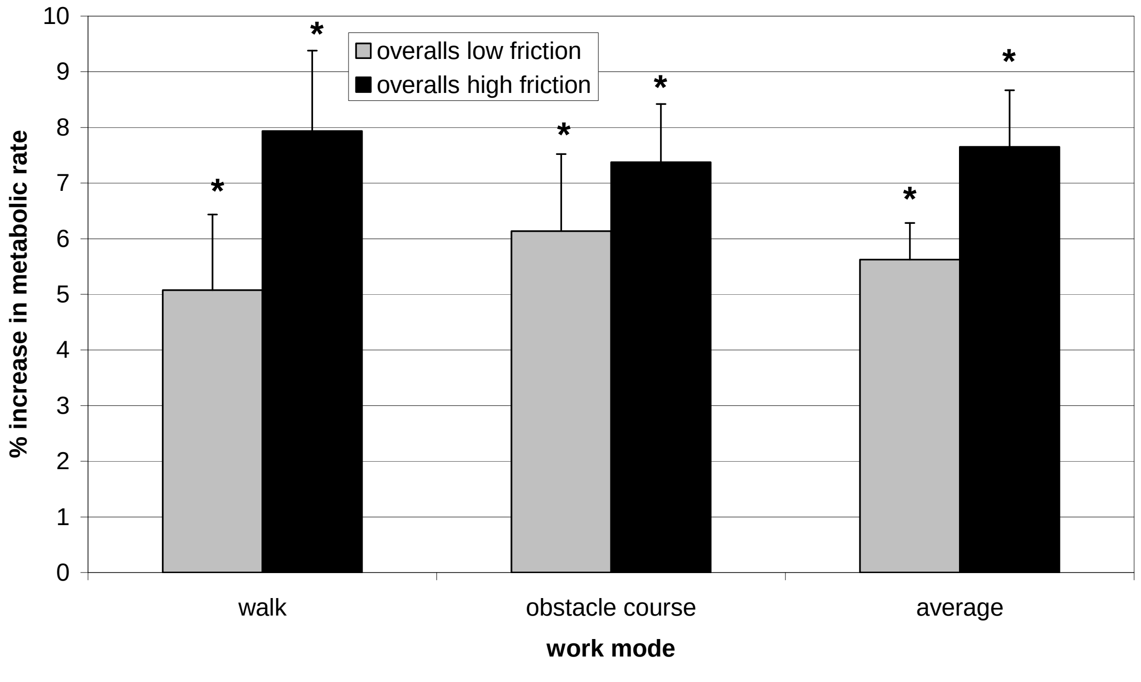

Figure 3.3. Percentage increases in metabolic rate relative to the control condition when wearing overalls with high friction layers (black bars) or low friction layers (grey bars) in between overalls when walking and completing an obstacle course (n=8). Significance compared to control, p<0.05 indicated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

3.5 Subjective results

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

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

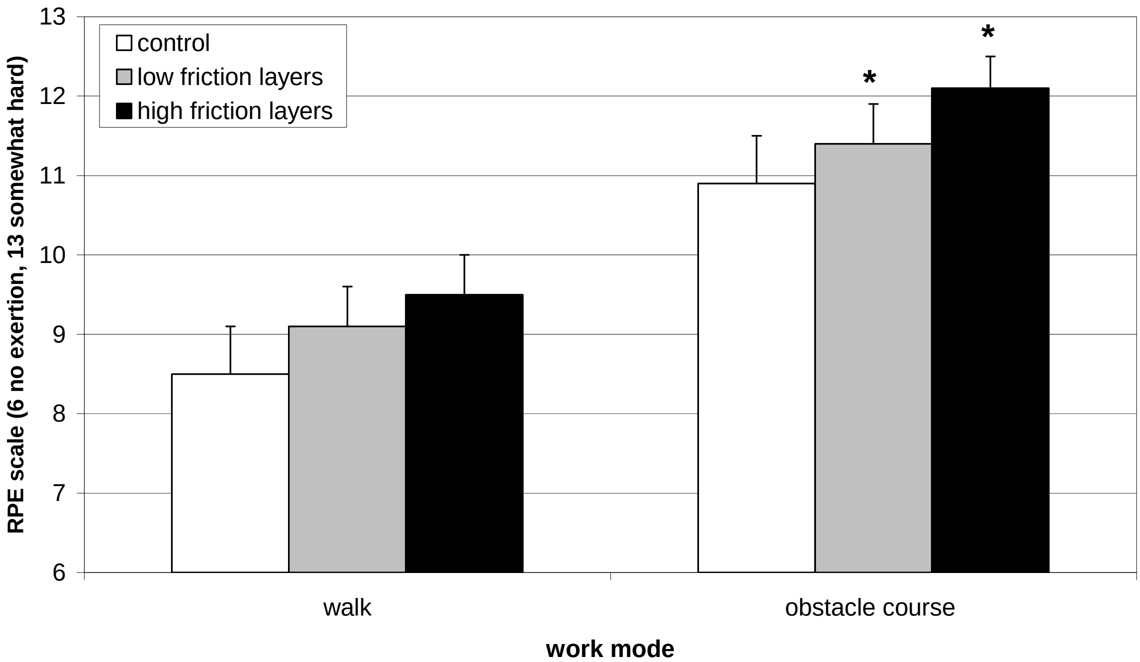

Figure 3.4. Rate of Perceived Exertion scores (n=8) for walking and completing the obstacle course in the control (white bars), low friction layers (grey bars) and high friction layers (black bars). Significance of p<0.05 compared to control indicated by *.

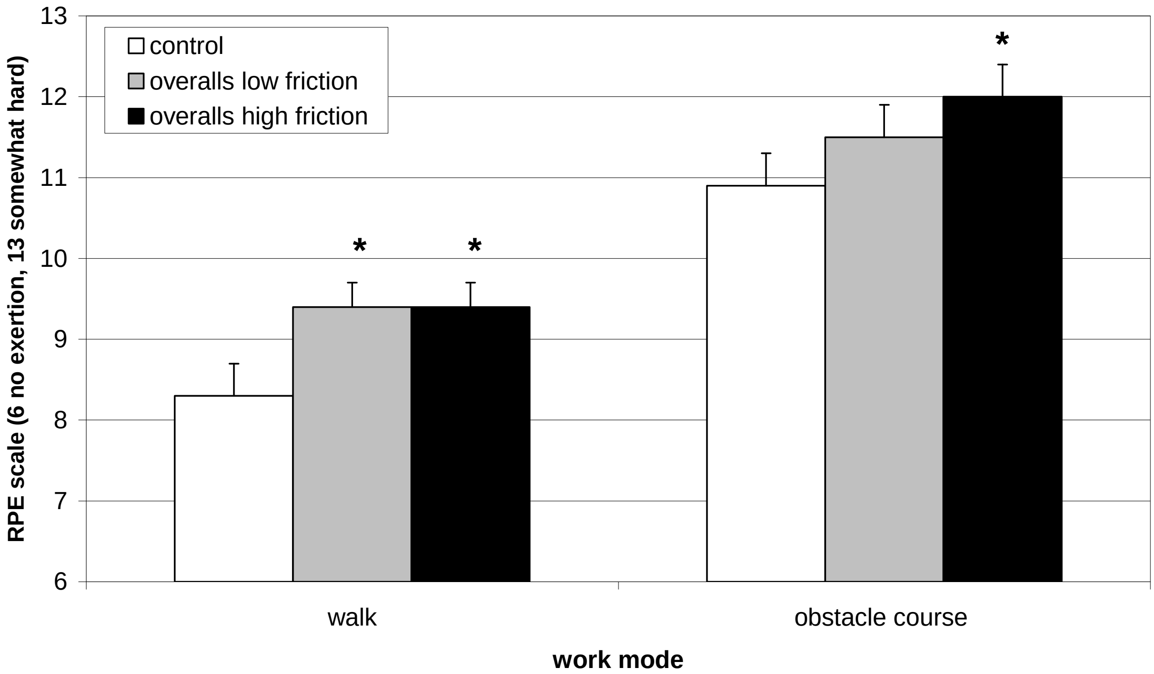

Figure 3.5. Rate of Perceived Exertion scores (n=8) for walking and completing the obstacle course in the control (white bars), overalls low friction (grey bars) and overalls high friction (black bars). Significance of p<0.05 compared to control indicated by *.

4. Discussion

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5. Chapter summary

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

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

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

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