EXAMINING THE IMPACT OF PROTECTIVE CLOTHING ON RANGE OF MOVEMENT

Lucy Dorman and George Havenith

Loughborough University, Environmental Ergonomics Research Centre.

European Union project THERMPROTECT G6RD-CT-2002-00846.

Report 2007-7

1. Introduction

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

1.1 Previous research

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

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

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

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

Range of movement

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

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

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

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

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

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

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

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

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

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

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

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

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

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

In summary, the literature reviewed has reported that;

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

There are two main groups of papers;

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

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

1.2 Aims

The aims of this study are;

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

2. Materials and Methods

2.1 Participants

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

Table 2.1. Participant details.

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

2.2 Clothing

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

2.3 Work modes

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

Figure 2.1. Photograph of participant walking on the treadmill.

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

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

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

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

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

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

 5.81; Right leg steps forward	 6.64; Left leg steps forward, right knee bends to floor	 7.47; Right foot steps forward
 8.30; Left leg over hurdle	 9.13; Right leg over hurdle	 9.96; Turn around

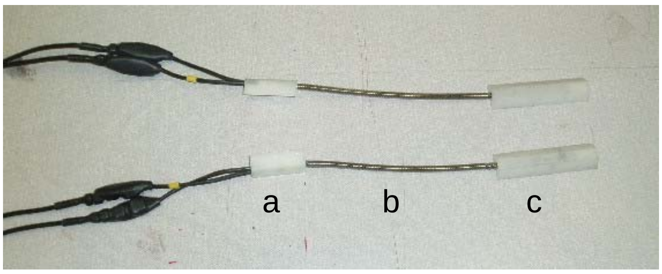
2.4 Measurements and calibration

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

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

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

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



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

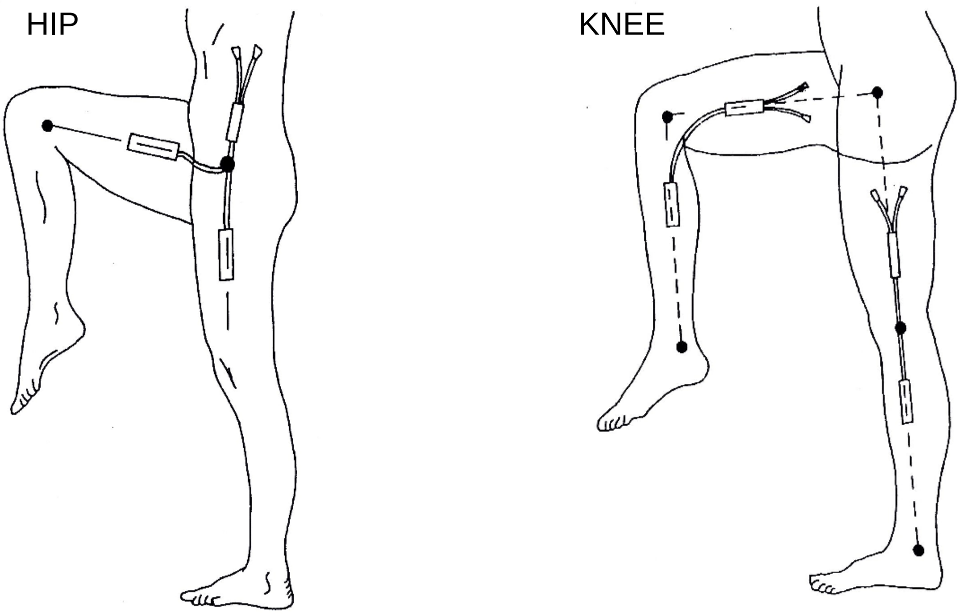
Figure 2.2. Photograph showing 2 goniometers

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

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

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

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



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

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

2.5 Experimental design

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

2.6 Procedure

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

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

2.7 Analysis

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

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

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

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

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

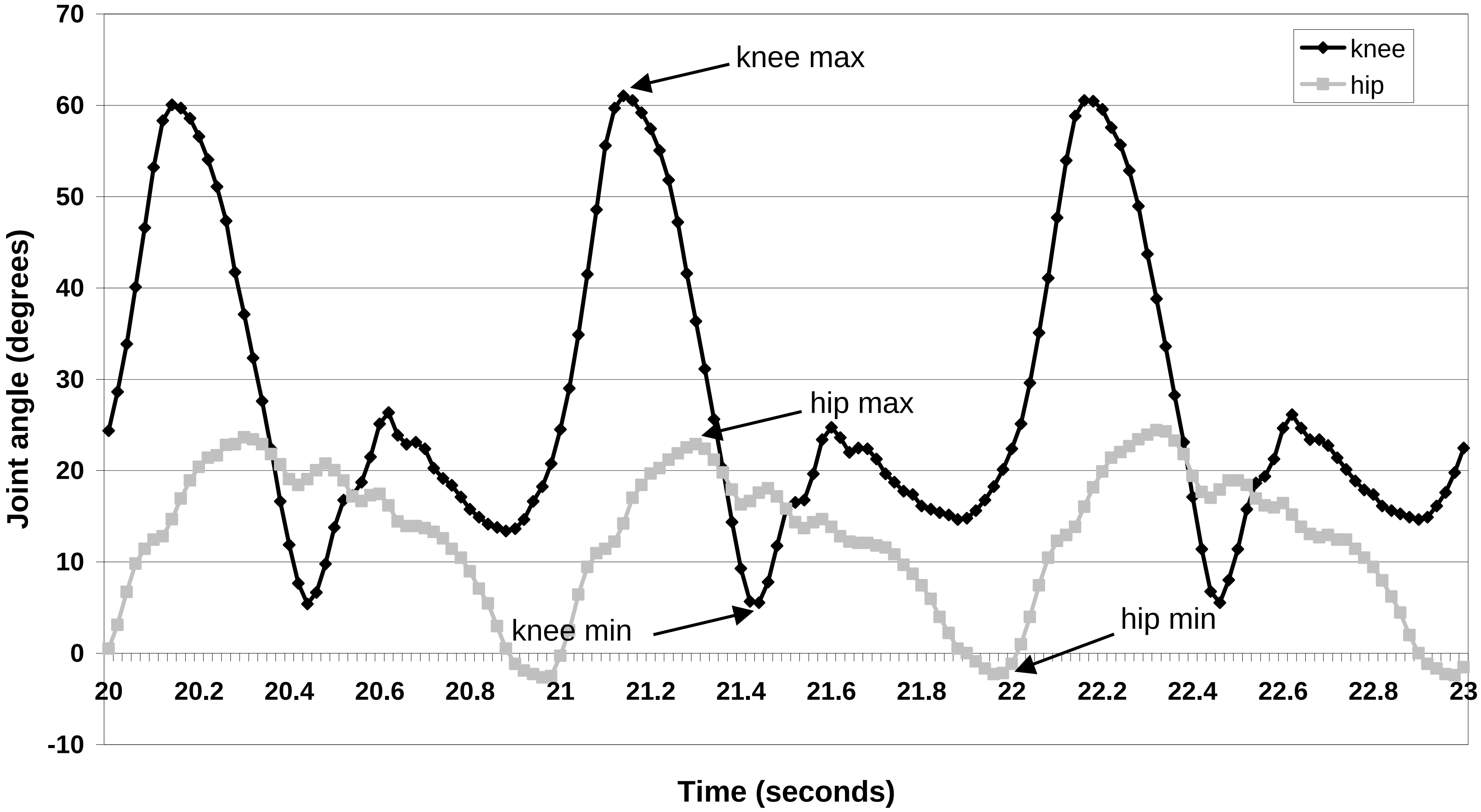


Figure 2.4. Plot of walking data for one participant in one garment.

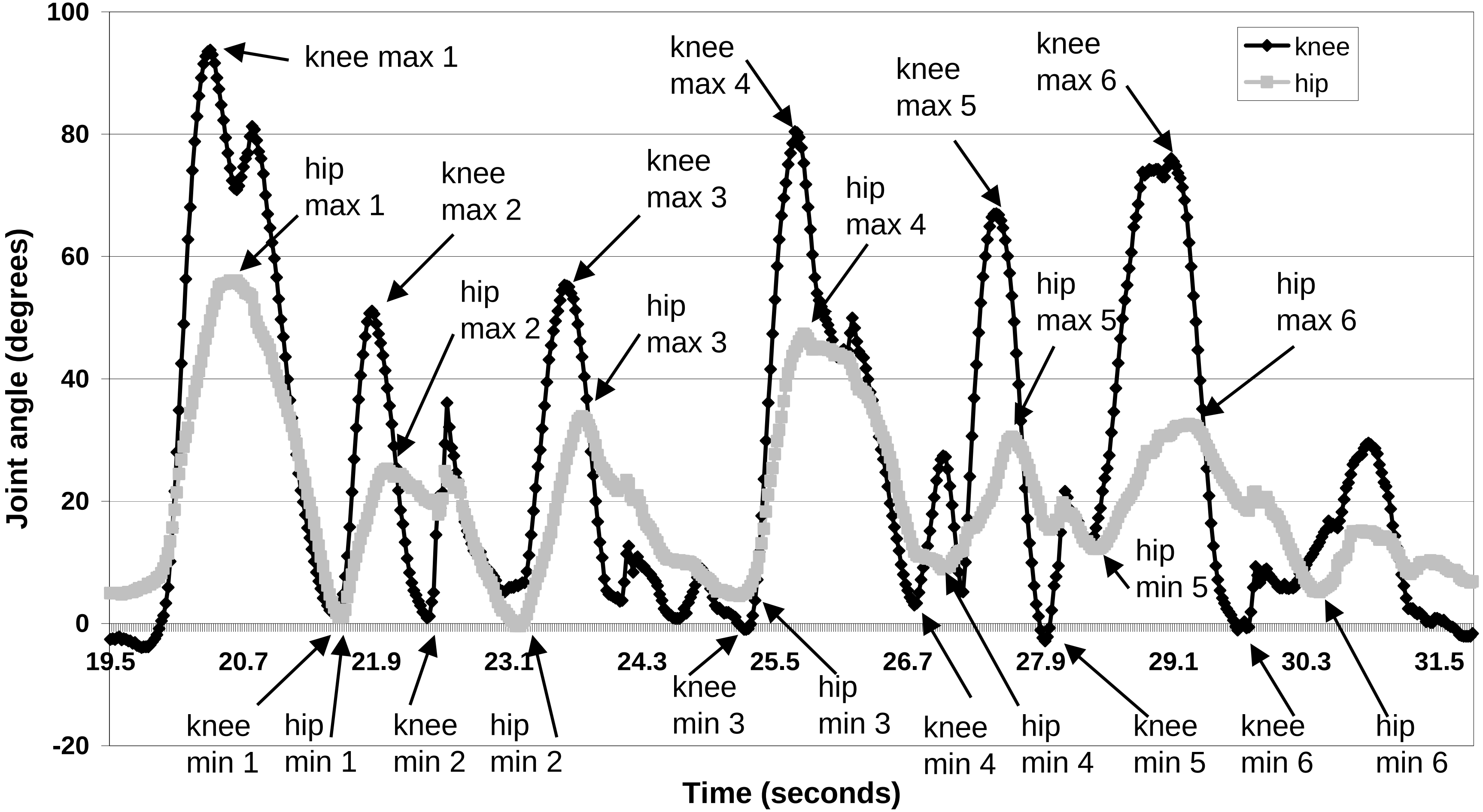


Figure 2.5. Plot of stepping data for one participant in one garment.

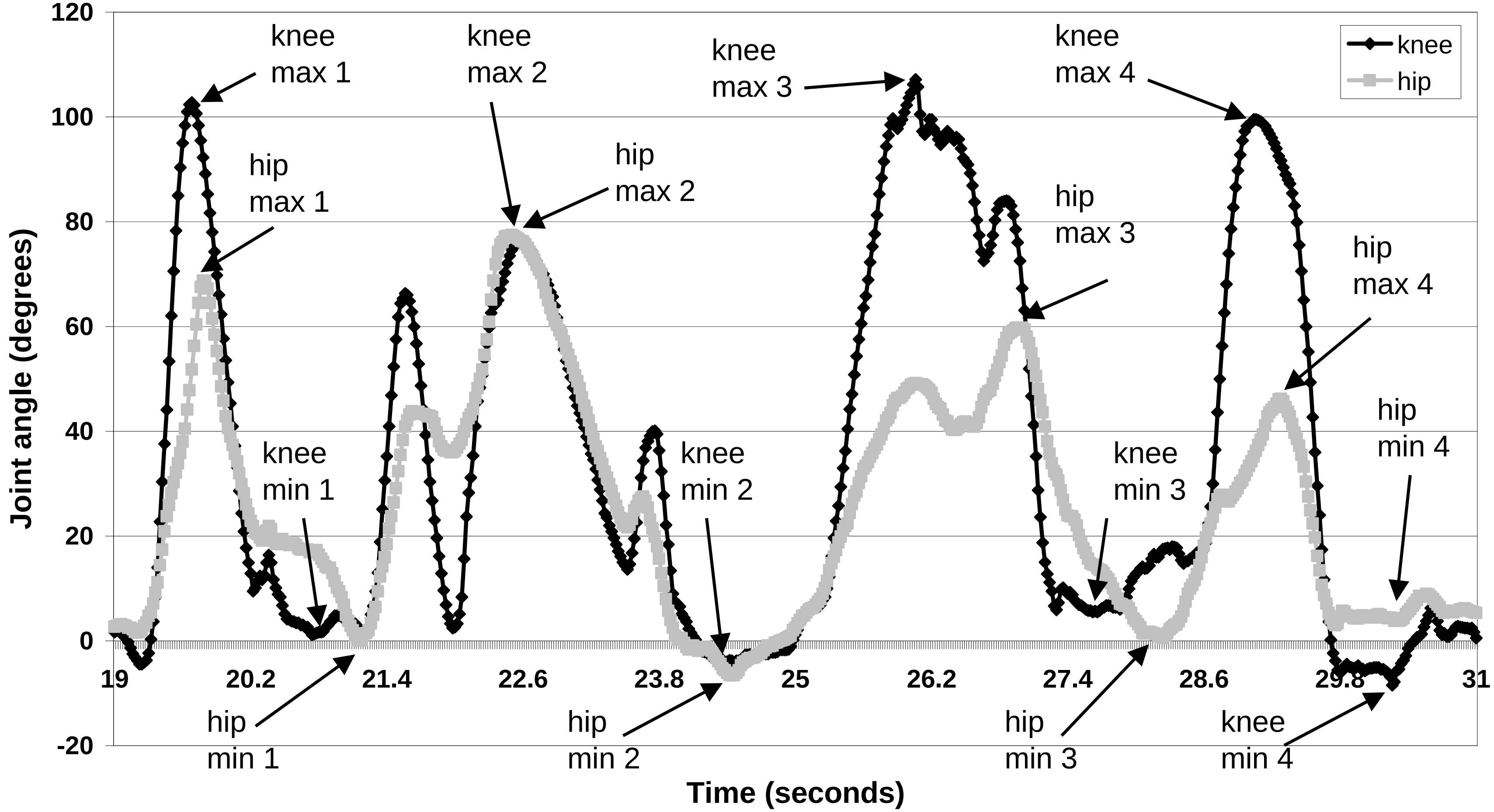


Figure 2.6. Plot of crawling data for one participant in one garment.

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

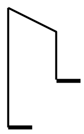
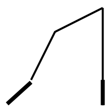
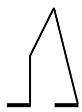
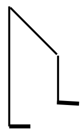
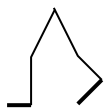
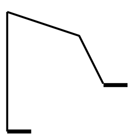
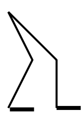
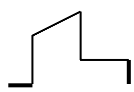
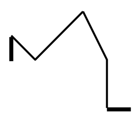
STEP 1 Right foot onto top step	STEP 2 Right foot down to floor	STEP 3 Right foot to base of steps	STEP 4 Right foot onto 1st step	STEP 5 Right foot down to 3rd step	STEP 6 Back to starting position
					
					

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

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

3. Results

3.1 Walking results

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

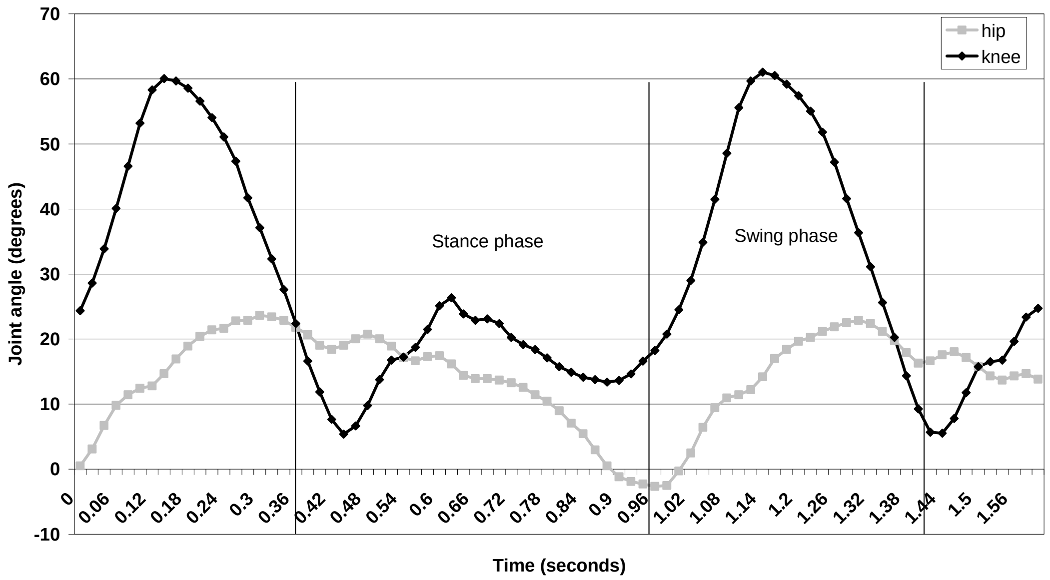


Figure 3.1. Hip and knee angles during walking gait.

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

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

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

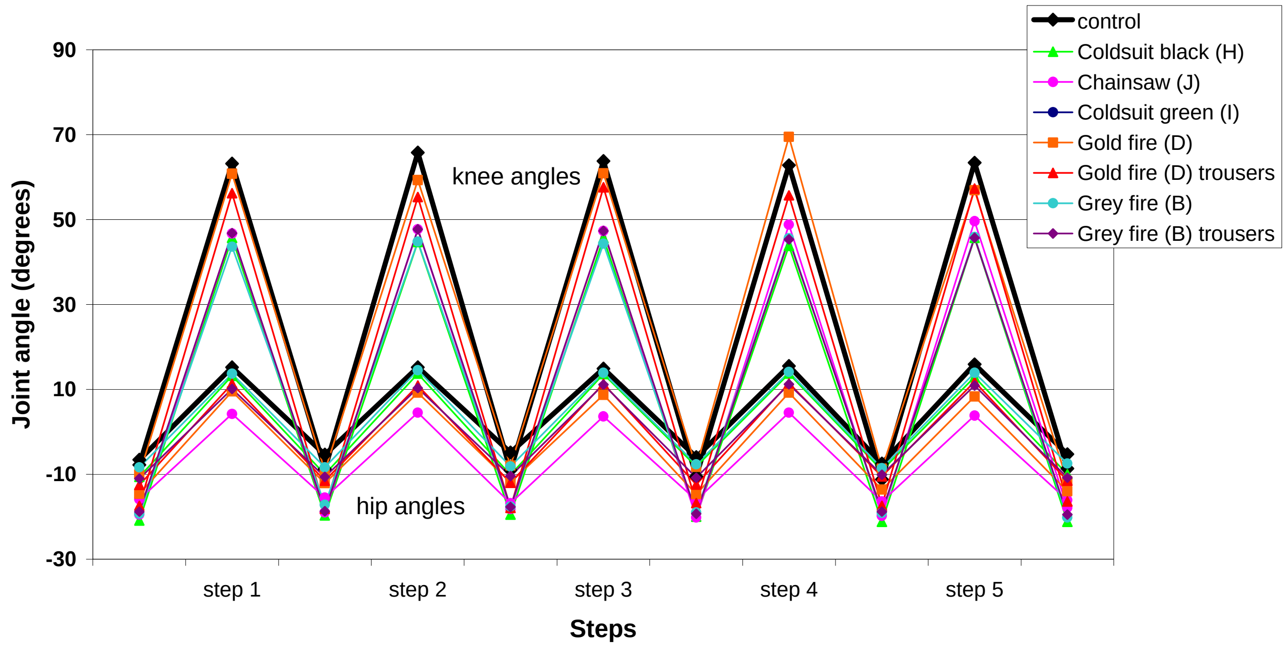


Figure 3.2. Summary graph of joint angles for Participant #2 when walking showing reduced knee and hip angles in clothing compared to control (hips data time shifted to allow maximum / minimum to coincide).

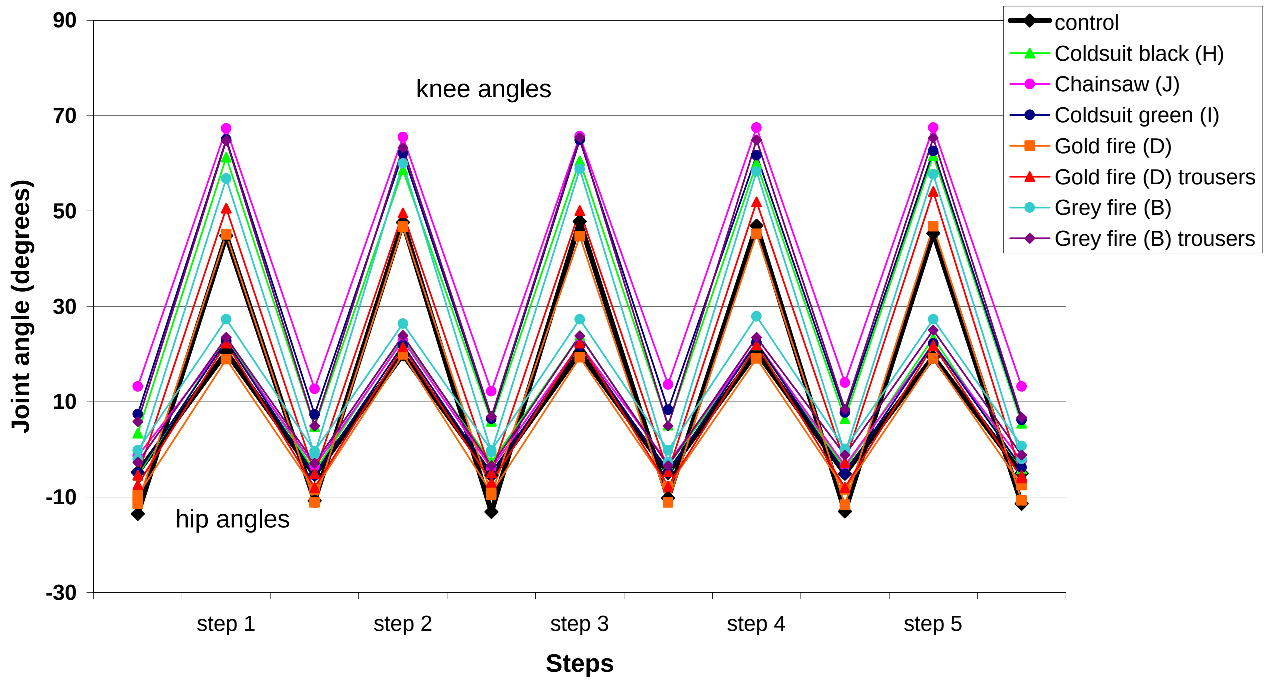


Figure 3.3. Summary graph of joint angles for Participant #4 when walking showing increased knee and hip angles in clothing compared to control (hips data time shifted to allow maximum / minimum to coincide).

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

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

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

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

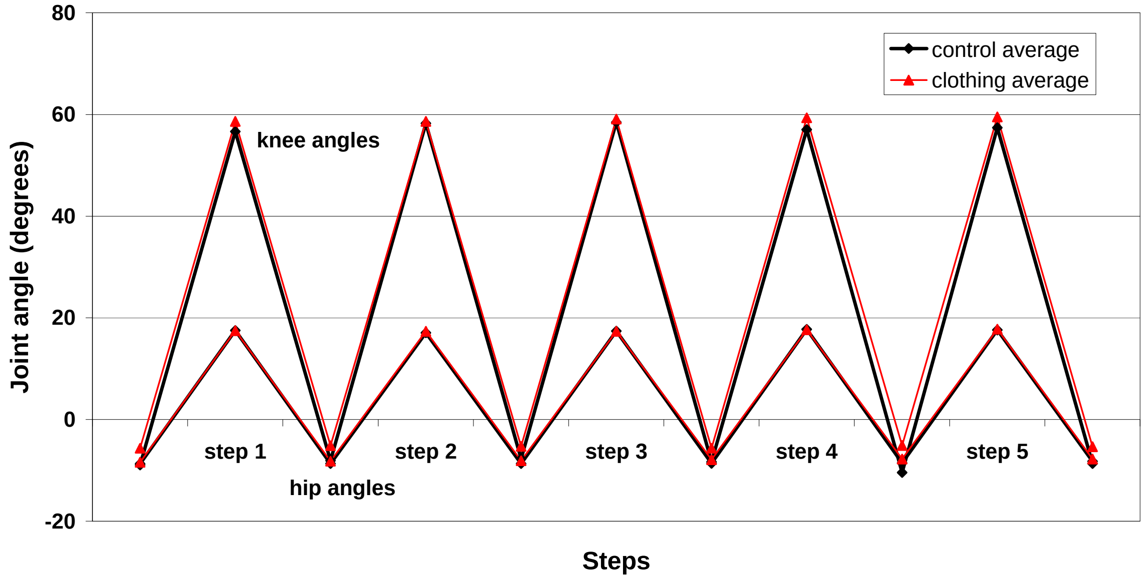


Figure 3.4. Graph of joint angles for control average and clothing average (7 garments) when walking (n=6) (hips data time shifted to allow maximum / minimum to coincide).

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

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

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

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

3.2 Stepping results

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

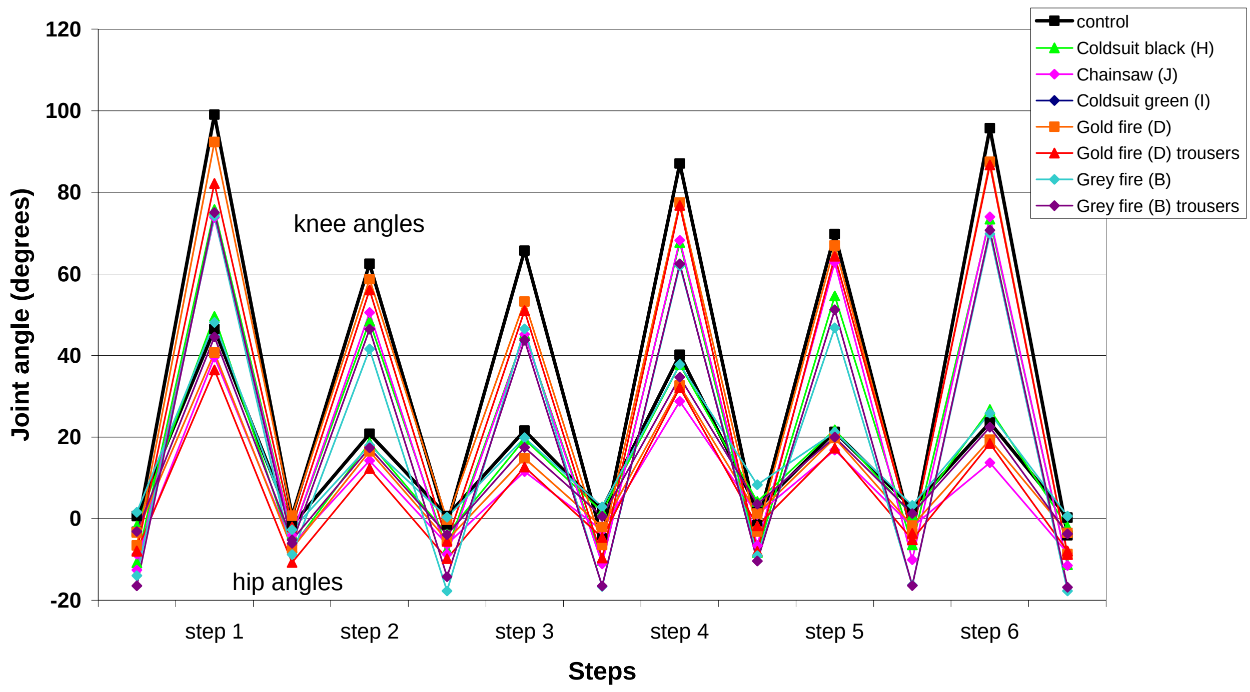


Figure 3.5. Summary graph of joint angles for Participant #2 when stepping showing reduced knee and hip angles in clothing compared to control (hips data time shifted to allow maximum / minimum to coincide).

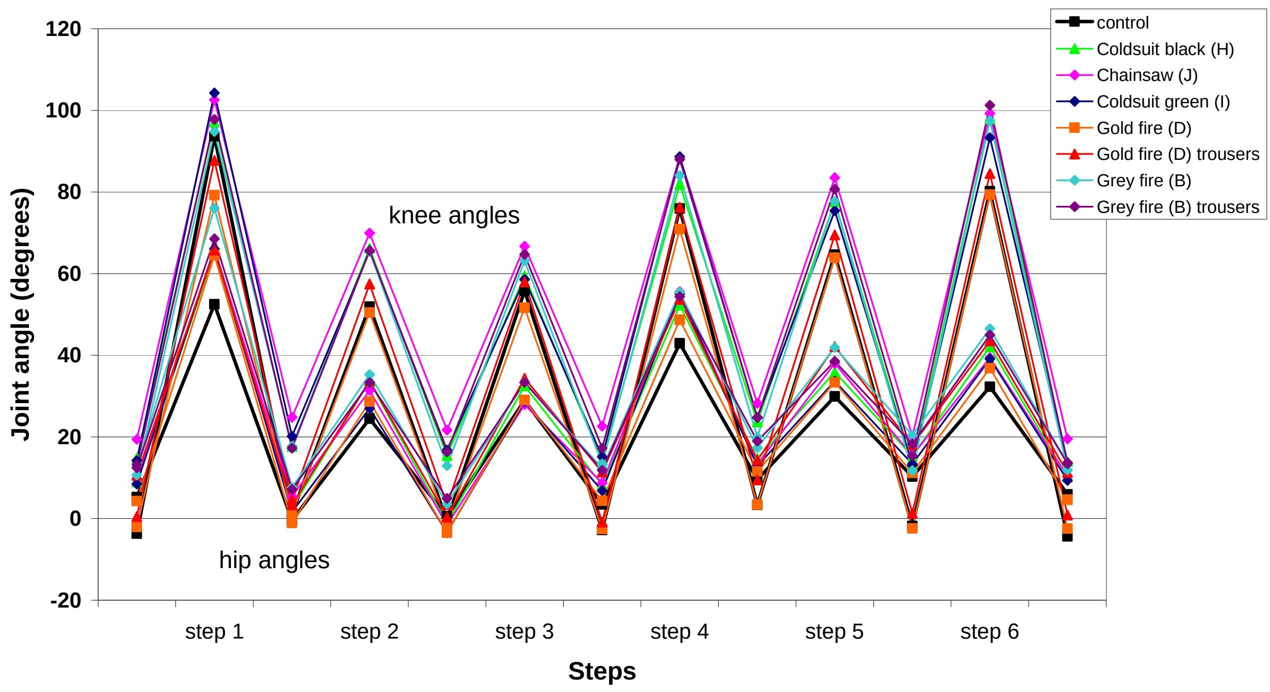


Figure 3.6. Summary graph of joint angles for Participant #4 when stepping showing increased knee and hip angles in clothing compared to control (hips data time shifted to allow maximum / minimum to coincide).

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

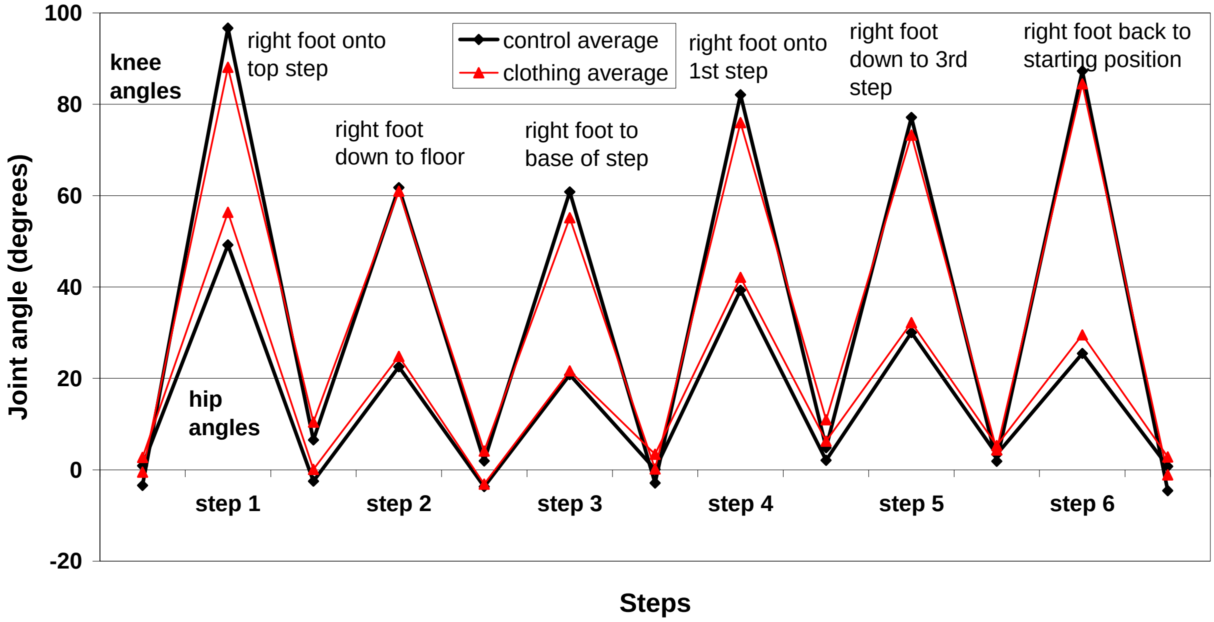


Figure 3.7. Graph of joint angles for control average and clothing average (7 garments) when stepping (n=6) (hips data time shifted to allow maximum / minimum to coincide).

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

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

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

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

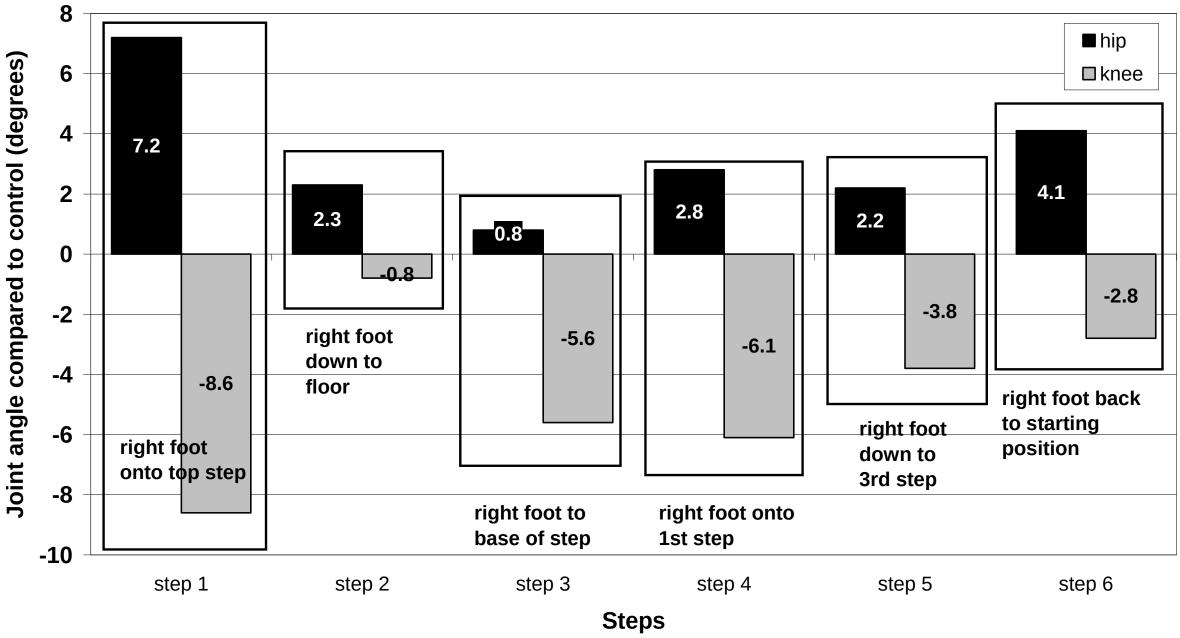


Figure 3.8. Difference in maximum joint angles compared to control for the hip and knee during all phases of the stepping sequence.

3.3 Crawling results

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

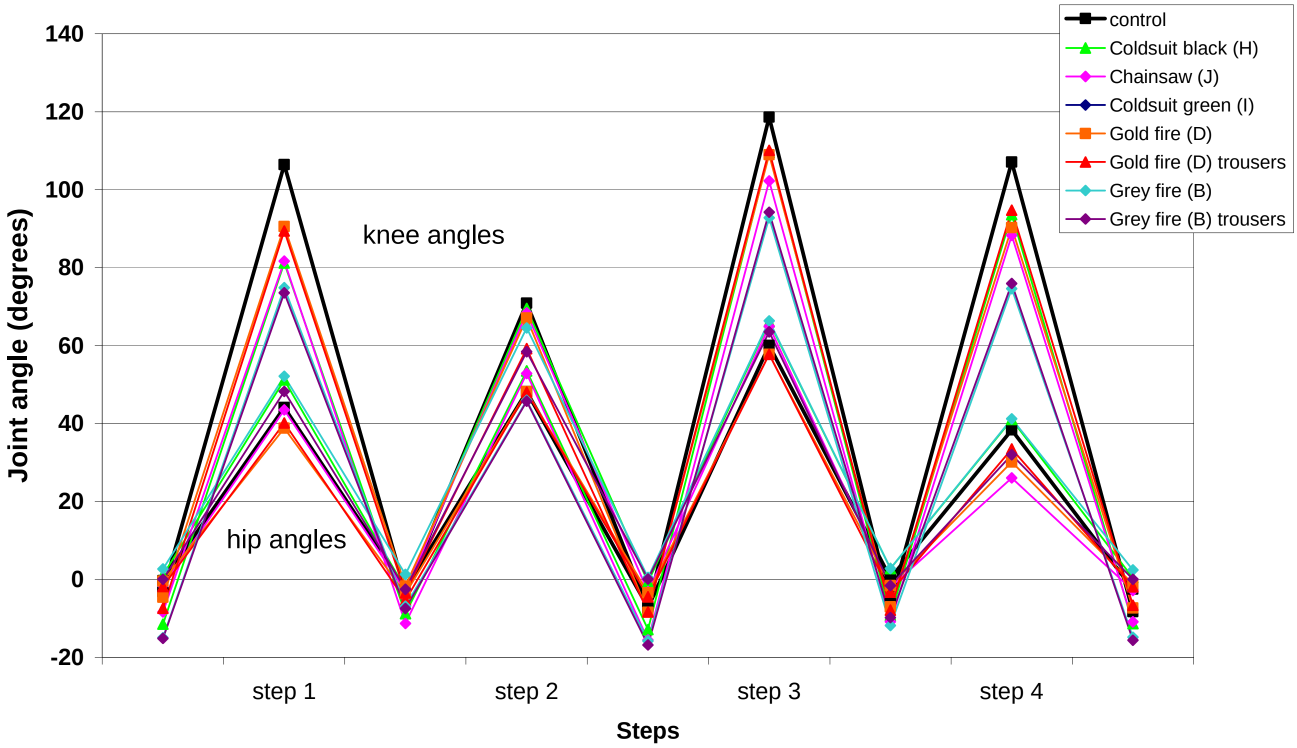


Figure 3.9. Summary graph of joint angles for Participant #2 when crawling showing predominantly reduced knee and hip angles in clothing compared to control (hips data time shifted to allow maximum / minimum to coincide).

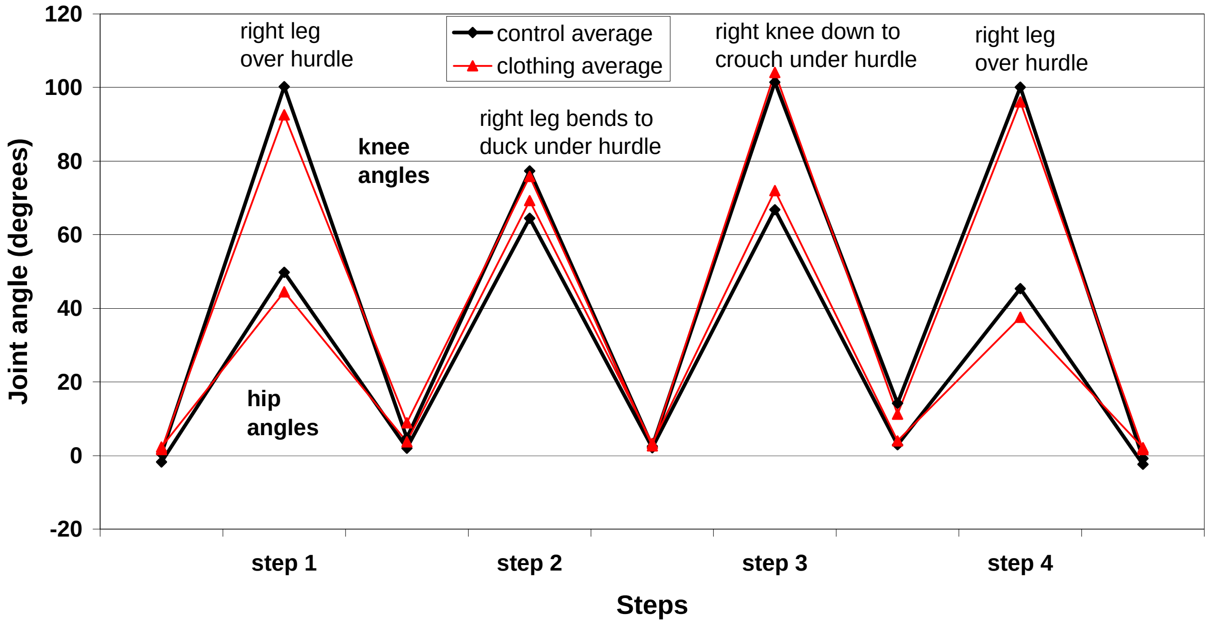


Figure 3.10. Graph of joint angles for control average and clothing average (7 garments) when crawling (n=6) (hips data time shifted to allow maximum / minimum to coincide).

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

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

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

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

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

3.4 Subjective results

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

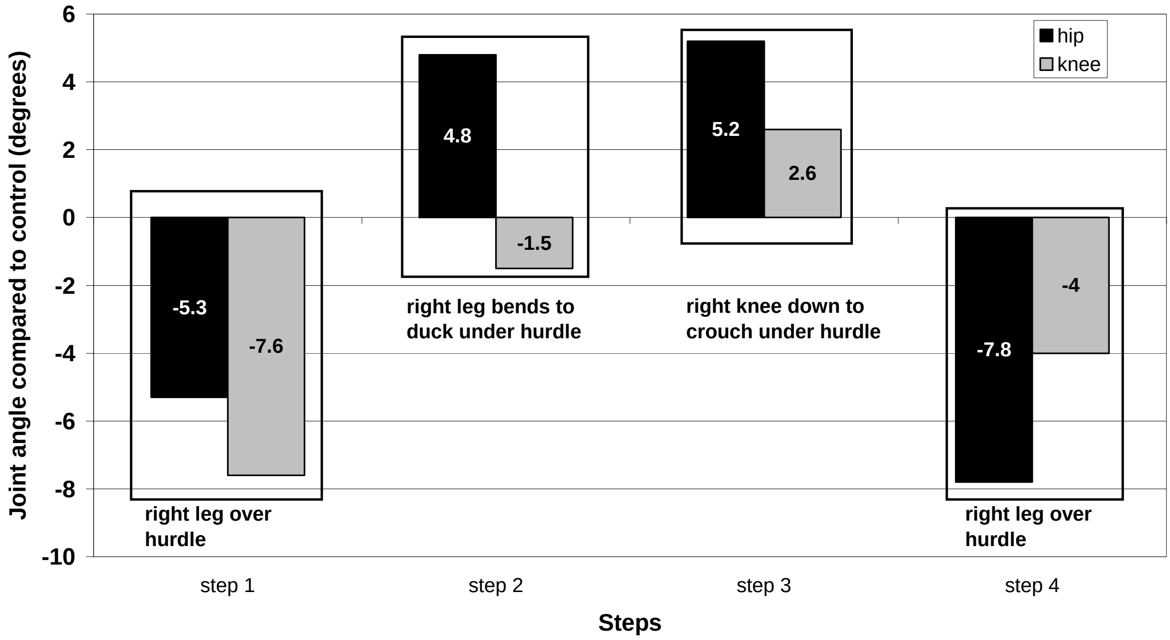


Figure 3.11. Difference in maximum joint angles compared to control for the hip and knee angles during all phases of the crawling sequence.

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

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

4. Discussion

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5. Chapter summary

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

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

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

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

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