Military Load Carriage: An innovative method of interface pressure measurement and evaluation of novel load carriage designs.

by

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Abstract

This thesis is concerned with the measurement and effects of pressure on the body as a result of military load carriage. High skin pressures are associated with impaired blood flow, brachial plexus disorders and user pain and discomfort. Load carriage research has largely overlooked this issue, mainly due to the lack of an appropriate methodology.

The thesis consists of two parts. The aim of part I was to develop and validate a novel method of measuring on-body interface pressures underneath military load carriage equipment. The Tekscan system was used, which provides 954 individual sensing elements over a total sensing area of 238.5cm^2. A number of small experiments were undertaken to establish appropriate calibration and measurement error. A five-point rating scale was developed, and included within the experimental procedure; to measure user discomfort at the shoulder area where 1 was 'no discomfort' and 5 was 'unbearably uncomfortable'. Following a pilot study the method was shown to produce reliable data that was sensitive to differences in design of load carriage systems within a comparative experimental design.

Part II of the thesis used the pressure measurement method to perform three initial experiments (n=8) where a total of twelve novel shoulder strap designs were evaluated. Participants tested each of the shoulder straps whilst carrying a backpack load of 18.5kg for one hour. The six best performing designs from the initial experiments were further evaluated in a final prototype analysis (n=18).

Of the seven interface materials investigated, the polyethylene closed-cell foam currently used as the interface material of British military backpacks was found to be the least effective. This material utilised the smallest surface area of the shoulder sensor (45.13 ± 5.7cm^2), resulting in the highest interface pressures with a mean overall pressure of 31.8 ± 5.2 kPa and also the highest discomfort ratings (3.25 ± 0.34). Mesh 6, a Monofillament double needle bar mesh, was found to be the most effective utilising the greatest amount of the shoulder area (96.7 ± 6.4cm^2) the lowest interface pressures with an average mean pressure of 15.7 ± 4.1kPa and the lowest discomfort ratings (2.25 ± 0.34).

Adding a layer of plastic superficial to the main interface material of a shoulder strap was found to be a beneficial design change regardless of the strength of the interface material. This led to an average increase in contact of 7.4cm^2 and a reduction in overall mean pressure of 5.1kPa.

In each of the four experiments correlations of between 0.55 and 0.69 were observed between interface pressure and discomfort. This indicates that shoulder pressure plays an important part in the discomfort of the user with implications for the design process. A preliminary investigation concluded that comparative data is unsuitable for the prediction of discomfort from interface pressure.

The thesis concludes that it is now possible to evaluate load carriage systems in terms of pressure and discomfort. As a result, load carriage research can move in an unexplored direction with positive health and comfort implications for the user and performance benefits for both the user and the military as a whole.

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Chapter 1 Introduction

1.1 Background to the Project

The Defence Clothing and Textile Agency (DCTA), an agency of the Ministry of the Defence is concerned with the design and development of equipment for the British Military. For the last six years they have worked alongside Loughborough University, funding scientific research on load carriage methods. The aim of this work has been to increase the knowledge of the mechanisms underlying the response to carrying load carriage equipment as well as to develop new methods of evaluating load carriage systems. Recently there has been a change of emphasis in load carriage research, moving away from the now well established work on the cardio-respiratory effects of load carriage. Work has instead begun to focus on how carrying equipment affects the user in terms of discomfort, injury and loss of performance. This has resulted in attempts to alleviate the strain on the soldier in order to improve the health and performance of the individual soldier.

One of the areas that has become of interest to researchers is the effect of pressure exerted on the body as a result of load carriage equipment. Excess pressure can be seen as the major attributing factor in the majority of pain and discomfort suffered by military personnel. It has also been suggested that pressure may be the primary factor in the incidence of a painful and disabling injury known as Rucksack Palsy.

This is an area that has not been studied in depth, mainly due to the lack of equipment available for accurately measuring body interface pressure. Recent developments in the technology of pressure measurement have now made such measurements possible and this has resulted in increased interest in this area.

However a robust methodology for measuring body interface pressure is required to further the research in this area. This would enable the evaluation of materials, which may distribute pressure effectively, which up until now has not been possible.

1.2 Objectives of the Project

1. To develop a methodology of quantifying the pressure effects of load carriage equipment using subjective and objective methods (Part I).

2. To investigate the effects of strap design and compositions on pressure distribution and the resulting effect on user comfort (Part II).

1.3 Structure of the Thesis

This thesis is divided into two main study areas. It begins with a review of literature regarding the effects of load carriage equipment (Chapter 2). Chapter 3 presents a discussion on the products available for pressure measurement and is followed by the development of the pressure sensing equipment (Chapter 4). The development of the experimental procedure and piloting of methods is dealt with in Chapter 5. Part II is concerned with the evaluation of various prototype shoulder straps. It begins with the background leading to the choice of interface materials to be investigated and the experimental procedure for all of the practical work (Chapter 6). Three individual experiments are then presented (Chapters 7,8 and 9). A fourth experiment (Chapter 10) performed a final prototype analysis, evaluating the two best performing straps from the first three experiments. The implications of the experimental work and a discussion of the findings within a military context are also presented in this chapter. Chapter 11 deals with the relationship between the objective and subjective data collected during the experimental work. The conclusions for both parts of the thesis are presented in Chapter 12, and the final chapter contains suggestions for future work (Chapter 13).

Chapter 2 Literature Review

2.1 Introduction

Throughout history man has been dependent on the manual carriage of loads for purposes of survival, migration and warfare. Although modern technologies have managed to liberate us from this in many situations, there are still many occupational tasks that require the carriage of heavy loads over long distances. The scientific field of load carriage research is a relatively new area, which initially was concerned with general load carriage such as the carriage of loads in rural and developing communities. In the last 20-30 years this emphasis has shifted towards the carriage of loads in the military with a large portion of the current research funded by the defence sector.

Infantry soldiers are continually required to carry heavy backpack loads over much longer distances than civilians who engage in recreational backpacking. Accomplishment of many military objectives often require that soldiers complete a road march as rapidly as possible whilst sustaining minimal fatigue and discomfort in order to complete the required tasks at the end of the march. Due to an increase in protective equipment and firepower, the loads carried by infantry soldiers have risen considerably in recent times (Knapik et al, 1992). As a result work investigating the effects of load carriage has become increasingly relevant.

This chapter will deal with the previous work carried out in the area of load carriage research. Such works have led to well known concepts about the optimum manner in which to carry load on the body.

2.2 Physiological Work

2.2.1 Metabolic Cost of Load Carriage

The majority of research carried out on the physiological costs of load carriage has concentrated on energy expenditure and providing recommendations as to the optimum way of carrying load on the body. Due to the lengthy exercises undertaken by foot soldiers whilst carrying heavy loads the issue of energy expenditure is an important one. It is often necessary for an infantry soldier to complete a long march, lasting several days with only minimal breaks for rest. Therefore, it is essential that load be carried in the most efficient manner in order to optimise performance and speed. Over such a long duration even a small change in energy expenditure may result in a significant effect on a march and importantly the ability to perform necessary activities at the end of it.

A lot of work has attempted to define the optimum method of carrying load on the body in order to minimise strain and maximise performance. In a study of seven modes of load carriage, Datta and Ramanathan (1971) found substantial differences in the physiological cost of load carriage. When carrying approximately 60% of their body weight, the most efficient method was a double pack, where the load is split between the front and the back of the trunk. This method resulted in an average 9% less energy expenditure than carrying the same weight in a traditional backpack where the load is carried solely on the back. The most efficient pack, the double pack, resulted in the least change to the body's centre of mass. The most inefficient method of carriage was hand carriage, which utilises the smallest muscle groups, with the other methods falling between these two extremes. Datta and Ramanathan's work provides support for the theory (Holewijn and Lotens, 1992) that for efficient load carriage weight should be kept close to the centre of the body and utilise large muscle groups.

Legg and Mahanty (1985) compared a number of load carriage methods in terms of their physiological, metabolic and subjective effects. The methods studied in this work were more suited for military use and aimed to keep the carried load as close to the trunk as possible. The systems evaluated included framed and non-framed backpacks, a double-pack, trunk jacket and a backpack and belt kit combination. Although the differences in physiological cost between the methods (measured by oxygen consumption, ventilation rate and heart rate) were not statistically significant, the participants rated the double pack the most favourable in terms of stability and comfort. This suggests that although there were differences between the load carriage methods, they were not large enough to influence physiological variables. From their results, Legg and Mahanty argue the importance of subjective reports and their effect on state of mind and consequently, performance.

There have been attempts by commercial backpack manufacturers to include the recommendations of Datta and Ramanathan and Legg and Mahanty in their designs. Lloyd and Cooke (2000) evaluated one such pack that used front balance pockets to distribute load between the front and back of the trunk whilst carrying 25.6 kg at various gradients. During downhill walking no significant difference in oxygen consumption was found between the new balanced backpack and a traditional pack where load was carried solely on the back. However, during uphill walking and walking on level terrain, the balanced backpack resulted in a lower oxygen consumption of between 6 – 9%.

These studies agree that splitting a load between the front and the back of the body is the most metabolically efficient method by which to carry load. However, both Datta and Ramanathan and Legg and Mahanty highlight possible practical problems with carrying load on the front of the body. Datta and Ramanathan state that although this method should be used whenever possible a special harness to split the load is required which is difficult to don and doff, an important consideration for military load carriage. Improvements in design such as the introduction of pockets onto a normal backpack harness such as in the Lloyd and Cooke (2000) study, however, may make frontal load carriage more practical.

Legg and Mahanty (1985) add that frontal load carriage may result in restriction around the chest. In their study, the double pack resulted in the lowest maximum voluntary ventilation. This is another important issue, as a large amount of military tasks require a high work rate. They also suggest possible thermal penalties as a result of frontal load carriage due to a smaller body area available for heat loss by evaporation. Other practical problems that may limit the application of frontal load carriage include visual impairments during walking which may adversely affect both military personnel as well as civilian hikers. Legg and Mahanty conclude that the optimum way of carrying load is dependent upon the individual task, distance and preference of the carrier.

The effect of smaller design differences on physiological parameters has also been investigated. For example, Kirk and Schneider (1992) compared internal and external framed backpacks. The use of a frame in a backpack has been shown to relieve pressure and discomfort on the upper torso (Legg and Mahanty, 1985), and therefore Kirk and Schneider hypothesised that an internal framed backpack would result in less metabolic and cardiorespiratory strain on the body. They suggested this would be due to the combined pack-user centre of mass being closer to the centre of mass of the unloaded body. As a result, less muscular activity would be required to maintain posture. A secondary aim of this work was to assess whether females have a different response to load carriage due to differences in body composition, aerobic capacity and anthropometry.

They found that for female participants, no physiological difference was found between the two backpacks in terms of ventilation rate, oxygen consumption and heart rate. This may have been due to the fact that the two pack types used very similar muscle groups and that the difference in load distribution over the body was not large enough to result in differences in physiological parameters. Also, This was backed up by the subjective data; the female participants appeared to have no preference for either a framed or non-framed backpack.

An interesting finding in this study was that the ratings of perceived exertion from the participants increased as the study progressed, a pattern that was not observed with the physiological parameters. Kirk and Schneider suggest that this is due to localised fatigue which was enough to affect subjective feelings but not sufficient to affect physiological measurements. Kirk and Schneider's results also support the inclusion of subjective measures in any evaluation of load carriage systems in addition to objective or physiological measurements. Although no change in the measured physiological parameters of the participants was found, if the exercise affects perceived exertion then it is probable that this will affect the motivation and performance of the individual. This is a key issue when considering load carriage within the context of military load carriage where motivation and high feelings of psychological well-being are crucial for the success of military operations.

2.2.2 Prediction of Energy Cost

With a view to predicting the energy cost of backpack load carriage, many researchers have attempted to discover the relationship between various factors and energy expenditure. The research in this area is plentiful and exhaustive and has shown that there is an increase in energy expenditure as the mass carried increases (Borghols, 1978; Goldman and Iampietro, 1962; Soule and Goldman, 1969; Soule et al, 1978). The same pattern has been shown to exist between speed of marching and energy expenditure (Goldman and Iampietro, 1962; Soule et al, 1978; Workman and Armstrong, 1963) and also gradient and energy expenditure (Borghols, 1978; Goldman and Iampietro, 1962; Pandolf et al, 1977). Terrain has also been shown to have this proportional effect (Haisman and Goldman, 1974; Pandolf et al, 1976; Soule and Goldman, 1972).

One of the first attempts to produce an equation to predict the metabolic cost of load carriage was made by Givoni and Goldman (1971). The developed model used the established relationships between energy expenditure and body weight, carried load, velocity and gradient. This equation was found to be valid for both men and women carrying loads of up to 70 kg when walking at speeds of between 2.5 – 9 km h^{-1} at gradients of up to 25% on a treadmill. The observed correlation coefficients between predicted energy cost and measured energy cost were in excess of 0.95.

This initial equation was further developed by Soule and Goldman (1972) to enable predictions to be made for different terrain. Six different terrain types were studied whilst carrying three different loads (8, 20 and 30 kg) at two different speeds (2.4 and 4 km h^{-1}). Terrain coefficients were created from the ratios between the measured energy cost compared to the energy cost on a treadmill. This made it possible to predict the energy cost of load carriage over blacktop road, dirt roads, light and heavy brush, swampy bog and loose sand. Pandolf et al (1976) supplemented the work of Soule and Goldman and looked at the effects of walking in the snow. Energy expenditure was found to increase linearly with the depth of footprint depressions and a new coefficient was introduced to account for this. Walking in the snow was found to have a severe fatiguing effect as the highly aerobically fit participants in the study quickly became exhausted when walking at moderate speeds. As a result of this, maximum speeds were recommended depending on the snow depth in order to keep work rate below $50\%VO_{2max}$ and allow prolonged marching. As a result of the fit participants in this study becoming exhausted at very low speeds Pandolf et al (1977) further modified the predictive energy cost equation to include load carriage whilst standing and walking at very low speeds.

In a study by Keren et al (1982) this prediction equation was found to overestimate the energy cost when travelling at speeds over 8 km h^{-1}, because of the probable increased efficiency of running over walking. Epstein et al (1987) responded to this by modifying the equation for a wider range of speeds and also loads and gradients. The predicted energy cost from this latest equation was found to have a high correlation ($r = 0.95$) with observed values and values taken from previous literature.

There have been a number of studies carried out to assess the validity of these equations, Cymerman (1981) concluded that the Pandolf et al (1977) equation was valid for altitudes of up to 4300m and for metabolic rates of up to 730W. Pimental and Pandolf (1979), on the other hand, found that the equation marginally overestimated energy expenditure when standing with a load but underestimated at slow walking speeds (1.8-km h^{-1}) at a grade of 10%. A further study (Pimental et al, 1982) found the equation to undervalue by up to 33% when predicting for level walking at 4 km h^{-1}. However, it was accurate for all uphill conditions.

Duggan and Haisman (1992) collected data from seventeen different combinations of grade (0-6%) and carried load (4.1 – 37.4 kg) at a speed of 6 km h^{-1}. From the results it was concluded that predicted energy costs from the Pandolf et al (1977) equation did not significantly differ from observed values and that the errors incurred were "acceptable for most practical purposes" (Duggan and Haisman 1992).

One possible limiting factor for prediction equations that is debated, is whether the energy cost of load carriage increases with time. Epstein et al (1988) found that when carrying load of 25 kg there was no increase in energy expenditure over time. However, when a load of 40 kg was carried, the energy expenditure per kg of carried load increased significantly over the two-hour duration. This effect was also supported by Patton et al (1991) who found that when carrying 31 and 49 kg at speeds of 4.8 and 5.8 km h^{-1}, energy expenditure increased by between 10 and 18% over a 2 hour period. Epstein et al (1988) suggested that this effect could be due to physical fatigue, which alters locomotion biomechanics. As skeletal muscle fatigue occurs, additional muscle mass has to be recruited to maintain the same work rate and this results in altered gait. Thus a higher power output is required to carry the same load. If $\%VO_{2max}$ continues to increase, this will lead to further increases in fatigue, decreased performance and ultimately, the discontinuation of the exercise. Consequently, energy expenditure may be greatly underestimated when considering load carriage over long durations or with very heavy loads that result in work rates in excess of $50\%VO_{2max}$.

In a separate study carried out by Sagiv et al (1994), however, the results of Epstein et al were contradicted. In this study, which consisted of very similar speed and load conditions to those of Epstein et al (1987) and Patton et al (1991), no increase in energy expenditure over a 4 hour duration was observed. However, the participants in Sagiv's study were considerably more aerobically fit and it is therefore possible that they did not become as fatigued as the participants in Epstein's and Patton's work. Also, the pack used in Sagiv's study was of a different design and incorporated a hip belt, which may have transferred some of the load from the shoulders onto the hips thus supported by the strong leg muscles. The packs used in the studies of Epstein et al (1987) and Patton et al (1991) did not have such a belt and therefore the smaller upper body muscles would have borne the majority of the load. It is probable, therefore, that this would have had a substantial effect on how quickly the relevant muscles became fatigued during prolonged load carriage.

The results from the work of Epstein et al (1987), Patton et al (1991) and Sagiv et al (1994) demonstrate possible shortcomings of predicting metabolic cost of load carriage. However, there is a general consensus that they provide a good practical estimate of moderate load carriage at moderate speeds for relatively fit individuals.

2.2.3 Capacities

There have been many attempts to determine the maximum load that should be carried by military personnel. As early as World War I overloading the infantry soldier was identified as a problem. In this case this was the result of mud and water soaking into clothing and equipment and increasing a 27kg load to 43kg. Although problems such as this have been overcome, the current problem facing the infantry soldier is the recent increase in the amount of equipment to be carried during both operational and training exercises as a result of improved communication and firepower technology.

The most commonly used measure of an individuals ability to carry load is maximum aerobic capacity (VO_{2max}) as this provides a measure of cardio-respiratory performance and an indication of an individuals ability to perform sustained work at a high rate. It is well established that by increasing VO_{2max} the ability of an individual to carry load will also increase. Recommendations have been made that active, well trained males should not work at levels that result in a work rate of more than 50% VO_{2max} over a working day (Astrand, 1956).

VO_{2max} has also been used as a measure when suggesting maximum loads that should be carried by military personnel. Schoenfeld et al (1977) proposed that individuals in good physical condition should not carry any more than 25kg for sustained activity such as a 20km march. This limit is also suggested by Davis (1983) in order to minimise fatigue. The US army bases their recommendations on work by Epstein et al (1988) that suggest that load should not exceed 30% of the individuals body weight for optimal carriage with a maximum load of 45% of body weight at any time.

In the case of the British Military, the basic 'marching order' which consists of the equipment and rations to sustain a soldier through a march of two or three days has a minimum weight of 40kg. However, when specialist equipment, communication equipment and firepower for the specific tasks are added, weights of up to 70kg are not untypical and have been observed in situations such as the Falklands conflict (McCraig and Gooderson, 1986). It is clear that laying down such limits as 25 – 50kg are essentially meaningless if these are habitually ignored in order to take all necessary equipment. As Haisman states, "the load that the soldier carries will always be a compromise between what is physiologically sound and what is operationally essential". Consequently, researchers have begun to focus on improving the way in which soldiers carry these heavy loads instead of attempting to restrict them.

2.3 Performance

More recent load carriage research has attempted to quantify the loss of performance as a result of carrying load on the body. Performance testing has also been used to compare different designs of backpack. All of the studies in this area have used similar activities as part of the testing conditions, designed to test stability, balance and freedom of movement. Some studies have also incorporated tasks involving smaller movements such as grenade throwing and marksmanship tasks which play an important role in military operations.

Martin and Nelson (1985) carried out one of the first attempts to determine the effects of load carriage on military type activities. They looked at different military load combinations ranging from carrying no equipment, to wearing just waist worn webbing to carrying a pack weighted to 37kg. Both male and female military participants were studied. Martin and Nelson found that decrement in performance was linearly related to increase in load. In addition, there was a clear difference in performance between male and female subjects and as load increased this difference became more pronounced.

Two pieces of work have attempted to quantify the effect of load carriage on loss of performance, defined as the decrease in performance compared with an unloaded condition. The first of these by Lotens (1986), found that performance on military type activities decreased by between 0 and 2% when wearing fatigues and a helmet rising to between 7 and 13.5% when carrying a weapon and a loaded backpack. From the results of this, a model for the prediction of loss of performance as a result of the load carried was developed. Holewijn and Lotens (1992) extended this study and separated absolute weight and the volume of a carried load. Participants carried different combinations of load and volume on different areas of the body: solely on the back, on both the back and the front, and around the waist. Holewijn and Lotens (1992) found that each kg of load carried resulted in an average loss in performance of 1%, and every litre of volume of load resulted in 0.2% loss in performance. The recommendation of this work was that in order to optimise performance weight should be kept close to the trunk and as close to the waist as possible. Volume may be carried over the front and back of the body without decrement in performance.

Performance testing has also been used by military researchers to evaluate different designs of load carriage equipment. Harman and Kirk (1998) used performance testing as part of a large scale study to evaluate a new model of load carriage equipment designed by the US military. The results from this were used to pinpoint design problems with the new prototype rather than to quantify the decrements in performance as a result of the different systems.

As part of a large evaluation and development programme in collaboration with the Canadian military, researchers at Queens University have used a mobility circuit to evaluate different characteristics of load carriage equipment. Objective measures of performance on the circuit as well as subjective reports by the participants indicated a number of factors that affect user mobility. It was recommended that to minimise the effects of load on mobility and agility a load carriage system should allow free movement of the lower body and hips, allow unrestricted forward bending and keep the centre of mass of the load close to the users back (Bryant et al, 1996; Doan et al, 1998 (1); Doan et al, 1998 (2).

2.4 Effects on Walking Gait

The effect of load carriage on walking patterns and posture has also been thoroughly investigated. Ghori and Luckwill (1985) showed that man, already inherently unstable because of his bipedal walking characteristics, becomes increasingly so during load carriage due to the raised centre of gravity. In this study, where participants were loaded with 10, 20, 30, 40 and 50% of their body weight, gait appeared to compensate for this instability by shortening the swing phase of the walking cycle and increasing double support time. This has also been demonstrated by Martin and Nelson (1986), who in addition found that the observed effects were more pronounced in female participants, presumably because of differences in stature and leg length. In the loaded conditions (up to 36 kg) male participants displayed greater stride lengths, single leg contact time and swing time and consequently lower stride rates.

As a result of this, during a prolonged march women may take many more steps whilst covering the same distance. Thus, when walking at an imposed speed, as in the case of military situations, women will work at a higher percentage of their maximal work capacity. This was supported by the participants being asked to describe the speed at which they were required to walk at. The majority of the men described it as a moderate and comfortable level whilst the majority of female participants rated the pace as fast. Taking more steps will subject the lower extremities to a higher degree of stress. Each time the foot makes contact with the ground it has to absorb the collective weight of the load and body weight, resulting in a greater chance of developing chronic and acute leg injuries. This, combined with the fact that deMoya (1982) demonstrated that female participants display relatively greater peak ground reaction forces than male participants, indicates that female participants may be at greater risk from leg injuries.

Martin and Nelson (1986) also demonstrated that changes in walking patterns induced by extra load are greater for females compared with males due to the same load representing a higher proportion of their body weight. It has been demonstrated however, that male - female differences in strength and performance persist even when size is taken into account (Asmussen, 1973, Martin and Nelson, 1985). The most likely reason for difference is the lower percentage of lean body mass in females, the component of the body that supports a carried load.

The effect of load carriage on posture was investigated by Bobet and Norman (1984) who measured the effects of placing a 19.5 kg load at different placements on the back muscles (mid-back and shoulder level). From this work they noticed that the activity in some muscle groups was lower when a load was applied. During unloaded walking, the line of gravity of the combined head, arms and trunk (HAT) was located slightly posterior of the lumbosacral joint. Because of this, the dominant moment was one of trunk flexion and to resist this moment required some activity of the erector spinae muscles. However, when a load is carried during walking, the weight on the back creates a back extension moment that partly offsets the flexion moment of the HAT, thereby reducing erector spinae activity. Obviously, the reduction in muscular activity will depend on the weight of the HAT, the angle of inclination adopted to balance the moments of force and the ability of the participant to maintain this balance during the accelerations and declarations associated with the walking stride.

Another difference in muscular activity between loaded and unloaded walking is in the upper trapezius. Higher muscle activity is observed during unloaded walking, probably due to the slightly abducted arm position during walking. When walking with a pack the arms can hold on to the shoulder straps reducing this muscular action.

Martin and Nelson (1985) did not find that altering the placement of load on the back had an effect on the static moments of the body, but that it did have a significant effect on the dynamic moments. The activity in the upper trapezius muscle was found to be significantly higher when the centre of gravity of load placement was at shoulder level. Some of this can be explained by the acceleration and deceleration of the trunk passing through the shoulder straps to the pack, hence increasing trapezius action. This, combined with the effect that the load is higher reduces the stability of the user and pack, increasing swaying, which must be compensated for by the trapezius muscle. From this Martin and Nelson concluded that a mid-back load placement is preferable as it is easier to control unexpected accelerations caused by stumbles and trips when the load is placed lower down.

A second aim of Bobet and Norman's (1984) work was to determine whether heart rate measures used as a correlate of metabolic rate differentiated between the two backpack load distributions. They found that heart rate did not change in response to differences in muscular tension. Suggested reasons for this are that although there may be differences in muscular tension, energy expenditure remained the same regardless of load placement and also the fact that the activity of one muscle group accounts for only a fraction of the total metabolic activity of the body. It was concluded therefore, that heart rate is not sufficient a measure to evaluate the physiological demands of differences in load placement on the back. Care must be taken not to disregard non-significant differences in metabolic cost between parameters as they may not pick up pain, fatigue or discomfort caused by excessive local muscle tension rather than excessive energy demands. This is support for the use of measures of subjective feelings such as ratings of perceived exertion used by some authors.

Bloom and Woodhull-McNeal (1987) investigated the effects of internal and external framed backpacks on body posture when carrying 22-32% of body weight (19 kg and 14 kg for males and females respectively). The general effect was that the participants lent forward regardless of whether the pack had an external or internal frame. The anterior-posterior position of the centre of gravity of the whole body relative to the ankles did not change significantly when loaded compared with the unloaded stance, therefore changes in body alignment can be seen as stabilising the whole body centre of gravity. The partial centre of gravity above the hips was significantly further back in the loaded condition resulting in a change of torque at the hips. This change was greater for internal framed rucksacks than external framed. The body bends forward to a greater extent whilst wearing an internal framed pack as the load is carried lower down. There is a trade off between the need to balance the body whilst on the other hand not leaning forward too much. The fact that the mass rests lower on the body is also an advantage for the internal framed pack in terms of stability.

Bloom and Woodhull-McNeal (1987) concluded that the choice of appropriate carriage method may be based on the type of terrain that has to be covered. An external framed rucksack may be preferable when the terrain is more even and where unexpected movements are more unlikely, whilst an internal framed rucksack may be preferable when the ground is more undulating.

Bloom and Woodhull-McNeal (1987) also addressed the question of which method is more preferable to the individual carrier. They found that the majority of female users preferred the external frame rucksack with the majority of male users preferring the internal framed pack. This finding contradicts the work of Kirk and Schneider (1992), who, in a more extensive study involving longer carriage periods and incorporating physical activity whilst load carrying, found no preference for either type of pack.

2.5 Injury

The types of injuries that result from load carriage are usually minor, however, they can significantly affect an individual's mobility and motivation. In a military situation this may greatly reduce the effectiveness of an entire unit. Research into this area has concentrated on two distinct types of injury, those resulting from just one load carriage exercise, and those that are sustained over long periods of regular load carriage.

Common injuries sustained during load carriage are foot blisters, which occur due to friction between socks and the skin. Although these are relatively minor injuries, they can be extremely painful and lead to several days of restricted activity. The major risk factor for increased incidence of foot blisters has been shown to be increased weight, which increases friction between the skin of the foot and the inside of the boot. Knapik et al (1993) demonstrated that when carrying very heavy loads (61 kg) the use of a double pack results in a lower blister incidence compared with a traditional backpack. Knapik suggests that this is due to increased movement of the foot inside the boot as a result of increased braking forces in the anteroposterior direction when carrying heavy loads solely on the back.

Another general disorder of the foot associated with load carriage is Metatarsalgia, the collective term for non-specific over use of the foot, resulting in pain and temporary disablement. Studies have shown this to be a widespread problem for infantry soldiers. Sutton (1976) reports that during a seven month training programme including regular load carriage, a 20% incidence of Metatarsalgia was reported (114/580). In another study Knapik et al (1992) reported a 3.3% incidence in just a single march (20 km, carrying 45 kg). The most important risk factor for this appear to be heavy loads which cause the foot to rotate anterioposteriorly around the distal ends of the metatarsals which, over a prolonged period results in mechanical stress and pain in this area.

A more serious disorder of the lower extremities, stress fractures, result in much longer periods of inactivity. These occur more frequently in military recruits than in trained soldiers, as previous inactivity is a shown risk factor, however it is still common enough to be a relevant problem in regular soldiers. During the Central Burma Campaign in World War II more than 60 stress fractures were reported from just one infantry unit during a load carriage excursion (Donald and Fitts, 1947). It would appear doubtful whether the method of load carriage could have an effect on the incidence of these types of disorders unless a method could be devised to significantly reduce the amount of stress imposed on the lower extremities during load carriage. Another injury related to general stress imposed on the legs is knee pain, although reports of its incidence have been mixed, it is a serious condition and can result in several weeks of inactivity.

The injuries that have been more closely associated with differing methods of load carriage are those that affect the upper body, especially the back and shoulders. Knapik et al (1992) surveyed a group of infantry soldiers whilst completing a 20 km march and found that 50% of the soldiers who were not capable of completing the march complained of low back problems. The exact cause of such pain may be difficult to define as damage to different structures may be to blame. Risk factors that have been identified include heavy load, which results in changes in trunk angle, thereby stressing the back muscles. In addition, large weights do not move in synchrony with the back, which causes cyclic stress of the muscles, ligaments and spine. Kinoshita (1985) suggests that the double pack results in a lower incidence of back pain as it allows the body to maintain a more normal posture and eliminates prolonged bending of the back.

Brachial plexus syndrome or 'rucksack palsy' as it has been termed is a debilitating injury that is associated with heavy backpack load carriage. The exact cause of this condition is not known but it is suggested that the shoulder straps of a backpack cause a traction injury of the nerve roots of the upper brachial plexus (at C5 and C6 level). Wilson (1987) conducted a survey to determine the individual symptoms of six individual military trainees suffering from brachial plexus injury. The pattern of this disorder was that as a result of carrying heavy loads, previously healthy individuals developed pain, muscle weakness, numbness and paralysis of the upper extremity. The acute symptoms abated with rest but varying degrees of motor and sensor dysfunction remained. Electromyography of the affected muscles showed denervation in the affected motor units. The muscles most affected were those of the shoulder girdle, and the deltoid in particular. The triceps and wrist extensors were also affected in some cases.

The symptoms associated with Brachial plexus syndrome can take as long as six months to heal with some cases resulting in permanent damage (Bessen et al, 1987) presumably exacerbated by further heavy load carriage. This condition also has serious implications for the performance of the soldier. If the user suffers from reduced control of the muscles in the shoulder and arms, then tasks that require small movements of these muscles will be adversely affected.

Holewijn (1990) conducted a study to investigate whether pack type has an effect on the rates of rucksack palsy reported. He found that the use of a frame and a hip belt, designed to reduce the pressure on the shoulder, lowered the numbers of cases. Other factors that have been shown to reduce the risk of rucksack palsy are reducing the load carried, reducing the carriage distance and distributing the load between more muscle groups (Bessen et al, 1987; Reynolds et al, 1990; Wilson, 1987).

A more general type of disorder that is commonly reported by soldiers engaged in heavy load carriage is localised discomfort and pain, especially in the feet, shoulders and back areas. This is most likely caused by blisters, abrasions or excessive pressure at a specific area of the body. Altering the design of load carriage equipment can affect such feelings. Use of a hip belt acts to remove some of the discomfort from the shoulders and neck (Holewijn, 1990), restricting feelings of discomfort and fatigue to mainly the lower trunk and legs. In addition, Holewijn and Lotens (1992) concluded from their study on the effect of load carriage on performance that less subjective discomfort was reported when load was primarily carried on the hips compared with shoulder carriage.

2.6 Effects of Pressure on the Skin

The skin and immediately underlying tissues are generally unaccustomed to bearing mechanical forces and when this is prolonged, breakdown may occur. This may appear initially as reddening of the skin but if load is sustained an injury that occurs throughout the entire body wall may develop.

Studies have been conducted to determine the relationship between applied pressure and breakdown of body tissues, and as a result there is a generally accepted relationship between applied pressure and reduction in blood flow. High pressures applied to the skin will also affect the deep tissues of the body, if muscle is pressed against underlying bone then muscle damage may result (Daniel et al., 1985). An example of this may be the reports by hikers of severe bruising over the illiac crest, termed "hip pointers".

Dinsdale (1974) examined the effect of applying sustained pressures of between 6 and 195 kPa for various durations. He observed changes in the underlying tissue that precede the development of pressure ulcers. Hussain (1953) demonstrated that pressure of 13kPa applied for 2 hours resulted in reduced blood flow to underlying muscles. When this pressure was sustained for 6 hours this resulted in complete muscle necrosis. Skin and subcutaneous tissue has been shown to experience a 30% reduction in blood supply when subjected to only 4kPa of pressure (Holloway et al, 1976).

The conclusion of these studies is that low or moderate pressure sustained over low or moderate durations may result in some damage but for healthy tissue this will be reversible. However, if pressure is sustained, or the force is excessive, then tissue breakdown may occur. A study by Kosiak (1961) showed that pressures of 9 kPa over a 2 hour period resulted in reduced blood flow in the underlying tissue, however lower pressures (5 kPa) over a 4 hour duration did not result in any reduction in blood flow.

The threshold for injury to skin is lower at thin skin sites over bony prominences. This is an important issue when considering pressure underneath load carriage equipment. Sangeorzan et al (1989) examined the effects of applying pressures between 0 and 16 kPa to the skin when directly covering bone (tibia) and skin covering muscle (tibialis anterior). It was found that a significantly lower pressure (5.6 kPa) was required to reduce the transuctaneous partial pressure of oxygen to zero when applied over bone. This was compared with a pressure of 9.5kPa which was required to reduce this to zero when applied to skin over muscle. This increased sensitivity to pressure is likely due to stresses being concentrated in a smaller amount of connective tissue between the bone and the surface.

It has been shown that if no other contributing factors are present then pressures of up 120 kPa may be endured for several hours without gross tissue damage (Daniel, et al., 1985). However, it is unlikely that any military load carriage will not involve such risk factors. The fact that high pressures are found at the shoulder area where the clavicle and scapula are close to the surface means that the skin at this area will be more susceptible to pressure. In addition, high temperatures and moisture also place the skin and underlying tissue at greater risk from pressure. This suggests that attempts to reduce the pressure on the body surfaces under load carriage equipment may have a significant effect on the health of the soldier preventing impaired blood flow to muscle.

The sensation of the individual as a result of applied pressure on the skin is obviously another important consideration when evaluating load carriage equipment. The skin and the underlying tissue contain sensory receptors that detect touch, movement and pain and pressure. When the stimulus these receptors are subject to is lower than tolerance levels then this is not normally attended to by the individual. However, when the force applied to the skin is too great or applied for too long then this will be attended to by the individual, eventually resulting in discomfort and pain. This may be the result of constant firing of the receptors resulting in neural fatigue or interruption in blood flow to the skin and the underlying muscles. Reducing interface pressure may have a large impact on those individuals whose daily tasks often involve the carriage of heavy loads in terms of both their comfort and health.

As this study is concerned with the ergonomic evaluation of military load carriage equipment, there are numerous consequences for improving pressure distribution underneath load carriage equipment. Ergonomic methods were developed with the intention of improving the health and safety of the worker as well as his/her efficiency in the work place. It has already been established from the published work above, that reducing pressure on body surfaces increases blood flow to the underlying tissues preventing long term damage to body tissues. However, it is also likely that reducing pressure over the body could result in improvements in the performance of the individual soldier. Due to the type of activities that have to be carried out by soldiers both during and following heavy load carriage, it is probable that reduced blood flow to the skeletal muscles could have a detrimental effect on such activities.

The benefits of improving pressure distribution over the body therefore may be three-fold: improving the health and wellbeing of the individual soldier, improving his/her performance on military activities and, as a result improving the efficiency of the system which the individual soldier is part, the military unit.

2.7 Pressure and Load Carriage

Holewijn (1990) was one of the first researchers to introduce the possibility of skin pressure being the limiting factor of load carriage. In this study pressure was recorded under the shoulder at fifteen individual points using small pressure transducers (8.4mm x 4mm). Pressure was recorded whilst the participant was standing still when carrying two different designs of backpack: a military type pack and a custom designed pack. Maximal pressures of 27 kPa were found under the straps of the military style pack when carrying a weight of 10.4kg compared with only 2 kPa when carrying the same weight in the custom built backpack. When the load in the military pack was increased from 5.4kg to 10.4kg skin pressure increased by 36%, however, no significant increase in pressure was observed when load was increased in the custom pack.

These results suggest that a well designed pack may reduce the effects of carrying heavy loads by effectively distributing pressure. Although this work was based on only 15 individual pressure readings over the shoulder area and was measured whilst the participant was standing, this does indicate that improvements in pressure may result from changing the design of a pack. During this study, the participants reported feeling more uncomfortable when carrying the military backpack. Holewijn concluded that these reports were due to pressures underneath the shoulder straps and that "the limiting factor was the pressure on the skin" (Holewijn, 1990).

With the advent of new measurement systems, more work has been undertaken on the issue of interface pressure underneath load carriage equipment. A number of studies have been undertaken by the Ergonomics Research Group at Queens University, Canada (Bryant et al, 1996; Doan et al, 1998 (1,2); Johnson et al, 1998). These studies used the Tekscan™ pressure measurement system, which consists of individual sensing elements, made up of pressure sensitive inks mounted upon flexible plastic. Pressure was measured underneath a pack placed on a load carriage simulator: a 50th percentile mannequin covered in a compliant skin like material, cycling vertically to simulate human movement. These studies found differences in pressure on the body depending on load location. In one study a 36kg load carried high on the back resulted in a mean pressure of 19.8 kPa compared with a mean pressure of 17.4 kPa when the same load was split equally between the front and back of the body (Johnson et al, 1998). In this study and in that of Bryant et al (1996) the mean pressure values found underneath the shoulder straps of all designs of backpack were in excess of the recommended 14 kPa for sustained contact with the skin (Stevenson et al, 1995).

These studies have shown that by altering the location of the carried load and also the design of the load carriage system, improvements in load distribution may be achieved. Now that pressure measurement technology has advanced, it is possible to comprehensively map pressure underneath load carriage equipment although up until now this has only been undertaken on a replicated model torso. The issue of measuring pressure on human participants whilst carrying load has not yet been undertaken.

2.8 Summary

The physiological effects of load carriage are well established: for efficient carriage load should be carried as close to the centre of mass of the body as possible in order to maintain posture. Load should be carried by the largest muscle groups in order to minimise fatigue and work rate should be kept below 50% VO_{2max} for exercise of long duration. To reduce the effects of load carriage on walking gait, load should be carried as close to the waist as possible to reduce instability and the compensations that gait cycle has to make for this.

Although some work has recommended maximum load to be carried by the military in order to keep work rate in acceptable limits, it is generally accepted that these cannot be adhered to in real military operations. This has led to a more ergonomic approach in load carriage research. Heavy load carriage can result in extremely high interface pressures underneath carried equipment. As well as causing severe discomfort for the individual user, this can also result in damage to the skin and underlying tissue. In addition, as a result of decreased blood flow to the skeletal muscles there are consequences for performance of the individual user and as a result the military unit to which they belong.

In commercial designs of backpack, which are used for recreational activities such as hiking, a well padded hip belt is used to transfer a large proportion of the load to the hips in accordance with the recommendations of Holewijn and Lotens (1992). In the British military, however, it is currently not possible to incorporate such a belt into the design of the backpack due to the waist worn webbing that is worn in addition to the backpack. This webbing consists of pouches attached to a belt and is supported by a shoulder yoke. This piece of equipment holds the essential equipment to enable a soldier to survive and complete necessary tasks at times when the backpack has been jettisoned. The presence of this webbing means that it is not possible to use a hip belt to transfer any of the load away from the shoulders. The backpack has to sit on top of the webbing and the 'waist' belt of the backpack typically ends up at the level of the user's abdomen. Tightening the belt around the body at this level will not result in the transfer of any of the load away from the shoulders. In addition, the compression of the soft tissue around this area may restrict the necessary movement of the abdomen required during breathing.

Although a portion of the load may in some instances be supported by the pouches of the waist worn webbing, the majority of the load of the backpack has to be supported by the shoulders. This weight can exceed 50 kg in many training and operational exercises. Considering the magnitude of these loads, the shoulders are at real risk of tissue damage and reduction in skeletal muscles blood flow.

Although there has been some interest in the issue of interface pressure underneath load carriage equipment, up until now this has been restricted to small scale evaluations, mainly due to the lack of an appropriate methodology. In the period since on-body pressure measurement has been possible, the use of this has been confined to measuring interface pressure on models of human torsos.

The first part of this thesis is concerned with the development and validation of a methodology to measure body interface pressure underneath load carriage equipment. This has not been available until now and a reliable and accurate method is required before the comparative evaluation of different designs of load carriage systems can be carried out. Following development of this method, the second part of the thesis will examine different designs of equipment and also interface materials that may improve pressure distribution. The effects of these materials on objective pressure measurements and the subjective sensations of the user will be examined, with the aim of recommending a new interface material for incorporation into the equipment in use by the British military. In addition, the relationship between interface pressure and subjective reports of comfort will be analysed with a view to developing a predictive equation for long term comfort of carrying equipment.

Chapter 3 Choice of Measurement Methods

3.1 Introduction

As discussed in Chapter 2, the evaluation of interface pressure is a relatively new method in the field of load carriage research. It was necessary therefore to begin the development of the methodology with an evaluation of the techniques available for pressure measurement; both objective and subjective, in order to determine the most appropriate for the needs of the study. This chapter begins with a description of the requirements for a pressure measurement system, followed by a review of possible systems and the rationale behind the choice of a system. In the second section of the chapter psychological measurement methods are considered with a discussion of the factors underlying the choice of method for the study.

3.2 Research Plan

The main objective of the first part of this thesis was to develop a measurement system to allow the mapping of pressure over body surfaces. The developed system will provide reliable and precise measurements so that judgements can be made regarding the performance of the different designs under investigation. In addition, subjective perceptions of comfort and discomfort were also collected alongside the pressure data. This combination of both objective and subjective data will build up a picture of how load carriage equipment affects interface pressure and how this in turn affects user sensations of comfort and discomfort.

3.3 Requirements

From a review of the relevant literature (chapter 2), and consideration of the demands to be made on the chosen system, the following criteria were developed for assessing designs of equipment. It was probable that the chosen system would need to be customised to a certain degree as the majority of the systems are designed for other uses such as in-shoe measurements and prosthetic development. One of the primary considerations was that the sensors were adaptable to the configurations required so that they could be used on various body surfaces such as the shoulder, hips and the back.

The diameter of the individual sensing elements should be small in order to ensure that there is good contact with the surface to be measured, an important consideration when measuring human subjects. As peak pressure analysis was desired this was especially important. From a review of the literature it has been recommended that the diameter of sensing cells used in peak pressure analysis should be no more than 14 mm (Ferguson-Pell, 1980).

Another factor to be given consideration was the thickness of the pressure sensors. It was essential that the sensors were as thin as possible to reduce the likelihood of the sensor itself affecting pressure distribution. The presence of a large pressure sensor underneath a loaded backpack may result in the sensor affecting either the pressure measurement or the subjective perception of comfort resulting in invalid reports of comfort. It is recommended that sensors should be no thicker than 0.5mm (Ferguson -Pell, 1980). The sensors should be flexible or mounted on flexible material so that they can conform to different body areas on different individuals.

The data capturing software provided by the system was also a relevant issue. Some packages do not allow easy capture onto computer files and are more concerned with real time monitoring of pressure values. The software will affect how mobile the equipment can be, for example, whether it will be possible to take field measurements in addition to those in the laboratory. It would also be preferable for the data to be transferable into statistical software programmes in order to facilitate data analysis.

3.4 Pressure Measurement Systems

3.4.1 Entran®

Entran is a French company specialising in the manufacture of pressure sensors, load cells and other electronic devices. Their background is for the most part in the Engineering industry with little experience in biomedical or ergonomic fields. It is questionable, therefore whether their pressure measurement systems could be adapted to the requirements of this study due to their lack of experience of providing sensors for use at body surfaces.

The diameter of the Entran sensors are 11mm, which is less than the recommended maximum for peak pressure analysis (< 14 mm), however, the sensors are all thicker than the 0.5mm recommended maximum for use at body interfaces (4.5mm). This may result in problems whereby the presence of the sensor affects the measurement. As the Entran sensors are metal transducers, adding weight on top of these may result in increased compression at the body surface. This may affect the validity of the subjective ratings of comfort where the presence of the large sensor is the predominant factor rather than the design of the load carriage system.

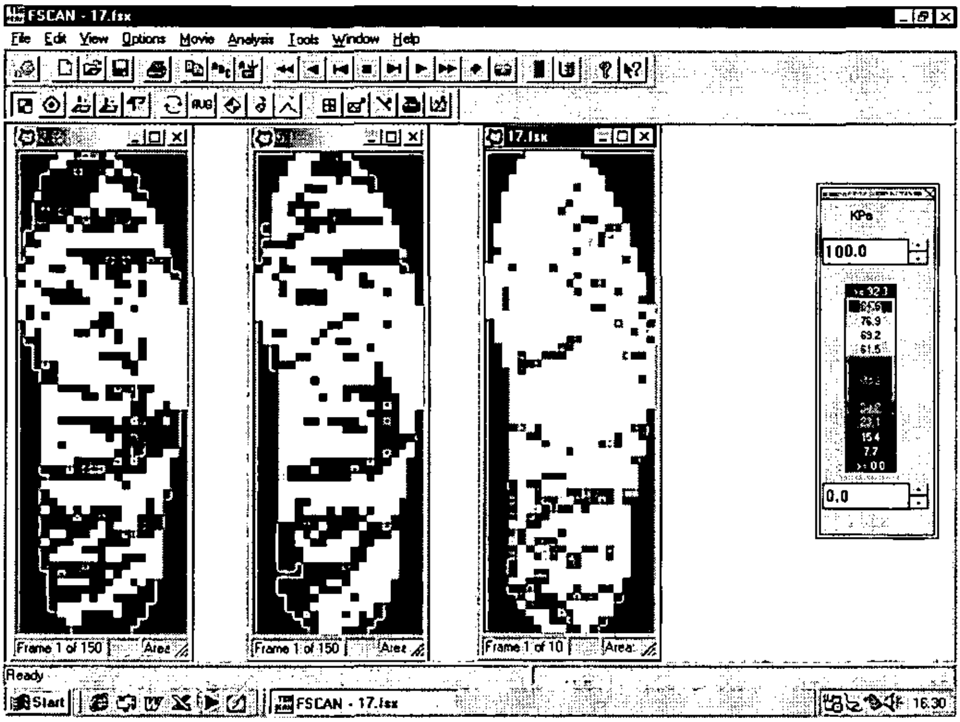
Data collection from the Entran sensors is by means of short-range telemetry from a microchip in the sensor to a computer. Data capture is in the form of absolute values requiring calibration from known pressures. Once calibration has been carried out, data can be transported into other computer packages for presentation and analysis.

3.4.2 Tekscan

Tekscan, an American company specialises in the clinical applications of pressure measurements such as orthotics and in-shoe pressure measurements. The Queens University Ergonomics Group in Canada has used the Tekscan system in their load carriage studies, although this work has been confined to use on human models. As the Tekscan technology is designed to provide in-shoe measurements it is flexible to different body shapes.

The sensor diameters are acceptable for peak pressure measurements (7mm) having been designed specifically for peak pressure analysis. The Tekscan sensors consist of pressure sensitive ink, mounted on a thin plastic background and are therefore very thin (0.1mm). The calibration method for the Tekscan is relatively straightforward, the company provides a pressure bladder for the purpose of calibration and there are tools built into the software for this purpose. The software provided with the system is sophisticated and this is one of the main benefits of the Tekscan system. It is specifically designed for the individual shape, size and layout of the sensor mat. Pressure is displayed in a real-time window (figure 3.1) and can be recorded by way of video type controls. The data 'movies' can then be played back within the Tekscan programme in a variety of ways and can be converted to ASCI text files, which can then be read by most data analysis programmes. The major drawback of the Tekscan system is the cost, however, when the system has been purchased replacement sensors are relatively cheap ($25 at the beginning of the project).

Fig 3.1: The Tekscan Screen



3.4.3 Talley Pressure Measurement System

The Talley Pressure Measurement System is a pneumatic system consisting of an air cell connected to an air reservoir. This system works on the basis that when the reservoir is of the same pressure as that applied to the sensor then the sensor will inflate. When this occurs, the pressure in the reservoir is the recorded applied interface pressure. The Talley system has been used extensively in research on car seat design. In an evaluation of the pressure technologies used in this field the Talley system was shown to produce the most accurate and reliable results and also scoring highly for measurement and thermal drift (Ferguson-Pell and Cardi, 1991).

The diameter of the Talley sensors is 20 mm which is considerably higher than that recommended for peak pressure analysis. In addition the resolution of the sensors is poor with gaps of up to 100mm between the centres of the cells. Another shortfall of the Talley system is the slow scan rate, which makes it suitable for static rather than dynamic measurements.

3.4.4 Discussion and Choice

From a review of the different pressure measurement systems available various pros and cons of each system were identified. The Entran sensors have a small enough diameter for peak pressure analysis, however; these sensors are much thicker than the other systems. It is possible that the use of these sensors would result in erroneous measurements, both subjective and objective, due to their presence as a secondary layer.

The Talley system although having been successfully employed in car seat studies was unlikely to be suitable for measurement on smaller, intricately shaped body surfaces such as the shoulder areas. The individual sensing cells have a diameter of 20mm, which would be too large to pick up small areas of high pressure. In addition to this, the backing material of the Talley sensors is prone to twisting and stretching and is easily damaged. It was probable that the experimental conditions in this study would damage the sensors.

The Tekscan system appeared to be the most suitable method for the requirements of this study. The diameter of the individual sensing cells are 7mm which is acceptable for peak pressure analysis, also the sensing mat is extremely thin (0.1mm) and therefore would remove the possibility of a secondary interface affecting the pressure measurements. The sensing mat is of an appropriate shape and size for measurement underneath backpack straps (203mm x 76mm).

For these reasons Tekscan was chosen as the pressure measurement system as this method met all of the requirements laid down for peak pressure analysis.

Due to the dynamic nature of load carriage which results in a degree of movement of the pack during movement it would have been ideal to have been able to quantify the effect of shear (tangential) forces within the pressure measurement. However, no suitable system was found which would allow the measurement of this on body surfaces or underneath load carriage equipment without introducing an additional interface.

Since the time when Tekscan was chosen as the pressure measurement system to be used in the project there has been no major new technology available for the measurement of on body pressure. Within the Tekscan range new sensors have been added, which along with updated hardware allows the simultaneous use of up to four separate sensors.

3.5 Subjective Measures

In 1969 Shackel et al, stated that subjective measures were 'the ultimate criterion of comfort against which other more convenient and more objective measures may be validated'. Few studies investigating body interface pressure ignore the valuable contribution of subjective measures. The vast majority of work examining the effects of military load carriage equipment has used subjective ratings as the final measure of a system's performance.

The relatively new ergonomic, user-centred approaches to load carriage equipment have resulted in the need for the development of suitable subjective scales. This is to enable the quantification of user comfort and discomfort, a valuable resource in this type of study. Due to the inability to accurately measure interface pressure until recently, the use of psychological measurements in this area has not been extensive. The use of subjective ratings of comfort and discomfort has mainly been confined to the design process and for this reason a new method of collecting subjective data had to be developed for this study. There were two purposes of collecting this data in this study, firstly: to quantify user-sensations during load carriage with the aim of correlating these with objective pressure measurements. The second aim was to provide extra information on the validity of the new method of pressure measurement.

The two main methods of subjective assessment used in the ergonomic evaluation of products and equipment are rating scales and the method of paired comparisons.

3.5.1 Rating Scales

Rating scales are the most popular method of psychological scaling in many fields of research due to the ease in which they can be administered. Although there are many categories into which they can be split, they all require placement of stimuli or sensation to a category or to a point along a line according to its intensity. This can then be assigned a number. The multitude of different types of rating scale available to researchers will not be discussed here, a comprehensive evaluation can be found in Guilford (1954).

One of the most common types of rating scale to be found in ergonomics research is numerical scaling. In this type, a series of numbers are presented with a written description attached to them. The rater responds with the number that most accurately describes the sensation or attitude asked for. A simple example that may be used in a study on comfort would be:

5 Very comfortable
4 Comfortable
3 Neither comfortable nor uncomfortable
2 Uncomfortable
1 Very uncomfortable

Although numbers are not always assigned to the statements this gives the rater a sense of equal spacing between the statements and continuity through the scale. Some scales assign the value 0 to the neutral response, in this case 'neither comfortable nor uncomfortable' and negative numbers to the statements below. It is widely regarded, however, that this suggests a break in the scale and reduces its continuity (Guilford, 1954).

When administering subjective rating scales, the researcher is forced to be confident that the participant is a precise and objective rater who will provide accurate and reliable observations. In order that this assumption can be made with some confidence, however, the pitfalls and sources of possible error and bias must be considered. Guilford (1954) provides a comprehensive list of all the possible problems, the ones particularly relevant to ergonomic research are considered here.

The error of central tendency refers to the inclination of the rater to avoid giving ratings towards the extreme of the scale. A way of counteracting this may be to space the differences in scale more at the two extremes and less towards the centre. This error must be taken into consideration when deciding on the 'anchors' of the scale, the description of stimuli attached to each number.

3.5.2 Paired Comparisons

This method of psychological scaling can be applied whenever the stimuli under investigation can be presented to the observer in pairs. The stimuli under investigation is presented to the rater in pairs in an order that ensures that each is presented first and second an equal number of times. From the results of this ranking system it is possible to produce a matrix showing the relative preferences of one system over another and an overall ranking for all systems under investigation.

This is a method, which is favoured by many ergonomic researchers, due to the ease for the researcher in administering the scale. It is also unchallenging for the participant due to the simple nature of the judgement they are required to give, "pack A is better than pack B". One of the possible problems with the method of paired comparisons is the issue of fatigue and boredom encountered by the observer. This is an issue especially relevant in load carriage research where the participants are required to carry loaded backpacks. It is probable that the ratings given to the pack presented second would always be affected by the fatigue induced by the first. Also, due to the number of systems under investigation, the participant would be required to make more than the recommended nine individual comparisons.

3.5.3 Discussion and Choice

There have been many attempts to develop an effective method of distinguishing between load carriage designs in terms of subjective comfort. One method that has been employed by a number of researchers is Ratings of Perceived Exertion (RPE). This method was developed by Borg (1970) in an attempt to quantify subjective feelings of effort. It was based on the premise that perceived exertion is the single best indicator of the physical state, as it encompasses information coming from the peripheral working muscles and joints, the cardiovascular system and the Central nervous system. From the load carriage work which has used this scale it would appear that RPE are sensitive only to design differences which are large enough to result in an underlying physiological change. Legg and Mahanty (1985) found significantly lower RPE when a load was situated on the front and back of the body in a 'double pack' or a trunk jacket than when the same load was carried solely in a traditional backpack. In the same study, however, no significant differences were found between backpacks with and without frames. This insensitivity to smaller differences in design is supported by the work of Wismann and Goldman (1976), Patton et al (1990) and Kirk and Schneider (1992).

As this method was designed to describe the physiological state it is unsurprising that RPE are not sensitive to small design differences such as the presence of a frame or variations in the distribution of pressure between the shoulder and hips. The change in load distribution by the use of a double pack from carriage solely on the back has been shown to result in a lower physiological cost (Datta, 1971, Legg and Mahanty, 1985) and it is this change that is the likely cause of the lower RPE in Legg and Mahanty's study.

In this study, various different interface materials will be investigated and it is unlikely that any of these will result in physiological change. Thus it was decided that Ratings of Perceived Exertion were not appropriate for use in this study.

It has been suggested that other techniques, assessing comfort, localised pressure or pinching of the skin may be more sensitive to design differences (Winsmann and Goldman, 1976). Perception of comfort was the variable of interest in this study and therefore a new method of quantifying this was required.

Legg and Mahanty (1997) attempted to combine two types of subjective perceptual methods to distinguish between small differences in load carriage design. The first was a 100-mm visual analogue scale (VAS) of perceived discomfort and the second a modified Corlett and Bishop (1976) regional discomfort scale. The regional discomfort scale was compiled by the sum of the reports of comfort on 12 body regions. Legg and Mahanty found that this regional discomfort scale was not sensitive to small differences in pack design. The written questionnaire providing information on interface comfort by way of a 100mm visual analogue scale, however, was found to be sensitive to small differences in design between backpacks.

The design of this study required participants to attend the laboratory on a number of occasions carrying a different load carriage system on each visit. Due to the demanding experimental protocol participants were required to carry up to a third of their body weight for up to an hour of walking. For this reason it was not possible for subjects to carry more than one system in one day. As civilian subjects were used in the study who were not used to heavy load carriage they may have been subject to some muscular discomfort following the measurement sessions. It is likely that, if more than one system were carried on each occasion the ratings given to the second pack would be affected by the discomfort caused by the first. This fatigue effect would be more than could be counteracted by randomisation of pack sequence. For this reason experimental sessions were separated by at least a week in order to allow the participant to recover from any soft tissue discomfort.

The main aim of the first part of this thesis was to provide a methodology that can assess the performance of a load carriage system in terms of increasing pressure distribution and as a result optimising user sensations of comfort. The data will be analysed to discover whether there is a strong enough relationship to enable the prediction of long term comfort from initial pressure measurements. Using paired comparisons, as a method for subjective assessment would not allow this relationship to be tested in the same way as using rating scales.

As a result of these factors it was decided to use rating scales as the subjective measure in this study, as this method would provide the most comprehensive data in terms of absolute sensations of comfort and discomfort. A rating scale would also provide data in a form allowing a possible relationship with objective data to be developed. Careful development of the scale with regard to placement of anchors was required in order to counter some of the problems discussed earlier in this section.

3.6 Development of the Rating Scale

Before the ratings scale could be developed it was necessary to establish exactly what was to be measured with the subjective scale in order to define the labels of the scale. The terms commonly used in scales of this type are ‘comfort’ and ‘discomfort’, however, there are problems with the precise definition of these concepts. Many researchers, especially in the ergonomic evaluation of office environments have attempted to measure both comfort and discomfort. However, there is currently no model that adequately explains the difference between these two sensations. Many practitioners have used the assumption that comfort and discomfort are two opposites on a continuous scale and that these sensations are different intensities of the same stimulus, which ranges from extreme comfort through a neutral point to extreme discomfort. However, the definitions of comfort that have been suggested indicate that comfort is affected by many factors and is not simply the opposite of discomfort. Slater (1985) provides a scientific definition of comfort as “a pleasant state or feeling of physiological, psychological and physical harmony”. Other researchers such as Hertzberg (1972) have referred to comfort as an “absence of discomfort. . . . a state of no awareness at all of a feeling". If this is so, and comfort is a neutral feeling, then only two strengths of the stimulus are possible either the presence or absence of comfort.

In a study on the effects of shoulder load carriage Legg et al (1992) used the anchors 'extremely comfortable' and 'extremely uncomfortable'. The question can be asked however, as to what the difference in sensation is between these sensations. If the definition of comfort is taken to be that an individual is free from discomfort then it may be argued that there cannot be varying degrees of comfort, a sensation is either comfortable or not.

As a result of these problems it was necessary to decide whether sensations of comfort or discomfort were to be measured in this study. As the sensations under investigation in this case are those from body areas underneath a heavily loaded backpack the likelihood of the participants feeling 'comfortable' is very low. For this reason it was decided that the subjective rating scale should measure discomfort rather than comfort.

One of the most important factors to consider in the design of the rating scale is that of the labels that describe the level of discomfort to be rated by the participants. In addition, as the sensations under investigation in this case are that of comfort under a heavily loaded backpack, it is acceptable to conclude that the likelihood of respondents reporting that they feel extremely comfortable is very low. For this reason the anchor at one end of the scale was labelled 'no discomfort' as this was deemed the most satisfactory rating possible under the experimental conditions. It is arguable that the label 'comfortable' could also have been used to mean the same sensation. As stated above, it is unlikely that the participants will use this rating, which is a requirement of an extreme anchor in this type of scale.

When considering the anchor at the other end of the scale, the same guidelines apply; the rating must be possible but unlikely to be used often. It was decided that 'unbearably uncomfortable' would be used which describes a sensation as so uncomfortable that the participant cannot complete the trial. Three points between these two were then required and these were defined to complete the rating scale as follows:

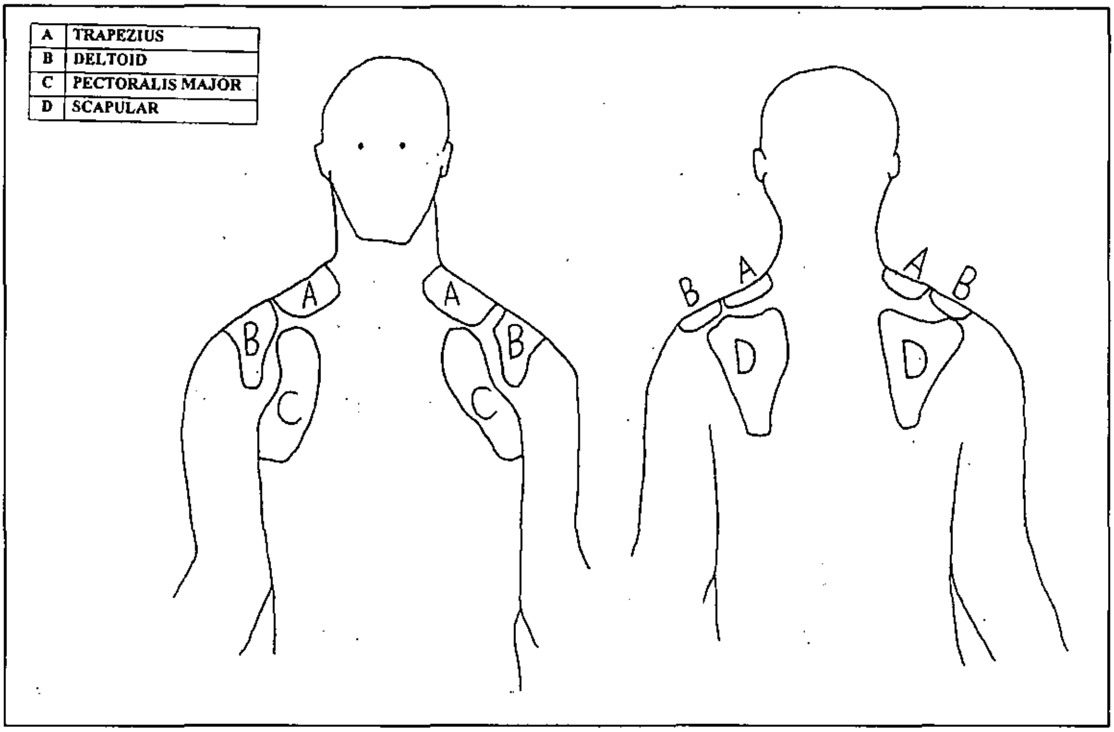
1. No Discomfort
2. Slightly uncomfortable
3. Uncomfortable
4. Very uncomfortable
5. Unbearably uncomfortable

Numbers were assigned from 1 (most satisfactory) to 5 (least satisfactory) to give the participant a sense of continuity through the scale.

Following the development of the rating scale it was necessary to consider the way in which it would be administered. Due to the intricate shaping of the human shoulder it was probable that sensations of discomfort would not be constant over the whole shoulder and therefore four distinct areas were identified. A body map was constructed to identify these to the participant (figure 3.2). The body map and rating scale were presented in front of the participant during the trial and they were asked to verbally state their rating, which was recorded by the experimenter. This was to negate any possible recall problems, which may have occurred by using of a post-trial questionnaire.

Before being used in the study it was necessary to pilot the rating scale and this was carried out during the pilot study described in the following chapter.

Fig 3.2: Body Map



Chapter 4 Experimental Protocol

4.1 Introduction

Following the discussion regarding the relative benefits of the three pressure measurement systems (section 3.4) and the decision to use the Tekscan system, it was necessary to develop the system for the use in this study. The following sections describe the initial experimental work carried out to modify the Tekscan equipment for measuring on body surfaces.

4.2 Sensor Type

Tekscan produces a wide range of sensors designed for specific applications. All sensors consist of a large array of independent sensing cells (sensels) and are available in various sizes, shapes and pressure ranges. It would have been ideal to have had a sensor designed specifically for the study requirements; however, this was not possible due to the high cost involved. It was necessary to decide on the correct Tekscan sensor for use in the study.

From examination of the Tekscan sensor catalogue and discussion with the company two sensors were highlighted for possible use in the study. The selected sensor would be the one that covered the interface area as completely as possible and provides the highest spatial resolution. In addition, Tekscan sensors are designed for specific pressure ranges, therefore the range of the two sensors had to be considered.

4.2.1 9811 Sensor

The 9811 sensor was designed for ergonomic investigations in mind and has been used in applications such as the design of handgrips and the fit of industrial and protective clothing. The sensing area is 203 mm x 76 mm and consists of 96 individual sensing elements providing a sensel density of 0.62 sensels / cm^2. The maximum pressure for this sensor is 517 kPa. As Tekscan sensors work most effectively over a range of 15:1 the 9811 sensor operates most effectively over a range of 35 - 517 kPa.

4.2.2 FSCAN 3000 Sensor

This sensor was designed for in-shoe measurements and has many clinical and research applications including the assessment and treatment of biomechanical disorders, the assessment of functional orthotics and pre and post-surgical evaluations. The sensors are foot shapes (figure 4.1) and therefore the sensing area is irregular shaped. The length of the sensing area is 300mm and the width is a maximum of 102 mm and a minimum of 35 mm. The FSCAN sensor consists of 954 individual sensing cells with a sensel resolution of 3.88 sensors /cm^2 and a sensor diameter of 5mm. The maximum pressure of this sensor is 345 kPa and therefore the optimum sensing range is 23 – 345 kPa.

4.2.3 Summary and Choice

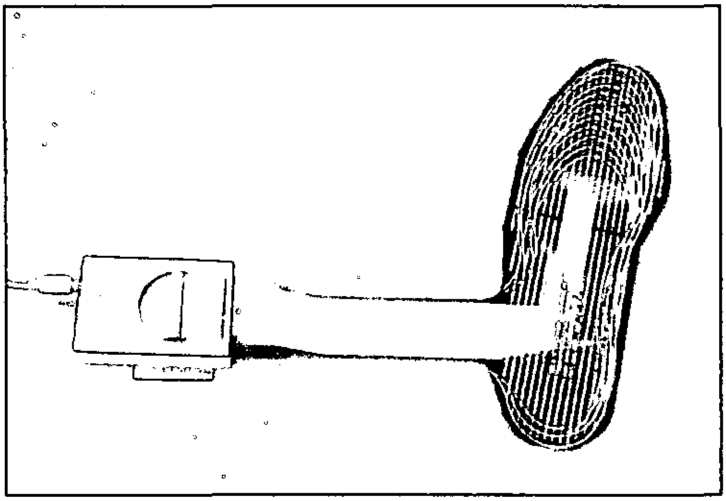
Both sensors have a similar range at which they are the most effective. It is unlikely that the pressures encountered during the study will exceed 200 kPa, as this is upper limit of interface pressure previously found under load carriage equipment (Holewijn, 1990; Bryant et al, 1996; Doan et al, 1998; Johnson et al, 1998). As both of the sensors work well under pressure way in excess of this, measuring high pressures will not be a problem with either sensor. However as one of the aims of the project is to increase pressure distribution it is equally important to be able to accurately measure lower pressures. The FSCAN sensor has a lower limit of optimum performance of 23 kPa compared with 35 kPa for the 9811 sensor. The FSCAN sensor would allow more accurate measurement of lower pressures.

When considering the dimensions of the sensor, the 9811 sensor (203mm x 76mm) is large enough to fit underneath the straps of most designs of backpack including the British military's in-service pack. However, it is probable that wider straps may be evaluated in the study that may exceed the width of the 9811 sensor. This may result in the sensor not recording pressures at the edges of the straps. The FSCAN sensor is longer than the 9811 sensor (300mm compared with 203mm) and this would ensure that the pressure underneath the whole shoulder and hip straps could be measured. In addition to this, the FSCAN sensor is also wider; it is unlikely that any designed prototypes would exceed this width reducing the likelihood of missing any interface pressures.

The major differences between the two sensors are the number of individual sensing cells (sensels) provided on the sensing mat. The 9811 sensor consists of 96 sensels each of a diameter of 11 mm, resulting in a spatial resolution of 0.62 sensels per cm^2. Although this is within the limits recommended for peak pressure analysis (Ø = < 14mm, Ferguson-Pell, 1980) there is a gap between each sensel of up to 6mm. This results in a high amount of dead space (non-sensing area) between each sensel and reduces the resolution of the sensor. The FSCAN sensor has a much higher sensor density with a total of 954 much smaller sensels (Ø = 5mm).

Due to the small, intricately shaped body areas under investigation it was decided to use the FSCAN sensor. This would result in a more complete pressure map, providing a greater amount of information and reducing the possibility of missing small areas of high pressures.

Fig 4.1: The FSCAN sensor



4.3 Exploratory Experiments

4.3.1 Equilibration and Conditioning

Due to the nature of the sensing material used in the Tekscan sensors (conductive and semi-conductive inks), it is inevitable that each sensing cell within the sensor mat is slightly different. This is partly due to the manufacturing process and partly to differences caused by certain areas becoming more sensitive as a result of variation in exposure to pressure. To counter this effect Tekscan recommends an equilibration function and incorporate this tool into the supplied software.

Equilibration is achieved by loading all of the sensing elements with a uniform pressure (by means of a pressure bladder); each one of the sensing cells should then produce the same output. When this is not the case the software determines a correction scale for each sensing element to account for the slight variation and ensure that all elements display the same reading. Before all of the experimental work using the Tekscan equipment, this equilibration process was carried out on the sensor.

Tekscan also recommend that before each measurement session each sensor should be 'conditioned', where the sensor is exposed to a pressure similar to the experimental conditions. This raises the temperature of the pressure-sensitive ink within the sensing cells to allow optimum performance of the pressure sensor.

4.3.2 Calibration

Standard Calibration

The Tekscan system includes in-built software to carry out a simple calibration. The company provided a purpose built bladder (fig 4.2) to allow a known, uniform pressure to be exerted on the sensor in order that the equilibration and calibration procedures can be run. The pressure in the bladder can be controlled between 0 - 15 PSI (0 - 103.5 kPa), an analogue dial displays pressure. To calibrate, the sensor mat is placed in the bladder at a certain, constant pressure and the calibration function is run. The slope of the calibration line is calculated based on this pressure and the output without any applied pressure. The software converts the raw digital output from each sensing cell to pressure units, the desired units can be chosen. The analogue gauge was treated as a gold-standard measure of pressure although calibrating this against a better measure such as dead-weight testing could have been carried out.

Tekscan state that once calibration has been carried out the sensor will 'hold' that calibration data for up to 6 hours. It was important to establish whether time had an effect on the sensor readings so that re-calibration could be carried out if necessary in experiments of longer duration.

In order to determine this, 5 new sensors were tested for accuracy at three different known pressures, 34.5, 68.9 and 103.5kPa (5, 10 and 15 PSI). Each sensor was equilibrated and calibrated as described above and then removed from the pressure bladder for 5 minute. It was then replaced and the bladder inflated to the pressure under investigation as displayed on an analogue dial. This pressure was maintained for six hours and pressure was recorded at six time intervals, an initial reading and after 5, 30, 60, 180 and 360 minutes. For each time period 5 individual frames were averaged and the mean and standard deviation pressure calculated, these are presented in table 4.1. Graphical examples are illustrated in figure 4.3.

Fig 4.2 : Calibration Bladder

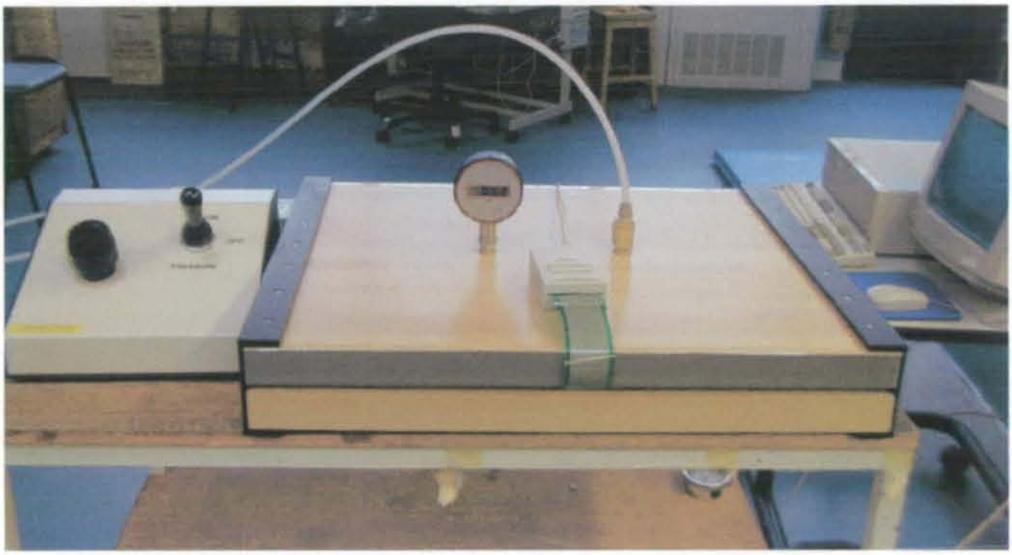
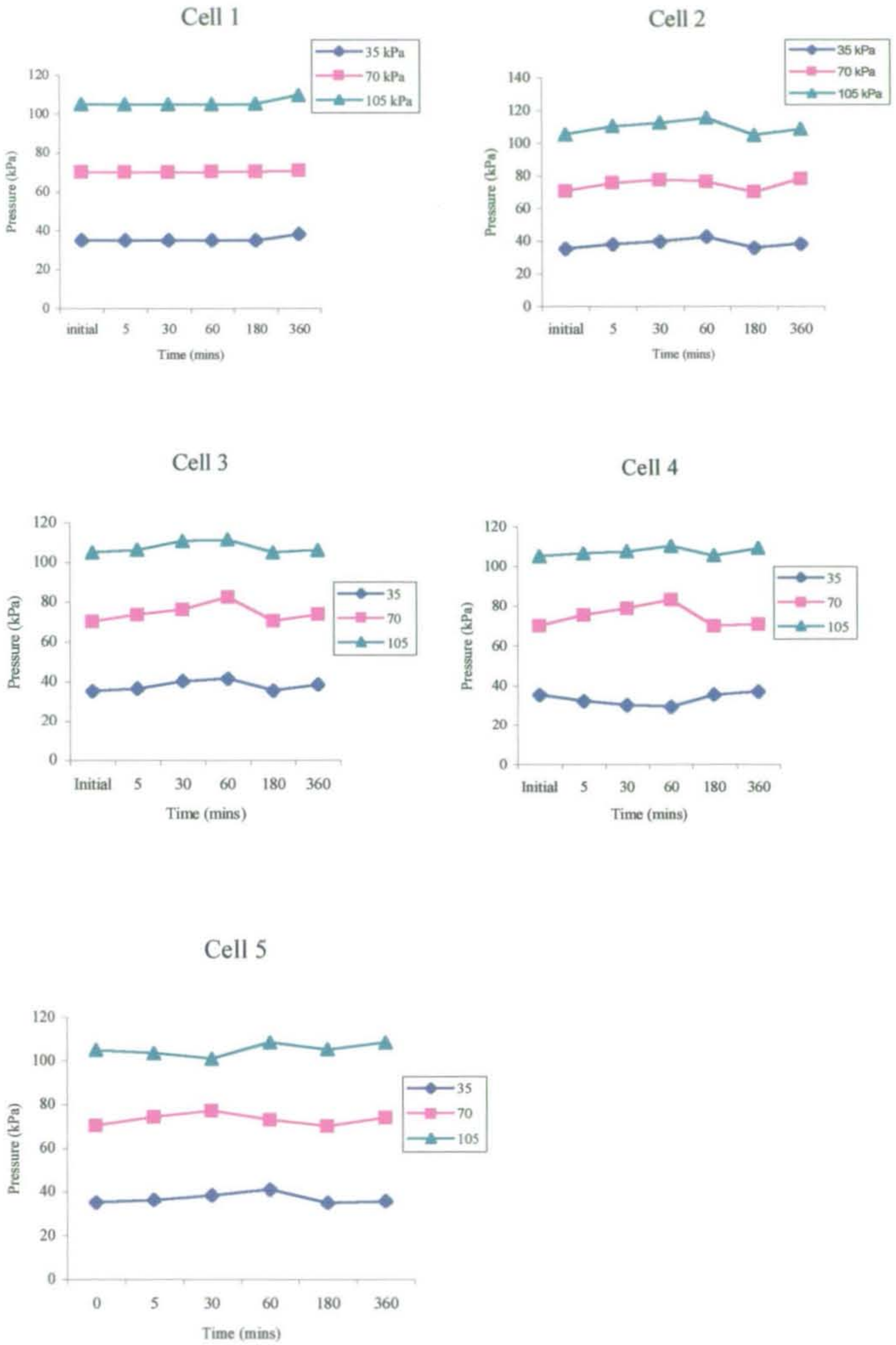


Table 4.1: Mean ± SD pressure readings over time

	Initial	5 mins	30 mins	60 mins	180 mins	360 mins
34.5 kPa	34.7 ± 0.2	34.7 ± 0.2	34.8 ± 0.3	34.8 ± 0.3	34.8 ± 0.4	37.4 ±1.2
69 kPa	68.9 ± 0.1	68.8 ± 0.2	69.0 ± 0.2	69.1 ± 0.2	69.1 ± 0.2	73.4 ± 3
103.5 kPa	103.4 ± 0.2	103.4 ± 0.2	103.5 ± 0.2	103.6 ± 0.2	103.6 ± 0.2	108.1 ± 1.4

It can be seen from Figure 4.3 that the Tekscan readings are reasonably constant over time and show a good level of association with actual pressures. For exposure of up to 3 hours the error in measurement equates to less than 1% in each. These differences were not found to be significant at the 0.05 level when analysed using a repeated measures ANOVA. When the sensors were exposed to pressure for 6 hours, however, this error increased substantially, in the case of the readings at 35 kPa, to nearly 7%. At the 6 hour reading, all of the sensors recorded pressure in excess of the actual pressure they were subjected to. This was a constant effect across all of the sensors indicating that it is likely to be due to the sensing material within the cells. The increases in pressure over six hours were found to be significant at the 0.05 level. From the results of this initial study it was concluded that each sensor should not be exposed to pressure for more than 3 hours in any experimental situation without re-calibration.

Figure 4.3: Pressure readings over time



Saving Calibration Files

The Tekscan software also provides an option whereby calibration information can be saved and re-loaded into the software at another time. This would be beneficial for taking in-field measurements, as it would remove the need for calibration before each measurement session. The effectiveness of this feature was tested using 5 new sensors.

The sensors were equilibrated and calibrated as described earlier and the calibration data file saved. The sensor was removed from the pressure bladder for five minutes and then replaced in the bladder, pressure was recorded at three known pressures (34.5, 69 and 103.5 kPa). Following this the sensor was taken out of the bladder and the computer was switched off. After three different time intervals (1, 6 and 24 hours) the computer was switched back on and the calibration file loaded into the software. The sensor was then placed in the pressure bladder at the same three pressures and pressure was recorded. Mean and standard deviation sensor pressure was calculated for each recording and these are presented in table 4.2.

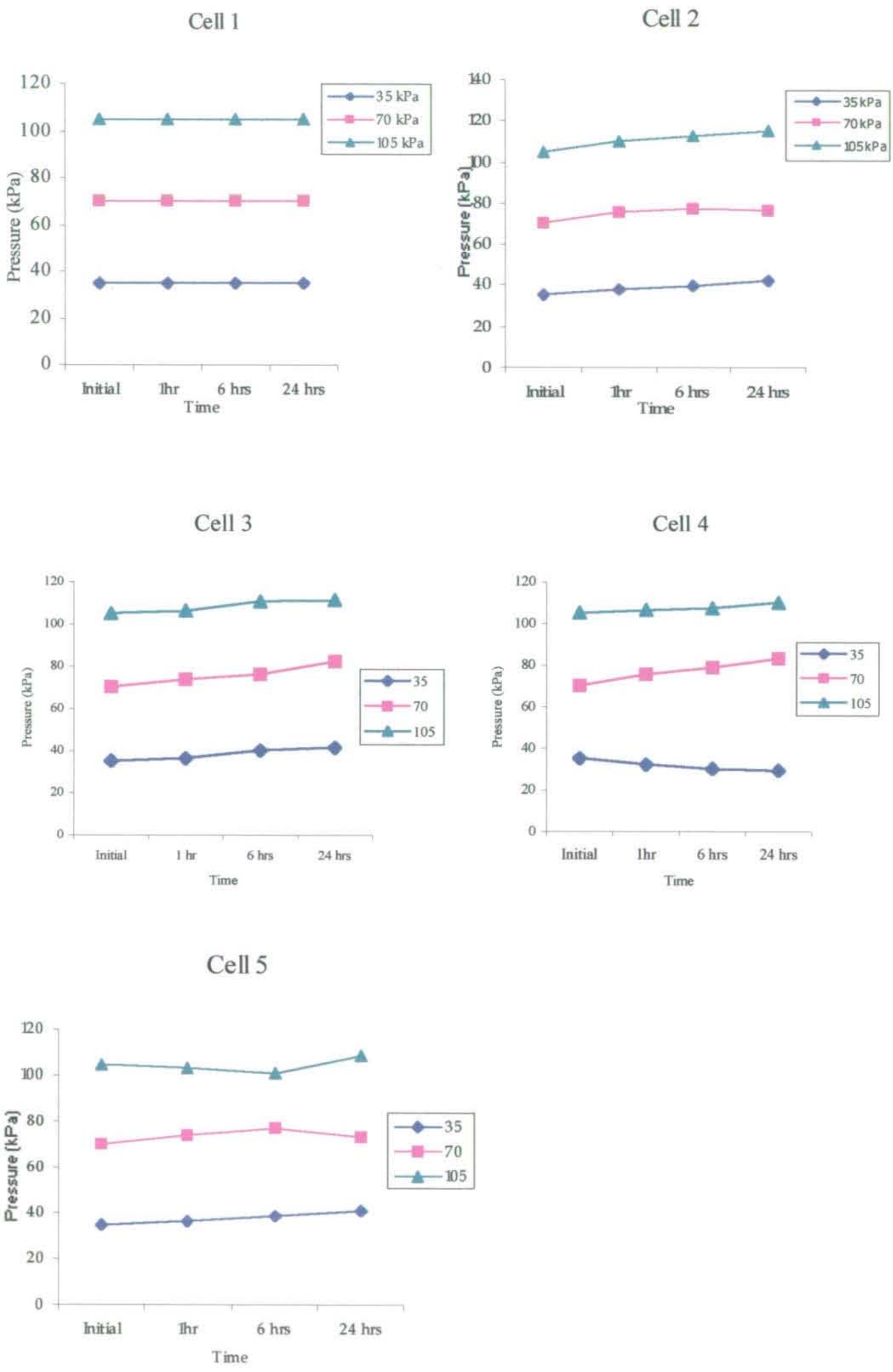
Table 4.2: Effect of Loading Calibration Files on Tekscan Output

n = 5 (mean ± SD)

	Initial Reading	1 hour	6 hours	24 hours
34.5 kPa	35.1 ± 0.1	35.72 ± 2.13	38 ± 4.65	38.96 ± 9.44
69 kPa	69.94 ± 0.65	72.34 ± 5.17	77.38 ± 8.96	79.02 ± 14.27
103.5 kPa	104.94 ± 0.16	107.18 ± 2.79	108.32 ± 4.57	111.48 ± 12.60

The results from this investigation show that re-loading calibration files into the sensors introduces a high amount error into the measurement and this can be seen clearly from the typical results in Figure 4.4. The average error introduced by this function was around 6%, but in some cases this rose to as much as 16%. It can be concluded, therefore, that this function should not be used and a new calibration should be carried out on each sensor prior to use. It is possible that the observed errors were simply the result of loading a file into the program as the data within the file would not be expected to change.

Figure 4.4: Effects of re-loading Calibration File



Calibration Issues

There is an issue of how closely the conditions under which calibration was carried out represent the condition at which the measurements were made. The pressure bladder used for calibration consisted of metal plates surrounding an air bladder. The conditions under which calibration was carried obviously differ from the nature of the interfaces they would be required to measure on, i.e. body surfaces. As there was no accurate method of on-body calibration available, this was the only method available. This has implications in terms of interpreting the absolute accuracy of the measurements taken. However, as this study was concerned with direct comparisons between different designs of load carriage equipment, if the reliability of the pressure measurements could be shown to be high then this should not affect the conclusions drawn from the results. This issue must be kept in mind, however, during the interpretation of the results.

4.3.3 Effect of Curvature

Due to curved and irregular shaping of the body surfaces it was necessary to evaluate any possible effects of curvature of the sensors. One of the problems associated with some methods of pressure measurement is that curvature of the sensing cells result in compression of the sensing material and inaccurate results. As a result of using the FSCAN sensor which provides a high density of sensing elements, it was hypothesised that moderate curvature of the sensor would not result in compression of the individual cells.

To establish this, a study was conducted. Four sensors were equilibrated and calibrated as described in section 4.3.2. The sensors were attached to four different metal cylinders each of different diameter (800mm, 600mm, 400mm and 200mm) by way of taping the non-sensing edges of the sensor to the cylinder. No pressure was applied to the sensors. The output of the sensors was recorded at three time intervals (after 1, 5 and 10minutes). The results from this are displayed in Table 4.3. It can be seen that as the diameter of the cylinder decreases the amount of erroneous pressure detected as a result of curving the sensor increases, with the smallest cylinder (Ø = 200mm) resulting in an overall mean pressure over the whole sensor of 4.7 kPa. When affixed to the largest cylinder (Ø = 800mm) this results in a much smaller amount of recorded interface pressure (0.03 kPa). This is in accordance with the supposition that the more curved the interface surface the greater the compression of the individual sensing cells hence the false registering of interface pressure.

Table 4.3: Effect of regular curved surface on Mean ± SD interface pressure

	Cylinder 1 Ø= 800 mm	Cylinder 2 Ø= 600mm	Cylinder 3 Ø= 400mm	Cylinder 4 Ø= 200mm
1 minute	0.04 ± 0.2	0.2 ± 0.32	0.37 ± 0.6	4.7 ± 3.2
5 minute	0.3 ± 0.1	0.1 ± 0.29	0.42 ± 0.52	3.8 ± 3.1
10 minute	0.1 ± 0.3	0.25 ± 0.35	0.51 ± 0.57	5.2 ± 4.0

As it has been shown that curvature of the Tekscan sensor results in the detection of some erroneous background pressure it was necessary to determine the effects of placing the sensors on curved body surfaces. To accomplish this, three participants attended the laboratory, they were asked to wear a tight fitting cotton t-shirt and tracksuit trousers. The participants (2 male 1 female) had a mean (range) age of 23.3 (21-25) years, weight of 73.7 (68 – 82) kg, height of 174.2 (163 – 187) cm and B.M.I of 24.3 (23.45 – 25.59) kg/m^2. Prior to the arrival of the participant a new FSCAN sensor was equilibrated and calibrated. The sensor was placed on the participants left shoulder on top of their T-shirt and attached with surgical tape by the non sensing edges of the sensor so that was the sensor was fitted closely and without creases. Interface pressure was recorded whilst the participant was standing still. This procedure was repeated for three other body surfaces, right shoulder and left and right hip. Overall mean pressure and maximum pressures were calculated (Table 4.4).

Fixing a pressure sensor on the body surface without any additional load does result in some registered interface pressure. This was higher on the shoulder area with the mean pressure on the shoulders ranging from 0.22 - 0.31 kPa and the maximum reading of any one sensel being 1.4 kPa. Assuming an overall mean pressure of 25 kPa underneath a backpack loaded with 20kg this equates to an error of between 0.7 – 1%. This was much higher than that recorded at the hip area, which ranged from 0.02 - 0.05 kPa with a maximum of 0.7 kPa. As the shoulder area is more curved and intricately shaped than the hip area these results support the earlier results that increased curvature results in increased error in pressure output.

Table 4.4: Effect of curved body interfaces on mean (max) interface pressure (kPa)

	Left Shoulder	Right Shoulder	Left Hip	Right Hip
Subject 1	0.30 (1.1)	0.3 (1.1)	0.03 (0.6)	0.04 (0.7)
Subject 2	0.24 (1.4)	0.22 (0.9)	0.02 (0.3)	0.03 (0.6)
Subject 3	0.31 (1.4)	0.27 (1.0)	0.02 (0.4)	0.05 (0.7)

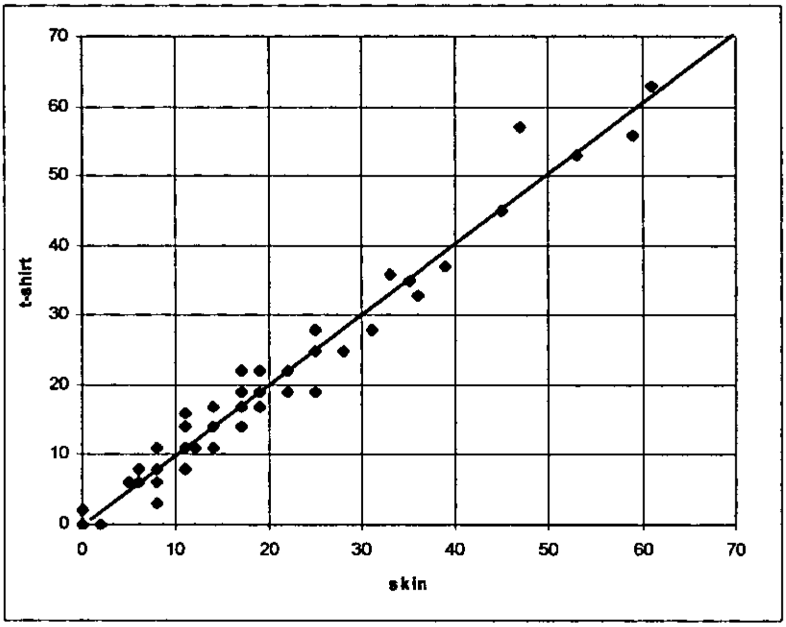
The observed error in pressure measurement is consistent between the three different participants who differed in sex and size. This suggests that the differences in anatomical structure between individuals are not sufficient to result in differences in erroneous pressure reading. It was decided that due to the comparative nature of this work that this small degree of error (~1%) as a result of the curved body interface was small enough to disregard. In the experimental work the placement of the pressure sensors was to be standardised for all of the conditions and for all of the participants. In addition, participants would act as their own control in a repeated measures design and therefore any small error due to the curved surface of the body would be equal for each condition. This issue does raise the question of whether the increased compression of the sensing elements as a result of curvature increases the sensitivity of the sensels to interface pressure. Should this be the case then it is possible that curving the sensor over a body interface may result in interface pressure being overestimated. As there is no gold standard system of precisely measuring on body interface pressure it is not possible to determine the absolute precision of the Tekscan sensors when placed on the body. This was another reason for using a comparative methodology in this study where the emphasis was upon reliable and consistent results in order to compare load carriage systems of differing designs. This issue has implications for the interpretations of the absolute values recorded by the system and care must be taken when relating the results to recommended maximum pressures found in the literature.

4.3.4 Effect of clothing layers

The issue of where to place the sensor during measurement raises the question of whether there is an effect of placing clothing layers on top of the sensor. It would be ideal to place the measurement instrument directly on the skin, as it is the sensation on the skin that is desired measure. In terms of practicality, however, it would be preferable to place the sensor on top of a layer of clothing, due to the presence of the cables attaching the sensor to the computer terminal. It would also be preferable in terms of the participants not to place the sensors directly on the skin. In order to determine whether there would be a difference in output depending on the location of the sensor, a small study was conducted using 5 different participants. In the first condition the sensor was placed directly on the skin with a cotton t-shirt worn over the top, in the second condition the participant wore a t-shirt and the sensor was placed on top of this layer. In both cases an identical pack was worn over the top. The measurements from each condition were compared.

Figure 4.5 shows the relationship between the individual sensing cell readings when placed on the two surfaces, on the skin directly and on the T-shirt. The line indicates where the points would fall were there no differences between the two locations. It can be seen that there is a good association between the two conditions and out of the 250 individual pressure readings all are situated near to the line with 174 readings being the same on the two occasions. Out of the remaining 76 measurements the mean error was 1.36kPa ± 0.77 (SD) with a maximum difference of 5 kPa. The intraclass correlation between these two sets of data was found to be 0.95, which can be considered high. This high figure indicates that the two conditions show the same pattern and that the fluctuations in the scores from the first to the second test all occur in a random manner and also that there is no significant difference in the means of the two groups. From this it can be concluded that there is no significant difference between the pressure measurements taken on these two interfaces and that measuring over a t-shirt layer does not consistently under or overestimate the interface. As a result of this it was decided that for reasons of ease of measurements and with the interests of the participant in mind that pressure measurements would be taken on top of one thin clothing layer.

Figure 4.5: Effect of clothing layer on pressure measurements



4.4 Summary

From the results of a number of experiments it has been shown that the factors that may confound measurement on body surfaces are controllable to enable accurate measurement to be made. The error incurred by measuring on a clothing layer and on curved body surfaces was found to be less than 2%, small enough to be disregarded. A maximum experimental duration of 3 hours was established before re-calibration of sensors was required. Saving and re-loading of calibration files resulted in a large amount of error and therefore it was decided that a new calibration process would be carried out immediately prior to each experimental session.

Chapter 5 Development of Procedure

5.1 Introduction

Following the choice of pressure measurement system and the initial experimental work into reliability and repeatability of this equipment, it was necessary to develop an appropriate methodology for the acquisition of objective pressure measurements. The relevant issues will be discussed here.

5.2 Sensor Placement

In order to collect valid results it was important that the pressure sensors were placed in exactly the same manner on each measurement occasion and were not moved during the measurement period. In order to achieve this the real-time monitoring function of the Tekscan software was used. This made it possible to match individual sensing cells up with particular anatomically bony landmarks.

The sensor mat was placed on the left shoulder as shown in figure 5.1. Due to the length of the sensor it was not possible to measure the whole of the shoulder area and therefore a decision had to be made as to where to place the sensor. It was decided that the front and tops of the shoulders were the areas most likely to be subject to the highest pressures. The reason for this being that when carrying load in a backpack the shoulder straps function to prevent the load falling back and down away from the body. Hence it is reasonable to assume that the highest pressures will result on the front and tops of the shoulders. Cell 34, 17 (row, column) was matched up with the superior aspect of the clavicle, 40mm from the sternal end. Sensel 34, 3 was matched up with the inferior aspect of the clavicle 140mm from the sternal end. The sensor was kept in place by taping the non-sensing edges to the participant's t-shirt. Once the participant had put on the backpack and fully adjusted the fit, the sensors were then checked for placement to ensure that they were still in the same position. Although the participant kept the t-shirt as tight as possible to resist against movement it is possible that some small displacement of the t-shirt layer occurred with the movement of the pack straps.

Fig 5.1: Placement of Shoulder Sensor

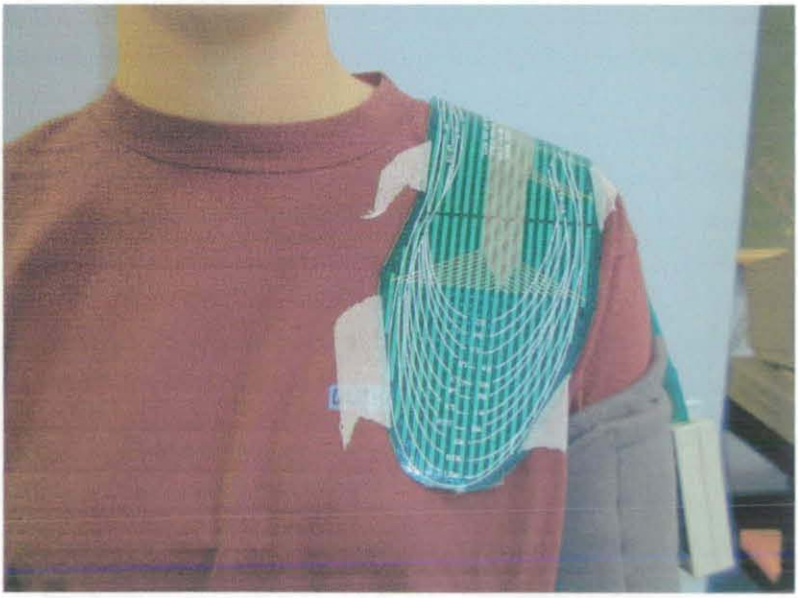


Fig 5.2 : Placement of Backpack over Pressure Sensor

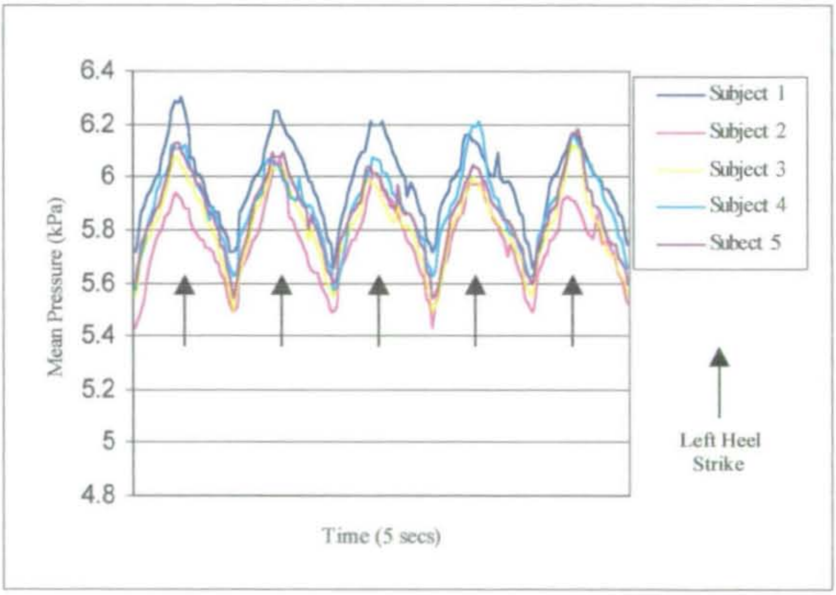
5.3 Stride Pattern

As pressure measurements were to be taken during treadmill walking it was important to consider how interface pressure changes through the stride pattern. Interface pressure on the left shoulder was measured on 5 different participants whilst carrying a loaded pack (18.5kg) and walking on a treadmill at a speed of 3.5 km/h^{-1}. The participants (3 males and 2 females) had a mean (± SD) age of 22.4 ± 2.7 years, weight of 75.8 ± 7.3 kg, height of 178.2 ± 7.4 cm and B.M.I of 23.8 ± 0.81 kg/m^2. Participants were asked to walk for 10 minutes in order to become accustomed to the speed of the treadmill, interface pressure was then recorded for 20 seconds, with a sampling rate of 10 frames per second. The pressure recording was started manually by the experimenter at left heel strike and the stride pattern was timed so that the data could be matched up to the points in the stride pattern.

Mean pressure over the whole sensor was analysed over time. Fig 5.3 presents the data from 5 gait cycles (approximately 5 seconds). It can be seen that the overall mean sensor pressure for all participants followed the same pattern through the stride pattern with the highest pressures occurring at the point of left heel strike. The likely cause of this peak is that at this point in the stride pattern the body starts to move upwards in the opposite direction to the pack which is still moving downwards. As peak pressures were to be one of the variables of interest during the experimental work, it was decided that pressure measurements would be taken at left heel strike. This also had the benefit of being an easily recognisable point in the stride pattern for the experimenter to start recording.

This investigation into the effects of the stride pattern also highlighted the need for consistency in the timing of the recording by the experimenter. In order to maintain a high level of repeatability in measurements it was essential that the pressure recordings were started at the same time in the stride pattern. This is wholly dependent on the ability of the experimenter to start recording at the correct point and is a possible source of error that may reduce the reliability of the pressure measurements. All of the experimental work described in this thesis was carried out by the same experimenter and therefore any error could be assumed to be less than if different experimenters were used. An alternative could have been to use a trigger attached to the shoe of the participant which would have been more precise in identifying heel strike.

Figure 5.3. Effect of stride pattern on shoulder pressure



5.4 Participants

A major issue that had to be given careful consideration was whether to use civilian or military participants and the relative benefits of using both groups will be considered here. This study was aimed at a very specific user group: those members of the military who regularly engage in sustained heavy load carriage. For this reason it was important to select participants appropriate for the experimental work. The most important consideration regarding choice of participants was the issue of discomfort ratings. As a result of previous experience military personnel may not be completely unbiased when giving ratings about various designs. It is possible that soldiers may be affected by the aesthetics of a particular design and that these views may affect their reports on other issues such as discomfort. In this study it was essential that the ratings obtained were the perceived comfort of the participants. For this reason it was decided that it would be preferable to use civilian participants to obtain reliable ratings. Civilian participants would be more unlikely to have preconceptions regarding one design over another. This is especially relevant when considering the possibility of looking at some more novel designs of load carriage such as frontal load carriage. Many soldiers have very specific opinions regarding the placement of load on places other than the shoulders and may let their opinions on this affect their ratings on other factors such as discomfort.

In terms of the objective pressure measurements, however, it may be preferable to use military participants. Heavy load carriage over long periods of time combined with the unique lifestyle of members of the armed forces will affect the anatomical make-up of areas such as the shoulders, resulting in a larger amount of muscle in this area. It is possible, although unlikely, that these differences in body composition may lead to differences between pressure readings on individuals who regularly carry loads and those who do not.

Taking these factors into consideration it was decided that civilian participants would be used. As the study was of a comparative nature participants would act as their own control, in addition, comparisons were to be made regarding the relative benefits of one design over another and not absolute judgements. For this reason differences in pressure due to body composition were deemed less important than the possibility of collecting subjective discomfort ratings that maybe invalid due to preconceived ideas on aesthetics of design. Another reason for deciding on civilian participants was that of convenience, as there were likely to be problems in sourcing military participants who could attend numerous testing sessions in Loughborough. Civilian participants would be matched in terms of weight, height and age to the specific military user group. Due to the athletic student population of the Loughborough area it was expected that this type of participant would be relatively easy to recruit.

It was decided that a mixed sample would be used in this study consisting of both male and female participants. Women now make up a considerable part of the armed forces in Britain and around the world taking up an increasing number of roles including front line roles. To exclude female participants from a study such as this with the aim of improving the health and well-being of the whole military population would be to reduce the external validity of the study. The issue of gender and whether this affects the relationship between interface pressure and perceived discomfort will be considered in detail in chapter 11 along with other possible influencing factors.

5.5 Asymmetries of Pressure Measurement

The Tekscan software only allows two sensors to be recorded at any one time. Since both shoulder and hip pressures were to be measured it would be ideal to measure on only one side of the body. It was necessary therefore to discover whether there were any differences in pressure measurements when measuring left and right shoulders and the left and right hip areas.

To achieve this, 8 individuals (4 male) with a mean ± SD age of 21.87 ± 1.8 years, weight of 76.25 ± 11.09 kg, height of 177.7 ± 9.8 and B.M.I of 23.99 ± 0.99 kg/m^2

participated in a small study consisting of two conditions. In each condition participants were asked to walk on a treadmill at a speed of 3.5km/h^{-1} whilst carrying a military type backpack. On the first occasion shoulder pressure was measured on both the left and right shoulders and on the second condition hip pressure was measured on the left and right side of the body. Placement of the sensors on the left-hand side of the body (as described in section 5.2) was mirrored on the right hand side of the body. Data was collected at heel strike: at left heel strike for measurement at left shoulder and hip and right heel strike for measurement at right shoulder and hip. Interface pressure from both sides of the body was compared to detect any differences and the results from this are displayed in tables 5.1 and 5.2.

Table 5.1 : Left and right shoulder pressures

	Mean Pressure		Max Pressure	
Subject	Left	Right	Left	Right
1	5.17	5.23	72	75
2	7.8	7.76	87	82
3	6.33	6.31	68	65
4	7.21	7.16	72	72
5	6.02	5.99	61	61
6	5.86	5.82	63	58
7	5.63	5.59	87	85
8	8.22	8.23	115	121
ΔS	0.03 ± 0.01		3 ± 2.3	

ΔS = magnitude of difference

Table 5.2 : Left and Right Hip Pressures

	Mean Pressure		Max Pressure	
Subject	Left	Right	Left	Right
1	4.32	4.33	47	48
2	1.89	1.95	45	39
3	3.56	3.57	38	35
4	4.07	4.1	32	32
5	3.11	3.06	48	45
6	2.85	2.82	50	47
7	5.99	6.03	86	86
8	3.98	3.97	45	47
ΔS (± SD)	0.03 ± 0.01		2.2 ± 1.9	

It can be seen from the results of this small study that there are only small differences between the left and right sides of the body. These differences were analysed for statistical significance using a paired t-test and were all found to be non-significant at the 0.05 level. It can be seen that one side of the body does not appear to register consistently higher pressures over the other side. Consequently it was decided that only one side of the body would be measured enabling pressure readings at both the shoulder and hips to be recorded simultaneously. The left side of the body was picked to be the site for measurement due to reasons of practicalities of collecting data whilst on the treadmill.

5.6 Weight

Since civilian participants were to be used in the study, careful consideration had to be given to the mass that would be carried during the experimental work. The desired load would be large enough so that differences in objective measures of pressure as well as discomfort could be detected, but not so large that any difference due to design would be masked by the extreme weight. Previous similar studies have used various weights to elicit different responses. When looking at the energy cost of load carriage Epstein et al (1988) found that carrying a load of 20 kg resulted in a constant energy cost over 2 hours, whereas increasing this load to 40 kg resulted in an increased energy expenditure over time. Most load carriage studies have used relatively moderate loads ranging from 15 kg to 30 kg unless specifically studying the effects of heavy load carriage.

A number of factors influenced the choice of weight used in this study: Weight was created by loading the packs with a bag designed to fit tightly with very little movement. This bag was filled with layers of rigid foam drilled with holes to allow the insertion of iron rods. As even slight variations in the position of the load may result in differences in pressure distribution and a reduction in the reliability of the method, this method was desirable as it resulted in the location of the mass of the pack being highly controllable. Using this method meant that all of the participants had to carry the same weight as it would be difficult to alter the weight for each participant and still keep the same level of control over the position of the load. This will result in larger participants carrying a lower proportion of their body weight, which may affect subjective ratings. It was decided, however, that the benefit of being able to control the position of the load was more important. The loading list for military personnel is the same regardless of size or weight and, therefore, not all infantry soldiers carry the same proportion of their body weight.

The weights that could be created using this method were 18.5 kg using two rods or 27kg with the addition of a third rod. As the participants in this study had little experience of heavy, sustained load carriage a lighter load than some of those used in earlier studies would be preferable to reduce the discomfort and fatigue sustained by the participants. Another factor limiting the weight to be used in the study was the use of both male and female participants resulting in participant groups of differing sizes. From the results of previous work recommendations have set an optimal load as 30% of body weight with 45% body weight as a maximal load (Epstein et al., 1988). For this reason the 18.5kg load was decided upon as the weight for the study. Taking this into consideration a load of 18.5 kg equates to 30% body weight of an individual weighing 60 kg and therefore this was taken as the minimum weight for participation in the study.

participants completed a health questionnaire (Appendix II) and from their responses, participants were excluded if they had ever suffered from any of a number of illnesses or disorders including muscoskeletal troubles or heart problems. Participants were also required to regularly engage in some physical activity and to have had some experience of carrying backpacks during leisure activity. They were asked to wear a cotton t-shirt and tracksuit trousers which were as close fitting as possible for ease of pressure measurements and to wear the same clothing on all experimental occasions. In addition they were asked to complete the trials in training shoes.

Once cleared for inclusion in the study participants were briefed on what would be expected of them during the trial and were shown the treadmill and how to stop the belt should they feel uncomfortable at any point during the trial. They were also introduced to the body map and scale that would be administered to obtain subjective feelings regarding perceived discomfort. At this point the participants were encouraged to ask questions about the procedure and were then asked to complete and sign a form of consent (Appendix III)

Prior to the arrival of the participant one FSCAN sensor was conditioned, equilibrated and calibrated under a known and uniform pressure as described in section 4.4. A new sensor was assigned to each participant and used for each of the four conditions. The participant was fitted with the pressure sensor on the left shoulder using the bony landmarks of this area to position the sensors as described earlier (section 5.2). They put on the backpack under investigation and the sensor was re-positioned if necessary. The participants were allowed to tighten the shoulder straps to position the pack as comfortably as possible before the start of the exercise but were told that once the exercise had started they would not be allowed to reposition the pack. The waist/hip belts of the backpacks were not used.

The participant was required to walk on a treadmill at a speed of 3.5 km/h^{-1} on a level grade for 30 minutes. During this time shoulder pressure was recorded at 3 time intervals: 5, 15 and 25 minutes. Each recording consisted of a total of 5

5.7 Exploratory / Pilot Study

Following the identification of possible sources of error in the pressure measurement method it was necessary to determine whether these were controllable in order to produce reliable results. To achieve this, an exploratory experiment was conducted to determine the reliability and sensitivity of the objective and subjective methods. This experiment also served as a pilot study to assess the ease of carrying out both the objective and subjective methods and to identify any previously undetected problems with the procedure.

In addition to this, the effect of gender on the interface pressure measurements will be examined. It is possible that differences in size, shape and body composition could affect pressure measurements and if this were the case then this may influence the chosen method of data analysis.

5.7.1 Procedure

In order to test the reliability of the developed method of pressure measurement 18 participants attended the lab on four separate occasions. The participants (11 male 7 female) had a mean (± SD) age of 22.5 ± 1.8 years, weight of 74.9 ± 10.8 kg, height of 177.5 ± 11.1 cm and B.M.I of 23.7 ± 1.49 kg/m^2.

Each participant carried two packs of different design on two different occasions leading to repetition of both the conditions (Ai, Aii, Bi and Bii). Pack A (figure 5.4) was a military backpack and Pack B a commercially designed backpack (figure 5.5) The designs of the backpack differed in the design of the shoulder straps; the straps of pack B were wider and more padded.

Participants were all unpaid volunteers from the general public who responded to advertisements placed around the Loughborough University campus. Potential participants were sent further details about the study (Appendix I). A criterion for acceptance into the study was a minimum weight of 60 kg. In addition frames collected over 0.5 seconds (sampling interval 0.1 seconds) and was initiated at left heel strike. Following the recording of shoulder and hip pressures, at 6, 16 and 26 minutes participants were asked to rate their perceived discomfort at four separate body areas highlighted on a body map presented in front of the participant (Figure 3.2) using a presented scale (Appendix V). The experimenter recorded the ratings given by the participant.

Fig 5.4: Pack A

Fig 5.5 : Pack B

5.7.2 Definition of Interface Pressure Variables

Due to this novel use of interface pressure measurement in load carriage research it was necessary to design a methodology for quantifying the data collected. On each measurement occasion, interface pressure was recorded at 3 different time periods over 30 minutes. At each time period, 5 frames were taken over 0.5 seconds starting at left heel strike. These 5 frames were then averaged to give mean pressure over this 0.5-second time period (sampling interval 0.1 seconds), resulting in 954 individual sensor readings for both the shoulder and hip areas. The reported results are the pressures and ratings taken after 25 and 26 minutes.

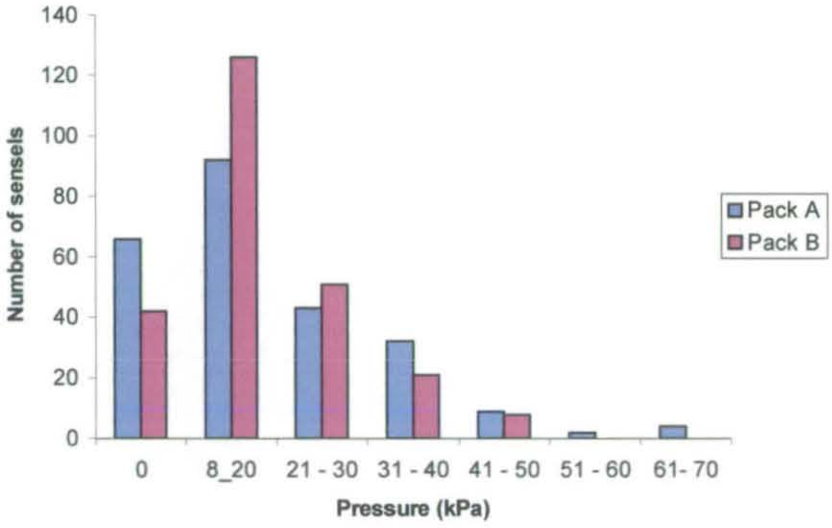
This amount of individual pressure readings would be unmanageable in terms of displaying and analysis and therefore it was necessary to develop a method for summarising and displaying this data.

The aim of the variables chosen was to indicate the ability of the interface material to distribute pressure over a body surface. This was based upon the premise that a good distribution of pressure equates to the utilisation of the largest surface area possible and equally spreading pressure over this area. Ideally all sensels under the straps would have the same pressure exerted on them. Effective pressure distribution would result in a high proportion of sensing cells recording low pressures and a low number recording higher pressures. The best way of demonstrating this would be to look at a frequency distribution of pressures over the sensing mat (table 5.3 and figure 5.6). The most appropriate statistical test for data of this type would have been a chi-square test. However, as the pressure measurements provide interval data it was decided that more powerful, parametric tests should be used. To achieve this the frequency data was converted into a form that could be subjected to parametric testing. The mean of the highest 120-sensel outputs (12.5% of the total) was calculated.

Table 5.3: Frequency distribution of shoulder pressures under two different packs for one participant

Pressure (kPa)	Pack A	Pack B
0	255	162
8 - 20	354	485
21 - 30	165	196
31 - 40	123	81
41 - 50	35	31
51 - 60	8	0
61- 70	15	0
Mean of highest 120 cell readings	42.98	36.91

Figure 5.6. Distribution of shoulder pressure under two designs of pack



In order to provide a complete picture of shoulder interface pressure in terms of range and distribution, a number of different indices needed to be calculated. The aim of these would be to give the clearest picture of the distribution of pressure in order to ascertain what effect the distribution of pressure has on user comfort. A number of indices were considered:

Table 5.4: Indices of Pressure Distribution

Overall mean pressure (kPa)	The total pressure applied to the sensor divided by the number of sensels registering interface pressure.
Interquartile Range (kPa)	The pressure range between which 50% of the pressure readings fall.
Decile Range (kPa)	The pressure range between which the middle 80% of the pressure readings fall.
Maximum pressure (kPa)	The single highest pressure value on the sensor mat
90th Percentile value (kPa)	The pressure which is exceeded by 10% of the readings.
Contact area (cm^2)	The area of the sensor mat registering interface pressure

Overall mean pressure was chosen as the necessary measure of central tendency. This would provide a measure of the overall pressure distribution over the area of the shoulder sensor with applied pressure. This will be affected by any increase in the surface area of the shoulder being used for load distribution.

A measure of peak pressure was required. It is possible that the points of highest pressure will have the greatest effect on the sensations of the user. Due to the delicate nature of the shoulder area it is the suggestion of this study that even distribution is the most preferable method of load distribution underneath backpack straps. If this is the case then there should be an association between user discomfort and peak pressure. Due to the large number of sensels on the shoulder mat (954 with approximately 300-400 registering pressure) the 90th Percentile value was chosen as the measure of peak pressure to be used in this study. This represents the value that is exceeded by the highest 10% of pressure values. This was chosen instead of a measure such as the maximum single pressure value or the mean of a number of high values as these measures may be affected by a single erroneous high pressure resulting from creasing or pinching of the pressure sensor. 10% of the area of the sensor represents approximately $10cm^2$.

A measure of the spread of the pressure values was required in order to evaluate which interface materials resulted in the best distribution of load on the underlying body surface. Due to the high number of pressure measurements the decile range was chosen as this accounted for 80% of the pressure values. Finally, the surface area of the shoulder sensor mat registering pressure was calculated.

5.7.3 Reliability

The data from the exploratory study was used to determine the reliability of the pressure measurement method. Each participant attended the laboratory on four separate occasions and completed both of the two conditions (described in section 5.7.1) twice resulting in test re-test data (Table 5.5).

Table 5.5: Summary Data for Shoulder Area mean ± SD (n=18)

	Pack A (i)	Pack A (ii)	Pack B (I)	Pack B (ii)
Mean pressure (kPa)	21.76 ±1.30	21.89 ± 1.23	17.85 ± 1.6	17.82 ± 1.7
Decile Range (kPa)	30.3 ± 4.47	30.28 ± 6.0	24.06 ± 3	24.11 ± 4.6
90th Percentile (kPa)	38.3 ± 3.5	39.47 ± 3.7	32.39 ± 3.8	32.44 ± 4.7
Discomfort rating	3.28 ± 0.67	3.17 ± 0.92	2.33 ± 0.59	2.44 ± 0.62

It can be seen from Table 5.6 that the intra class reliability values between the test-retest conditions are all above 0.94, which are very high reliability values. As a general rule R_1 values above 0.90 are considered high. It can be concluded therefore that there is a high level of reliability between measurement occasions. Due to the many possible sources of error that could affect reliability this result indicates that these can be controlled sufficiently to allow reliable data to be collected.

Table 5.6: Intra -class reliability (R_1) between conditions

	Mean pressure	Decile Range	90th Percentile
Pack Ai - Aii	0.98	0.96	0.94
Pack Bi – Bii	0.99	0.97	0.97

5.8 Effect of Measurement Conditions on Reliability

Each participant was assigned a new pressure sensor on his or her first measurement session. The same sensor was then used for each of the four trials following re-conditioning, equilibration and calibration. It was necessary to ascertain whether the measurement conditions affected the reliability of the pressure sensors. To determine this each sensor was placed in the calibration bladder under a pressure of 34.5 kPa both before use (15 minutes after calibration) and immediately after the participant had completed each trial. Interface pressure was recorded. Mean sensor pressure and change in pressure between pre and post trial was calculated for each sensor (Table 5.7).

It can be seen from that there was a slight increase in mean pressure between each pre and post trial measurements after each of the four trials, indicating that the measurements conditions increased the sensitivity of the sensing material. However, there were no large differences between the pre-trial pressures for each of the 4 trials. The mean pressures from each sensor were analysed using repeated measures Analysis of Variance, no difference was detected between any of the trials at the $\alpha = 0.05$ level. It can be concluded that equilibrating and calibrating each sensor before the next trial 'resets' any change in sensitivity resulting from previous measurement session ensuring that at the beginning of each trial the sensitivity of the sensor to pressure is equal.

Mean post-trial pressure was compared for each of the 18 sensors using repeated measures analysis of variance. No differences were detected and it can be seen that there is not a trend of either increase or decrease in mean pressure through the four trials.

From this it can be concluded that although the sensitivity to pressure increases as a result of the measurement conditions, however, when the sensor is re-equilibrated and calibrated this increased sensitivity is reversed. The magnitude of the pressure change between pre and post trial is not affected by the number of times that the sensor has been used before.

Table 5.7:Effect of Measurement Conditions on Reliability

mean ± SD pressure (kPa)

	Pre-trial	Post-trial	ΔS x (range)
Trial 1	34.561 ± 0.23	34.911 ± 0.22	0.35 (0.1 – 0.6)
Trial 2	34.567 ± 0.21	34.922 ± 0.31	0.36 (-0.1 – 0.7)
Trial 3	34.533 ± 0.23	34.828 ± 0.31	0.29 (-0.3 – 0.6)
Trial 4	34.572 ± 0.24	34.956 ± 0.27	0.38 (0 – 0.9)

5.9 Sensitivity of Method

Due to the novel nature of measuring interface pressure under backpacks another necessary factor to consider is the sensitivity of the method. A measuring instrument has to be sensitive enough so that real differences between conditions are detected. However the method must also be robust enough that it guards against detecting as significant the slight error in measurement between repeated conditions. From the reliability data it can be seen that there is a good association between the test re-test data and that the variation between measurement conditions is too small to be deemed statistically significant.

In addition to this it is important that a method is sensitive enough so that actual differences between systems are detected. In order to test this the data collected during the exploratory study described in section 5.7 was analysed. It was hypothesised that differences in design would result in variation in pressure distribution and consequently differences in subjective perceptions of shoulder discomfort. Pack B, a commercially produced backpack, designed more with the comfort of the user in mind consisted of anatomically shaped straps and more extensive padding compared with the military pack A. Therefore it was hypothesised that pack B would result in more effective pressure distribution than pack A.

Before any data analysis could be conducted it was necessary to address the issue of which significance levels should be used in this study. When deciding upon the significance level to be used to determine statistical significance, the aims of the study type must be borne in mind. This study was concerned with detecting improvements between different designs of load carriage equipment in terms of pressure distribution and user comfort. There are two types of error that may be incurred depending on the choice of significance level. Type I errors result in the conclusion that a difference exists between two conditions when in fact no difference actually exists. This may occur when the significance level chosen is too lenient, for example a level of 0.1 rather than a level of 0.01. Type II errors may occur when the chosen level is too stringent and a difference is not detected when it does exist.

The implications of committing these errors must be considered. Incurring a type II error in this study would result in not detecting a real difference between two different designs. This could result in a beneficial interface material not being identified and the potential effects of this not being further investigated, such as reductions in body interface pressure and improvements in user comfort. Using a more lenient significance level would guard against this type of error, however this would increase the likelihood of detecting a difference between two designs of pack when in fact no difference exists.

It can be argued that in a study such as this, the implications of a type II error are more serious than those of a type I error. If a design of pack is recommended for use that does not have any real benefits over another, then the user will not be adversely affected. However, if a beneficial design is ignored because of a significance level that is too rigorous then the user will never have the opportunity to benefit from such a design. In other words, increasing the likelihood of detecting a beneficial design is worth the slight increase in the risk of detecting a difference where one doesn't exist. Consequently, it was decided that statistical significance should be accepted at the 0.05 level when comparing different experimental conditions in this study.

The data from conditions Ai and Bi are presented in Table 5.8. Visual examination of the data shows that the pressure variables are sensitive to different designs of load carriage system. There are differences in the mean values for all three pressure variables (figure 5.7) and these results were found to be statistically significant at the 0.05 level when subjected to paired t-tests (table 5.9).

Table 5.8. Summary statistics mean (SD) n = 18

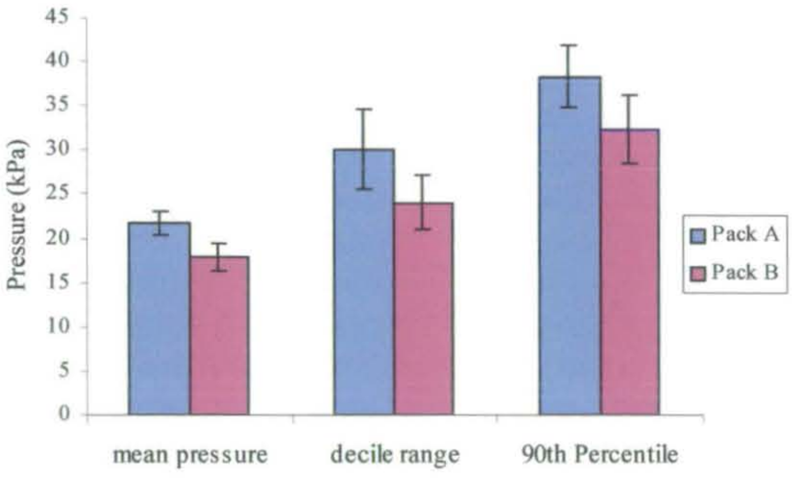
	Pack A	Pack B
Mean pressure (kPa)	21.76 (1.3)	17.85 (1.6)*
Decile Range (kPa)	30.3 (4.5)	24.1 (3)
90th Percentile (kPa)	38.3 (3.5)	32.39 (3.8)*
Mean discomfort rating	3.28 (0.67)	2.33 (0.59)

* significant difference at $p = < 0.05$ level

Table 5.9: Results of Paired sample t-test (Pack A – Pack B)

	95% C.I of the difference	t	df	p value
Mean pressure	2.59 – 5.22 kPa	6.28	17	= < 0.05
Decile Range	2.75 – 9.79 kPa	3.76	17	= < 0.05
90th Percentile	3.11 – 9.77 kPa	4.08	17	= < 0.05

Fig 5.7 : Effect of pack type on pressure variables mean(SD)

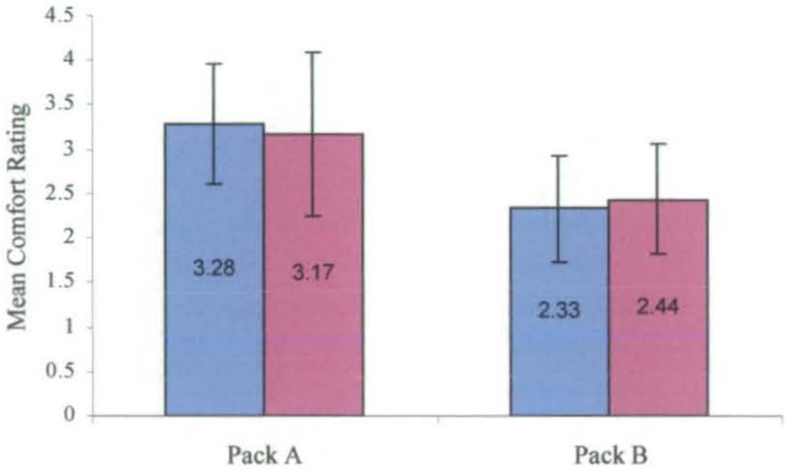


The subjective data collected during the exploratory experiment was analysed to discover whether the differences detected by the pressure measurement system were sufficient to elicit differences in reports of discomfort by the participants.

The subjective ratings were tested for statistical significance using the Wilcoxon Signed Ranks Test and it was found that Pack A resulted in significantly higher discomfort ratings than Pack B ($p = < 0.05$). The results from this are displayed in Figure 5.8. This accordance between the pressure measurements and the discomfort data supports the postulation that effective pressure distribution over a body interface will result in improved comfort for the user. Furthermore it provides evidence that the two methods utilised in this study are internally valid, that they are sensitive to differences in pressure distribution and the resultant differences in discomfort sensation.

During this exploratory experiment the participants easily understood the rating scale although slight changes were made to the display of the scale in terms of size and position in relation to the participant.

Fig 5.8 : Mean comfort rating (range)



5.10 Effect of Gender on Measurements

5.10.1 Pressure Measurements

Before the analysis of the results could be undertaken it was necessary to determine whether interface pressure was affected by gender. It was possible that differences in size, shape and body composition could affect pressure measurements and if this were the case then this would influence the method of data analysis

It can be seen from Table 5.9 that there is a high level of association between the means of both groups for all three of the pressure variables. Although there are small differences in the mean between the male and female groups these are irregular, neither the male or female group results in consistently higher values. This data was analysed using an independent sample t-test and this confirmed that there was no difference in interface pressure between the two groups.

In addition, the magnitude of the change in pressure between the two conditions was analysed to determine whether gender affected the size of this change (Table 5.10). If male and female participants experienced a different effect or size of effect as a result of design differences then it may be necessary to analyse the two groups separately. This data was also subjected to an independent sample t-test where no significant difference between the two groups was detected. From this it was concluded that the change in interface pressure due to the design differences in conditions A and B was not affected by the gender of the participant. Therefore, it is appropriate to treat both male and female participants as a single cohort for the analysis of pressure measurements.

5.10.2 Subjective Measurements

With regard to the ratings given by the participants during conditions Ai and Aii, the female participants mean rating for pack A was 3.5 with the ratings ranging from 2-4 (slightly uncomfortable to very uncomfortable). The male participants rated the same pack on average 3.04 with a range from between 1-4 (no discomfort to very uncomfortable). This difference between the two gender groups was found to be significant when subjected to a Mann-Whitney test. Due to the differences in terms of size, weight and strength between males and females this difference is unsurprising.

When the change in ratings between the two pack types are examined (table 5.10) there was no significant difference in the magnitude of the change in perceived comfort from conditions A to B. As this study was of a repeated measures design the participants would act as their own control and therefore differences in the absolute values of their ratings would not affect the statistical analysis. Both male and female ratings, therefore, can be treated as one group when detecting differences between conditions. In Chapter 11 the relationship between interface pressure and user comfort will be investigated. During this process, the differing effects of factors such as gender, weight and age on variation in discomfort ratings will be evaluated.

Table 5.9: Comparison of Variables according to gender – Pack A (mean and range)

	Male (n=11)	Female (n=7)
Mean Pressure (kPa)	20.05 (16.1 – 23.8)	19.42 (16.2 – 23.58)
Decile Range (kPa)	27.23 (21 –34)	27.14 (20– 34)
90th Percentile (kPa)	35.91 (28 –42)	35.14 (27 –40)
Mean discomfort rating	3.04 (1 - 4)	3.5 (2 - 4)

Table 5.10: Mean ± SD change between conditions according to gender (Ai – Bi)

	Male (n=11)	Female (n=7)
Mean Pressure (kPa)	4.16 ± 2.2	4.3 ± 1.71
Decile Range (kPa)	8.09 ± 4.36	9.14 ± 3.44
90th Percentile (kPa)	8.55 ± 4.64	7.14 ± 4.02
Mean discomfort rating	0.91 ± 1.3	1.04 ± 0.7

5.11 Effect of Time on Discomfort Ratings

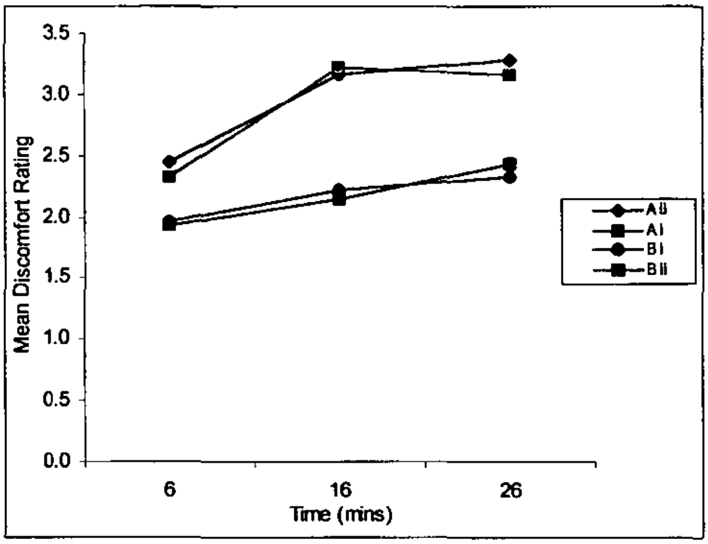
In this exploratory study the participants were asked to rate their perceived discomfort at the four shoulder areas after 6, 16 and 26 minutes of walking. In order to decide on an appropriate duration for each experimental condition, the trend of discomfort ratings over time was considered (table 5.11). Should the discomfort ratings follow the same pattern regardless of the pack under investigation then this would provide an argument for the use of short-term ratings in the data analysis resulting in a shorter evaluation process.

It can be seen from figure 5.9 the ratings given for packs A and B follow different patterns over time. The discomfort ratings under pack A increase at a greater rate between 6 and 16 minutes than for pack B, although similar increases occur between 16 and 26 minutes. These results indicate that the duration of each measurement session should be as long as is practically possible in order to collect discomfort ratings that are a valid estimate of long term discomfort. For this reason, the measurement sessions were extended to 60 minutes, with pressure measured at 15, 35 and 55 minutes and discomfort recorded at 16, 36 and 56 minutes.

Table 5.11: Discomfort Ratings over time - mean ± SD (n=18)

	Pack A (i)	Pack A (ii)	Pack B (I)	Pack B (ii)
6 minutes	2.44 ± 0.56	2.33 ± 0.71	1.94 ± 0.59	1.92 ± 0.75
16 minutes	3.17 ± 0.64	3.22 ± 0.66	2.22 ± 0.63	2.14 ± 0.79
26 minutes	3.28 ± 0.67	3.17 ± 0.92	2.33 ± 0.59	2.44 ± 0.62

Fig 5.9: Discomfort Ratings over Time



5.12 Summary

Possible sources of error were identified and taken into account within the methodology. As a result of an exploratory experiment it was found that the pressure measurement system had a high level of reliability and therefore it was concluded that it is possible to control sources of possible error to obtain reliable results. The pressure measurement system was found to be sensitive to differences in design that affect pressure distribution and these objective measurements were backed up by the developed rating scale. A procedure for quantifying, analysing and displaying the large amount of data was also developed.

Chapter 6 Experimental Procedure

6.1 Introduction

The aim of the second part of this thesis was to investigate the effects of different design and composition of load carriage straps on load distribution, pressure and discomfort. Until now it has not been possible to evaluate body interface pressure underneath load carriage equipment due to the lack of an effective measurement method. Using the methodology developed and validated in Part I, this part of this thesis will consider these materials and their effects on load distribution and user discomfort.

6.2 Aims

6.2.1 Strap Design and Composition

In Chapter 2 the effects of applying pressure to the skin on injury and blood flow were discussed in detail, the conclusion of this work is that high interface pressures can lead to deep tissue damage and a reduction in blood flow to the skeletal muscles. Such effects may have implications on the health and safety of the user, their individual performance and the performance of the military unit to which they belong. In addition to this, increased discomfort and pain may have a detrimental effect on psychological feelings of well being, reducing further the motivation and performance of the soldier.

As a result of this, improving the distribution of a carried load with the aim of improving interface pressure and user comfort can be seen as a crucial consideration during the evaluation or development of a load carriage system. Ergonomic methods were developed principally with the intention of promoting health and safety, improving the health and well being of the worker and efficiency of both his/her performance and the efficiency of the system as a whole. A poorly designed system may lead to increased risk to the health of the user and ultimately the performance of the individual and the unit to which they belong.

The issue of interface pressure underneath load carriage equipment has not been dealt with extensively up until now due to the lack of suitable technology for measuring interface pressure. Part I of this thesis dealt with the development of a methodology for measuring on body pressure using the Tekscan pressure measurement technology. This method provides both objective pressure measurements as well as subjective ratings of discomfort on a 5-point scale. This method was shown in Chapter 5 to be reliable and sensitive to differences between load carriage systems when used in a comparative experimental design. Due to the lack of a gold –standard method of on body pressure measurement the method is restricted to determining the relative benefits of one system over another. The moderate to high correlations between interface pressure variable and the subjective ratings of discomfort provide added support for the validity of the method.

In commercial designs of backpack, which are used for recreational activities such as hiking, a well padded hip belt is used in order to transfer a large proportion of the load to the hip area and away from the sensitive and delicate shoulder areas. In the British military however, it is not possible to incorporate such a belt due to the waist worn webbing that is worn in addition to the backpack. This webbing, which consists of pouches attached to a belt and supported by a shoulder yoke, holds the essential equipment to enable a soldier to survive and complete necessary tasks during times when the backpack has been jettisoned. The presence of the webbing means that it is not possible to use a hip belt to transfer any of the carried load away from the shoulders. The presence of the waist webbing means that the backpack has to sit on top of the webbing and that the 'waist' belt of the backpack ends up at the level of the user's abdomen. Tightening the belt around the body at this level will not transfer any of the load away from the shoulders and the compression of the soft tissue around this area may restrict the necessary movement of the abdomen required during breathing.

The consequence of this is that the majority of the load of the backpack has to be supported by the shoulders, a weight that can exceed 30 kg in many training and operational exercises. Considering the magnitude of these loads, the shoulders are at a real risk of tissue damage and impairment to skeletal muscles blood flow.

One of the ways in which it may be possible to improve load distribution and hence lower shoulder pressures is to alter the design and composition of the shoulder straps themselves. Currently the material used in the interface of the British Military backpack is an open cell polyethylene foam, this material having been chosen mainly for considerations including durability, safety in nuclear, biological and chemical situations and cost. The question of interface material has not been investigated from the perspective of the effect on the user before now. The aim of the experimental work of this study was to investigate the effects of altering the design of backpack straps, considering both interface material and also the size and shape of the straps.

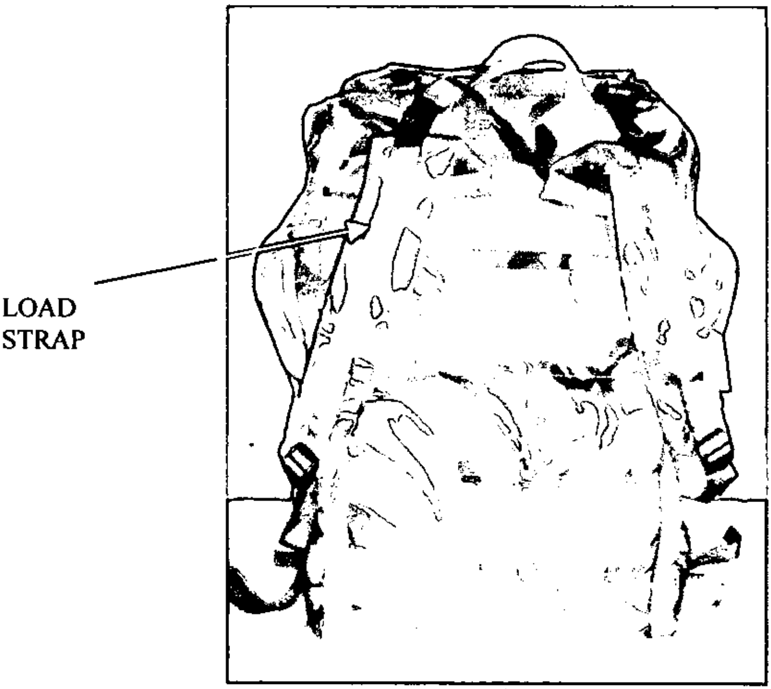
There are two main approaches to the distribution of pressure on the body: to distribute force in a uniform way or to concentrate the load on the most suitable areas of the body. The appropriate pressure patterns for specific individual-product interfaces are largely known making design recommendations difficult. Some research, especially in the area of bed and chair design has suggested that the theory of concentrating load on certain areas is preferable. Krouskop et al (1985) demonstrated that in mattress design, those designs that uniformly distribute pressure result in a restless night's sleep and other products have followed this theory including wheelchairs. The experimental work of this study will provide data to ascertain which of these methods is the most preferable for the distribution of force underneath load carriage equipment.

In commercial designs of backpack attempts have been made to load the strongest parts of the body by using rigid hip belts designed to transfer load from the shoulders to the hips. However, as previously discussed (section 2.8), in military load carriage the shoulders have to bear a high proportion of the carried load. The force supported by the shoulders during load carriage prevents the movement of the pack downwards and backwards. It is inevitable, therefore, that the tops of the shoulders and the front of the chest are the areas supporting the majority of the force. Even if it were possible to target any of this force elsewhere on the shoulders it is questionable whether any 'suitable' area could be identified. The delicate nature of the shoulder and the prominence of bones such as the clavicle make the whole area unsuitable for heavy load carriage in terms of user discomfort, potential damage to body tissues and the risk of developing brachial plexus injuries. For this reason it is suggested that an even distribution of pressure at the shoulder interface will be the most preferable for the user and this will be investigated in the following experiments.

Due to the delicate nature of the shoulders and their susceptibility to injury, an effective shoulder strap should distribute this load as evenly as possible reducing the number and magnitude of pressure peaks. In order to optimise load distribution underneath a shoulder strap a good fit between the strap and the body surface is essential in order to distribute the load of the pack over a larger area.

The interface material, and in particular the rigidity of the material of a backpack strap will influence greatly the load distribution and fit of a strap. A material that is rigid will not conform effectively to the intricate shape of the shoulder area. For example, when considering the front area of the shoulder where the clavicle protrudes, a material that is too rigid will not conform to fit around the bone and fit closely to the whole area. A backpack strap made up of such a material may result in a high load being borne by the clavicle resulting in high pressure concentrated on the bone instead of utilising a larger area for pressure distribution. A more compliant material will conform more easily to intricate body areas such as the shoulder, which may result in more contact between the strap and the body. However, the compressibility of this type of material may reduce its effectiveness at distributing an applied load over the whole width of the strap. The load of a backpack is transferred to the shoulder strap by way of a thin material 'load strap' which is sewn along the centre of the front of the shoulder strap (Figure 6.1). This strap is at a high tension when heavy loads are being carried and if the underlying interface material are too compliant then compression may occur at the point where the load strap is in contact with this material. This may result in good contact at this point, but may result in less contact at the edges of the strap. This could result in a concentration of high pressures underneath the centre of the strap and low or no pressure at all underneath the edges of the strap. A more rigid material however may be more effective at distributing load across the width of a strap as it would be less susceptible to compression in the centre of the strap where the load strap is attached.

Fig 6.1 : The shoulder 'load strap'



It would appear that an effective material for backpack straps should be of a moderate rigidity. A material that is too rigid will not conform to fit the body surface and one that is too compliant may be ineffectual at distributing the carried load across the whole width of the strap. An effective material must be compliant enough to conform to body surfaces but also rigid enough to distribute applied load.

The first aim of the experimental work was to investigate materials of varying composition and rigidity and their effects on load distribution, interface pressure and user discomfort.

The second aim of the initial experiment was to investigate the effects of adding other material to the main interface material of a shoulder strap, namely the addition of a layer of hard plastic superficial to the interface material. This design feature has been used in some commercial backpacks with the aim of increasing contact between the body surface and the backpack strap. It is suggested here that introducing an incompressible layer on top of the interface material may prevent the tension of the load strap compressing the centre of the underlying interface material. Due the rigid nature of the plastic, this layer would press more evenly onto the interface material and hence increase the contact between the strap and the body. This improved fit would then result in a larger surface area of the body bearing the load of the pack resulting in lower pressure and improved comfort for the user.

The effect of adding a layer of plastic into a backpack strap will be evaluated comprehensively in this experimental work to determine whether this results in any benefit in terms of load distribution, interface pressure and user discomfort. The effects of adding a layer of plastic onto different types of interface material will also be investigated to determine whether any effect is dependent upon the type of material that is underneath it.

6.2.2 Interface Pressure and Discomfort

The second aim of the experimental work was to collect data to enable the relationship between interface pressure and discomfort to be investigated. The method of measuring on-body interface pressure is a time consuming process, which requires sophisticated and expensive equipment and can currently only be performed in a laboratory under controlled conditions. Due to this expensive and time-consuming process it would be useful to develop a shorter method of ergonomic evaluation for load carriage equipment.

The extensive method of pressure analysis developed in part I of this thesis provides both objective and subjective data. The objective pressure data requires the use of the Tekscan pressure sensing equipment and the data collection is time-consuming process for both the collection and analysis of the data. The subjective ratings of discomfort collected as part of this method however do not require any specialised equipment and the resultant raw data is straightforward to analyse.

If a strong relationship between interface pressure and discomfort could be established then this could lead to a much faster evaluation process which could be applied in cases when it is not possible or practical to perform the complete evaluation procedure. Conducted in a controlled manner, this could be used in the early stages of equipment development to exclude designs that result in high interface pressures and severe discomfort for the users. Designs that have performed well on this initial testing method could then be tested more thoroughly using the full analysis method. This would cut down the expense and time involved in conducting a large-scale evaluation process of load carriage equipment.

All of the data collected during the practical work will be used to establish the strength of the relationship between interface pressure and discomfort and the influence of such factors as gender, age, size and physical activity.

6.3 Experimental Hypotheses

1. An interface material that uses the largest surface area of the shoulder for load distribution will result in the lowest interface pressures and user discomfort.

2. The addition of a layer of plastic superficial to the interface material of a backpack strap will result in an increase in contact between strap and body resulting in reduced interface pressure and user discomfort.

3. A uniform distribution of pressure at the shoulder interface will be the most preferable in terms of user comfort.

6.4 Equipment and Materials

6.4.1 The Prototype Backpack

A specialised backpack was designed for the specific needs of this study (Fig 6.2). This pack was identical to the design of the currently issued backpack to the British Army although designed with detachable shoulder straps. This allowed the evaluation of different designs of strap to be carried whilst controlling the other characteristics of the pack. No waist or hip belt was used.

The dimensions of the pack were height 680 x width 430 x depth 250 mm. The prototype backpack was weighted by adding a custom-made bag designed to fit tightly within the pack without any movement. This bag consisted of rigid foam with holes drilled through in order to add iron rods of differing sizes to create a load. In all of the experimental work of this study two rods were used in the holes nearest to the participant's back (Fig 6.3). The mass of the pack without any added load or straps was 2.45 kg, when the pack was loaded with the iron rods the mass of the pack without any straps attached was 18.5kg.

Fig 6.2 : The Prototype Backpack

Fig 6.3 : Load Bag Inside the Prototype Backpack

6.4.2 Shoulder Strap Prototypes

Twelve prototype straps were constructed consisting of different combinations of interface materials with and without the addition of plastic layers superficial to the main interface material. Each strap was fitted with identical press-studs and buckles for attachment to the prototype pack. Photographs of all prototype straps can be found in Appendix VI.

Seven different materials were investigated: one foam and six different Monofillament double needle bar meshes.

Table 6.1 : Interface Materials

Material	Thickness (mm)	% Compression under 200 kPa (BS 4098)
Foam 1 (Polyethylene Closed Cell)	10.4	21%
Mesh 1	8.0	27%
Mesh 2	9.0	25%
Mesh 3	7.5	26%
Mesh 4	9.9	32%
Mesh 5	9.0	34%
Mesh 6	12.2	43%

6.5 Experimental Design

A full discussion on the choice of experimental designs that may have been used in this study can be found in part I of this thesis. Briefly, due to the lack of a 'gold standard' pressure measurement system, the developed method is currently restricted to performing comparative evaluations. An experimental design incorporating paired comparison was also discounted due to the likelihood of the participants experiencing some muscular discomfort which would have adversely affected the ratings given for the system carried second in such a comparison. For this reason, a comparative methodology was used with the participants carrying only one backpack on each measurement occasion with each laboratory session separated by at least seven days to allow the participant to recover from any muscular discomfort.

Due to the high number of prototype straps under investigation (12), it was necessary to split the prototypes into similar groups with a final prototype analysis of the best performing prototypes from each group. This method would also have the benefit of ensuring that the prototypes in the final analysis would have been evaluated twice in total using a completely different sample of participants increasing the validity of the conclusion drawn about these prototypes. In addition this would provide data from a much greater number of participants for the work investigating the relationship between interface pressure and discomfort (Chapter 11).

The twelve shoulder straps were split into three groups of four straps. Each group was subjected to the comparative methodology measuring both interface pressure and the perceived discomfort of the participants. The two prototype straps from each group that performed the best in terms of pressure distribution and subjective discomfort would be then included in the final prototype analysis.

Group 1 (Chapter 7)

Group 1 consisted of the straps A, B, C and D which all consisted of the closed cell polyethylene foam which is used as the interface material in the current backpacks of the British military. There were two main objectives of this experiment; firstly to examine the effect of varying the width of shoulder straps consisting of standard closed cell polyethylene foam on load distribution and user discomfort. The second aim was to investigate the effect of adding a layer of plastic on top of the interface material.

Group 2 (Chapter 8)

Group 2 consisted of straps E, F, G and H. Straps E, F and G all consisted of a different air mesh material and the first aim of this experiment was to investigate the different effects of these air meshes on load distribution, shoulder pressure and user discomfort. The second aim was to investigate the effect of adding a layer of plastic to an air mesh strap by comparing straps G, which consisted of air mesh 3 with strap H, which was identical except for the addition of a plastic layer.

Group 3 (Chapter 9)

Group 3 consisted of straps I, J, K and L. Straps I, J and K consisted of three different air mesh materials and the first objective of this experiment was to determine the effect of these differing interface materials on shoulder interface pressure and participant discomfort. The second main objective was to determine the effect of adding a layer of plastic on top of the mesh 6 by directly comparing straps K and L.

6.6 Experimental Procedure

The same experimental procedure was followed in experiments 1, 2, 3 and 4, except in Experiments 1, 2 and 3 each participant attended the laboratory on four separate occasions and in experiment 4 each participant attended the laboratory on six separate occasions.

6.6.1 Participant Selection

Participants were all unpaid volunteers from the general public who responded to advertisements placed around the Loughborough University campus. Potential participants were sent further details about the study (Appendix I). A criterion for acceptance into the study was a minimum weight of 60 kg. In addition participants completed a health questionnaire (Appendix II) from their responses, participants were excluded if they had ever suffered from any of a number of illnesses or disorders including muscoskeletal troubles or heart problems. Participants were also required to regularly engage in some physical activity and to have had some experience of carrying backpacks during leisure activity. They were asked to wear a cotton t-shirt and tracksuit trousers which were as close fitting as possible for ease of pressure measurements and to wear the same clothing on all experimental occasions. In addition they were asked to complete the trials in training shoes.

Once cleared for inclusion in the study participants were briefed on what would be expected of them during the trial. The treadmill was demonstrated and the participants were shown how to stop the belt should they feel uncomfortable at any point. They were also introduced to the body map and scale that would be administered to obtain subjective feelings regarding perceived discomfort. The weight and height of the participant was measured. At this point the participants were encouraged to ask questions about the procedure and were then asked to complete and sign a form of consent (Appendix III)

For experiments 1, 2 and 3 each participant was randomly assigned to one of four groups consisting of two participants. For experiment 4, each participant was randomly assigned to one of six groups consisting of three participants. A simple matrix was constructed to assign the order in which the trials would be completed in order to eliminate the possibility of an order effect affecting the results (fig 6.4 and 6.5)

Fig 6.4 : Matrix used to assign participants to groups (experiments 1, 2 and 3)

	Trial 1	Trial 2	Trial 3	Trial 4
Group 1	A	B	C	D
Group 2	D	A	B	C
Group 3	C	D	A	B
Group 4	B	C	D	A

Fig 6.5 : Matrix used to assign participants to groups (experiments 4)

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6
Group 1	A	B	C	D	E	F
Group 2	F	A	B	C	D	E
Group 3	E	F	A	B	C	D
Group 4	D	E	F	A	B	C
Group 5	C	D	E	F	A	B
Group 6	B	C	D	E	F	A

Each participant attended the lab on either four or six separate occasions completing the experimental trial in exactly the same manner. Each trial was separated by at least seven days to allow recovery from any muscular discomfort or stiffness from the previous trial.

Fig 6.6: Participant completing experimental condition

[redacted]

6.7 Trial Procedure

Prior to the arrival of the participants at the laboratory one FSCAN sensor was conditioned, equilibrated and calibrated under a known and uniform pressure as described in section 4.4. Each participant was assigned a new pressure sensor. The same sensor was then used for each of the four trials following re-conditioning, equilibration and calibration. During the equilibration and calibration process the sensors were checked for 'rogue' sensels, individual sensing elements which either registered no applied pressure or displayed an erroneous pressure readings (± 2 kPa). Any sensors that contained any of these rogue sensels were discarded. If this occurred when the participant had already completed one or more of the trials using this sensor they were informed that they were no longer required to complete the rest of the trials and were thanked for their participation. Another participant was then recruited who was assigned a new sensor. Participants were not asked if they were prepared to restart the study (with a new sensor) as this may have affected the validity of the subjective ratings given by the participant as they would have completed more trials than the other participants.

The participant was fitted with the pressure sensor on the left shoulder using bony landmarks to position the sensors as described earlier in section 5.2. They were assisted to put on the backpack and allowed to tighten the shoulder straps to position the pack as comfortably as possible before the start of the exercise, but were told that once the exercise had started they would not be allowed to reposition the pack. Following adjustment of the backpack the position of the sensor was checked by the experimenter and re-positioned if required. The cuff units were attached to the arm of the participants by way of a Velcro sleeve and the wires leading to the computer were tied up safely.

Once fitted correctly with the backpack and pressure sensing equipment the participant stood astride the belt of the treadmill. The treadmill was started at the lowest possible speed and the participant was asked to step onto the belt when they were comfortable. After prior warning the speed of the treadmill was gradually increased to 3.5 km/h^{-1}. The participant then walked continuously at this speed at a 0% grade for 60 minutes.

During this period shoulder interface pressure was measured at three time intervals: after 15, 35 and 55 minutes of walking. Recording was initiated by the experimenter and the participant was unaware of when each recording was made to help ensure that normal walking pattern was maintained. Each recording was started at left heel strike and captured 5 frames taken over a 0.3 second time period.

Immediately following each pressure recording the participant was asked to rate their perceived discomfort at four different points over the shoulder area using a provided rating scale ranging from 1 to 5 where 1 was the most comfortable and 5 the most uncomfortable (Appendix V). The body areas were labelled A – D on a body map in front of the treadmill alongside the rating scale (Appendix IV). The participant gave their ratings verbally and the experimenter recorded these.
Once the participant had completed the trial they were helped off with the backpack and the pressure sensors and were invited to rest and have a drink before leaving the laboratory.

Each pressure recording resulted in five individual frames or snapshots of pressure taken over a 0.3-second time period with each frame consisting of 955 individual pressure readings. In order to account for possible slight differences in the timing of the recording each of the individual sensel pressure readings were averaged to give the average pressure at each sensel over the 0.3 second time period. The pressure variables that would then be used for data analysis were calculated from this final averaged frame (table 6.3). These variables and the rationale for their choice is discussed fully in section 5.7.2

The discomfort ratings given by the participants after 56 minutes of walking were examined to determine differences in perception of discomfort between the conditions. Analysis of the discomfort ratings collected during the pilot study

(Chapter 7) found that the ratings given for the two different packs followed different trends over time. The ratings after 56 minutes were the last ratings given by the participants and, therefore, would be the most valid indication of long-term shoulder discomfort. It is possible that ratings given after 16 and 36 minutes of walking may not pick up areas of discomfort due to the short duration. After 56 minutes of walking the participant would have got used to carrying the pack and this would be a long enough duration for any potential benefits of the strap design to have made a difference to discomfort.

Table 6.3 : Indices of Pressure Distribution

Mean pressure (kPa)	The total pressure applied to the sensor divided by the number of sensels registering interface pressure.
90th Percentile (kPa)	The pressure which is exceeded by only 10% of the readings.
Decile Range (kPa)	The range between which the middle 80% of the pressure readings fall.
Contact area (cm^2)	The area of the sensor mat registering interface pressure

Chapter 7 Experiment 1

7.1 Introduction

The aim of the second part of this thesis was to investigate the effects of different design and composition of shoulder load carriage straps on load distribution, pressure and discomfort. Until now this type of evaluation has not been possible due to the lack of an effective methodology. Using the method developed and validated in Part I, this section of the thesis will consider different materials and their effects on load distribution and user discomfort.

7.2 Aims

The first interface material investigated was the closed cell polyethylene foam currently used as the interface material in the shoulder straps of the British Military standard issue backpack (foam 1). This was deemed an appropriate starting point as it would allow the evaluation of the current design along with other designs incorporating the same material. The first aim of this experiment was to examine the effect of varying the width of shoulder straps consisting of standard polyethylene foam on load distribution and user discomfort. Three strap widths were investigated: 70 mm, the width of the current strap used by the British military and a narrower (45 mm) and wider version (88 mm).

The second aim was to investigate the effect of adding a layer of plastic on top of the interface material. This design feature has been used in some commercial backpacks to increase the contact between the body surface and the strap with the aim of improving load distribution and lowering interface pressure.

In most current backpack designs the weight of the pack is transferred to the shoulder strap by a thin material strap which is sewn along the front of the shoulder strap (fig 6.1). When carrying a heavy load this strap is at a high tension and this will result in the strap pressing on the underlying material. Depending upon the rigidity of the interface material this may result in compression at the point where it is contact with the strap. This would lead to good contact between the shoulder and the strap at this point but may not distribute the load evenly over the whole width of the shoulder strap. The result would be pressure peaks concentrated in the centre of the shoulder strap rather than utilising the whole width of the strap and distributing the load more evenly.

The theory behind adding the layer of plastic is that this will introduce an incompressible layer into the interface between the foam at the body surface and the front of the shoulder strap where it is attached to the body of the pack. The incompressibility of the plastic layer this will prevent the tension of the load strap compressing only the centre of the underlying interface foam. The plastic layer would be pressed evenly onto the underlying interface foam leading to an improved fit between the foam and the surface of the body. This improved fit would lead to a larger surface area of the body bearing the load of the pack resulting in lower pressure and hopefully improved comfort for the user.

7.3 Hypotheses

1. Shoulder strap width will affect the distribution of pressure underneath the strap:
    1.1 Narrowing the strap will reduce the surface area of the shoulder used for load distribution resulting in elevated pressure and discomfort

1.2 Widening the shoulder strap will increase the surface area of the shoulder used for load distribution resulting in lower pressure and discomfort.

2. Introducing a layer of plastic superficial to the interface material of a backpack shoulder strap will increase the contact between the strap and the shoulder area, resulting in improved pressure distribution and comfort.

7.4 Participants

Eight participants (five male) took part in this experiment, they had a mean ± SD age of 23.25 ± 1.38 years, height of 1.79 ± 0.08m and weight of 73.25 ± 6.25 kg. This sample was compared with that of an extensive anthropometric survey of the British Army (Gooderson, 1982). The mean age, weight and height of this sample were found to be within 1 standard deviation of the army population. One participant had completed two measurement sessions when their sensor was found to contain two rogue sensels. This participant was informed that they were not required to complete the study and thanked for their participation. Another participant was recruited and completed the study.

7.5 Experiment 1 Results

7.5.1 Effect of Strap Width

Analysis of Variance with repeated measures was used to determine statistical variance in pressure between conditions A, B and C. Following the identification of a significant difference between two or more of the conditions, post-hoc analysis was carried out using Tukeys Honestly Significant Difference test. Significant differences between the discomfort ratings given for each condition were detected using the non-parametric Friedman test for related samples.

Statistical significance was accepted at the 0.05 level. Reported results are means ± SD.

Table 7.1 shows the summary data of the interface pressure measurements underneath straps A, B and C and these are displayed graphically in figure 7.1. It can be seen that strap B, the narrowest strap resulted in the highest values for each of the three pressure variables. Mean pressure underneath strap B was 32.1 kPa, significantly higher than straps A and C which were 28.4 kPa and 27.2 kPa respectively. Strap B also resulted in the highest decile range (45.2 kPa) and 90th Percentile value (60.1 kPa) which were also significantly higher than straps A and C. The surface area of the shoulder sensor registering pressure underneath strap B was 24.3 cm^2, significantly lower than that for straps A, and C.

Strap C, the wider strap resulted in consistently lower pressure variables than strap A, the standard width strap although these differences were not large enough to be deemed statistically significant, this is visible in Figure 7.1. This was also the case for the mean contact area of strap C, 42.6cm^2, slightly higher than that for strap A (39.9 cm^2).

The subjective discomfort ratings given by the participants followed the same pattern as the pressure data (table 7.1). Strap B was rated significantly less comfortable than the other two straps with a mean rating of 3.48, midway between the 'uncomfortable' and 'very uncomfortable' anchors. The standard width strap A and the wider version C evoked similar ratings with no statistically significant difference between the two. However, although strap C resulted in consistently slightly lower pressure variables than strap A, it resulted in slightly more perceived discomfort than the standard width strap (2.79 compared with 2.52). When the ratings from each shoulder area are examined (Fig 7.2) it can be seen that the pattern for areas A, B and C is the same as for the overall ratings, with strap B rated the most uncomfortable and straps A and C eliciting very similar ratings. However, for area A, the trapezius area, strap C resulted in a mean rating of 3.87 one point higher than that of strap A (2.87) and also higher than strap B

(3.5). It was the higher ratings at this area that resulted in strap C being rated overall more uncomfortable than strap A.

Table 7.1 : Effect of Strap Width on Measured Variables (n=8)

	Strap A (standard)	Strap B (narrow)	Strap C (wide)
Mean pressure (kPa)	28.4 ± 1.7	32.1 ± 2.3 ↑	27.2 ± 2.91
Decile Range (kPa)	36.5 ± 4.8	45.2 ± 7.4 ↑	32.2 ± 3.5
90th Percentile (kPa)	49.9 ± 8.6	60.1 ± 7.5 ↑	47.3 ± 3.6
Contact Area (cm^2)	39.9 ± 6.1	24.3 ± 4.0 ↓	42.6 ± 3.6
Discomfort rating	2.52 ± 0.4	3.50 ± 0.3 ↑	2.81 ± 0.4

↑ significantly **higher** than other two straps ($p = <0.05$)
↓ significantly **lower** than other two straps ($p = <0.05$)

Fig 7.1 : Effect of Strap Width on Pressure Variables

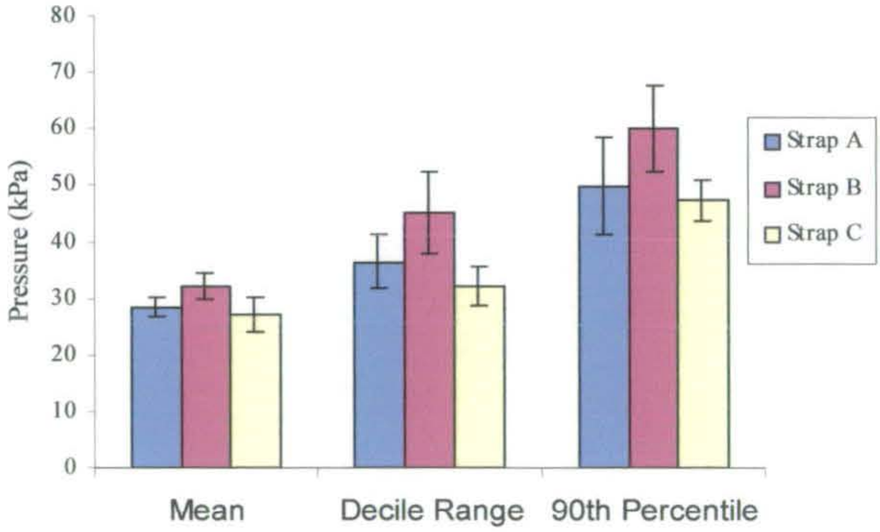
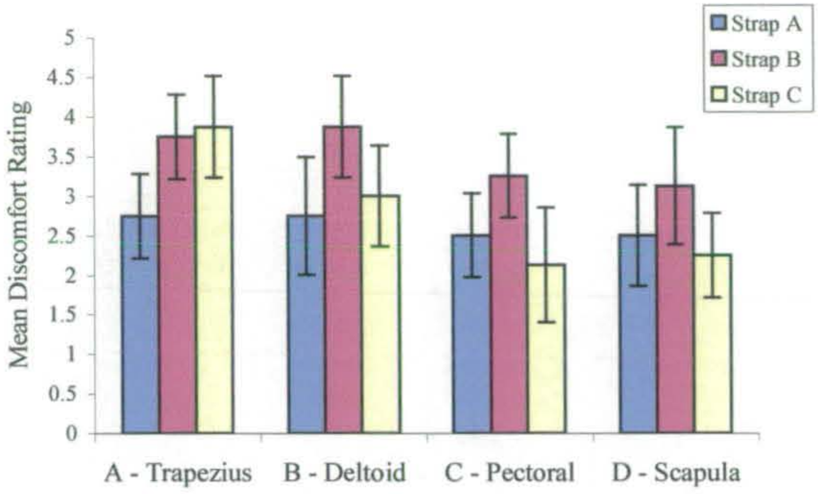


Fig 7.2 : Effect of Strap Width on User Discomfort



7.5.2 Effect of Plastic Layer

Paired sample t-tests were used to detect statistically significant variance between the two conditions A and D. Statistical significance was accepted at the 0.05 level. Reported results are means ± SD.

Strap D, which was of standard width but included a plastic layer on top of the polyethylene foam, resulted in lower values than strap A for each of the three pressure variables (Table 7.2 and figure 7.3). The inclusion of a plastic layer significantly reduced the mean shoulder pressure from 28.4 kPa (strap A) to 24.1 kPa, the decile range from 36.5 kPa to 22.8 kPa and the 90th Percentile value from 49.9 kPa to 37.9 kPa. Strap D resulted in a greater surface area registering interface pressure (49.3 cm^2) compared with strap A (39.9cm^2)

Strap D also resulted in significantly lower ratings of discomfort when compared with strap A eliciting a mean rating of 2.17, just above the 'slightly uncomfortable' anchor compared with 2.52 for strap A. From Figure 7.4 it can be seen that the areas A and B showed the largest difference between the two straps with only small differences in discomfort at areas C and D.

Table 7.2 : Effect of Plastic Layer on Measured Variables (n=8)

	Strap A	Strap D	ΔS (range)
Mean pressure (kPa)	28.4 ± 1.7	24.1 ± 1.4 *	4.73 (1 –10.2)
Decile Range (kPa)	36.5 ± 4.8	22.8 ± 4.2 *	16.63 (5 – 31)
90^{th} Percentile (kPa)	49.9 ± 8.6	37.9 ± 5.7 *	20.88 (5 – 36)
Contact Area (cm^2)	39.9 ± 6.1	49.3 ± 4.5 *	9.38 (-1 – 19)
Discomfort rating	2.52 ± 0.4	2.17 ± 0.5 *	0.29 (0.83)

* difference significant at $p = < 0.05$ level

ΔS = magnitude of difference

Table 7.3 : Results of Paired t-tests between conditions A and D

	Mean diff.	t	p	95% C.I of the mean
Mean Pressure	4.22	5.29	< 0.05	2.33 – 6.11
Decile Range	13.62	5.66	< 0.05	7.93 – 19.3
90^{th} Percentile	12.00	3.31	< 0.05	3.4 – 20.5

Fig 7.3: Effect of Plastic Insert on Pressure variables

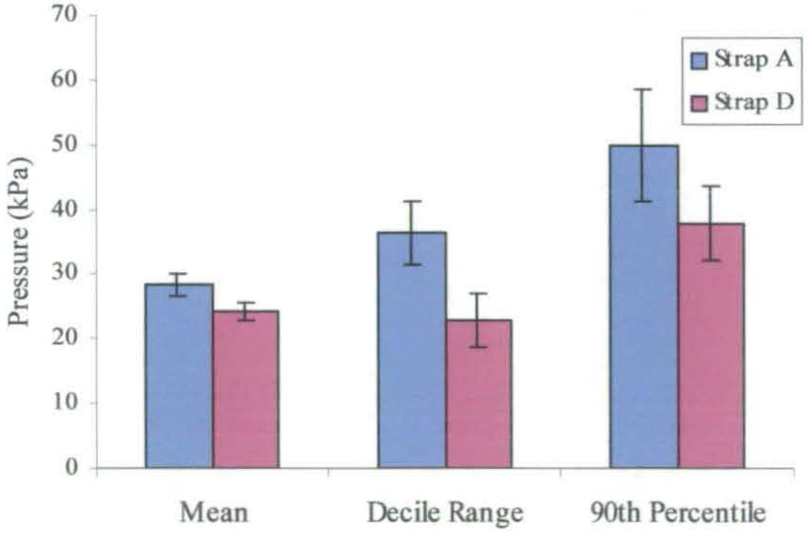
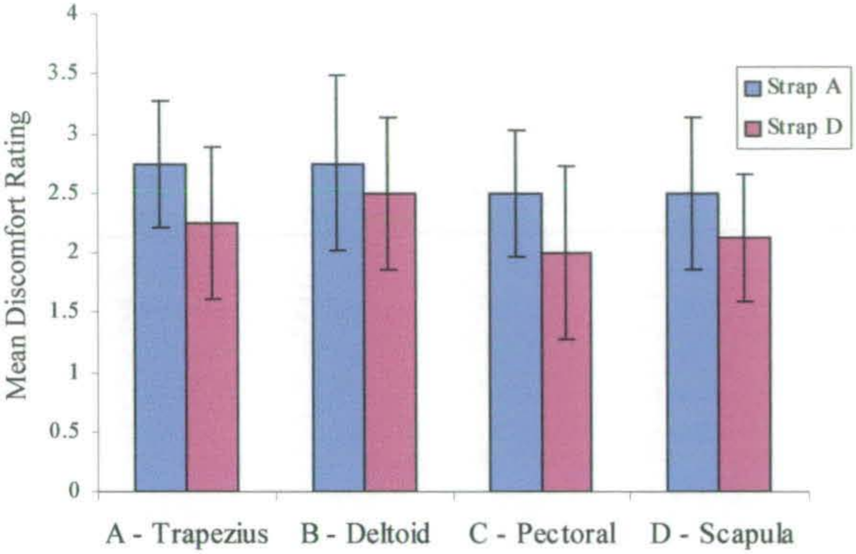


Fig 7.4 : Effect of Plastic Insert on User Discomfort



7.5.3 Interface Pressure and Contact Area

Table 7.4 displays the correlation co-efficients between the contact area of the shoulder sensor with applied pressure and the pressure variables for each of the four conditions. These range from -0.49 for the 90th Percentile value to - 0.59 and -0.60 for the decile range and mean pressure. These are all statistically significant moderate negative correlations indicating that in this experiment up to 36% of the variation in interface pressure was caused solely by differences in the amount of the shoulder sensor registering pressure. This supports the hypotheses presented in section 7.3 that increasing the contact between a shoulder strap and the body will aid load distribution. The correlation between contact area and 90th percentile value is slightly lower at –0.49. The 90th percentile value illustrates the magnitude of the highest pressures underneath the straps and this value indicates that only 24% of the variation within this variable was accounted for by changes in contact area. This suggests that there are other factors affecting the presence of high peaks of pressure. Such a factor would undoubtedly include the nature of the interface material itself, which will be considered fully in the next chapters.

Table 7.4 : Correlation Co-efficient between contact area and pressure variables

	r
Mean Pressure	- 0.60
Decile Range	- 0.59
90th Percentile	- 0.49

7.5.4 Interface Pressure and Discomfort

Table 7.5 shows the correlation co-efficients between each of the pressure variables and the discomfort ratings given by the participants. All of these are in excess of 0.5 with the highest value observed between mean pressure and discomfort (0.62). These are all statistically significant moderate positive correlations indicating that in this experiment interface pressure accounts for up to 40% of the variation in the discomfort reports of the participants. This positive relationship between subjective and objective data gives support for the validity of the measurements and the conclusions drawn from these results. This association between the objective and subjective data also provides positive implications for the possibility of developing a predictive equation for user comfort that will be discussed in chapter 11.

Table 7.5 : Correlation Co-efficient between discomfort ratings and pressure variables

	r
Mean Pressure	0.62
Decile Range	0.56
90th Percentile	0.62

7.6 Discussion

7.6.1 Strap Width

Of the three differently sized straps under investigation, strap B, the narrowest strap, resulted in the highest interface pressures. This was in accordance with the hypothesis presented in section 7.3. As the packs were identical in design and weight it was logical to predict that the narrowest strap would result in higher pressures due to the carried load being distributed over a smaller area. This was shown to be the case with strap B utilising the smallest surface area of the shoulder for pressure distribution resulting in the highest values for each of the pressure variables. Strap B also resulted in the highest discomfort ratings suggesting that the participants were sensitive to the higher shoulder pressures.

When the discomfort data for strap B is compared with the standard width strap (A) it can be seen that the largest differences in perceived discomfort occur at areas A and B ('trapezius' and 'deltoid' areas). It has been shown that the threshold for developing injury and impaired blood flow as a result of applied pressure is lower at thin skin sites over bony prominences (Sangeorzan et al, 1989). Due to the prominence of the clavicle at the trapezius and deltoid areas and the fact that these areas have to bear a large portion of the carried load these areas are at the greatest risk of damage. Therefore, these areas are also the most likely to benefit from an improvement in load distribution and a reduction in applied pressure. For the same reasons it is unsurprising that it is areas A and B that result in the highest discomfort rating and that under strap B, when load is more concentrated and pressures higher that these ratings are higher still. These findings support the hypothesis stated in section 6.3 that a uniform distribution of pressure at the shoulder interface will be the most preferable in terms of user comfort.

It can be concluded that in these experimental conditions reducing the width of a polyethylene foam shoulder strap from 70mm to 45mm and the resultant concentration of load lead to higher pressures at the shoulder area and increased user discomfort.

Increasing the width of the polyethylene shoulder straps from the standard 70mm to 88mm (strap C) resulted in small but consistent reductions in shoulder pressure. However, these were contradicted by the mean ratings of the participants, which favoured the standard width strap. Examination of the discomfort ratings for each area of the shoulder indicated that the higher mean ratings under strap C were the sole result of the ratings given for area A (trapezius). This area was rated on average just below the 'very uncomfortable' anchor for strap C compared with just below the 'uncomfortable' anchor for strap A. If the width of a shoulder strap is increased then it is logical to assume that interface pressure will decrease as the contact area on the body is increased and indeed the results in this experiment have shown this to be the case. However, it is also logical to assume that there must be an upper limit above which, benefits in terms of pressure distribution are outweighed by other factors. A very wide strap could encumber normal movement of the upper body or rub against or dig in the neck on the medial side of the strap. The high discomfort ratings given to strap C for this area of the shoulder indicate that this may have been the case for this wide strap.

In an evaluation such as this, the relative benefits of interface pressure and user sensation must be considered. A small, consistent reduction in pressure was observed underneath strap C, however this was accompanied by a considerable increase in discomfort at one specific area. It can be concluded, therefore, that in this case the benefit to the user of the small improvement in load distribution does not outweigh the detrimental effect on the feelings of well being of the user.

This finding illustrates the importance of collecting subjective measures and the fact that pressure data can only be used within the context of other parameters that affect military load carriage. In the case of strap C the discomfort reports given by the participants contradict the pressure data, a finding that would go undetected in an evalution focusing solely on pressure measurement.

7.6.2 Effect of Plastic Layer

The second aim of this experiment was to investigate the effect of adding a layer of plastic on top of the interface material on pressure distribution and user discomfort.

Strap D, which was of the same size, shape and composition, as strap A apart from the inclusion of a plastic layer significantly, improved the pressure distribution underneath the strap. This pressure data was supported by the subjective ratings with strap D rated significantly more comfortable than strap A for each shoulder area. The participants reported the greatest improvement in pressure at areas A and B, the tops of the shoulders. These areas have to bear the majority of weight of the pack and this is highlighted by more discomfort reported at these areas compared with C and D. Due to prominence of the clavicle these areas may also be at increased risk of both injury and discomfort and therefore improving pressure distribution may significantly reduce the risk of developing injury. The large reduction in discomfort at these areas indicate that in this experiment including a plastic layer results in a large enough reduction in pressure to affect the sensations of the user. Therefore, in addition to the health benefits of reducing interface pressure such a layer may also improve the feeling of well being and motivation of the user, which if observed in a militarycontext could improve performance.

The mechanism for this improvement appears to be the increased contact between the shoulder strap and the body, which distributes the load of the pack over a greater area. This effective pressure distribution results in a larger amount of individual sensels registering lower interface pressures, indicated by the much lower mean pressure value than any of the other straps. The lower observed decile range values under strap D illustrate a more even distribution of the load and this is supported by the lower 90th percentile value indicating that there are less peak pressures.

In section 7.2 it was suggested that including a plastic layer would improve contact between the strap and the body by acting as a rigid layer, evenly distributing the load of the pack from the thin load strap to the underlying interface material. From the results of this experiment it would appear that this indeed is the case demonstrated by the large increase in contact area and the resultant reduction in shoulder pressure.

The implications of improving shoulder load distribution and reducing interface pressures will be considered fully in Chapter 10 along with a discussion of the findings of this experiment within a military context. It can be concluded, however, that if the findings of this experiment could be observed in a real military situation then an improvement in pressure distribution by the introduction of a plastic layer may have a two-fold benefit for the user. Lowering the risk of impaired performance due to reduced blood flow and also deep tissue damage. This is in addition to the benefits on psychological feelings of well being and motivational factors due to improved user comfort.

7.7 Conclusions

To conclude, strap D resulted in the most effective pressure distribution and consequently the most favourable discomfort reports. Strap B resulted in the highest shoulder interface pressures and also the highest discomfort reports. No significant difference was found between straps A and C.

It was decided that straps A and D would be carried forward to the final prototype testing. Strap D because this resulted in the most effective load distribution and also the most favourable discomfort ratings. Strap A was also carried forward, this being the strap currently used on the backpacks of the British Military. This strap was included in order to have a baseline strap present in the final prototype analysis stage. This was necessary to allow conclusions to be made about potential improvements and benefits of new prototype straps in the final analysis stage.

Chapter 8 Experiment 2

8.1 Introduction and Aims

Martin and Hooper (1999) first proposed Monofillament airmesh as an effective interface material for load carriage equipment. This research was conducted to determine whether a mesh of this type improved the ability of a user to lose excess heat when exercising in a warm climate. The material provided an 8mm thick open-mesh at the back area considerably increasing the surface area of the body available for evaporative heat loss and was found to improve thermal comfort. A bi-product of this study was that the participants reported significantly improved general comfort underneath the air mesh straps compared with standard backpack straps consisting of the closed cell polyethylene foam (foam 1) investigated in Chapter 7. Martin and Hooper suggest the reason for this improvement to be a better fit of the air mesh material with the shoulder area due to increased compressibility. The authors proposed that this improved fit increased the surface area used to bear the load of the pack, consequently lowering the pressures at the shoulder. This piece of work led to the suggestion that air mesh materials may provide benefits in terms of improving pressure distribution and user discomfort when incorporated into the user interface of backpack straps.

The first aim of this experiment was to evaluate the effects of different air mesh materials of differing rigidity and composition on load distribution, interface pressure and user discomfort. Three different air mesh materials (meshes 1,2 and 3) were evaluated.

This experiment also quantified the effect of adding a layer of plastic on top of the interface material, a design feature which has been shown to improve pressure distribution when added to a polyethylene closed cell foam strap (Chapter 7). This experiment aimed to discover whether a plastic layer would have the same effect when placed over an air mesh material. Prototype strap 'H' was constructed from mesh 3 with a layer of plastic added superficial to the mesh. Studying the effect of plastic on all of the different air meshes would have resulted in too great a number of prototypes to test so it was decided that the general effect of plastic on air mesh would be investigated rather than the effect on specific meshes.

8.2 Hypotheses

1. The compressibility of an air mesh material will affect load distribution, pressure and discomfort when incorporated into the interface of load carriage equipment.

2. Introducing a layer of plastic superficial to the interface material of a backpack shoulder strap will increase the contact between the strap and the shoulder area, resulting in improved pressure distribution and comfort.

8.3 Participants

Eight participants (four male, four female) took part in this experiment, they had a mean ± SD age of 21.25 ± 2.35 years, height of 1.77 ± 0.11m and weight of 71.87 ± 8.06 kg. This sample was compared with that of an extensive anthropometric survey of the British Army (Gooderson, 1982). The mean age, weight and height of this sample were found to be within 1 standard deviation of the army population.

8.4 Experiment 2 Results

8.4.1 Effect of Mesh Type

Analysis of Variance with repeated measures was used to determine statistical variance between conditions E, F and G. Following the identification of a significant difference between two or more of the conditions, post-hoc analysis was carried out using Tukey's Honestly Significant Difference test. Significant differences between the discomfort ratings from each condition were detected using the non-parametric Friedman test for related samples. Statistical significance was accepted at the 0.05 level. Reported results are means ± SD.

Table 8.1 presents the measured variables for each of the three different air mesh materials and these are displayed graphically in figure 8.1. It can be seen that strap F (mesh 2) resulted in significantly higher values for each of the three pressure variables than for straps E and G. Mean shoulder pressure underneath this strap was 28.4 kPa compared with 21.1 kPa and 21.6 kPa for straps E and G respectively. The decile range of pressures (31.9 kPa) and 90th Percentile values (48.4 kPa) were also significantly higher than under straps E and G.

No significant differences were detected between straps E and G for any of the pressure variables. The two straps resulted in very similar mean pressures of 21.1 kPa and 21.6 kPa respectively, decile ranges (25.9 kPa and 21.1 kPa) and 90th Percentile values (37.2 kPa and 38.1 kPa). These slight differences did not show a pattern of one strap consistently resulting in higher values.

Strap F utilised the smallest area of the pressure sensor (29.9cm^2). This value was significantly lower than the area registering pressure underneath straps E (51.75cm^2) G (54.13cm^2). Again there was no significant difference between straps E and G.

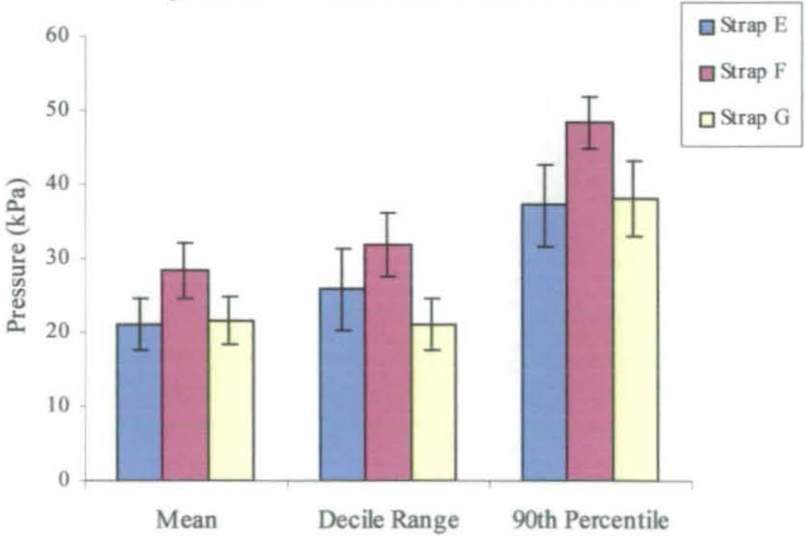
The ratings of perceived discomfort given by the participants followed the same pattern as the pressure measurements with strap F rated significantly less comfortable than the other two mesh materials. The mean rating for this strap was 3.12, just above the 'uncomfortable' anchor. In contrast to the objective data, the participants in this study did detect differences between straps E and G rating strap E significantly more comfortable. Strap E resulted in a mean rating of 2.29 compared with 2.79 for strap G. It can be seen from fig 8.2 that this pattern was the same for each of the four of the shoulder areas with strap F rated the most unfavourable and strap E consistently resulting in the lowest ratings of discomfort for each shoulder area.

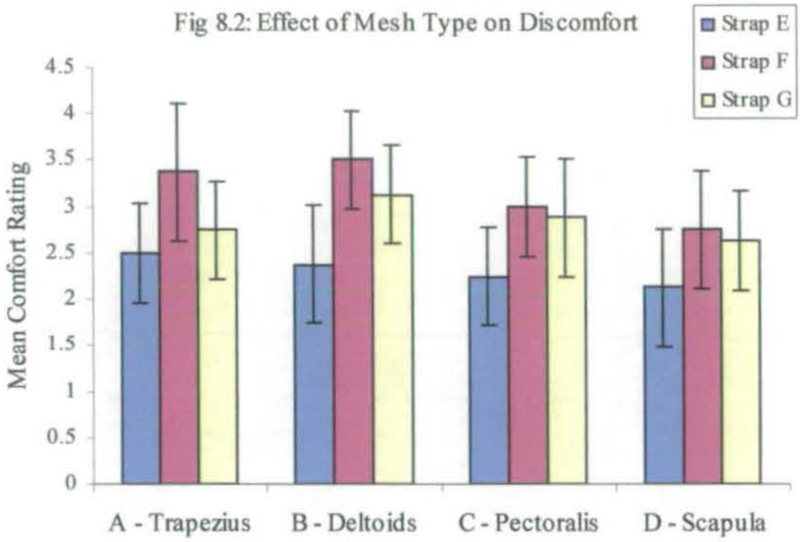
Table 8.1 : Effect of Mesh Type on Measured Variables (n=8)

	Strap E	Strap F	Strap G
Mean pressure (kPa)	21.1 ± 3.5	28.4 ± 3.8 ↑	21.6 ± 3.2
Decile Range (kPa)	25.9 ± 5.5	31.9 ± 4.4 ↑	21.1 ± 3.4
90th Percentile (kPa)	37.2 ± 5.49	48.4 ± 3.5 ↑	38.1 ± 5.11
Contact Area (cm^2)	51.75 ± 6.2	29.9 ± 5.3 ↓	54.13 ± 6.9
Discomfort rating	2.29 ± 0.58 ↓	3.12 ± 0.55 ↑	2.73 ± 0.58

↑ significantly **higher** than other two straps ($p = <0.05$)
↓ significantly **lower** than other two straps ($p = <0.05$)

Fig. 8.1 : Effect of Mesh on Interface Pressure





8.4.2 Effect of Plastic

Paired sample t-tests were used to detect statistically significant variance between conditions G and H. Significance was accepted at the 0.05 level. Reported results are means ± SD.

It can be seen from table 8.2 that introducing a layer of plastic on top of mesh 3 (strap H) resulted in a reduction in interface pressure. Mean pressure was reduced from 21.1 kPa underneath strap G to 17.9 kPa underneath strap H with an improvement of 8.2 kPa observed in one participant. The addition of a plastic layer also resulted in a significant reduction in the 90th percentile value from 37.2 kPa to 31.9 kPa. The mean values for the decile ranges for straps G and H were 25.9 kPa and 20.8 kPa, however, there was not a consistent trend of improvement under strap H with three out of eight participants experiencing an increase in the decile range pressure underneath this strap.

This general trend of improvement is supported by the contact area data. The mean contact area across all eight participants underneath strap H was 60.1 cm^2, significantly higher than that for strap G (54.13 cm^2). This was a consistent effect with all eight participants showing an increase in surface area in condition H, the largest increase being 16 cm^2

The participants' ratings of discomfort supported this objective data. Seven out of eight participants reported less discomfort underneath strap H with a mean rating of 2.19, just above the 'slightly uncomfortable' anchor. This was significantly lower than the mean rating given for strap G, which was 2.73, just below the 'uncomfortable' anchor. Fig 8.4 presents the mean ratings for each of the four individual shoulder areas, it can be seen that strap H results in improved comfort at all four areas. Areas A and B, the tops of the shoulders, showed the largest improvement in comfort, 2.75 to 1.87 for area A and 3.12 to 2.25 for area B with smaller improvements observed at areas C and D.

Table 8.2 : Effect of Plastic Layer on Measured Variables (n=8)

	Strap G	Strap H	ΔS x (range)
Mean pressure (kPa)	21.1 ± 3.5	17.9 ± 2.8	3.62 (-1.9 – 8.2) *
Decile Range (kPa)	25.9 ± 5.5	20.8 ± 2.9	0.38 (-5 – 4)
90th Percentile (kPa)	37.2 ± 5.49	31.9 ± 4.79	6.25 (1 – 11) *
Contact Area (cm^2)	51.75 ± 6.2	60.1 ± 4.4	6.00 (2 –16) *
Discomfort rating	2.73 ± 0.58	2.19 ± 0.4	0.66 (-0.5 – 9.8) *

* difference significant at $p = < 0.05$ level

Table 8.3 : Results of Paired t-tests between conditions G and H

	Mean diff.	t	p	95% C.I of the mean
Mean Pressure	3.62	2.75	< 0.05	0.51 – 6.73
Decile Range	0.38	0.34	0.747	-2.27 – 3.01
90th Percentile	6.25	4.84	< 0.05	3.19 – 9.31
Contact Area	6.00	3.31	< 0.05	1.71 – 10.29

Fig 8.3 : Effect of Plastic Insert on Pressure

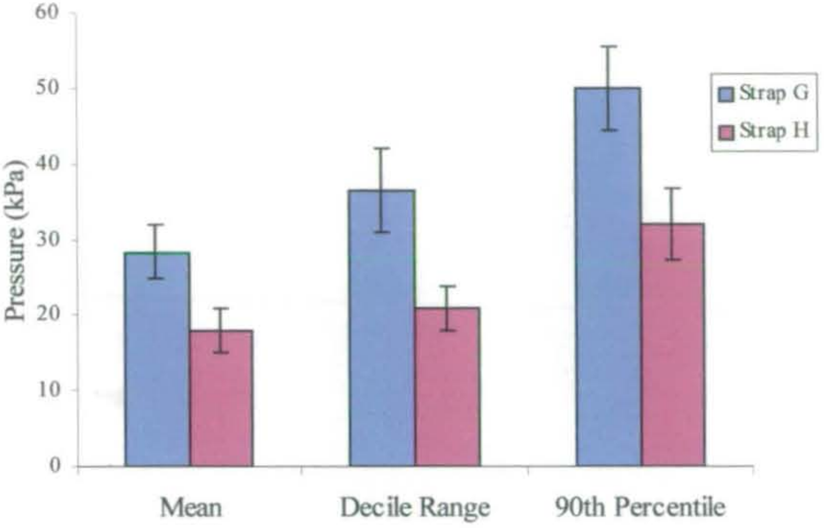
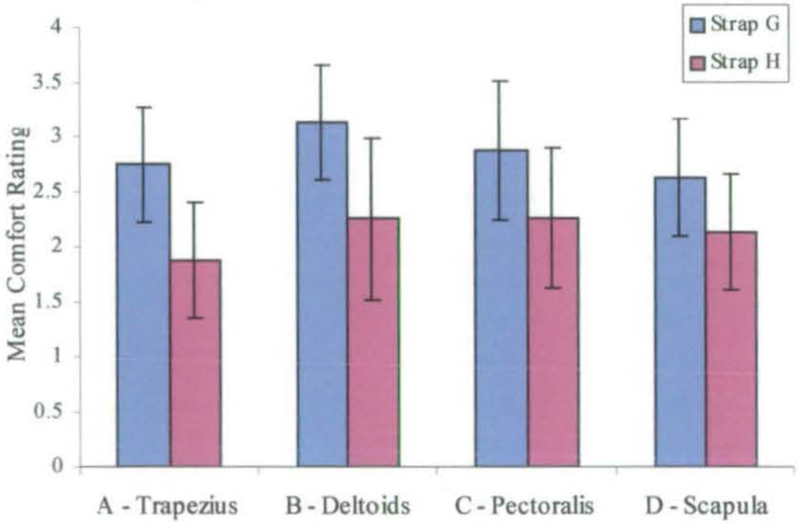


Fig 8.4: Effect of Plastic Layer on Discomfort



8.4.3 Contact Area and Pressure

Table 8.4 displays the correlation co-efficients between the contact area of the sensor registering pressure and each of the pressure variables. These range from -0.59 to -0.75, all moderate to high negative correlations indicating that as much as 56% of the variation in the mean pressure and the 90th percentile values could be accounted for by the contact area data. This relationship supports the experimental hypothesis presented in section 6.3 that increasing the area of the shoulder in contact with the shoulder strap will reduce average pressure and also reduce the magnitude of pressure peaks. Designs of strap that improve contact by the use of different interface materials or by the inclusion of plastic have been shown to improve load distribution.

Table 8.4 : Correlation Co-efficient between pressure variables and contact area

	r
Mean Pressure	- 0.75
Decile Range	- 0.59
90th Percentile	- 0.75

8.4.4 Interface Pressure and Discomfort

Table 8.5 shows the correlation co-efficients between the discomfort ratings given by the participants and each of the three pressure variables. These ranged from 0.53 to 0.66; all moderate positive correlations, and indicate that in this experiment variation in pressure alone accounts for up to 43% of the variation within the discomfort ratings. These correlations are similar to those obtained in experiment 1 and this agreement provides further support for the validity of the methods used in this study. This relationship will be examined further in chapter 11 where the issue of predicting discomfort from interface pressure will be investigated.

Table 8.5 : Correlation Co-efficient between pressure variables and mean discomfort rating

	r
Mean Pressure	0.66
Decile Range	0.54
90th Percentile	0.53

8.5 Discussion

The major aims of this experiment were to investigate the effect of different air mesh materials and the addition of plastic layer on load distribution, interface pressure and user discomfort.

8.5.1 Interface Material

Of the three interface materials under investigation, strap F (mesh 2) resulted in significantly higher interface pressures at the shoulder area. The mechanism behind this appeared to be the smaller area of the shoulder being used for load distribution illustrated by the significantly lower area of the shoulder sensor registering pressure compared with straps E and G.

The rigidity of mesh 2 is a possible reason for the poor contact between the body and the shoulder strap resulting in the higher pressures under strap F.
The aim of an interface material is to ensure good contact with the body surface whilst at the same time distributing the load of the pack as evenly as possible over this area. In order to create good contact with the body surface, especially one as intricately shaped as the shoulder the material should be compressible enough so that it will take the shape of the surface that it is applied to. A material that is not compliant enough will not conform to fit the intricacies of the clavicle and therefore pressure may be concentrated on the bony prominence of the shoulder instead of the surrounding area. Strap F consisted of mesh 2, which was the least compressible of all the meshes under investigation (table 6.1). However, this material was only slightly more rigid than meshes 1 and 3 and it is unlikely compressibility alone accounted for the observed differences in pressure between these straps.

The discomfort reports for this strap followed the same pattern as the pressure data, indicating that the participants in this experiment were sensitive to the higher pressures underneath strap F. Areas A and B, the tops of the shoulders, were rated consistently higher than C and D irrespective of strap type and as these parts of the shoulder have to bear the majority of the load of a carried pack this is unremarkable. When the ratings for each area were looked at individually it was found that interface material had the largest effect at areas A and B although smaller differences were also detected at areas C and D. The anatomical structure of areas A and B with the prominence of the clavicle result in this area being very intricately shaped. Consequently, an interface material that improves fit will have the greatest effect at an area such as this compared with the areas C and D which are of a less irregular shape.

As a result of both the objective and subjective data and the agreement between the two, it was concluded that out of the three interface materials studied, mesh 2 was the least effective in distributing load, resulting in the highest shoulder pressures and discomfort reports.

Although no significant differences were detected by the objective measurements, strap E was rated significantly less uncomfortable than strap G by the participants with seven out of the eight participants giving lower ratings for strap E. It is clear and indeed unquestionable that there are factors affecting user sensations other than interface pressure, including shear forces and friction and it would appear that this is the case here. This again, provides support for the use of subjective measurements in a study of this kind.

No difference in contact between the body and the shoulder strap was detected between meshes 1 and 3 and as a result of this the pressure distribution under these straps was also very similar. However, consistent differences in user discomfort were identified at all four shoulder areas with seven out of the eight participants rating strap G as less comfortable than strap E. Although this greater discomfort under strap G could not be explained in terms of load distribution or interface pressure this finding supports the importance of incorporating subjective measures in an evaluation of load carriage equipment. On the basis of both subjective and objective data it can be concluded that the mesh 1 performed significantly better than mesh 2.

In attempting to apply the findings of this experiment to the real life military situation there a number of issues to consider, including the effects of longevity of use on mesh performance and the effects of carrying heavier loads. These will be discussed in detail in Chapter 10.

8.5.2 Effect of Plastic Layer

In Chapter 7 the inclusion of a layer of plastic was shown to have beneficial effects when placed on top of a polyethylene closed cell foam strap. The contact between strap and the body resulted in lower pressures and improved user comfort. The second aim of this experiment was to determine whether adding the same plastic layer would have the same effect on an air mesh interface material to determine whether this design feature provides a general beneficial effect or whether this is dependent upon the nature of the interface material.

Strap H, which was identical to G except for the inclusion of plastic superficial to the air mesh material, significantly improved the contact between the shoulder and the strap, by as much as 16cm^2 in one case. This improved fit resulted in significantly lower mean pressure and 90th Percentile pressure values, although no significant difference in the decile ranges was found between the conditions.

These results demonstrate that adding a layer of plastic into an airmesh backpack strap improves load distribution by increasing the contact between the strap and the shoulder. The proposed mechanism for this improvement is the same as that suggested in Chapter 7, that the plastic layer provides a rigid layer, which distributes the load of the pack evenly onto the underlying interface material. The even pressing of the strap onto the shoulder results in a larger surface area of the shoulder bearing the carried load and the resultant observed lower pressure variables. As in experiment 1, the participants were sensitive to this reduction in pressure, rating strap H consistently more comfortable than strap G at each of the four shoulder areas.

As a result of the combination of both the objective and subjective data it was concluded that the inclusion of plastic in strap H significantly improved load distribution resulting in lower interface pressures and lower ratings of discomfort than strap G which contained only the mesh 3. Larger improvements in comfort were observed at the tops of the shoulders (areas A and B) again indicating that these areas benefit the most from improvements in load distribution and reductions in applied pressure.

8.6 Conclusions

Mesh 2 (strap F) was the least effective material, resulting in the highest shoulder pressures and the most unfavourable ratings of participant comfort. Although there were no differences between meshes 1 (strap E) and 3 (strap G) in terms of pressure distribution, mesh 1 was rated significantly more comfortable by the participants. The introduction of a plastic layer on top of mesh 3 (strap H) increased the contact between pack and shoulder and as a result improved load distribution and comfort.

Prototype straps E and H were carried forward for the final prototype analysis as taking into both pressure and comfort data these were the straps that performed best overall.

Chapter 9 Experiment 3

9.1 Introduction and Aims

There were two main aims of this experiment, firstly to evaluate three mesh materials of varying compressibility. Strap I (mesh 4), J (mesh 5) and K (mesh 6) were identical in design except for the interface material and these three straps were directly compared to establish the effect of these materials on load distribution, interface pressure and user discomfort

The second aim was to determine the effect of adding a layer of plastic to a shoulder strap consisting of mesh 6. In chapter 7 this design feature was shown to increase the contact between a strap and the shoulder area improving load distribution and user comfort when placed on top of closed-cell polyethylene foam. In chapter 8, improvements were observed when the same plastic layer was added to mesh 3, which had a compressibility of 74%. To determine whether this design feature improves load distribution regardless of the interface material on which it is placed a further prototype strap L was constructed. This strap consisted of mesh 6 which was more compressive than either mesh 3 or foam 1 with a compressibility of 57% (table 6.1). The results of this experiment would provide more information on the effects of this design feature and whether it can be recommended for inclusion in a backpack strap regardless of the composition of the main interface material.

9.2 Hypotheses

1. The compressibility of an air mesh material will affect the distribution of a carried load, interface pressure and user discomfort when incorporated into the shoulder straps of a military backpacking rucksack.

2. Introducing a layer of plastic superficial to mesh 6 will increase the contact between the strap and the shoulder area, resulting in improved pressure distribution and user comfort.

9.3 Participants

Eight participants (four male) took part in this experiment, they had a mean ± SD age of 22.12 ± 2.9 years, height of 1.75 ± 0.07m and weight of 73.5 ± 5.52 kg. This sample was compared with that of an extensive anthropometric survey of the British Army (Gooderson, 1982). The mean age, weight and height of this sample were found to be within 1 standard deviation of the army population. Two participants did not complete the study as their sensors were found to contain rogue cells (one after 1 trials, the other after 3 trials). These participants were informed that they were no required to complete the study and thanked for their participation. Two additional participants were recruited and both completed all four measurement sessions.

9.4 Experiment Three Results

9.4.1 Effect of Mesh Type

Analysis of Variance with repeated measures was used to determine statistical variance between conditions I, J and K. Following the identification of a significant difference between two or more of the conditions, post-hoc analysis was carried out using Tukey's Honestly Significant Difference test. Significant differences between the discomfort ratings from each condition were detected using the non-parametric Friedman test for related samples. Statistical significance was accepted at the 0.05 level. Reported results are means ± SD.

Table 9.1 presents a summary of the measured variables for each of the three different air mesh straps and these results are displayed graphically in figure 9.1. It can be seen that strap K, which consisted of mesh 6, resulted in significantly lower values for all three pressure variables than straps I and J. Mean pressure underneath this strap across all eight participants was 16.4 kPa compared with 18.6 kPa and 19.6 kPa for straps I and J respectively. The decile range figure of 17.1 kPa and 90th percentile value of 26.8 kPa for strap K were also significantly lower than those for the other two straps.

These lower pressures underneath strap K were mirrored by the contact area of the shoulder sensor registering pressure which was 92.1 cm^2, significantly higher than that for straps I and J.

When comparing straps I and J, strap J resulted in consistently slightly higher pressure variables, however, these were not large enough to be deemed statistically significant at the $\alpha = 0.05$ level. Mean overall pressures underneath straps I and J were 18.9 kPa and 19.6 kPa respectively. Strap J also resulted in slightly higher decile range of 25.7 kPa compared with 22.4 kPa for strap I, this pattern was the same for the 90th percentile value which was 35.8 kPa compared with 32.4 for strap I.

The surface area of the shoulder sensor used by these two straps was very similar, 76.25cm^2 and 75.88 cm^2 for straps I and J respectively.

The ratings of discomfort given by the participants in this experiment supported the pressure ratings. Strap K was rated significantly less uncomfortable than the other two mesh straps with a mean rating of 2.59, mid-way between the 'slightly uncomfortable' and 'uncomfortable' anchors. Straps I and K resulted in very similar ratings of 3.13 and 2.97 respectively, which were both around the 'uncomfortable' anchor. Figure 9.2 illustrates the ratings given for each individual area of the shoulder. It can be seen from this that although strap K resulted in consistently lower ratings at each area of the shoulder the differences were most pronounced at areas A and B, the tops of the shoulders. It can also be seen that straps I and J elicited very similar ratings on all areas apart from the scapula (D) where there was a noticeable difference between the straps. At this area strap I resulted in a mean rating of 2.87 compared with 2.5 for strap J.

Table 9.1 : Effect of Mesh Type on Measured Variables (n=8)

	Strap I	Strap J	Strap K
Mean pressure (kPa)	18.7 ± 1.43	19.6 ± 1.5	16.4 ± 1.4 ↓
Decile Range (kPa)	22.4 ± 4.5	25.7 ± 3.6	17.1 ± 1.6 ↓
90th Percentile (kPa)	32.4 ± 4.47	35.8 ± 3.6	26.8 ± 2.12 ↓
Contact Area (cm^2)	76.2.5 ± 7.9	75.8 ± 10.5	92.1 ± 5.6 ↑
Comfort rating	3.13 ± 0.48	2.97 ± 0.6	2.59 ± 0.58 ↓

↑ significantly **higher** than other two straps (p = <0.05)
↓ significantly **lower** than other two straps (p = <0.05)

Fig. 9.1 : Effect of Interface Material on Interface Pressure

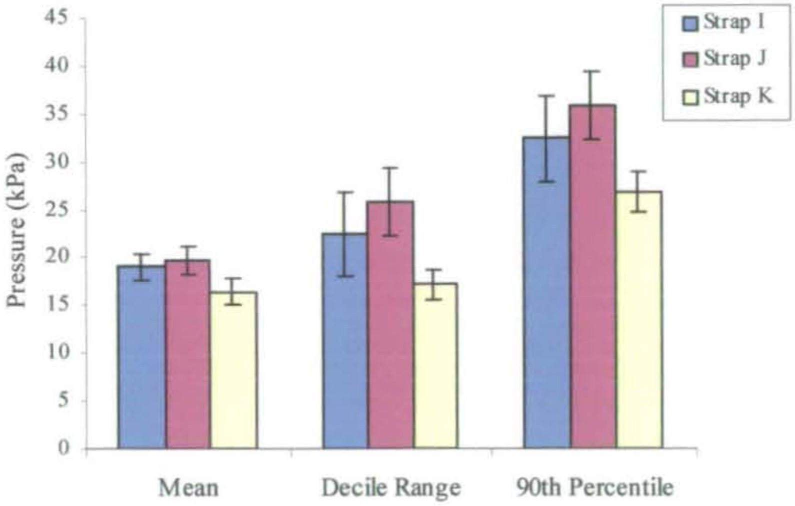
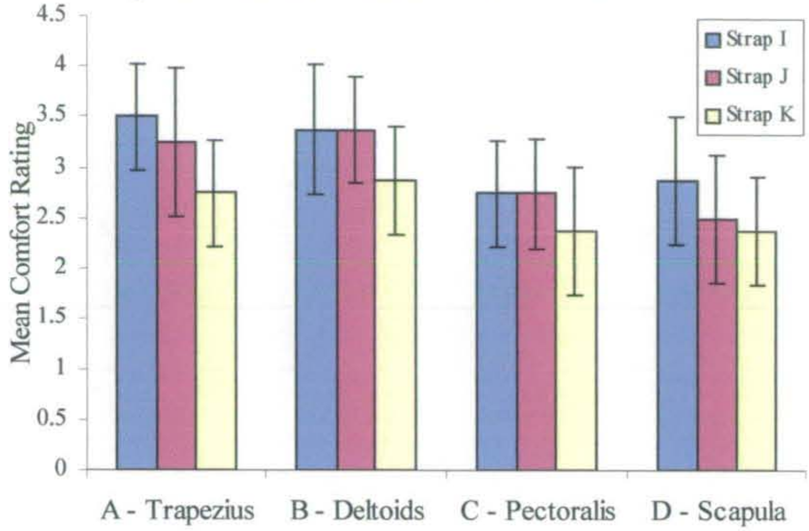


Fig. 9.2 : Effect of Interface Material on User Discomfort



9.4.2 Effect of Plastic

Paired sample t-tests were used to detect statistical significant variance between conditions K and L. Significance was accepted at the 0.05 level. Reported results are mean ± SD.

Table 9.2 presents a summary of all measured variables for straps K and L. These two straps consisted of the same interface material except for in strap L a layer of plastic was added superficial to the interface material. The addition of this plastic layer resulted in a small but statistically significant reduction in mean pressure from 16.5 kPa to 15.0 kPa. A lower mean pressure underneath strap L was observed in all eight of the participants.

Although the mean decile range values across all eight participants was reduced from 17.1 kPa to 13.5 kPa this reduction was not sufficient to be significant at the 0.05 level. Two of the eight participants had exactly the same value in each condition and another three participants showed an improvement of less than 3kPa. A trend of improvements was not observed across the whole sample.

Strap L resulted in a significant reduction in the 90th percentile values from 26.8kPa for strap K to 23.1 kPa for strap L. This trend was consistent throughout the sample with all eight participants showing an improvement in this value with an improvement of 10 kPa observed in one participant.

The addition of a layer of plastic into strap L resulted in a significantly greater amount of the shoulder sensor being used for load distribution. The mean contact area underneath strap L was 99.6 cm^2 compared with 92.1 cm^2 for strap K. This increase in contact area underneath strap L was again consistent across all eight participants with the largest increase being 14 cm^2.

The observed improvement in load distribution underneath strap L was supported by the participants' rating of discomfort. Strap L resulted in a significantly lower mean rating of 2.28 compared with 2.59 for strap K. Six of the eight participants rated strap L more comfortable than strap K with one participant giving identical ratings for the two straps. Fig. 9.4 shows the ratings for each shoulder area for straps K and L. From this it can be seen that the participants were most sensitive to differences between the two straps at areas A and B. Under strap L the mean discomfort rating at area A was reduced from 2.75 to 2.375 and at area B the mean rating was 2.375 compared with 2.875 underneath strap K.

Table 9.2 : Effect of Plastic Layer on Measured Variables (n=8)

	Strap K	Strap L	ΔS x (range)
Mean pressure (kPa)	16.4 ± 1.4	15.0 ± 0.9	1.43 (0.36 – 3.6) *
Decile Range (kPa)	17.1 ± 1.6	13.5 ± 3.1	3.63 (0 – 7)
90th Percentile (kPa)	26.8 ± 2.12	23.1 ± 3.4	3.75 (-3 – 10) *
Contact Area (cm^2)	92.1 ± 5.6	99.6 ± 7.9	7.50 (1 –14) *
Discomfort rating	2.59 ± 0.58	2.28 ± 0.45	0.31 (-0.25 – 0.5) *

* difference significant at $p = < 0.05$ level

Table 9.3 : Results of Paired t-tests between straps K and L

	Mean diff.	t	p	95% C.I of the mean
Mean Pressure	1.43	3.255	< 0.05	0.39 – 2.47
Decile Range	3.63	3.629	< 0.05	1.26 – 5.98
90th Percentile	3.75	2.546	< 0.05	0.26 – 7.23
Contact Area	7.50	5.081	< 0.05	4.01 – 10.99

Fig. 9.3: Effect of Plastic Insert on Pressure Variables

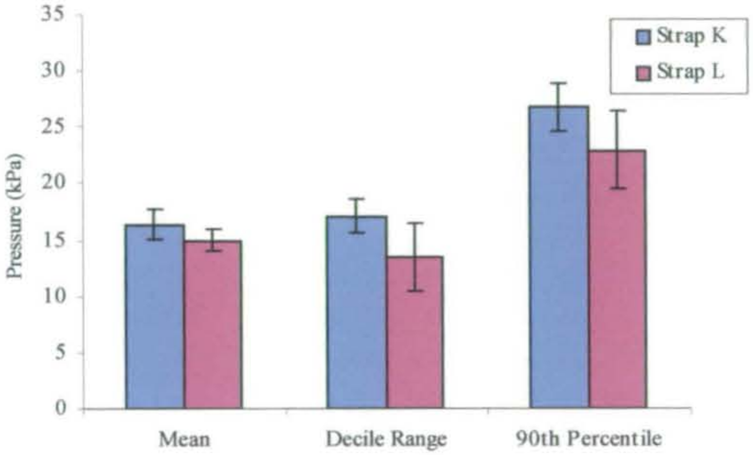
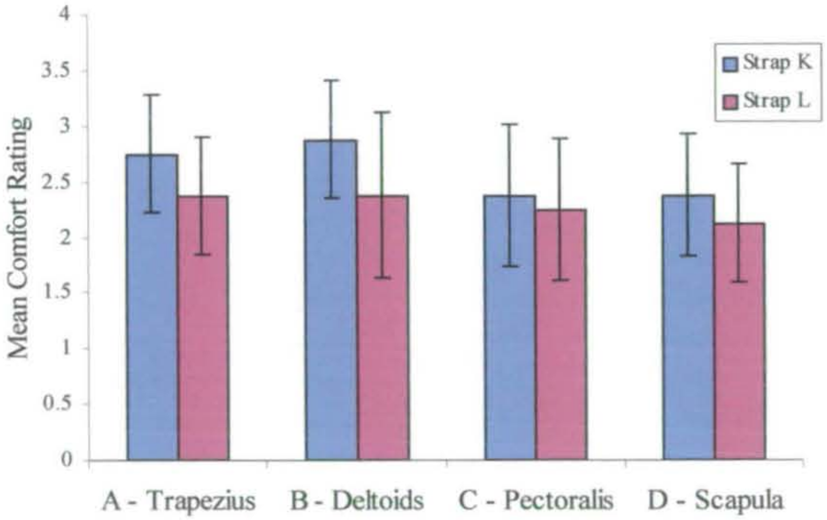


Fig. 9.4 : Effect of Plastic Layer on User Discomfort



9.4.3 Contact Area and Interface Pressure

Table 9.4 presents the correlation co-efficients between contact area and the three pressure variables. These range from –0.62 to –0.70, which are all moderate to high negative correlations indicating that up to 49% of the variation within the overall mean pressure values was accounted for by variation in the contact area. These correlations are in a similar range to those found in experiments 1 and 2 (Chapters 7 and 8). The strength of the association between contact area and pressure supports the experimental hypothesis stated in section 6.3 that increasing the contact between a shoulder strap and the shoulder area will improve pressure distribution and reduce the number and magnitude of pressure peaks. In this experiment as in the previous two it has been shown that straps that utilise the largest surface area of the shoulder sensor result in the lowest pressure variables.

Table 9.4 : Correlation Co-efficient between pressure variables and contact area

	r
Mean Pressure	- 0.70
Decile Range	- 0.62
90th Percentile	- 0.64

9.4.4 Interface Pressure and Discomfort

The correlation co-efficients between the discomfort ratings given by the participants in this experiment and the three pressure variables are shown in Table 9.5. These ranged from 0.62 to 0.69, which were all statistically significant moderate to high positive correlations. These demonstrate that up to 48% of the variation within the discomfort ratings can be explained solely by variation in interface pressure. This agreement between the collected objective and subjective data provides support for the hypothesis stated in section 6.3 that improving load distribution and lowering interface pressure at the shoulder will reduce discomfort for the user. These associations provide positive implications for the possibility of developing a relationship that could result in prediction of user discomfort and this will be investigated further in chapter 11.

Table 9.5 : Correlation Co-efficient between pressure variables and mean discomfort rating

	r
Mean Pressure	0.62
Decile Range	0.68
90th Percentile	0.69

9.5 Discussion

The two major aims of this experiment were to evaluate the effects of different mesh materials and the inclusion of plastic on load distribution, interface pressure and user discomfort.

9.5.1 Interface Material

Of the three straps I, J and K, which all consisted of a different mesh material, strap K (mesh 6) was found to be the most effective in distributing load, resulting in the lowest pressure variables and discomfort ratings. The reason for the observed lower pressures appeared to be the increased contact between the strap and the shoulder area, illustrated by the significantly greater area of the shoulder sensor registering interface pressure compared with straps I and J.

The likely mechanism for this improved fit between strap K and the shoulder area was the nature of the interface material, namely compressibility. As discussed earlier, the interface material of a shoulder strap should be compliant enough to ensure good contact with the shape of the shoulder yet strong enough so that the load is supported and distributed evenly onto the underlying body surface.

Mesh 6, which made up strap K had a compression figure of 57% compared with 68% and 66% for straps I and J. It would appear that straps I and J resulted in less contact with the shoulder area due to being less compressible than strap K. These materials may have been too rigid to effectively distribute the load over the whole width of the strap. Due to the intricate shape of the shoulder area a material which is not conformable may not effectively fit to this area. This may lead to the concentration of load on the bony prominence such as the clavicle.

The material within strap K appears to be very effective at fitting the shoulder area illustrated by the very high values for the contact area of the shoulder sensor registering applied pressure. As a result of this good contact, pressure was distributed more evenly, indicated by the lower over mean pressures and decile range of pressure values. The magnitude of the highest pressures underneath this strap was also reduced as indicated by the lower 90th percentile values.

These conclusions regarding the effectiveness of strap K are supported by the fact that the participants in this experiment rated strap K significantly less uncomfortable than the other two straps. This indicates that the participants in this study were sensitive to the more effective pressure distribution underneath strap K. The most noticeable differences in ratings between strap K and the other two straps occurred at areas A and B, the trapezius and deltoid areas. As these are the areas which consist of the bony prominence of the clavicle it is likely that due to its intricate shape, this is the area of the shoulder that would benefit the most from a material that increases the fit between a strap and the body surface. The lower ratings of discomfort at these areas for strap K suggest that this strap conformed more effectively to the shape of the clavicle resulting in a more even distribution of pressure around this area. A strap that does not mould to the shape of this area may concentrate pressure on the bone, which in addition to causing damage to the underlying tissue would result in discomfort for the user.

No significant differences in either interface pressure or the discomfort ratings of the participants were detected between straps I and J. Both straps resulted in very similar contact area values and the compressibility of each material were also similar (68% and 66% respectively). This provides support for the hypothesis that the amount of surface area of a body surface used for load distribution will be the dominant factor in affecting interface pressure and resultant user discomfort.

As a result of both objective and subjective data collected in this experiment it was concluded that strap K, consisting of mesh 6 was the most effective in distributing load, resulting in the lowest interface pressures and the least perceived discomfort for the user. No significant difference was found between straps I and J. In attempting to generalise these findings to a military context, the specific load carried in this experiment must be considered. In most training and operatinal situations the load carried in the backpack would exceed 18.5 kg and could in many cases be in excess of 40 kg. The performance of the highly compressable mesh 6 under such loads, therefore, may be considerably different than that observed in these experimental conditions. This and other considerations for the application of the findings of thi study will be considered fully in Chapter 10.

9.5.2 Effect of Plastic Layer

In chapter 6 it was hypothesised that adding a layer of hard plastic into a backpack shoulder strap superficial to the interface material would improve the distribution of an applied load by increasing the contact with the body surface. In Chapter 7 this design feature was indeed found to have beneficial effects on pressure distribution and user discomfort when incorporated into a closed cell polyethylene foam strap. In Chapter 8 the same effect was found when plastic was added to a mesh material with a compressibility of 74%. The second aim of this experiment was to further investigate the effect of including such a material in the strap of a backpack to discover whether this is a beneficial design feature regardless of the interface material it is placed upon.

When straps K and L were directly compared, strap L, which was identical to K apart from the addition of the plastic layer, was found to utilise a significantly greater area of the shoulder sensor for load distribution. Although strap K itself resulted in a high amount of contact with an average of 92.1cm^2 this was further increased by an average of 7.50 cm^2 with an increase in contact of 14 cm^2 observed in one participant. This high contact between strap L and the shoulder resulted in significant reductions in the three measures of pressure distribution.

The proposed mechanism for this improvement is that the rigid plastic layer results in a more even spreading of the carried load onto the underlying interface material. Without the layer of plastic, load is concentrated along the centre of the strap where the load transfer strap is attached. This results in good contact between this area and the underlying body surface but fails to utilise the whole width of the strap for the most effective load distribution. In the case of strap L, the load strap transfers the carried load onto the layer of plastic, which pressed more evenly onto the underlying material, which in turn presses onto the shoulder area increasing the area of the shoulder with applied pressure.

This even pressing of the interface material onto the body surface will have a beneficial effect on irregular shaped surfaces such as the front of the shoulder where the clavicle protrudes. This area is likely to be affected the most by an improvement in contact between the strap and the body. If the strap fits more effectively to the area around the clavicle then less pressure would be exerted directly onto the protruding clavicle, as the surrounding area would also support the load. This appears to be the case in this experiment illustrated by the significant improvements in the discomfort ratings given by the participants for areas A and B (Fig 9.4). It is likely that the improvements in user discomfort at these areas are as a result of reduced pressure on the clavicle as it has been shown that bony areas have an increased sensitivity and risk of damage from applied pressure (Sangeorzan et al, 1989).

The subjective ratings given by the participants in this study support the conclusions drawn from the objective data with six out of the eight participants rated strap L as more comfortable. It can be concluded that placing a plastic layer on top of a mesh with 57% compressibility improves the distribution of an applied load resulting in lower interface pressures and reduced user discomfort.

9.6 Conclusions

Out of the three different mesh materials, mesh 6 (strap K) was the most effective in terms of load distribution resulting in the lowest interface pressure variables and the lowest discomfort ratings. There were no objective or subjective differences between straps I and J. Introducing a layer of plastic into strap L significantly reduced interface pressure and subjective discomfort by using a larger area of the shoulder for load distribution.

Prototype straps K and L were carried forward for the final prototype analysis as these were the straps that performed best overall. Material K was the most effective at distributing load and improving comfort for the user. This was further improved by the inclusion of an rigid layer of plastic (strap L).

Chapter 10 Experiment 4

10.1 Introduction and Aims

In experiments 1,2 and 3 the two most effective prototype straps in terms of both distribution of load and user comfort were recommended for further evaluation. Due to the lack of a gold standard method of on-body pressure measurement the Tekscan method is currently restricted to making comparative evaluations. As a result, it was not possible to compare the data gathered from the separate experiments as these were taken from completely different samples. In order to make confident recommendations about the relative benefits of each strap, therefore, it was necessary to directly compare the six best performing straps within the same experiment, using the same sample of participants. This experiment therefore compared straps A, D, E, H, K and L.

The major aim of this experiment was to substantiate the differences between the straps detected in the preceding experiments using a larger sample. This was to result in a final recommendation of the most suitable interface material (or combination of interface materials) for the interface of military backpacks. In addition, the experimental hypotheses in section 6.3 were further investigated to determine the generic effects of different interface materials and plastic on load distribution, interface pressure and user discomfort. Finally, this experiment provided more data on the association between contact area, interface pressure and user discomfort.

The implications of the experimental work and a discussion of the results within a military context are also presented in this chapter.

10.2 Hypotheses

1. Improving the contact between the shoulder area and the shoulder strap will improve pressure distribution, reduce the magnitude of pressure peaks and reduce user discomfort.

2. Introducing a layer of plastic superficial to the interface material of a backpack shoulder strap will increase the contact between the strap and the shoulder area, resulting in improved pressure distribution and comfort.

10.3 Participants

Eighteen participants (ten male, eight female) took part in this experiment, they had a mean ± SD age of 21.38 ± 2.91 years, height of 1.79 ± 0.09m and weight of 75.11 ± 8.51 kg. This sample was compared with that of an extensive anthropometric survey of the British Army (Gooderson, 1982). The mean age, weight and height of the sample were found to be within 1 standard deviation of the army population. Three participants did not complete the study as their pressure sensors were found to contain rogue cells (two after 3 trials, the other after 5 trials). These participants were informed that they were no required to complete the study and thanked for their participation. An additional three participants were recruited. Of these three participants, two completed all six measurement conditions. The sensor of the other participant was found to contain rogue cells after the first measurement session. Again this participant was thanked for their time and informed that they were no longer required for the rest of the study. Another participant was recruited who successfully completed all six measurement sessions.

10.4 Results – Experiment 4

Analysis of variance with repeated measures was used to determine statistical significance between the six conditions. Following the identification of a significant difference, post-hoc analysis was carried out using Tukey's Honestly Significant Difference test. Significant differences between the discomfort ratings given for each condition were detected using the non-parametric Friedman test for related samples. Statistical significance was accepted at the 0.05 level. Reported results are mean ± SD.

10.4.1 Effect of Interface Material

Table 10.1 presents a summary of the measured variables for prototype straps A, E and K and these are displayed graphically in figure 10.1. These three straps were made up of different interface materials without the addition of any plastic layers. Strap A consisted of a closed-cell polyethylene foam and is the strap of the packs currently issued by the British military. It can be seen from table 10.1 that this strap resulted in the highest values for each of the three pressure variables. Mean pressure was 31.8 kPa, decile range 40.2 kPa and the 90th percentile value 46.2 kPa. These values were all found to be significantly higher than the values for the other five prototype straps.

The surface area of the shoulder sensor registering applied pressure under strap A was 45.13 cm^2. This was significantly lower than for materials E and K, which were 64.4cm^2 and 88.6cm^2 respectively.

When straps E and K, which consisted of different interface materials without the addition of plastic, were compared, Strap K resulted in a significantly lower overall mean pressure of 21.2 kPa compared with 24.0 kPa for strap E. However, the values for the other two pressure indices were very similar. Mean decile range was 23.7 kPa and 25.8 kPa for straps E and K respectively and the mean 90th percentile values were 31.4 kPa and 31.5 kPa. No significant differences were detected between these variables. Strap K utilised a significantly larger amount of the shoulder sensor for load distribution, 88.6 cm^2 compared with 64.4 cm^2 underneath strap E.

Strap A elicited the highest discomfort ratings of these three straps with a mean rating of 3.25. Fifteen out of the eighteen participants rated strap A as the most uncomfortable out of all six different prototype straps. In accordance with the objective data, strap K resulted in slightly lower discomfort ratings, 2.83 compared with 2.9 for strap E. Although this difference was not sufficient to be deemed statistically significant, twelve out of the eighteen participants gave a lower mean rating for strap K compared with strap E. Figure 10.2 shows the discomfort ratings given for each strap split up into the four separate shoulder areas. The same pattern was followed for each area with strap A rated consistently more uncomfortable although the differences between this strap and straps E and K were larger at areas A and B (trapezius and deltoid). Strap K is rated on average slightly lower or the same as strap E for each shoulder area.

Table 10.1: Effect of Interface Material on Measured Variables (n=18)

	Strap A	Strap E	Strap K
Mean pressure (kPa)	31.8 ± 5.2 ↑	24.0 ± 3.7	21.2 ± 4.2 ↓
Decile Range (kPa)	40.2 ± 4.63 ↑	23.7 ± 3.9	25.8 ± 5.2
90th Percentile (kPa)	46.2 ± 5.01↑	31.4 ± 4.4	31.5 ± 4.5
Contact Area (cm^2)	45.13 ± 5.7↓	64.4 ± 5.5	88.6 ± 6.3 ↑
Discomfort rating	3.25 ± 0.34	2.9 ± 0.3	2.83 ± 0.46

↑ significantly **higher** than other two straps (p = <0.05)
↓ significantly **lower** than other two straps (p = <0.05)

Fig. 10.1 : Effect of Interface Material on Interface Pressure

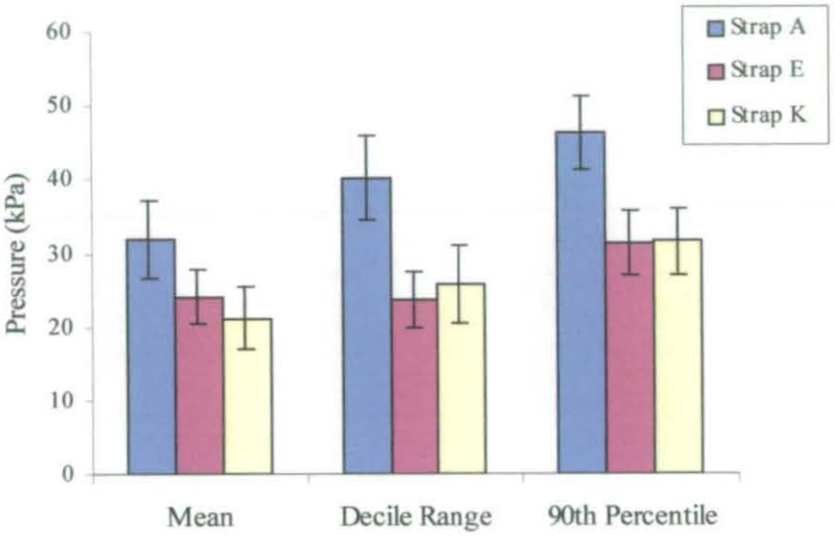
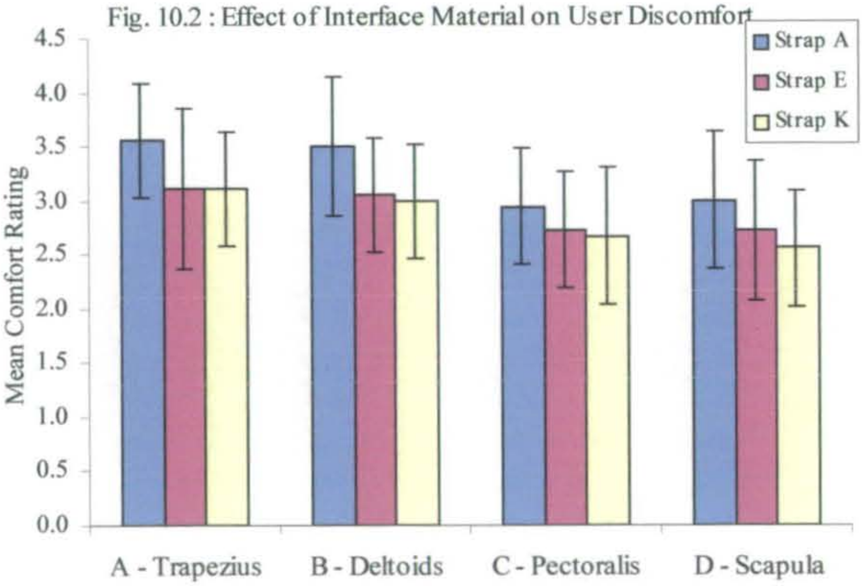


Fig. 10.2 : Effect of Interface Material on User Discomfort



10.4.2 Effect of Plastic

Tables 10.2 and 10.3 compare the measured variables from straps A and D and straps K and L where plastic has been added to the interface material. These are displayed graphically in figure 10.3.

When the differences between straps A and D are examined (table 10.2) it can be seen that strap D resulted in significantly lower values for all three pressure variables. Mean overall pressure of 25.8kPa compared with 31.8 kPa for strap A, decile range of 32.8 kPa compared with 40.2kPa. A decrease in these variables from condition A to D was observed in all of the eighteen participants with the mean reduction across all participants in mean pressure of 4.6 kPa and decile range of 7.3 kPa. A reduction in mean pressure of 12.7 kPa was observed in one participant and a reduction in decile range of 13.5 kPa was observed in a different participant. A reduction in the 90th percentile value was observed in all but one of the participants who showed an increase of 11 kPa.

These consistent reductions in pressure were mirrored by increases in the contact area of the sensor underneath strap D which were observed in sixteen out of the eighteen participants. A slight decrease in contact area (<2.5cm^2) was observed in the other two. These consistent improvements are reflected in the 95% confidence intervals which all indicate a substantial improvement as a result of adding plastic to interface material A.

Again, the subjective data supports the pressure data with strap D rated consistently more comfortable than A. The mean rating for strap D was 2.99 compared with 3.25 for strap A. Out of the eighteen participants, 12 rated strap D more comfortable. Large improvements in user comfort were observed at areas A and B (Figure 10.4). Mean user discomfort was reduced by 0.5 and 0.44 at these areas compared with a reduction of 0.17 at area C (front of the chest) and a slight increase (0.06) at area D (scapula).

Table 10.3 presents a summary of the measured variables for straps K and L, which both consisted of mesh 6 with a layer of plastic added in strap L. It can be seen that the plastic strap L results in significantly lower values for each of the three pressure variables (figure 10.5). Mean overall pressure across all eighteen participants was 15.7 kPa compared with 21.2 for strap K. Decile range was 17.1kPa compared with 25.8 kPa and the mean 90th percentile value was 24.9 kPa, significantly lower than 31.5 kPa underneath strap K.

This pattern of improvement in condition L was consistent for each of the measured variables. Seventeen out of the eighteen participants had an observed reduction in mean pressure with a very slight increase (0.1 kPa) occurring in the other participant. A reduction of more than 10 kPa was observed in two of the participants. All of the participants showed a reduction of at least 4kPa in decile range underneath strap L with a reduction of 13.5 kPa observed in one case. A very slight increase in 90th percentile value (1.5kPa) was observed for one of the participants with all other cases showing a marked reduction with the largest change being 12.7 kPa.

This pattern of improvement underneath strap L was followed by the contact area values. All eighteen participants showing an increase in the surface area of the shoulder sensor used for load distribution. An average increase of 8.1cm^2 was observed with increases of more than 15cm^2 observed in three cases.

Thirteen of the eighteen participants rated strap L on average more comfortable than strap K resulting in a mean rating of 2.25 compared with 2.83. Five participants rated strap L, the strap with added plastic, more comfortable by more than one point on the rating scale. It can be seem from figure 10.6 that improvements in user comfort occurred consistently across all four shoulder areas. Larger improvements were observed at areas A and B of 0.78 and 0.56 compared with 0.5 at areas C and D.

Table 10.2: Effect of Plastic Layer on Measured Variables (n=18)

	Strap A	Strap D	ΔS x (range)	95% C.I
Mean pressure (kPa)	31.8 ± 5.2	25.8 ± 3.1	4.65 (0.8 – 12.7) *	3.08 – 6.22
Decile Range (kPa)	40.2 ± 4.63	32.8 ± 3.5	7.37 (3 – 13.5) *	5.77 – 8.9
90th Percentile (kPa)	46.2 ± 5.01	38.9 ± 4.3	7.34 (-11 – 14.38) *	4.53 – 10.1
Contact Area (cm2)	45.1 ± 5.7	57.8 ± 6.0	6.70 (-2.2 – 14.01) *	4.26 – 9.12
Discomfort rating	3.25 ± 0.34	2.99 ± 0.3	0.26 (- 0.5 – 0.75)	

* difference significant at p = < 0.05 level

Table 10.3: Effect of Plastic Layer on Measured Variables (n=18)

	Strap K	Strap L	ΔS x (range)	95% C.I
Mean pressure (kPa)	21.2 ± 4.2	15.7 ± 4.1	5.4 (-0.15 – 11.2) *	4.07 – 6.8
Decile Range (kPa)	25.8 ± 5.2	17.1 ± 2.9	8.72 (4.0– 13.5) *	7.16 – 10.3
90th Percentile (kPa)	31.5 ± 4.5	24.9 ± 3.0	6.64 (-1.5 – 12.7) *	4.92 – 8.35
Contact Area (cm^2)	88.6 ± 6.3	96.7 ± 6.4	8.1 (0.37 – 25.2) *	4.76 – 11.57
Discomfort rating	2.83 ± 0.46	2.25 ± 0.34	0.58 (-0.5 – 1.25) *	

* difference significant at p = < 0.05 level

Fig. 10.3: Effect of Plastic on Interface Pressure

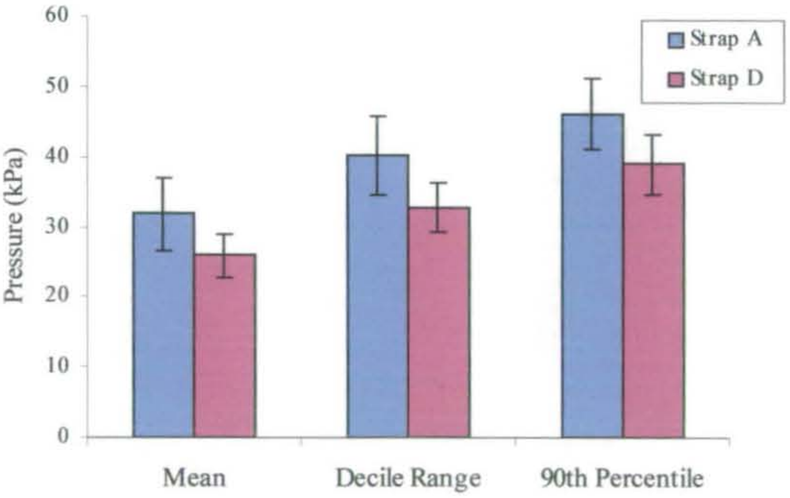


Fig. 10.4 : Effect of Plastic Layer on User Discomfort

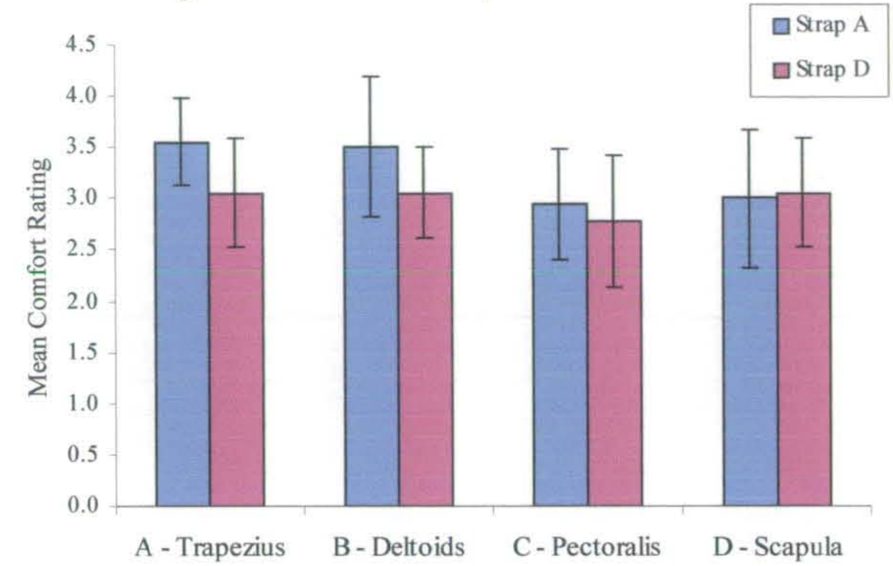


Fig. 10.5 : Effect of Plastic on Interface Pressure

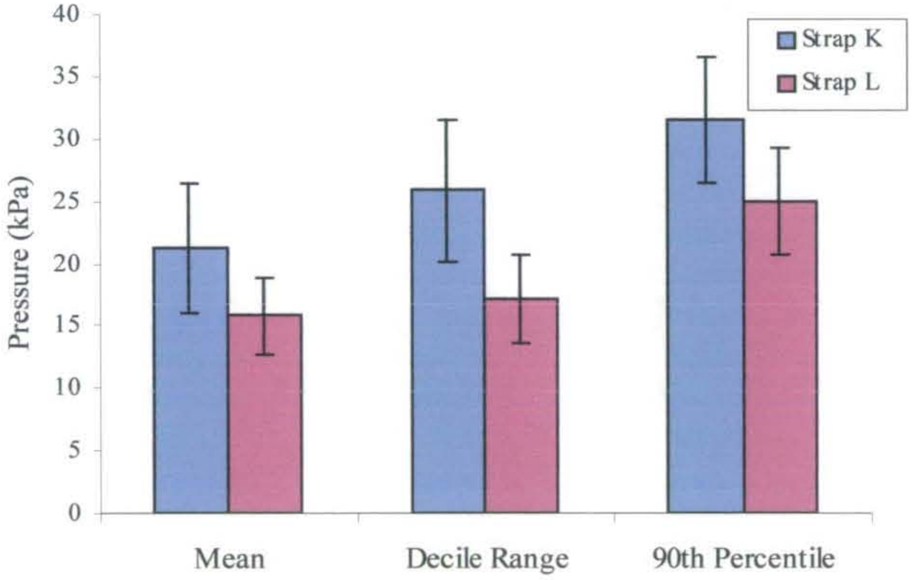
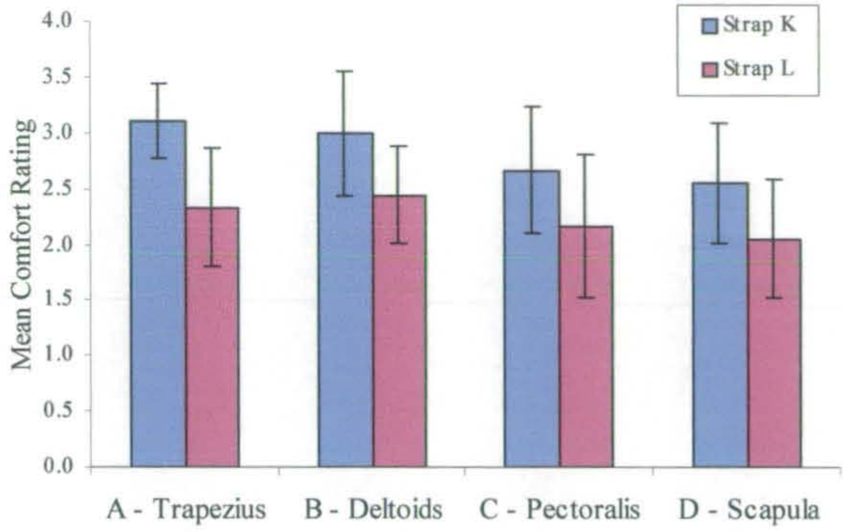


Fig. 10.6 : Effect of Plastic Layer on User Discomfort



10.4.3 Interface Pressure and Contact Area

Table 10.4 shows the correlation co-efficients between each of the pressure variables and the contact area of the sensor utilised by the straps. These ranged from -0.72 for mean overall pressure to -0.78 for the 90th percentile value, all statistically significant moderate to high negative correlations. These values, which are compiled from 18 participants over six conditions, are in the same range as those found in the previous three experiments. These confirm the experimental hypothesis in section 6.3 that increasing the contact between strap and shoulder will improve load distribution and reduce pressure peaks. In this experiment, as in the previous three, the straps that utilised the largest area of the shoulder sensor resulted in the lowest pressures and the most effective load distribution.

Table 10.4: Correlation Co-efficient between pressure variables and contact area (n=18)

	r	R^2
Mean Pressure	- 0.72	0.52
Decile Range	- 0.78	0.61
90th Percentile	- 0.74	0.54

10.4.4 Interface Pressure and User Discomfort

Table 10.5 shows the correlation co-efficients between each of the three pressure variables and the ratings of perceived discomfort given by the participants. These ranged from 0.55 for the 90th percentile value to 0.66 for mean overall pressure. All are moderate to high correlations that indicate that up to 43% of the variation within the ratings can be accounted for by variation in the measured pressure variables.

The agreement between objective and subjective data observed in this and the preceding three experiments demonstrates that users are sensitive to changes in design which improve pressure distribution and reduce the magnitude of pressure peaks. This also provides further support for the effectiveness and appropriateness of the methods of measurement and analysis used in this study. This relationship will be investigated further in Chapter 11 with a view to developing a predictive equation that can estimate user comfort from interface pressure.

The positive relationship between pressure and discomfort observed in this and the previous three experiments supports the theory stated in section 6.2.2 that a uniform distribution of pressure is the most appropriate at the shoulder interface. In each of the four experiments the strap that utilised the largest area of the shoulder and resulted in the most even pressure distribution was rated the most comfortable by the participants. This supports the experimental hypothesis stated in section 6.3 that due to the delicate anatomical design of the shoulder area an even distribution of force over as large an area as possible is the most preferable in terms of user comfort.

Table 10.5: Correlation Co-efficient between pressure variables and subjective discomfort ratings (n=18)

	r	R^2
Mean Pressure	0.66	0.43
Decile Range	0.57	0.32
90th Percentile	0.55	0.30

10.5 Discussion

10.5.1 Interface Material

This experiment aimed to evaluate the differing effects of the three best performing interface materials from experiments 1,2 and 3 (A, E and K). Strap A, the strap currently incorporated into the British Military backpack, resulted in the least effective pressure distribution. The reason behind this appeared to be the smaller area of the shoulder in contact with the strap compared with straps E and K. Material A, a closed-cell polyethylene foam, was the most rigid of the three materials with a compression of 79% underneath 200 kPa. It is important for an interface material to be conformable enough to mould to the shape of the body area underneath. It is probable that this foam was too rigid to fit the shape of the shoulder effectively, a theory that is supported by the low contact area of the shoulder sensor with registered pressure.

If a material is not conformable enough to mould to the shape of the protruding clavicle, for example, then this may result in a concentration of pressure on the bone rather than utilising the surrounding area. The significantly higher decile range values for strap A suggest that this strap did not distribute load as evenly as materials E and K and a likely reason for this is the increased rigidity of the interface material. Additional support for the improved pressure distribution underneath straps E and K is provided by the significantly lower 90th percentile values underneath these straps. These two materials reduced the magnitude of the pressure peaks on the shoulder sensor presumably by increasing the surface area used for load distribution and more evenly distributing the applied load.

Under strap A the discomfort ratings given for areas A and B were noticeably larger than those given for areas C and D. As the tops of the shoulders (areas A and B) are the areas which have to support the direct force of the carried load this is unsurprising. It has been suggested previously in this thesis that a conformable material will result in an improved fit between a strap and the body and this will have the greatest effect on complicated body areas such as the trapezius and deltoid areas of the shoulder. The smaller differences in user discomfort at areas C and D back this up. Both of these areas are smoother and more regularly shaped and therefore will not benefit greatly from a more conformable material. The large observed improvements in comfort underneath the more conformable straps E and K compared with strap A support this hypothesis. It can be concluded that areas A and B benefit the most from improved load distribution due to the combined effects of their shape and the high pressure that they are subject to. The improved comfort at these areas indicates that this improved fit and more even distribution of load results in a noticeable benefit for the user.

It was concluded that straps E and K resulted in more contact between the strap and the shoulder area, which reduced the magnitude of the pressures on the shoulder. These objective findings were supported by the improved user comfort under these new straps when compared with strap A, the strap currently used in the British military backpack. Strap K utilised a greater surface area of the shoulder for load distribution, which resulted in a small but significant reduction in mean shoulder pressure. However, the magnitude of the highest pressures and the spread of the pressure values were not reduced. In addition, no significant improvement in user comfort was observed and therefore it was concluded that there was no significant difference between straps E and K in terms of load distribution and user comfort.

10.5.2 Effect of Plastic

In Experiments 1, 2 and 3 the inclusion of a layer of plastic superficial to the interface material was shown to consistently improve load distribution by increasing the contact between the strap and the shoulder area. This has been further substantiated by the results of this experiment.

In Chapter 7 (experiment 1) including a layer of plastic on top of a closed-cell polyethylene foam, was found to increase the surface area of the shoulder in contact with the strap. This resulted in a significant reduction in all three pressure variables and an improvement in user comfort. This experiment, which repeated the comparison between straps A and D using a larger and completely different sample ratified these initial results.

This experiment also confirmed the results of experiment 3 (Chapter 9). Adding a layer of plastic to material K resulted in strap L significantly increasing the surface area used for load distribution and reduced the magnitude of the interface pressures at the shoulder.

Material K was a mesh material with a compression of 57% underneath 200 kPa. This material was more compressive than material A and when the results of experiment 2 are also taken into account, plastic has been shown to have a beneficial effect on materials of widely varying rigidity. A recommendation can therefore be made that adding a layer of hard plastic on top of an interface material has a beneficial effect on materials with a compressibility of between 57% and 79%.

In order to determine what type of material is most benefited from the addition of a plastic layer the magnitude of the improvements between conditions A and D and K and L were examined. In terms of contact area, adding plastic to material K resulted in an average increase in contact area of 8.17cm^2, compared with 6.7cm^2 for material A. As material K was a more compliant material this supports the mechanism of improvement suggested previously. Due to the plastic's rigid nature it will prevent the tension of the thin load transfer strap compressing only the centre of the interface material. This results in the plastic evenly pressing the underlying material onto the body surface where it can mould to the body shape.

It is reasonable to assume that a more compliant and less rigid material will be more effective at conforming to the complicated shape of the shoulder. The larger improvement in contact area when plastic is added to material K compared with A supports this. Although a more even load on top of a rigid material such as material A will improve the contact between the body and the strap, this will be limited by the degree to which the material will conform to the shape of the shoulder. If for example the material will not conform to the shape of the protruding clavicle then load will still be concentrated on the bone resulting in increased pressure and discomfort.

However, this larger increase in contact between the strap and the shoulder did not result in larger improvements in the three pressure variables. It was hypothesised that the greater improvement in fit would result in greater improvements in terms of pressure distribution and the magnitude of pressure peaks. The mean change between conditions A and D and K and L were analysed using paired t-tests, which did not detect any significant differences in the magnitude of change between the two materials in terms of pressure. This suggests that there may be a limit to the improvement in pressure distribution perhaps due to the nature of the body surface itself.

Although the magnitude of improvement from condition K to L was not significantly greater than from A to D, material K was already significantly more effective in terms of load distribution, interface pressure and user comfort. Adding the plastic layer has therefore increased the performance of both materials in a uniform manner with material K still the most effective of the two.

10.6 Implications

The results of this study have shown that altering the interface material of a shoulder strap and introducing an additional incompressible layer results in significant improvements. Mean overall pressure has been reduced, load has been distributed more evenly and the magnitude of the pressure peaks has been reduced. In Chapter 2 the empirical research on the effects of applied pressure on the body was discussed, this work concludes that a reduction in the magnitude of applied pressure on the skin can significantly reduce the risk of sustaining tissue damage and injury.

There is a generally accepted relationship between applied pressures and reduction in blood flow. Research has shown that the skin and underlying tissue can experience a 30% reduction in blood flow when subjected to an applied pressure of only 4 kPa (Holloway et al, 1975). The conclusion of the work carried out in this area is that low or moderate pressure applied over low or moderate time periods may result in short term damage that should be reversible for healthy tissue. Sustained high pressure however, may result in tissue breakdown. The pressures found underneath the shoulder straps evaluated in this experiment can be seen as moderate to high, the recommended maximum skin pressure during sustained load carriage equipment being 14 kPa (Stevenson et al, 1995).

When referring to suggested maximum pressures, however, the nature of load carriage should be taken into consideration. Such recommendations are usually based upon clinical recommendations for the prevention of bedsores and other chronic conditions. Load carriage is a dynamic activity; pressures at body interfaces including the shoulders are not sustained due to the movement of the body during normal walking gait.

It has been shown that if no other contributing factors are present then the skin may endure pressures of up to 120 kPa without sustaining damage, (Daniel et al. 1985). However, military load carriage will inevitably involve high risk factors. The threshold for injury is significantly lower at thin skin sites that cover bone (Sangeorzan et al, 1989) which is a significant factor considering the anatomical structure of the shoulder. Additionally, increases in temperature and moisture increase the susceptibility of the skin and underlying tissue to applied pressure. These factors, which place the skin and tissue at the shoulder area at even greater risk, mean that any reduction in applied pressure as a result of load carriage will have a significant effect on the likelihood of sustaining tissue damage.

A study by Kosiak (1961) showed that over a two-hour duration an applied pressure of 9 kPa reduced blood flow to the underlying tissue. However, when this was reduced to 5 kPa the blood flow returned to normal. This suggests that even small improvements in applied pressure may significantly reduce the chance of impaired blood flow. It can be concluded therefore that the improvements in shoulder pressure observed in this experiment may significantly reduce the likelihood of the muscles of the upper body experiencing reduced blood flow.

Reducing shoulder interface pressure may reduce the risk of a user developing both chronic and acute injury. Daniel et al (1985) showed that when high interface pressure is applied to the skin this can result in muscles being pressed onto underlying bones which can result in deep muscle damage. Due to the prominence of bones around the shoulder area this is a significant risk to the infantry soldier for whom heavy load carriage makes up a significant part of their everyday activities. This experimental work has shown that altering the interface material of a strap and adding an incompressible plastic layer increases the contact with the shoulder area. Increasing this contact means that the area surrounding the bones of the shoulder area is also used for load distribution, which reduces the pressure applied directly to the clavicle and the scapula. As a result, the muscles surrounding these bones should be less susceptible to this sort of damage due to the reduced interface pressure.

In addition to the risk of developing injury, when considering the types of activities that have to be performed by infantry soldiers both during and immediately following heavy load carriage, disturbances to the blood supply of muscles may have a serious detrimental effect on performance. Required tasks may include operating small pieces of equipment such as radios as well as firing weapons, all tasks that require a high degree of control of the upper limbs. Reduced blood flow to the muscles of the arms and shoulders may reduce the control and strength in the hands and the arms, which may seriously affect these types of activities.

Extreme examples of motor and sensor dysfunction as a result of load carriage have been observed in patients suffering from Brachial plexus syndrome. This disorder is caused by the shoulder straps of a backpack causing a traction injury of the nerve roots of the upper brachial plexus (at C5 and C6 level). As the symptoms of this condition include numbness, paralysis and loss of control of the upper limbs, reducing the incidence of this condition is clearly an important issue. This condition also has serious implications for the performance of the soldier. If a user suffers from reduced control of the muscles in the shoulder and arms, then tasks that require small movements of these muscles will be adversely affected. High shoulder pressure has been identified as a major risk factor in developing this condition (Bessen et al, 1987; Holewijn, 1990). Using materials that improve load distribution and reduce interface pressure will reduce the likelihood of users developing brachial plexus injuries. Although this condition is an extreme condition which is by no means wide spread among infantry soldiers, any functional impairment however small may have a serious effect on performance.

The magnitude of the improvements observed in these four experiments simply as the result of altering the interface material of the shoulder straps can be seen as a significant improvement. Stevenson et al (1995) recommends that pressure underneath load carriage equipment should not exceed 14 kPa for sustained pressure and should never exceed 18kPa. When bearing in mind these limits the reductions in interface pressure observed in this study can be seen as significant improvements.

When the main interface material is considered, the current interface material used within the straps of the British military backpack was material A. Out of the seven different materials tested in this study this was found to be the least effective in terms of load distribution and user comfort. Material K, a compliant mesh material, resulted in the lowest interface pressures and discomfort ratings due to the large amount of contact between strap and the shoulder. Mean overall pressure across all eighteen participants was reduced from 31.8 kPa underneath strap A to 21.2 kPa underneath strap K. Taking into consideration the recommendation of Stevenson et al (1995) reducing the overall mean pressure on the shoulder to 14kPa should be the aim this piece of work. Bearing in mind that caution should be taken when dealing with the absolute accuracy of the measured pressures values, it can be concluded that altering interface material has gone a significant distance toward accomplishing this by reducing mean pressurc by a third. Similar improvements were achieved in the decile range of the pressure values and the 90th percentile values.

Improvements of this magnitude may reduce the likelihood of shoulder injury and damage developing. Kosiak (1961) showed that reducing a sustained applied pressure of 9 kPa to 5 kPa returned impaired blood flow to normal. In the context of load carriage the reductions observed in this study can be seen as an improvement which may significantly reduce the likelihood of the user suffering from acute blood flow impairment and the decrement in performance which may result from this.

This study has shown the addition of a layer of plastic on top of the interface material further improves the distribution of load and reduces the magnitude of pressure peaks by increasing the contact between the shoulder and the strap. In the four individual experiments the effect of plastic on three different interface materials was investigated (A, G and K). When the data from these conditions was combined the average increase in contact between strap and shoulder was 10.89 cm^2. This results in a reduction in mean shoulder pressure of 4.8 kPa. As discussed earlier in this section a reduction of this magnitude may improve the blood flow to the muscles of the upper extremities. This design feature has also been shown to result in an improved distribution of the pressure values with a mean improvement in decile range of 6.6 kPa. The 90th percentile value was also reduced by an average of 6.8 kPa showing the magnitude of the highest pressures are also reduced by the addition of a plastic layer.

These changes were consistent across all three materials that were investigated. Therefore, these are further improvements that occur in addition to those as a result of changing the main interface material itself. These additional improvements will further reduce the likelihood of the user sustaining the acute and chronic conditions that have been discussed above.

In addition to the observed improvements in objective measurements such as pressure the reductions in the subjective reports of the participants regarding their perceived comfort provide further evidence for the benefits of altering the composition of backpack shoulder straps. Allowing for some inevitable inconsistency of the collected ratings, the perceived comfort of the participants followed the same pattern as the pressure data. When change in interface material is considered, the differences in shoulder pressure between materials A and K were supported by sixteen out of the eighteen participants who rated strap K on average more comfortable resulting in a mean rating of 2.83 compared with 3.25 for strap A. This good level of association between the pressure variables and the discomfort ratings resulted in the most effective strap in terms of pressure distribution, strap L, also resulting in consistently lower discomfort ratings. Fifteen out of the eighteen participants rated this strap the most comfortable of all six prototype straps.

This provides evidence for the experimental hypothesis that distributing carried load as evenly as possible over the largest surface area and reducing high pressures is the preferred method in terms of user comfort. This is due to the nature of military load carriage which means that there is no part of the load bearing area, the tops of the shoulders, which is suited to heavy load carriage.

The reduction in user discomfort between straps A and L means that in addition to the objective benefits resulting from reductions in shoulder pressure there are also benefits in terms of improved feelings of well-being. Feelings of comfort and well being can play a significant role in the motivation of a soldier especially in difficult or demanding circumstances. Although these effects are difficult to quantify it is indisputable that improvements in the psychological state of the soldier can only benefit performance of the individual as well as that of a whole military unit.

To conclude, the experimental work of this study began with the evaluation of the shoulder strap currently in use by the British military in order to provide a baseline to gauge any improvement against. The results of this final prototype analysis has shown that significant improvements in load distribution and user comfort can be achieved as a result of using a different interface material (K) and adding a layer of plastic on top of this material (Figure 10.7). The combined effect of these two factors resulted in an improvement of between 47% and 57% for each of the pressure variables and a reduction of 1 point on the five point discomfort scale.

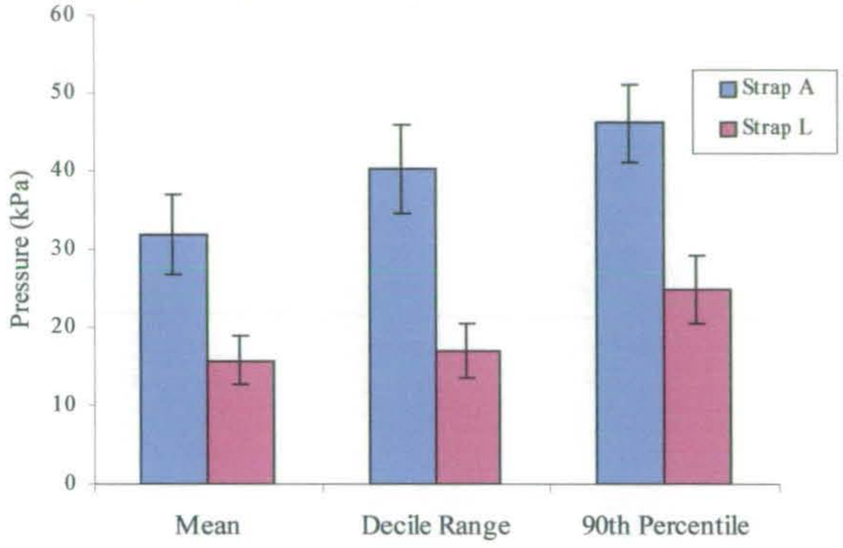


Fig 10.7 : Improvement in pressure from Standard Strap

The question must be asked here of how far these findings can be generalised to the specific military populations. The conditions in this study have been very well controlled, a necessary requirement for a scientific evaluation such as this. Before strap L, or indeed any of the prototypes can be recommended for inclusions into military load carriage equipment it is necessary to review the findings within the military context.

A load of 18.5 kg was used in this study. Although backpack loads in training and operational situations will normally exceed this; this load was chosen in order to allow a wider range of participants to be included in the sample. It was felt that this was a heavy load for civilian participants to carry for an hour on up to six occasions. A very heavy load, although closer to the real loads carried in military situations, may have masked potential differences in design. It is possible that the materials under investigation in this study may behave differently under heavier, or indeed lighter, loads. It is essential, therefore, that before recommendation as a suitable interface, any material is tested under a wide range of loads.
The military backpack was the focus of this experimental work, however, it should be remembered that this is worn in addition to waist-worn webbing. The pouches of this webbing function to support the load of the backpack to some degree and, therefore, a shoulder load of 18.5 kg may not be unrealistic. A load

carriage system that utilises the hips as a site for load bearing must remain the ultimate aim for the designer of military equipment and this should take into account the many combinations of equipment carried by military personnel. However, this would mean getting rid of, or at least a radical re-design of the waist worn webbing to free the hip area and to use this area to transfer load away from the delicate shoulders. This would be very unpopular with large sections of the military. Until this suggestion is accepted by the military, this study has shown that the current equipment can be significantly improved by the use of novel interface materials and small design changes.

Other considerations to bear mind are the long-term properties of these materials, which could not be investigated in this study. All of the prototype straps were brand new at the start of this study and use was confined to the laboratory, not typical military environments. The effects of normal wear and tear and handling by military personnel on the durability of these materials is a relevant issue. Additionally, any material chosen for the interface of military equipment has to be able to withstand varying environmental conditions including extreme hot and cold, damp and NBC conditions. Although these issues are outside of the scope of this study they are considerations for the wider application of the results.

In order to achieve reliable results and to control for possible confounding factors, the participants were not allowed to adjust the fit of the backpack once they had started walking. In real-life situations, military personnel would tighten and loosen the fit of the pack throughout a march, to rest fatigued muscles, to improve comfort or to increase stability when traversing uneven terrain. It was not possible to measure the effects of this within the controlled experimental conditions of this study and this highlights the need for in-field measurements.

This study has concentrated solely on the interface of the military backpack. It must be pointed out here that there are other items of equipment that may be worn in addition to this including webbing and body armour. Investigation of the effects of a combination of these items on body pressures is necessary. The materials identified as beneficial in this study may also be suitable for inclusions in the interface of other equipment carried on the body.

The development of an appropriate method of on-body pressure measurement, which was achieved in part I of this thesis, has enabled load carriage research to move in a completely new direction. As a result, the findings of the second experimental section can be seen as a very initial investigation within this new area of load carriage research. Although a significant improvement in load distribution and interface pressure has been observed within the controlled experimental conditions, much further work is needed to validate this.

Chapter 11 Interface Pressure and Discomfort

11.1 Introduction and Aims

Ratings of user discomfort were collected during this study for a number of purposes. Firstly, to validate the new method of interface pressure measurement that was developed in Part I of this thesis. The ratings of discomfort given by the participants provided extra data that completed the picture given by the objective data. In each of the four experiments the prototype strap that resulted in the lowest pressure variables was also the strap rated most comfortable by the participants. Moderate to high positive correlations were detected between the subjective ratings and each of the pressure variables indicating that as the values of these increased so did the discomfort of the participants. This agreement supported the experimental hypothesis that an even distribution of load is the preferred method over the shoulder area. This also confirms the effectiveness of the developed methodology in detecting differences between designs of load carriage equipment that have a real effect on the user in terms of comfort, performance and risk of developing injury.

The ultimate aim of a subjective scale, however, is to establish a strong enough relationship with objective physiological data in order to make a confident prediction of one from the other. This has been attempted with scales such as Ratings of Perceived Exertion (Borg 1970), where relationships with physiological variables have been attempted. In this chapter the data from the experimental work of this study is examined to determine whether a relationship exists that could allow the prediction of user discomfort from pressure variables.

The first part of this thesis describes a new experimental tool designed to shorten the evaluation process used by the British military for the evaluation of load carriage equipment. Currently, this does not employ any quantitative processes; designs are evaluated by means of troop trials and individual consultations with military personnel. As a result, equipment design evolves by way of small changes, which is both a costly and time-consuming process. This project has developed a scientific tool that measures interface pressure underneath load carriage equipment, an important factor when considering the effects on user health and comfort. This tool allows pressure comparisons to be made between different designs of load carriage equipment. This is demonstrated by the practical work in this study, where twelve possible shoulder straps were compared in terms of interface pressure and comfort. Out of these, one material (mesh 6) performed consistently better in terms of pressure and discomfort. Other designs that may have had possible benefits that were found not to result in any improvement when compared with the baseline strap A and were disregarded. By using this method, a large number of designs can be quickly evaluated. Those that result in no benefit or indeed increase pressure or discomfort can be quickly rejected.

This evaluative methodology, however, is still a relatively time-consuming process due to the need for a sample of human participants. Although conclusions can be drawn from the pressure data alone, the discomfort data does complete the picture. If user discomfort could be accurately predicted from interface pressure then this would result in a much simpler, shorter evaluation process. In addition, if a method could be devised for measuring interface pressure underneath load carriage equipment without the use of human participants the process would be shortened still further. There will always be the need to conduct a thorough user trial on any piece of equipment before it could be accepted for use, however, a method such as this would ensure that only the most effective designs would make it through to this expensive stage. The less effective designs could be detected and rejected much earlier in the process, saving the expense of trialing these.

11.2 Factors influencing Discomfort

Shoulder interface pressure has been shown to correlate with discomfort ratings on the 5 point scale used in this study. Correlations between 0.53 and 0.69 were observed in the four individual experiments, all moderate to high positive correlations. It is obvious, however, that pressure is not the only factor that affects the discomfort ratings given by the participants. Possible effects can be categorised into two main types: those that may be accounted for by quantifiable factors and those that are not measurable.

Some factors are easily accounted for including variables such as age, sex, height and weight. The discomfort ratings given by a user are dependent upon his or her perceived sensations; i.e. how uncomfortable they feel at the shoulders. This will be dependent upon a number of factors. The size of the participant will affect the discomfort ratings, especially in an experimental design such as this where the load carried during the experimental work was the same for each participant (18.5kg). For each participant the load represented a different proportion of his or her body weight. The larger participants will tend to be stronger and therefore carrying the load will result in a lower general strain and this is likely to be reflected in the discomfort ratings. Also related to this is the issue of gender, as males are on average both larger and stronger than females. This is a factor that should be taken into account in any regression equation.

Factors that are more difficult to quantify may include differing perceptions of pain and discomfort that cannot be attributed to differences in age, sex or size. These will introduce an inevitable error factor into any predictive equation. Two individuals who may be matched for the types of factors mentioned above are extremely unlikely to rate a particular sensation in the same way due to past experiences and other unquantifiable differences that will alter their perception of discomfort. In addition, when using a scale such as the one in this study where anchors such as 'slightly uncomfortable' and 'uncomfortable' are used, variation in the perceptions of these phrases are introduced adding further possibility of error.

11.3 Multiple Regression Analysis – Individual Experiments

The first step in attempting to identify the variables that may allow the prediction of user discomfort is to examine the data from each of the four individual experiments. Standard regression diagnostics were applied to identify any outlying points that may have affected the regression model (normal distribution plots, standardised residual plots, leverage and Cook's distance). The samples used in the experimental work can be considered small for regression analysis, however, this was intended only to give an initial impression of the factors that affect user discomfort with a view to directing further attempts at prediction.

In each case the dependant variable was the mean discomfort ratings given by the participants after one hour of load carriage. The first independent variable to be added to the equation was the variable (mean overall pressure, decile range, 90th percentile value, contact area, participant age, weight and height) which explained the greatest amount of variation (R^2 adjusted) in the discomfort ratings. Other independent variables that contributed further to the explanation of discomfort were included provided that they did not seriously reduce the significance of the model ($P < 0.05$). The risk of multicollinearity affecting the regression model was identified and a Variation Inflation Factor (VIF) of 3 was taken to be the upper limit acceptable for inclusion of independent variables into the equations.

Data from the male and female participants was treated separately.

11.3.1 Experiment 1

Table 11.1 presents the best-fit regression model for the data from all four conditions for the 5 male participants. Only one independent variable met the criteria for inclusion in the model. Contact area accounted for 40.4% of the variance in the discomfort ratings.

Table 11.1 : Regression model for prediction of Discomfort (males n = 5, k = 4)

Variable	R^2(adjusted)	Regression Co-efficient (B)	Standard Error of B	Intercept	F
Contact Area	0.404	- 0.0404	0.011	4.363	13.897

Contact area was also the independent variable that was entered to the best-fit model for the female participants accounting for 67.1% of the variation within the discomfort ratings (Table 11.2). Although the small sample size resulted in only 12 individual data points for each variable this statistic was performed to provide information in order to drawn general conclusions regarding the factors that affect subjective discomfort.

Table 11.2 : Regression model for prediction of Discomfort (females n =3, k = 4)

Variable	R^2(adjusted)	Regression co-efficient (B)	Standard Error of B	Intercept	F
Contact Area	0.671	- 0.054	0.11	4.81	23.409

11.3.2 Experiment 2

Three independent variables met the requirements for inclusion into the best-fit regression for the male participants, decile range, participant height and age (Table 11.3). These combined to account for 82.5% of the variance within the discomfort ratings. The decile range of the pressure values made the greatest contribution to the R^2 value illustrated by the larger standardised co-efficient of 0.635 compared with the other two variables.

Table 11.3 : Regression model for prediction of Discomfort (males n = 4, k = 4)

Variable	R^2 (adj.)	Regression co-efficient (B)	Standard Error of B	Standardised co-efficient	VIF	Intercept	F
Decile Range	0.666	0.056	0.011	0.635	1.261		30.93
Height	0.764	- 2.206	0.793	- 0.351	1.067		25.85
Age	0.825	- 0.113	0.048	- 0.276	1.188	7.220	24.50

The 90th percentile pressures values explained 48.7% of the variance of the discomfort ratings given by the female participants (Table 11.4). No other independent variable met the criteria for inclusion in the best-fit model.

Table 11.4 : Regression model for prediction of Discomfort (females n = 4, k = 4)

Variable	R^2(adjusted)	Regression co-efficient (B)	Standard Error of B	VIF	Intercept	F
90th Percentile	0.487	0.05514	0.014	1.00	0.476	15.225

11.3.3 Experiment 3

Sensor contact area, participant age and weight were the independent variables that satisfied the criteria for inclusion into the regression model for the male participants (Table 11.5). This model accounted for 63.5% of the discomfort ratings variation. Contact area made the greatest contribution to the variation with a standardised co-efficient of -0.796 compared with 0.426 and -0.362 for age and weight respectively.

Table 11.5 : Regression model for prediction of Discomfort (males n = 4, k = 4)

Variable	R2 (adj.)	Regression co-efficient (B)	Standard Error of B	Standardised co-efficient	VIF	Intercept	F
Contact Area	0.360	- 0.0262	0.005	- 0.796	1.113		9.43
Age	0.526	0.06137	0.023	0.425	1.107		9.33
Weight	0.635	- 0.0304	0.14	- 0.362	1.101	5.790	9.70

When the data from the female participants was analysed the regression model was found to account for 80% of the discomfort variation (Table 11.6). Like the equation for the male participants participant weight and age were found to meet the criteria for inclusion and the standardised co-efficients for these variables were similar (0.366 and 0.343). The largest contribution however was made by the 90th percentile pressure value with a standardised co-efficient of 0.561.

Table 11.6 : Regression model for prediction of Discomfort (females n = 4, k = 4)

Variable	R^2 (adj.)	Regression co-efficient (B)	Standard Error of B	Standardised co-efficient	VIF	Intercept	F
90th Percentile	0.461	0.0569	0.12	0.561	1.088		13.84
Weight	0.706	0.08619	0.32	0.366	1.339		19.01
Age	0.80	0.09083	0.34	0.343	1.248	-6.829	20.96

11.3.4 Experiment 4

Table 11.7 presents the best-fit regression model for the 10 male participants for each of the 6 conditions. The two independent variables that met the requirements of the statistical procedure were mean pressure and the 90th percentile pressure values (an acceptable level of multicollinearity was observed by a VIF of 1.930). Combined, these accounted for 41% of the variation within the discomfort ratings, with mean pressure contributing to more of the variance illustrated by the higher standardised co-efficient.

Table 11.7 : Regression model for prediction of Discomfort (males n = 10, k = 6)

Variable	R^2 (adj.)	Regression co-efficient (B)	Standard Error of B	Standardised co-efficient	VIF	Intercept	F
Mean pressure	0.374	0.02831	0.009	0.415	1.930		35.95
90th Percentile	0.410	0.0163	0.008	0.295	1.930	1.641	26.11

For the female participant's data (n=8) for the same six conditions mean pressure was again the independent variable which accounted for the most variation within the discomfort ratings. Participant weight also contributed to the best-fit model resulting in the whole model accounting for 56.6% of discomfort variation.

Table 11.8 : Regression model for prediction of Discomfort (females n = 8, k = 6)

Variable	R^2 (adj.)	Regression co-efficient (B)	Standard Error of B	Standardised co-efficient	VIF	Intercept	F
Mean pressure	0.515	0.0656	0.009	0.716	1.001		50.96
Weight	0.566	0.0285	0.009	0.242	1.001	- 0.346	31.60

11.3.5 Combined Data

The data from all four individual experiments was combined and again the male and female data was tested separately to achieve normally distributed data. This resulted in a total of 23 male participants and 19 female participants completed either four or six separate conditions resulting in 112 and 92 data sets for the male and female participants respectively.

Table 11.9 presents the best-fit model for the male data. In accordance with the previous equations it is a measure of pressure, mean overall pressure, that accounts for the largest amount of variation in the discomfort ratings and this is the only independent variable that meets the criteria for inclusion in the model.

When the female data is combined, the 90th percentile value is the variable that accounts for the largest part of the discomfort ratings the same variable as the equations for the data from experiments 2 and 3. Weight also makes a significant contribution to the variance of the discomfort ratings.

The R^2 values from these two equations are much lower than those described previously. In the male equation only 21.6% of the discomfort variance is explained and 28.9% in the case of the female equation.

Table 11.9 : Regression model for prediction of Discomfort (males n = 112)

Variable	R^2 (adj.)	Regression co-efficient (B)	Standard Error of B	Standardised co-efficient	VIF	Intercept	F
Mean pressure	0.216	0.0416	0.006	0.472	1.00	1.742	31.57

Table 11.10 : Regression model for prediction of Discomfort (females n =92)

Variable	R^2 (adj.)	Regression co-efficient (B)	Standard Error of B	Standardised co-efficient	VIF	Intercept	F
90th Percentile	0.225	0.030	0.005	0.501	1.01		26.11
Weight	0.289	0.0368	0.012	0.255	1.01	- 0.643	18.11

11.4 Summary

It can be seen from the above equations that when all the possible pressure variables (or contact area) were entered into the stepwise function one of these variables was found to be the most important in explaining discomfort. In all but one of the equations only one of these variables fulfils the criteria for entry into the best-fit model. This is the result of the high level of association between the variables meaning that a significant increase in R^2 would not be achieved by the addition of other pressure variables. The only time two of these variables were included was in the equation for the males in experiment 4 where both mean pressure and 90th percentile pressures values met the requirements for inclusion. The slightly lower correlation co-efficient between these variables in this case ($r = 0.65$) than for the other conditions meant that they added further to the explanation of variance without a significant decrement in the F value of the model. This slightly lower correlation also ensured that the multicollinearity level was not exceeded.

With further investigation on a larger sample, the most consistently important of these variables could be identified leading to the exclusion of the others. For example when the female participants are considered, in three of the five equations the 90th percentile value was found to be the pressure variable that was the most important in predicting discomfort. In addition, when the equation from experiment 4 is examined, using this variable instead of mean pressure which is chosen by the stepwise function reduces the R^2 value only slightly (53.8% compared with 56.6%) with no significant decrement in the F value.

It would appear that females shoulder comfort is most affected by the highest pressures underneath the shoulder straps of backpacking rucksacks. This is an important conclusion that has implications for the design process. Designs that reduce the magnitude and number of pressure peaks at the shoulder may result in significant improvements in female user comfort. This may also have important implications for the design of further evaluation trials. If the highest pressures are the most important in determining discomfort then this issue could be concentrated on. This would considerably shorten and simplify the evaluation process.

In three of the five equations for the female participants, including the combined data participant weight was shown to contribute to explanation of discomfort, however, in each case this did not follow the predicted pattern. It was hypothesised in section 11.2 that as the same load was carried by each participant the heavier participants would give lower discomfort ratings due to increased strength. In the one male equation which included weight as a variable the hypothesised pattern was observed, the heavier male participants giving lower discomfort ratings, however, this was the opposite for the female participants. There may be a number of possible reasons for this observed pattern including general differences in body composition between males and females at the shoulder area.

It is also possible that this finding was to a certain extent the result of a self-selected sample. This study was relatively demanding, particularly for the smaller participants, requiring the carriage of heavy loads for an hour on six separate occasions. As a result of this, it is conceivable that the smaller participants were stronger, more active and fitter simply because females of around 60-65 kg who were not very physically active were unlikely to volunteer for such a study. The experimental conditions in this study, which required the carriage of a heavy load whilst walking for an hour would have imposed a substantial cardiovascular strain. The less aerobically fit participants would have become more fatigued and this may have made them more aware and sensitive to discomfort under the shoulders straps of the backpack.

Analysis of the data from the male participants did not identify one single pressure variable that was highlighted in the majority of the models. However, in each equation, one of either of the three pressure variables or contact area was the independent variable that explained the greatest amount of user discomfort. This was a consistent finding across all ten models and provides further support for the use of interface pressure in the evaluation of different designs of load carriage equipment.

Other than the influence of interface pressure no participant variable consistently contributed to the explanation of discomfort variance. In two of the five models participant age met the requirements for inclusion in the regression equation. In experiment 2 an increase in age was shown to result in a reduction in shoulder discomfort, however, in experiment 3 the opposite pattern was identified with an increase in age resulting in an increase in discomfort. Due to the small sample sizes contradictions such as these are unsurprising.

This initial investigation into the association between discomfort and pressure and the other variables which affects this relationship could be further developed by a much larger scale study. Other variables to investigate could include fitness and anthropometric measures of body composition. By using a larger sample participants could be matched for variables such as these and a more confident prediction could be made.

The significantly lower R^2 values for the combined data compared with the individual experiments, however, indicate problems with attempting to produce prediction equations from this type of data.

The large part that psychological and other unquantifiable factors play in such an undefinable sensation as 'discomfort' will result in a high amount of error in any prediction equation. Although participants can be matched on all sorts of factors: age, sex, height, body composition, fitness, this cannot be done for all of the variables that affect discomfort such as personal experience and differentials in terms of pain threshold.

In a comparative situation such as this where each participant evaluated up to six different prototype straps it is likely that a degree of comparison went on in the mind of the participant. For example if the participant thought that a particular strap was the most uncomfortable out of all they had experienced then this would be reflected in the given ratings which would probably be the extreme of the scale. Conversely, if a participant perceives a particular prototype as being the most comfortable then this will be rated towards the comfortable end of the scale. In the case of strap A, for example, in experiment 1 when this prototype was the second most effective strap in terms of load distribution the mean rating given was 2.63. However, in experiment 4 when strap A was observed to be significantly less effective in relation to the other straps under investigation the mean rating was 3.25.

When the ratings for the straps from the final prototype study (experiment 4) are compared with those given for the first three experiments for the same straps this phenomenon can be clearly seen (Table 11.11). With the exception of strap L each strap was rated more comfortable in the initial experiment where it was one of the most effective straps. In the case of strap D for example, in experiment 1 when this strap was the most effective in terms of pressure and comfort the mean rating was 2.17. In experiment 4 when this strap performed less well when compared with the other five straps the rating was 2.99. It appears that the participants rank the packs in their mind and this is reflected in their ratings.

This is a consistent finding across straps A, D, E, H and K. The case of strap L also confirms this theory. The ratings for this strap are very similar (2.28 and 2.25 for experiments 3 and 4 respectively). In both cases this prototype strap resulted in the lowest interface pressures and therefore in each case was the most preferable strap in terms of user discomfort and the ratings reflect this.

Table 11.11: Comparison of Discomfort Ratings

Prototype	1st Rating (experiment 1/2/3)	2nd Rating (experiment 4)	Difference (2-1)
A	2.52 ± 0.4	3.25 ± 0.34	0.73
D	2.17 ± 0.5	2.99 ± 0.3	0.82
E	2.29 ± 0.58	2.9 ± 0.3	0.61
H	2.19 ± 0.4	2.51 ± 0.33	0.32
K	2.59 ± 0.58	2.83 ± 0.36	0.24
L	2.28 ± 0.45	2.25 ± 0.34	-0.03

As a result of this, it can be concluded that experimental conditions such as this where the participants gave rating for more than one prototype results in data which cannot be used to produce reliable predictive equations. The comparisons that appear to be made by the participants are dependent upon the relative benefits of one design over another. Independent data where each participant completes only one experimental condition would appear to be the best data to allow predictive relationships to be developed.

However, the factors that make comparative data unsuitable for predictions are what gives the ratings strength when used as part of the evaluative methodology developed in part I of this thesis. The repeated measures design and statistical methods used in this case means that the comparisons made by the participants are likely to be the cause of the quality of the discomfort ratings in terms of the agreement between the ratings given between the different participants. If the comparative nature of the developed methodology was taken away it would be very difficult to draw conclusions regarding the benefits of one design over another. Although it is possible to match participants for variables such as sex, height, weight and body composition other variables that affect perceived discomfort such as past experiences and perception of pain and discomfort are much more difficult to quantify.

It can be argued that ratings of this kind can never be truly uncomparative. Even civilian participants will have some sort of experience of load carriage with which to compare the stimulus under investigation be it recreational hiking or even the carriage of small schoolbag style daypacks. Reported discomfort will to some extent be influenced by these past experiences and these will be different for each participant resulting in error when relating discomfort to objective measurement such as pressure.

A possible solution to this problem may be to 'train' the participants to use the rating scale by exposing them to all of the sensations included in the scale within the particular context of the study. This approach is used by the ratings of perceived exertion (RPE) developed by Borg (1970) and used extensively within physiological research. Previous experience of the RPE scale is a pre-requisite for all participants. The theory is that if an individual has not experienced a true maximal effort ($F_c \cong 200$bpm) then they cannot judge how a heart rate of 160 bpm feels in relation to it. In the same way, participants who experience the full range of sensations as a result of sustained load carriage will be able to judge what is truly 'unbearably uncomfortable' in order what is comparatively 'slightly uncomfortable' within the context of load carriage.

It may be argued that using military personnel would eliminate this problem, as all individuals should have similar experiences, i.e. long, heavy load carriage using the same equipment. However, there are still potential problems with using military personnel to evaluate load carriage equipment. Experienced soldiers will be used to the configuration and design of the in-service equipment, which may result in preference for, or bias against, the current designs.

Unquantifiable differences between individuals, such as differences in the perceptions of discomfort, are inevitable and will also exist within a military sample. Undetected damage to deep body tissues as a result of heavy load carriage may exist in some soldiers which may also affect perception of pain and discomfort.

The correlations co-efficients ranging from 0.53 to 0.66 observed between the ratings of discomfort and the pressure variables indicate that one of the major contributing factors to the comparisons made by the users in this study was pressure. The sensitivity to differences in pressure distribution displayed by the participants provides further support for the measurement of pressure in an evaluation of this kind.

The conclusion of this work is that a lot of importance is placed upon relating data such as discomfort ratings with quantifiable objective data and that this has consistently been shown to be problematic and unattainable. Within the experimental conditions of this study, human participants who are inexperienced in the use of any of the designs have been shown to be reliable in making judgements and comparisons concerning the benefits of one design over another. It can be concluded therefore that the rating scale developed here is a crucial part of the evaluation method and provides both support for the objective measures and in some cases extra information which cannot be accounted for by variation in the objective data.

It is suggested that the emphasis should change to using subjective measures alongside objective measures and accepting that the variation within such ratings can never been completely accounted for by objective data. However, in any ergonomic evaluation equal importance should always be placed upon such ratings and this is especially valid in situations such as military load carriage where psychological factors play a crucial part in both the health and performance of the worker.

Chapter 12 Conclusions and Recommendations

12.1 Introduction

This chapter presents the final conclusions from the main areas of the thesis: the development of the pressure methodology, the experimental work and the investigation into the relationship between interface pressure and discomfort.

12.2 Pressure Measurement Method

The aim of Part I of this thesis was to develop a suitable method for the measurement of interface pressures underneath military load carriage equipment. In chapter 2, pressure was identified as an area largely ignored within the field of load carriage research due mainly to the lack of appropriate technology, which could be adapted for use under load carriage equipment.

Recent developments in pressure measurement technologies have led to more suitable and affordable systems. The Tekscan system was chosen for use in this study as the most appropriate, due to the nature of the sensor elements: small sensors mounted on extremely thin plastic.

In chapters 3, 4 and 5 the Tekscan system was developed for the measurement of shoulder pressures underneath load carriage equipment, and the reliability and accuracy of the system thoroughly evaluated. The system was found to be a reliable and valid experimental tool allowing confident comparisons to be made between pack designs. As human participants were used in the developed method subjective rating of user discomfort could also be collected. This combination of objective and subjective data results in a completely novel method allowing comparisons, which before had not been possible.

During the exploratory study described in Chapter 5, the measurement method was shown to be sensitive to differences in design of load carriage equipment in terms of overall pressure distribution and the magnitude and number of pressure peaks. These objective differences were supported by the ratings of discomfort collected from the participants supporting the validity of the methodology. This agreement between pressure and user discomfort, which was continued in all four individual experiments, illustrates the importance of including pressure analysis in the evaluation of load carriage equipment. Additionally, this association indicates that interface pressure plays a significant role in the perceived discomfort of the user.

The positive relationship between shoulder pressure and user discomfort observed in all four experiments supported the theory put forward in Chapter 6 regarding the optimum method of distributing load over body surfaces. Previous work has shown that at some body surfaces a concentration of force at the strongest point maximises user comfort. This study hypothesised that, due to the delicate structure of the shoulder and the nature of military load carriage, a uniform distribution of pressure would be appropriate under backpack shoulder straps. This hypothesis was supported by the fact that in all four experiments the strap rated by the participants as the most comfortable was the strap that resulted in the most even pressure distribution. From this finding a design recommendation can be made that a uniform distribution of shoulder pressure should be the aim of any new design of shoulder strap.

Currently, the pressure measurement method developed in this study is restricted to use in comparative settings. The lack of a gold standard method of on body pressure measurement means that the absolute accuracy of the measurements cannot be ascertained. In addition, the Tekscan method is not able to measure shear force. These two factors combine to prevent complete confidence when drawing conclusions about the observed pressures and their relation to the recommended maximum interface pressures underneath load carriage equipment. The high level of reliability of the pressure measurements, however, ensured that by using a comparative experimental design confident conclusions could be drawn regarding the relative benefits of one design over another.

The fact that shear forces could not be measured using the Tekscan method meant that the collected pressure values were likely to underestimate the true combination of perpendicular and tangential forces. This does not affect the improvements in load distribution and pressure observed during the experimental work. In addition, it can be argued that if this method underestimates pressure at the shoulder interface then attempts to improve load distribution and lower pressures are even more necessary.

It is indisputable that the evaluation of military load carriage equipment must take into consideration a number of factors other than pressure including physiological, subjective, practical and effects on performance. The results of this study indicate that any such evaluation must also include the measurement of interface pressure. The agreement observed throughout the practical work of this study between measured pressure and user discomfort illustrates that lowering interface pressure plays a significant part in lowering user discomfort. The large amount of empirical research on the relationship between high skin pressures and impaired function and damage to body tissues provide further evidence for the importance of pressures measures.

The methodology developed in this study may provide a good starting point for the evaluation of novel designs of load carriage equipment. As a relatively quick and cheap process it may allow the early identification of initial design problems or ineffective materials in order to allow only the potentially beneficial designs to be investigated further saving both time and expense.

12.3 Experimental Work

The major aim of the experimental work described in Part II of this thesis was to investigate the effects of incorporating different materials into the interface of military load carriage equipment. The final prototype analysis (experiment 4 – Chapter 10) evaluated the prototype shoulder straps that were found to be the most effective in terms of load distribution and user discomfort.

Out of the seven different main interface materials investigated, the foam currently used in the interface of British military backpacks was found to be the least effective. The highest interface pressure values and subjective discomfort ratings were found underneath this prototype. This provided support for the direction of this study and the hypothesis that changing the interface material of military backpacks may significantly benefit the user. Mesh 6 (strap K) was found to be the most effective material, utilising the greatest amount of the shoulder for load distribution and resulting in the lowest values for each of the three pressure variables. These findings supported the experimental hypotheses in section 6.3 that the interface materials that use the largest surface area of the shoulder and result in the lowest pressure would be the most preferable in terms of user comfort.

Another aim of the experimental work was to examine the effect of adding a layer of plastic on top of the interface material to aid load distribution. This design feature was added to three different interface materials (foam 1, mesh 3 and mesh 6). Adding this layer consistently increased the surface area of the shoulder sensor used for load distribution resulting in lower pressures. This design feature was also found to be preferable in terms of user comfort.

The separate effects of altering the interface material of a shoulder strap and adding a layer of plastic superficial to this interface material resulted in the identification of the best performing prototype. Strap L, which consisted of mesh 6 with a layer of plastic placed superficial to this, resulted in consistently lower values for each of the three pressure variables. In the final prototype analysis (experiment 4 - chapter 10), fifteen out of the eighteen participants rated strap L as the most comfortable of the six straps under investigations.

It has previously been recommended that sustained pressure underneath load carriage equipment should not exceed 14kPa (Stevenson et al, 1995). In experiment 4, the mean overall pressure underneath strap A across all eighteen participants was 31.83 kPa, compared with 15.78 kPa for strap L. Although care must be taken with the absolute values collected using the Tekscan method; this can be seen as a significant step towards this suggested maximum pressure. Combined with the subjective data, it can be concluded that the combination of a novel interface material and the use of a plastic layer resulted in a significant improvement in load distribution when compared with the strap currently in use.

The observed lower interface pressures at the shoulder may have important implications for both the health and performance of the user. Clinical research has shown that high pressures applied to the skin result in impaired blood flow to the underlying tissue and can cause tissue damage and injury. The consequences of such a disruption in blood flow may be serious for the health, motivation and performance of the individual user and ultimately the performance of the entire unit to which they belong. Significant reductions in shoulder pressure were achieved in this study simply as a result of altering the material of the interface of a backpack. It can be concluded that improving the distribution of load underneath load carriage equipment is a highly achievable aim with important and far-reaching benefits.

12.4 Recommendations

This thesis has demonstrated the relevance and importance of interface pressure measuring within the evaluation of load carriage equipment. Before now it has not been possible to obtain such measurements due to the lack of an appropriate methodology. This is now possible; the methodology developed in Part I of this thesis has been shown to produce valid and reliable measurements. A high level of association between the objective pressure data and the ratings of discomfort given by the participants was observed. This provides evidence for the role of interface pressure in the sensations of the user and the importance of this measure in any evaluation of load carriage equipment.

The design of British military load carriage equipment is currently an unscientific process relying on small step-by-step design changes which are often only identified as problematic when they reach the large scale, expensive user-trial stage. It is recommended that this pressure measurement method should be incorporated into the design process. The methodology would allow the objective testing of more radical design features than is currently possible and also allow the consideration of a much greater number of prototypes than is currently possible. A larger number of designs could be initially evaluated with only those identified as potentially beneficial taken forward for further evaluation. Designs found not to provide any benefit could then be rejected at the earliest opportunity.

It is accepted that decisions on the design of military load carriage equipment can not be made solely on the basis of interface pressure. A number of factors have to be taken into consideration including physiological effects, practicality, effects on performance and the functionality of the equipment. However, when the role of interface pressure on the health, performance and feelings of well being of the user is considered it is clear that pressure measurements should be incorporated into the evaluation process. As a result of this study, a reliable method is now available and a more complete evaluation process is now a reality.

Out of the twelve different prototype straps evaluated during part II of this thesis, strap L (consisting of the monofillament mesh 6 and a superficial plastic layer) performed significantly better than any other strap, resulting in greater contact with the body, lower pressures and improved user comfort. It is recommended that the mesh 6 be considered for use as the interface material within British military backpacks. Although other factors need to be considered including cost, durability and NBC effects this study has indicated that this material may significantly reduce the pressures at the user's shoulder improving both user health and comfort.

Another design feature shown to improve the distribution of load over the underlying body surface was the inclusion of a plastic layer superficial to the main interface material. This effect was consistent across three different materials of various strengths and composition. A recommendation can be made that, subject to further testing on the specific interface material, this is a simple, relatively cheap design change which may further improve the distribution of a carried load over the body interface.

A general recommendation can be also made that any new designs of load carriage equipment should attempt to distribute pressure at the shoulder as evenly as possible. The positive relationship between each of the three pressure variables observed throughout the experimental work of this study supports the theory suggested in chapter 6 that a uniform distribution of force is the most preferable at this particular user-product interface.

12.5 Summary

This study has tackled a new and crucial issue in the field of load carriage research. Previously, work in this area has mainly concentrated on cardio-vascular, metabolic and biomechanical issues. It has recently been recognised that an ergonomic approach to the design and evaluation of load carriage is essential and research has begun to incorporate ergonomic methods. Skin pressure was first suggested as a possible limiting factor for heavy military load carriage by Holewijn (1990) who conducted an initial study into this area although this was limited due to the technology available at the time.

As a result of this research project, which utilises new pressure measurement technology, it is now possible to reliable measure on-body interface pressure under load carriage equipment. This is an important development in the field of load carriage research. Now that it is possible to compare load carriage system in terms of pressure and discomfort in a scientific way there are extensive possibilities for further research.

The results of this study, which indicate that user discomfort is positively correlated with interface pressure, provides a starting point for research evaluating the relationship between pressure at various body surfaces and discomfort. This will allow design recommendations to be made as to the areas of the body most suitable for load bearing. Work on the effects of different interface materials, which has been initially investigated in this project, can also be furthered.

Chapter 13 Suggestions for Further Work

13.1 Pressure Measurement Method

The most valuable addition to the experimental methodology developed in this research project would be a method of calibrating on body pressures. This would allow confident conclusions to be drawn regarding the absolute accuracy of the collected pressure data. It would also be possible to compare data collected from different experimental conditions, provided thorough sampling techniques had been conducted. Removing the comparative nature would result in a simpler, quicker and cheaper experimental method that would also reduce the time commitment for each participant.

Another important addition to this methodology would be a measure of shear force. There is currently no method available for the measurement of this that would be suitable for measuring under load carriage equipment. As a result, it is likely that the methodology underestimates to a degree the real pressure situation on the body. The dynamic nature of load carriage means that the contribution of shear forces may be significant and therefore, a measure of this would add to the complete picture of pressure.

Although the essential first step in the development of an evaluative tool, this methodology is currently restricted to the controlled environment of the laboratory and the treadmill. The development into an in-field measurement tool that could map interface pressures whilst traversing different terrain and completing different activities would allow greater generalisation to the specific user population.

13.2 Experimental Work

In the experimental work of this study mesh 6, a monofillament double needle bar mesh material, was shown consistently to result in the most effective distribution of load over the shoulder area. However, these conditions were extremely controlled, the necessary first step of any scientific evaluation. Before this material can be recommended as an appropriate interface material other factors must be considered. Although found to be effective when carrying weights of 18.5kg, as discussed in chapter 2 the loads typically carried by infantry soldiers are significantly greater than this and the effects of such larger loads should be fully investigated.

In this study, also to control possible confounding variables, civilian participants were used. Further testing of the materials found to be effective is necessary involving military personnel. In addition to providing more information on user discomfort in the field, the views of experienced soldiers on the practical aspects of any new designs of load carriage equipment are essential before changes can be implemented.

The effects of load carriage on the shoulders were the focus of this experimental work. Although this is the area that bears the majority of the carried load in military load carriage, the evaluation of pressure on other body surfaces such as the back and the hips should also be examined. Recent technological developments have resulted in a new Tekscan system that allows the simultaneous recording of four individual pressure sensors rather than the system used in this study, which is restricted to only two sensors.

Throughout the experimental work of this study the tops of the shoulders (areas A and B) were the areas where improvements in pressure were most noticeable to the participants. When the participants perceived differences in discomfort between conditions it was these areas which led to the differences. The observed improvements were attributed to the fact that these areas bear the majority of the shoulder load and are likely to be the most sensitive due to the complicated and delicate anatomy of the pelvic girdle. Further investigation of this area could be achieved by separate pressure evaluation of distinct areas of the shoulder, which could correspond to the areas displayed on a body map for discomfort ratings. This would help to identify the individual contributions of pressure to discomfort at specific points of the body and may also discover useful relationships for the prediction of user discomfort.

The measurement of interface pressure should be combined with other factors that affect the choice of a load carriage system to provide a comprehensive evaluation method. The final method should include the measurement of thermal, physiological and biomechanical effects and also take into account practical issues of cost, functionality and durability.

13.3 The Prediction of User Discomfort

The initial investigation into the relationship between interface pressure and user discomfort discussed in Chapter 11 concluded that data collected from a comparative experiment cannot be used to develop a predictive equation. This was due to the apparent comparison between designs made by the participant resulting in the rating given to one design being dependant upon the other designs under investigation. If, as suggested in section 12.5, a method of on-body calibrating can be developed, then it would be possible to use independent experimental groups rather than using repeated measures. This type of data would not be based on comparisons with other designs and, therefore, may allow the development of an equation for the prediction of user discomfort from interface pressure. Other variables, such as fitness and anthropometric data, which have been suggested to affect discomfort ratings, may also play a significant role in the prediction of user discomfort. Subjective ratings over a longer period than the hour used in this study should also be collected to provide an idea of long term user discomfort.

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INFORMATION FOR PARTICIPANTS

LOUGHBOROUGH UNIVERSITY, DEPARTMENT OF HUMAN SCIENCES

The evaluation of novel designs of Military Load Carriage equipment

BACKGROUND

In the area of human load carriage research the majority of work has concentrated on the physiological effects of different load distributions. A gap in this area of research, however, is the measurement of skin pressures caused by the carriage of heavy loads. The aim of this study is to develop a method to allow the measurement of interface pressures underneath load carriage equipment and also to evaluate different designs of equipment.

STUDY DESIGN

All participants will be asked to attend the laboratory on either four or six separate occasions. Each occasion will be separated by one week. On each visit participants will walk on a treadmill for one hour whilst carrying a different prototype backpack weighted to a total mass of 18.5 kg (less than a third of your body weight). During this time pressure measurements will be taken via a sensor placed on the shoulder over a t-shirt layer. Participants will also be asked to rate how comfortable you feel at various time intervals.

EXPERIMENTAL PROCEDURES

Before being exposed to the experimental conditions, there will be a briefing period where we will discuss and complete with you a confidential questionnaire regarding your health and physical activity. This will also provide an opportunity for you to ask questions. You will also be required to sign a form to confirm your consent to take part in the study.

Before commencing the study your height and weight will be recorded. You will then be fitted with a pressure sensor (consisting of thin, flexible plastic). This will be placed on your left shoulder and top of your chest (over your t-shirt) and will be secured with tape. Once the sensor is in place you will be helped on with the backpack under investigation and you will then be able to adjust the shoulder straps. The experimenter will then check the placement of the shoulder sensor to ensure that it is in the correct place.

You will then be asked to walk on a treadmill at a moderate walking speed for one hour. During this time the experimenter will initiate pressure recordings at various time intervals, you will not be aware of when these are taken. At four different time intervals during the hour you will be asked to rate how comfortable you feel underneath the shoulder straps of the backpack.

Remember, the weight of the pack on each occasion will be the same!

After walking for an hour you will be helped off with the backpack. You are then free to go, but please feel free to rest and have a drink in the laboratory for as long as you want.

HOW MUCH TIME WILL THE TESTS TAKE?

Each visit to the laboratory should take no more than 1 hour 45 minutes.

POSSIBLE RISKS AND DISCOMFORT

You may feel some minor discomfort or aching on the skin where the pack comes into contact with the body. You may like to know that to carry one third of body mass is an accepted load at the upper level for everyday hiking.

You are free to pull out of the study at any time without having to give a reason.

CONFIDENTIALITY

Although information will be stored on computer, each subject will be entered as a number. Your name and other details will only be known to the experimenter and will be confidential.

Any questions about the procedures used in this study are encouraged. If you have any doubts or questions, please ask for further explanations by contacting Jennifer Martin on 01509 223086 (Office), or by e-mailing j.l.martin@lboro.ac.uk.

HEALTH SCREEN FOR STUDY VOLUNTEERS

Name or Number ....

It is important that volunteers participating in research studies are currently in good health and have had no significant medical problems in the past. This is to ensure (i) their own continuing well being and (ii) to avoid the possibility of individual health issues confounding study outcomes.

Please complete this brief questionnaire to confirm fitness to participate:

1. **At present,** do you have any health problem for which you are:
   - (a) On medication, prescribed or otherwise yes ☐ No ☐
   - (b) Attending your general practitioner Yes ☐ No ☐
   - (c) On a hospital waiting list yes ☐ No ☐
2. **In the past two years,** have you had any illness, which require you to:
   - (a) Consult your GP Yes ☐ No ☐
   - (b) Attend a hospital outpatient department Yes ☐ No ☐
   - (c) Be admitted to hospital Yes ☐ No ☐
3. **Have you ever** had any of the following:
   - (a) Convulsions/epilepsy Yes ☐ No ☐
   - (b) Asthma Yes ☐ No ☐
   - (c) Eczema Yes ☐ No ☐
   - (d) Diabetes Yes ☐ No ☐
   - (f) Head injury Yes ☐ No ☐
   - (h) Heart problems Yes ☐ No ☐
   - (i) Problems with bones or joints Yes ☐ No ☐
   - (j) Disturbance of balance/co-ordination Yes ☐ No ☐
   - (k) Numbness in hands or feet Yes ☐ No ☐
   - (l) Disturbance of vision Yes ☐ No ☐
   - (m) Ear / hearing problems Yes ☐ No ☐
   - (n) Back pain or back problems Yes ☐ No ☐

Additional question for female participants

- (a) could you be pregnant? Yes ☐ No ☐

If YES to any question, please describe briefly if you wish (e.g. to confirm problems was/is short lived, insignificant or well controlled.)

....

ACTIVITY LEVEL EVALUATION

1. Do you engage in regular physical activity? YES / NO

   If so, what type? ____________________

   How many days per week?____________________

   How much time per session (please circle one)?

Less than 15 minutes	15 to 30 minutes
30 to 60 minutes	More than 60 minutes

2. Do you play competitive sport? YES /NO

   What sport?____________________

   Current playing level? ____________________

3 Do you ever experience shortness of breath during exercise? YES / NO

4. Do you ever experience chest discomfort during exercise? YES / NO

5. If so, does it go away with rest? YES / NO

6. How would you describe your state of well being at this time? (please tick one)

Very, very good	Poor
Very good	Very poor
Good	Very, very poor
Neither good not poor	

7. Have you had any experience of carrying backpacks (hiking, Duke of Edinburgh? etc.) YES / NO

STATEMENT OF INFORMED CONSENT

I have read the description of the format and procedures involved in "The evaluation of novel designs of Military Load Carriage equipment", and I understand what will be required of me as a participant. I have had the opportunity to ask for further information and clarification with regard to the demands and procedures. I am aware that I have the right to withdraw from the study at any time with no obligation to provide reasons for my decision.

I agree to take part in the evaluation of novel designs of Military Load Carriage equipment

Signed ____________________________ Date ____________________

1	NO DISCOMFORT
2	SLIGHTLY UNCOMFORTABLE
3	UNCOMFORTABLE
4	VERY UNCOMFORTABLE
5	UNBEARABLY UNCOMFORTABLE

Strap A

Strap B

Strap C

Strap E

Strap L