# *Human load carriage: the ergonomic assessment and development of military load carriage systems*

**Human Load Carriage:**

**The Ergonomic Assessment and Development of Military Load Carriage Systems.**

by

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Abstract

There were two main aims to the thesis: (1) to develop a mobile 'in-field' pressure measurement system to assess pressure at Body-Load Carriage System (LCS) interfaces (shoulders and hips). (2) To evaluate and compare prototype LCS designs in-field and to provide human factor requirements for design improvement. To satisfy the aims of the thesis in-field trials were carried out in a realistic military context. The purposes of these trials were to: (1) compare the standard issue British military LCS against a prototype LCS design in terms of pressure and subjective comfort; (2) increase the understanding of the properties of the shoulder and hip interfaces; (3) assess the relationship between loading at the shoulder and hip; and (4) identify whether other ergonomic issues are also important to consider. By assessing these areas human factors requirements for design were then determined. An additional (minor) aim was to develop a new prototype LCS with a greater degree of compatibility between the components of a military LCS (backpack and webbing), incorporation of material advances, and with a greater consideration for fit and posture.

Four main experimental trials were performed the first (n = 11) assessed the affect of clothing layers at the body-LCS interface on transmitted pressure. Results showed that clothing layers even worn in multiple have no effect on pressure transmission. Thus, no relief from pressure exists for the user. This highlighted the importance of the materials in the shoulder and hip straps. The second trial (n = 10) was a laboratory based comparison of two backpacks, the first the standard issue British military pack, the second a new prototype. Results found significant difference in subjective comfort and also peak pressure at the shoulder interface. The prototype backpack being associated with reduced peak pressure and increased comfort. The third trial (n = 10) assessed whole LCSs (backpack + webbing) in field with civilian participants. The standard issue LCS was compared against a prototype LCS. No significant difference in pressure was identified between the two LCSs, although differences in subjective comfort ratings were still significant indicating a preference for the prototype LCS. The final trial (n = 30) was military in-field trial. Military personnel and loadings were utilised. Again no significant difference in pressure data was identified although differences in subjective ratings remained significant with the prototype LCS design being preferred.

Research findings highlighted the continued need for subjective assessment. The relationship between pressure loading at the shoulder and hip interfaces, along with locations of peak pressure within each interface were found to be important factors affecting comfort. Increased pressure distribution at the interfaces via new materials and design was also associated with increased comfort. Other areas which appeared important were the effect of posture and other physical forces not measured (i.e. shear and friction). Human factors guidelines were created for further LCS designs and future research ideas were presented.

# Acknowledgements

I would like to thank my late supervisor Dr. Robin Hooper for his continuous advice, guidance, patience and friendship throughout my research. I was deeply saddened to hear the tragic events. Robin was one of life's 'good guys' and will always be remembered fondly as an intelligent, kind hearted gentleman, with a vast knowledge of not just ergonomics and physiology but also many disciplines. Also, Robin was someone who could party hard, keeping up (usually setting the pace!) for students and staff. He will be sorely missed...

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# Publications.

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Two of the main experimental trials detailed in this thesis have been peer reviewed, published and presented.

1. **The Clothing Study** (Trial 1 - chapter 6) was published in the Applied Ergonomics journal. "The effect of single- or multiple-layered garments on interface pressure measured at the backpack-shoulder interface". Jones, G. R.; Hooper, R. H. (2005) pp. 79-83 Applied Ergonomics, volume 36; number 1.

2. **The Military In-field Trial** (Trial 4 - chapter 7) was presented to the International Ergonomics Association and published in the conference proceedings. "The 'in-field' assessment of military load carriage systems using a novel mobile interface pressure measurement system". Jones, G and Hooper, R (2003) Proceedings of the International Ergonomics Association conference. Aug $24^{th}$-$29^{th}$, Seoul, South Korea.

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# Chapter 1: Introduction

## 1.1 Research Background

The carriage of loads on the human body is an essential requirement for all of the three British Military Forces: Army, Royal Navy, and Royal Air Force. These loads have to be carried in a bespoke military load carriage system (LCS). The responsibility for the maintenance and development of such LCS's belongs to the Defence Logistics Organisation (DLO), part of the Ministry of the Defence (MoD). Loughborough University itself has been involved in this process for the past decade, carrying out scientific research concerning the assessment of military LCS, and creating human factors requirements for design. The physiological effects of carrying loads on the human body have been extremely well documented (Astrand, 1956; Epstein, 1988; Schoenfield et al, 1977) however certain 'ergonomic' considerations have not.

The aim of Loughborough's research has been to assess considerations such as subjective user comfort/discomfort, injury and performance when using different military backpack designs (Martin, 2001). The effect of the integration between the body and backpack has specifically focused upon the interface pressure. Previous research has suggested that high peak pressures can lead to increased discomfort, reduced performance and in the extreme, injury (Knapik et al 1996; Wilson, 1987). Using this increased knowledge interface design requirements can be specified leading to a reduction in peak pressures and thus reducing negative effects as previously recorded.

Interface pressure whilst carrying military backpacks has been studied in laboratory settings with civilian participants (Martin, 2001), but as yet has not been assessed 'in-field' with military participants, military loads, and during military exercises. The findings of Martin's work lead to an experimental backpack design which enabled less pressure at the interface, increased user comfort and reduced heat stress. However, this work only assessed the backpack alone. It is important to understand that a military LCS consists of two items, a 'backpack' and 'webbing' (described in detail in chapter 2). It is not known whether via improving one aspect of a system these advantages still function when the system is worn as a whole, thus there is a need to assess the whole LCS. Important to consider here is that soldiers also have to carry a weapon, possibly also a radio, medical kit or other specialised equipment and also wear a helmet and body armour, in addition to the LCS.

Hence one of the main aims of this thesis is to assess the whole LCS in military contexts, with military personnel, equipment and loading weights. The research sponsors (DLO) will use the outcomes provided by this research in the development of new LCS designs, in particular the findings will link into the current major equipment development project termed 'FIST' (Future Integrated Soldier Technology). The current standard issue British military LCS was designed over 14 years ago, with a lack of ergonomic consideration. By providing ergonomic requirements for design this should lead to improved LCS's which should enable soldiers to carry out their duties more comfortably with reduced injury risk and increased effectiveness. The DLO are actively involved with moving LCS equipment forward by reducing the discomfort, increasing the utility and reducing the injury risk to the soldier load carrier. Research work considering these three factors is critical, hence this PhD work.

## 1.2 Objectives of the thesis

1. To develop a mobile 'in-field' method of measuring and quantifying interface pressure at the body-LCS interface (shoulders and hips) using objective and subjective methods.

2. To evaluate and compare LCS designs in-field and to provide human factor requirements for design improvements.

An additional (minor) aim was to develop a new prototype LCS with a greater degree of compatibility between the components (backpack and webbing), incorporation of material advances (as highlighted by previous research), and a consideration for fit and posture.

The objectives of the thesis will allow in-field trials to be carried out in a realistic military context. The purposes of these trials are to: (1) compare the standard issue British military LCS against a prototype LCS design in terms of pressure and subjective comfort; (2) increase the understanding of the properties of the shoulder and hip interfaces; (3) assess the relationship between loading at the shoulder and hip; and (4) identify whether other ergonomic issues are also important to consider. By assessing these areas human factors requirements for design can then be determined.

## 1.3 Structure of the Thesis

There are 9 chapters in this thesis. Chapter 2 provides a review of relevant scientific literature concerning human load carriage in the military and non-military contexts, and also discusses in detail the rationale behind the research, the limitations of the current military LCS, and links with research work to date. Chapter 3 is concerned with the subjective views of military personnel on the current LCS. Chapter 4 describes the development of the 'in-field' interface pressure measurement system. Chapter 5 details the objective and subjective methodologies for the experimental trials. Chapter 6 describes two laboratory trials, the first assessing the effect of clothing layers at the body-LCS interface on pressure readings; and the second comparing the standard issue British military backpack and a prototype design. Chapter 7 concerns two field trials: these trials compared two LCSs; the standard issue system versus a new prototype design. The first trial employed a civilian sample, the second utilised military participants. Chapter 8 is a discussion of findings and conclusions. Finally, chapter 9 deals with future work and defines human factors requirements for LCS design.

# Chapter 2: Literature Review and Background to the thesis

## 2.1 Introduction

The need for continued research and improvement of military LCS designs remains prevalent. Soldiers are required to carry differing loads in different manners as military technology progresses, thus the military requirement for new LCSs is ever present. The designers of these new LCSs must also consider the latest research findings in order to create the most suitable designs.

Carrying extreme military loads has been found to have an adverse effect on performance (Knapik et al, 1996), an increased injury risk (Wilson, 1987) and has also directly or indirectly led to soldier fatalities (Lothian, 1922; Renbourn, 1954). By continued development of assessment techniques (leading to improved design requirements) a reduction in injury risk and increased performance will lead to increased effectiveness of military units. Evidence has shown that well designed LCS can enhance the likelihood of mission accomplishment by reducing localized stress and fatigue (Knapik, 2004).

Although much scientific research has been performed attempting to define physiological limits for human load carrying, there still remains somewhat of a void in the literature when it comes to a full range of ergonomic detail relevant for military LCS. It is important to understand firstly what a military LCS consists of; two items: (1) backpack and (2) webbing.

The webbing consists of a number of pouches which (in standard issue guise) are worn around the waist and supported via a shoulder harness and hip belt (termed 'Belt webbing'). The webbing is ALWAYS worn by the soldier as this contains all the essential items required for fighting and basic survival. The backpack (or 'Bergen', as the standard issue backpack is named) is worn on top of the webbing, containing mostly non-essential but also a small number of larger essential items.

When in a hostile environment the soldier will advance toward the enemy carrying the whole LCS (webbing + backpack). When contact is made with the enemy the Bergen is immediately 'dumped' and the soldier goes forward wearing the webbing only. This point is extremely important to understand as the literature almost exclusively only considers the backpack and not the whole LCS. If design requirements are defined via studies which only assess one item of the system, and these advantages are applied to the backpack only, then any new design may not provide the expected benefit when both the webbing and backpack are worn together. In short, a system approach to design, assessment and ergonomic evaluation must be adopted in order to make real advances in design.

## 2.2 Background Literature

Since their first existence human beings have been carrying loads supported by the body. Simple day to day living is associated with numerous load carrying tasks. Even in the year 2005, where human aids and advanced technology are commonplace, in some situations it is not possible to transport heavy loads in any other manor than on the body. This fact is especially relevant to the infantry soldier, who is required to carry heavy loads over long distances, often over uneven and difficult terrain and in adverse environmental conditions. When situations demand, the soldier must also still be physically able to engage and (if needs must) fight the enemy.

Prior to the 18th century it has been suggested that soldiers did not routinely carry more than 15kg whilst marching, however since then the loads carried by the soldier have risen progressively, presumably due to the weight of the weapons and equipment that allow increased protection, firepower, communications and mobility (Knapik, 2004). This increase in military loads has attracted research seeking to ensure that the soldier is able to carry out his roles without being plagued by discomfort and injury. The first research of this type was carried out with the British military after the Crimean war, where an attempt to define realistic soldiers loads associated with the specific roles was undertaken, and also early advances in LCS design were seen (Lothian, 1922).

More recently the US Army Development and Employment Agency attempted to define a major approach for improving soldier mobility (Knapik, 2004), this involved five factors: (1) to develop components which are lighter for the soldier to carry; (2) to use the 'Soldier Planning Model', a computer programme which works out desirable loads for each situation using factors such as the mission goal, number and location of the enemy, type of terrain, number of troops, and time to carry out the mission; (3) to develop specialised load carriage devices, such as all terrain vehicles and 'handcarts', used to reduce the load carried on the body; (4) to re-evaluate current doctrine influencing what is carried by soldiers and (5) to develop a physical training regime to improve soldier strength and fitness to carry loads. This US research project was very valuable, but it can not easily be applied to British troops due to the types of roles they are required to carry out. Many of these roles do not allow carriage of loads in any other manner except on the body, and thus factor (3) becomes somewhat redundant. Research on British military LCS needs to concentrate on factors 1, 2, 4 and 5 of the US model.

This PhD research work is primarily concerned with factor 1, and links into the LCS development work that has shown a particular increase over the past two decades. With the advent of new materials and manufacturing processes, the realm of the simple canvas rucksack is no more. The use of new plastics and composite materials has enabled incredibly strong, durable and waterproof rucksacks to be constructed.

Another important factor leading to the development of much improved designs derives from broader ergonomic approaches. At present, much consideration is given to ergonomic principles when designing new equipment and this consideration enables the creation of more suitable designs. Indeed, poorly designed load carriage equipment, with a lack of ergonomic consideration has been shown to be a cause of debilitating injury (Bessen et al, 1987; Wilson, 1987).

Load carriage equipment currently in use by the British Military is one such example of this. The Bergen backpack and Belt webbing combination (as previously discussed) are the standard issue equipment. The problem lies with the incompatibility of these two items, where the Belt webbing frequently prevents use of the backpack hip belt. Due to this much of the load has to be supported by the shoulders. The natural anatomical load bearing region of the body is the hips, and when heavy loads are supported elsewhere the possibility for injury/discomfort exists. It is important to fully understand the role of the infantry soldier. Soldiers are routinely required to walk extremely long distances (during the Falklands conflict certain British soldiers were required to walk the length of the island (75 miles), fully laden and fighting as they moved) with very heavy loads (typically between 50-100% of body weight) during day and night, over varying terrain (McCraig & Gooderson, 1986). The nature of operations in wartime scenarios also means that soldiers suffer from a lack of sleep and rest – and also are subject to adverse environmental conditions.

A great deal of research has been carried out identifying the correct clothing, correct food types and calorific values, and the most suitable methods for surviving and fighting in differing environments, but relatively little work has been carried out developing specific load carriage systems for military use. Most work has involved assessing only a single element of the load carriage system – the backpack, and most of this work is primarily concerned with civilian backpacks. To date there have been no studies looking specifically at how the standard British LCS (Bergen backpack and Belt webbing) performs 'in-field' in terms of both interface pressure data and subjective comfort ratings.

## 2.3 Methods and Modes of Load Carriage

Many studies have been undertaken to identify the optimum method of carrying loads in order to attempt to minimise energy cost. However, it is important to consider that to date none of these studies have been able to determine a single 'best' method of load carriage for all military contexts (Knapik, 2004). Datta & Ramanathan (1971) studied seven different modes of load carriage: rucksack, double-pack (load is split between front and back of body), sherpa (pack is supported by a head strap), rice bag (sack is held by hands or hooks over each shoulder), yoke (load supported by a bamboo strip across the shoulders), hand, and head. They found clear differences in energy cost between the different modes. The modes were placed in order of ascending physiological demand: double pack, head, rucksack, sherpa, rice bag, yoke, and hands. The double pack (the most efficient mode) resulted in the least change to the body's centre of mass. Hand carriage (the least efficient mode) utilised the smallest muscle groups.

These findings provide support for the view that loads should be kept close to the centre of the body and utilise large muscle groups for the most efficient load carriage. Legg & Mahanty (1985) compared a number of modes more relevant to the military than the modes tested by Datta & Ramanathan. A backpack and belt kit combination, non-framed backpack, framed backpack, double-pack, and trunk jacket were assessed. These modes all attempted to keep the load as close to the body as possible. Subsequently, no significant difference in physiological cost between the modes was identified. However, subjective ratings did differ with the double pack being rated the most comfortable and stable. Legg & Mahanty's interpretation of this was that even if no physiological difference is found between load carriage systems, a subjective difference may be found, which could lead to decreased motivation and subsequently decreased performance of the individual carrying the load. This is an interesting finding as it raises the question that if there is no physiological difference, then what physical factor is being sensed so that the subjective reporting differs. It could well be interface pressure under the shoulder and hip contact areas. This finding may indicate the need to shift away from solely assessing physiological factors and to seek to understand other forces at work. Also, for the military this fact is very pertinent and highlights the importance of the use of subjective data. The suggestions made by Datta & Ramanathan and Legg & Mahanty have been further studied in a recent paper by Lloyd & Cooke (2000). They evaluated a commercial rucksack incorporating front balance pockets to distribute load between the front and rear of the body. Participants carried a load of 25.6kg, whilst walking on various gradients. The commercial rucksack was compared with a traditional rucksack where weight is totally carried on the back. When walking downhill no significant difference in oxygen consumption was found between the commercial balanced backpack and the traditional rucksack, however during uphill and level walking the balanced commercial backpack resulted in 6-9% decrease in oxygen consumption.

Whilst the findings of these three studies indicate the double pack is the most energy efficient method to carry loads, the double pack may cause problems due to the load on the front of the body. Datta & Ramanathan (1971) highlighted the difficulty when donning and doffing a double pack due to the special harness required. This may be of great relevance to the military where packs must be removed and replaced quickly. Designs which incorporate the principle of double packs, i.e. weight is distributed between the front and back of the body, but do not use a special harness (such as the commercial pack tested by Lloyd & Cooke) may make frontal carriage more acceptable to the military. Another possible problem is that carrying loads on the front of the body may result in restriction around the chest – this was illustrated in Legg & Mahanty's study (1985) where the double pack resulted in the lowest maximum voluntary ventilation. Again, this has particular relevance to the military, due to the high metabolic rate at which tasks have to be performed, leading to decrements in performance.

Two other factors are also of relevance: thermal and visual. When carrying loads on the front of the body the visual field may be impaired where the soldier may not see the ground ahead and such things as trip wires and other obstacles, which would undoubtedly compromise individual performance. Thermal problems may arise due to a reduction in surface area of the body available for heat loss by evaporation. Heat stress can become very serious especially when working at high rates, and for the military this must be avoided at all costs. Legg & Mahanty (1985) concluded that the optimum way to carry a load depends on three factors; (1) the individual task, (2) the distance, and (3) the preference of the carrier. Another issue to consider is that of profile appearing larger when wearing a double pack and hence providing a larger target for the enemy. Also, the double pack can hinder movement when troops are required to 'leopard crawl' stealthily toward the enemy.

Load carriage systems with more subtle design changes have also been studied. In recent years, internal frame backpacks have become an increasingly popular design. It allows the centre of gravity of the load to be carried closer to the body than that of an external frame backpack (Kirk & Schneider, 1992). Kirk & Schneider compared internal and external frame backpacks, via physiological and perceptual responses of 11 female participants. Previous work by Legg & Mahanty (1985) illustrated that the use of a frame in a backpack has been shown to relieve pressure and discomfort on the upper torso. Thus, Kirk & Schneider hypothesised that an internal frame backpack would result in less metabolic and cardio-respiratory strain on the body. They suggested this was due to the fact that less muscular activity is required to maintain posture, as the combined pack-user centre of mass is closer to the centre of mass of the unloaded body.

When comparing the external and internal framed backpacks, Kirk & Schneider found no physiological difference (in terms of ventilation rate, oxygen consumption and heart rate) between them. They suggested the reason for this was that both backpacks used similar muscle groups and that the difference in load distribution over the body was not large enough to result in differences in physiological parameters. Subjective ratings given by the participants support this finding as no preference for either internal or external frame backpacks was identified.

The ratings of perceived exertion (RPE) recorded during testing showed an increase over time; however, physiological parameters did not show any such increase. This was thought to be due to localised fatigue in these areas which is enough to affect subjective feelings, but not sufficient to affect physiological measurements. Kirk & Schneider (1992) concluded that differences in backpack frame design were not great enough to produce significant differences in the energy cost or perception of carrying a moderately heavy load on the back. These results further indicate the importance of including subjective ratings when assessing load carriage systems.

## 2.4 Maximal Loading Capacity for Military Personnel

For many years researchers have attempted to identify loading limits for military personnel. The problem of overloading personnel remains consistent for the military, moving from an environmental cause (i.e. problems experienced during world war one, where mud and water saturation of clothing and equipment increased the average load from 27kg to 43kg) to a technological cause (i.e. nowadays soldiers are in danger of overloading due to increased firepower and communication technology which must be carried). The need to avoid overloading of troops is obvious if they are to remain able to carry out necessary tasks and duties without becoming exhausted (Knapik et al, 1992).

The ability of an individual to carry load will ultimately depend on their physical capacity, level of fitness and previous load carriage experience. It is not possible to define a maximum load and apply this to military personnel of both sexes and all shapes, sizes and fitness levels. Consequently the most common method for assessing an individual's ability to carry load is to determine their maximum aerobic capacity ($VO_{2max}$). The $VO_{2max}$ illustrates the extent to which an individual can perform sustained work at a high rate. As a person's $VO_{2max}$ increases (via aerobic training) so will their ability to carry loads.

Exhaustive research conducted by Astrand (1956) resulted in the recommendation that for young, active, well trained males, a work rate of 50% $VO_{2max}$ should not be exceeded over a working day. Maximum theoretical military loads have been defined from $VO_{2max}$ data. It has been suggested that individuals in good physical condition should carry no more than 25kg load, for sustained activity (Schoenfeld et al, 1977), and to minimise fatigue (Davis, 1983). Studies conducted by Epstein & colleagues (1988) have resulted in the US army adopting Epstein's recommendation that load should not exceed 30% of an individual's body weight for optimal load carriage, with a maximum load of 45% body weight at any time. Defining limits for whole body $O_2$ demand is informative, but in terms of load carriage, it is possible that uneven or unbalanced loading will affect different muscles to different extents. For example, if the pectoral girdle muscles are working at a higher percentage of their maximum, whilst other muscles (i.e. the lower limb) are working much lower, then whole body criterion will be met, even though the possibility for marked fatigue will exist. If fatigue is crucial to performance, this will be affected. This fact needs to be considered when applying limits to load carriage.

Although the above recommendations for the safe carriage of loads have been made, putting theory into practice is not always possible. Haisman (1988) stated that "the load that a soldier carries will always be a compromise between what is physiologically sound and what is operationally essential". The findings of McCraig & Gooderson (1986) illustrate the relevance of Haisman's statement. They observed that during the Falklands conflict British troops were carrying loads of up to 70kg, even though the typical loading for a three day march was a maximum of 40kg. This was due to the fact that when including specific equipment such as communications and firepower, necessary to fulfil the task, the load carried was much heavier. Thus, in such situations it is obvious that applying theoretical limits on load will not be possible. The emphasis now is more focused on how load carriage systems can be configured to be more comfortable for the soldier when carrying heavier loads, instead of attempting to restrict the loads themselves.

## 2.5 Injury and Medical Considerations

Load carriage can cause acute medical problems. Whilst these are generally minor in a military situation they can still lead to reduced effectiveness of military units. Military load carriage injuries generally fall into two categories: (1) injury incidence after a single military excursion, and (2) injury sustained over longer periods of regular load carriage. Work conducted on incidence of injury after a single exposure show differing results. Injury incidence ranged from 24% (Knapik et al, 1992) to 90% (Dalen et al, 1978). A consistent finding from injury reports is the majority of injuries involve either the lower extremities or the back (Knapik et al, 1996). Specific injuries caused by load carriage include foot blisters, knee pain, low-back injuries, metatarsalgia, stress fractures and rucksack palsy.

Foot blisters are the most common of these injuries, resulting from friction between the skin and sock. Although they sound relatively benign, blisters actually cause extreme discomfort and can prevent troops from carrying out their normal duties (Knapik et al, 1996). In addition, if blisters are not treated they can progress into serious problems such as cellulitis or sepsis (Akers & Sulzberger, 1972). The weight of the carried load is important in terms of blister incidence, with heavy loads resulting in a higher incidence (Knapik et al, 1993). Kinoshita (1985) suggested that heavy loads possibly cause higher blister incidence due to increasing pressure on the skin and causing more movement between the foot and boot through higher propulsive and breaking forces.

An interesting finding from Knapik et al (1993) is that when loads are very heavy (61kg), decreased blister incidence is found with the double pack method of load carriage (where load is carried in two packs, one on the back and the other on the front of the body). Knapik et al (1996) has also suggested that regular training with load carriage may induce skin adaptations that reduce the probability of blisters (i.e. the skin is hardened). However, it has been suggested that keeping the feet dry is the most effective method of avoiding blisters (Knapik et al, 1996) and is a more important consideration (in terms of blister incidence) than the type of load carriage equipment used.

Metatarsalgia (non-specific, painful, and disabling overuse injury of the foot) can be a result of heavy load carriage. Kinoshita (1985) suggested that walking with heavy loads may be a predisposing factor for metatarsaglia since this may cause the foot to rotate anteroposteriorly around the distal ends of the metatarsal bones for more prolonged periods of time resulting in more mechanical stress in this area. Knapik et al (1992) reported a 3.3% incidence after a single strenuous walk with a 45kg load over 20km, whereas Sutton (1976) reported a higher incidence of 20% during a strenuous seven-month physical training program which included regular heavy load carriage.

Low-back injuries can be common during load carriage. Knapik et al (1992) found that during one study 50% of the troops who failed to complete a strenuous 20km walk reported problems associated with the back. Indeed it has been suggested that heavy loads may be a risk factor for back injuries (Reynolds et al, 1990). There have been two suggestions why this risk is so. The first is that heavier loads lead to changes in trunk angle that can stress back muscles (Hale et al, 1953); (Harman et al, 1992); (Norman, 1979). The second is that heavy loads do not move in synchrony with the trunk (Norman, 1979) causing cyclic stress of the back muscles, ligaments and the spine (Harman et al, 1992); (Norman, 1979). Following on from this view it has been suggested that the double pack may help reduce the incidence of back problems as it results in a more normal posture and eliminates prolonged bending of the back (Kinoshita, 1985).

Lower extremity stress fractures have been found to be common in both military recruits and in trained soldiers. However, stress fractures occur more frequently in new recruits, due to previous inactivity being a risk factor (Jones, 1983; Jones et al, 1989). The common nature of this complaint was illustrated by the high incidence of stress fractures reported during the central Burma campaign in World War II. During this campaign, 60 stress fractures were reported in a single infantry unit during a 483 km load carriage march (Donald & Fitts, 1947). There are several risk factors for stress fractures, which are relevant to the military, such as white ethnicity, older age (Brudvig et al, 1983), prior inactivity, and tall stature

(Gilbert & Johnson, 1966). Also, it has been suggested that load carriage distance (Jones et al, 1989) and walking style (Gilbert & Johnson, 1966; Ozburn & Nichols, 1981) may increase the risk of stress fractures.

Brachial Plexus Syndrome or 'Rucksack Palsy' is the most debilitating of the load carriage injuries. It causes such symptoms as: pain in the shoulder girdle, elbow flexors, and wrist extensors, muscle weakness, numbness, and paralysis of the upper extremity. Long thoracic nerve injuries are usually also present, with 'scapular winging' occurring due to weakness of the serratus anterior muscle (Bessen et al, 1987; Wilson, 1987). Electromyography of the affected muscles of the shoulder girdle, in particular the deltoid, illustrated denervation in affected motor units (Wilson, 1987). The exact cause of this condition is unknown, but it is thought that rucksack palsy occurs when the shoulder straps of rucksacks cause a traction injury of the C5 and C6 nerve roots of the upper brachial plexus. In minor cases the result is long thoracic nerve entrapment (Knapik et al, 1996).

Research has shown that the use of a framed rucksack and hip belt reduces the incidence of rucksack palsy (Bessen et al, 1987) presumably by reduction of pressure at the shoulder interface (Holewijn, 1990). Several hypothetical risk factors for rucksack palsy have been proposed; particularly heavy loads, uneven or inadequate load distribution, and long carriage distances (Bessen et al, 1987; Reynolds et al, 1990). Damage to muscles caused by this syndrome can take up to six months to heal, with some cases resulting in some form of permanent damage (Bessen et al, 1987). Rucksack palsy also has implications for task performance (section 2.6), where tasks such as marksmanship and grenade throwing may be adversely affected by damage to the muscles in the shoulder and arm. A consideration of load distribution and location of peak pressures at the shoulder and also the hip shall be made by the experimental work of this thesis (chapters 6 & 7).

Knee pain has long been closely associated with load carriage; however the incidence of such injury shows some variation between different studies. Dalen et al (1978) reported 15% incidence of knee pain from a load carriage study, whereas

Knapik et al (1992) reported knee pain incidence of only 0.6% after a single strenuous march, however the two cases recorded were serious enough to cause a total of 14 days injury. Although findings seem somewhat mixed and further research is needed it is important to consider knee pain due to its links with several disorders such as; patellar tendonitis, bursitis, and ligamentous strain.

Not only injury, but also pain and discomfort can result in a loss of performance when carrying loads. It has been suggested that load carriage over long distances results in local pain and discomfort in the shoulder, back and feet areas of troops (Dalen et al, 1978; Gupta, 1955); (Knapik et al, 1991). This is most likely caused by blisters, abrasions, and/or excessive pressure on a specific part of the body. Holewijn (1990) has suggested that shoulder discomfort may be caused by the rucksack straps which place pressure on the shoulders.

Much work has been carried out on the discomfort perceived when wearing different load carriage designs. For backpacks, both framed and frame less, the majority of discomfort exists in the neck and shoulder regions. Backpacks with hip belts help to alleviate some of the discomfort in the shoulders and neck, and are thus associated with discomfort in the mid-trunk and upper legs (Legg & Mahanty, 1985). Overall it has been found that less subjective discomfort is experienced when carrying weight on the hips, rather than on the shoulders (Holewijn & Lotens, 1992). Local fatigue in muscles during backpack load carriage has been observed. This was studied by examining isometric strength changes in 11 muscle groups after completing a series of marches, carrying loads of up to 28kg. The muscles showing the greatest decrements in strength as a result of this carriage were the trunk extensors, hip extensors, and knee flexors (Clarke et al, 1955).

## 2.6 Human Task Performance

One of the most important considerations for the military is how well soldiers are able to perform tasks both during and after load carriage. Studies have been carried out attempting to quantify loss of performance due to load carriage. and also loss of performance caused by different load carriage designs. Different load carriage designs have subsequently been assessed on grounds of effect on task performance. For the foot soldier *freedom of movement, balance, and stability* are considered to be some of the most important characteristics affecting task performance. Subsequently, research in this area utilises activities that test these characteristics. Also, more event specific tasks such as marksmanship and grenade throwing ability/accuracy have been studied. Research has highlighted the importance of such factors as load, volume, and load distribution, these being the main determinants of performance when carrying loads (Knapik et al, 1996).

Martin & Nelson (1985) conducted one of the first studies aimed at assessing the effect of load carriage on task performance. They studied several loading combinations: no load, webbing only, webbing and rucksack. Martin & Nelson identified a negative linear relationship between load and task performance. A significant amount of work on the effect of load carriage on performance has been carried out by Lotens (1986). Lotens performed an exhaustive study looking at the effect of different clothing and equipment items on performance. Of the various items tested; fatigues, insulative liner and helmet resulted in a 0-2% loss in performance; outer garment, combat boots and respirator account for 4%; NBC suit and weapon account for 6-7%; while the worst item by far was fighting order (loaded backpack in addition to weapon and other items) which resulted in a 13.5% loss in performance. A study performed by Holewijn & Lotens (1992) looked at the loss of physical performance due to weight and volume, restriction of shoulder motion, and interference with balance. Ten different backpack configurations were studied, where load was carried on three main areas of the body: back, front and back, and waist.

A performance battery included an obstacle course, jumping, running, sprinting, hand grenade throwing, and a mobility test. Average loss of performance of 1% per kg mass and 0.2% per litre of backpack volume was found. Motion restriction of the shoulders did not result in significant performance losses. Balance disturbance resulted in a 1.5% performance decrement. In order to minimise the loss of performance, it was suggested that weight should be centred around the waist, and volume may be distributed over the chest and back without extra performance decrements. Holewijn & Lotens (1992) also suggested that loads of greater volume inhibit movement under obstacles, and also that the load distribution within a rucksack can influence performance on specific tasks.

Researchers from Queens University Canada (Bryant et al, 1996; Doan et al, 1998 (1); Doan et al, 1998 (2)) provide recent and specific work on the effect of load on performance. The use of a specifically designed load carriage simulator, consisting of a computer controlled, moving, anthropometric torso allowed objective measurements to be made on the interaction between load carriage equipment and the human torso during (simulated) walking. Subjective testing was also employed by the group involving the use of questionnaires – where participants were asked to rate different fighting order configurations after completing a performance circuit. The conclusion from the research was that in order to minimise the detrimental effects of load carriage on agility and mobility, three factors should be accounted for: (1) free movement of the lower body and hips; (2) unrestricted forward bending of the torso; (3) centre of the mass of the load to be kept as close to the persons back as possible.

Another critical aspect is post-carriage performance; this is how task performance is affected after carrying loads. Highly strenuous marches have been shown to produce post-march decrements in marksmanship and grenade throw distance. These marksmanship decrements have been suggested to be due to small movements of the rifle resulting from fatigue of the upper body muscle groups, fatigue-induced tremors, or elevated heart rate or respiration (Knapik et al, 1993; Knapik et al, 1991; Tharion & Moore, 1993).

Decrements observed in grenade throw distance may be due to a nerve entrapment syndrome (Bessen et al, 1987; Wilson, 1987) or possibly due to pain in the shoulders caused by pressure from the rucksack straps. Performance decrements are also observed in lower body muscular power (measured by the Wingate and vertical jump tests) which does appear to be affected by prolonged rucksack load carriage (Knapik et al, 1991; Patton et al, 1991).

## 2.7 Body Posture and Walking Gait

Carriage of load on the human body results in changes in body posture and gait patterns. Ghori & Luckwill (1985) suggested that "man, already inherently unstable because of his bipedal walking gait, becomes increasingly so during load carriage due to the raised centre of gravity of the body". They demonstrated that when loaded with 10-50% of their body weight, humans will compensate for this instability by increasing double support time (when both feet are on the ground) and shortening the swing phase of the gait cycle. This finding is supported by Martin & Nelson (1986) who observed that the effects were more prominent in females, presumably due to differences in stride lengths and statures. Thus, during a prolonged march women would take many more steps than males to cover the same distance and, when walking at an imposed speed (as with a military march), women will have to work at a higher percentage of their maximal working capacity in order to keep pace.

This fact has possible implications for injuries. Taking more steps may subject the lower limbs to a higher degree of stress, as each time a foot hits the ground it has to absorb the collective weight of the body and any load carried. This may result in an increased chance of developing acute and chronic leg injuries. Martin & Nelson's finding is further strengthened by deMoya's work (1982) which demonstrated that females display relatively greater peak ground reaction forces than males, thus further increasing their risk of leg injuries.

However, whether taking more steps would increase the risk of leg injury could be questioned. If more steps are taken, then the lower limb will move less distance and thus peak ground reaction forces could actually be less than if the swing phase of the gait cycle remained the same as unloaded walking. Thus, the risk of leg injury may not be increased as has been suggested. Changes in walking patterns induced by extra load are greater for females compared with males as the same load represents a higher proportion of their body weight (Martin & Nelson, 1986). However, research has demonstrated that female-male differences persist even when size is taken into account. This is most likely due to the lower percentage of lean body mass in females which is the component of the body that has to bear stress of a carried load (Martin & Nelson, 1985).

Bobet & Norman (1984) investigated the effect that different load placements have on the back muscles. They found that activity in some muscle groups was lower when a load was applied. Whilst walking unloaded, the line of gravity of the combined head, arms and trunk (HAT) was located slightly posterior of the lumbosacral joint. Thus, trunk flexion was the dominant moment and activity of the erector spinae muscles was needed to resist this moment. But, when a load is carried during walking, a back extension moment occurs due to the weight on the back. This partly offsets the flexion moment of the HAT thereby reducing erector spinae activity. The reduction in muscular activity will depend on 3 factors: (1) the weight of the HAT, (2) the angle of the inclination adopted to balance the moments of force and (3) the ability of the participant to maintain this balance during the accelerations and declarations associated with the walking stride. Muscular activity of the upper trapezius also shows differences between unloaded and loaded walking. Higher muscular activity is observed during unloaded walking, probably due to the slightly abducted arm position. With loaded walking the arms can hold onto the shoulder straps of the backpack, which reduces the muscular action required when walking unloaded.

In a further study Martin & Nelson (1985) found that altering the placement of the load on the back actually had no effect on the static moments of the body *but* did have an effect on the dynamic moments. The activity in the upper trapezius muscle was found to be significantly higher with the centre of gravity of load placement being at shoulder level. This may be due to the acceleration and deceleration of the trunk passing through the shoulder straps to the pack, thus increasing trapezius action. Combined with the fact that the load is higher reduces the stability of the user and backpack, thus increasing sway which must be compensated for by the action of the trapezius muscle. Martin & Nelson (1985) suggested that mid-back load placement is preferable as it is easier to control unexpected accelerations caused by stumbles and trips with the load placed lower down.

The effects of internal and external frame backpacks on body posture when carrying 22-32% body weight where investigated by Bloom & Woodhull-McNeal (1987). They found that regardless of frame type participants always lent forward and the mean centre of gravity remained the same as when unloaded. Hence, changes in body alignment can be seen as stabilising the whole body centre of gravity. However, the centre of gravity at the hips is not as well controlled. When carrying backpacks this is shifted backwards resulting in a change of torque at the hips. This change is greater for internal frame backpacks, where the body is further bent forward due to the mass being positioned lower down. The fact that the mass is positioned lower down with the internal frame pack is also an advantage in terms of stability. Bloom & Woodhull-McNeal (1987) identified gender differences with regard to which type of backpack is preferred. They found that the majority of females prefer the external frame backpack, whilst the majority of males prefer the internal frame backpack.

This finding contradicts that of Kirk & Schneider (1992) who, in a more extensive study involving longer load carriage periods and incorporating physical activity whilst load carrying, found no preference for either internal or external frame backpacks. However, neither of these studies appeared to take into account other parameters which could influence pack preference, such as hip belt/shoulder strap design, pack back length and types of padding/materials used. Without taking such parameters into consideration it could be questioned whether such findings are true reflections of a preference for internal or external frame packs.

## 2.8 Interface Pressure

There have been many suggestions as to what the limiting factor of load carriage may be, such as the individuals $VO_{2max}$, the weight of the load carried, and the mode of carriage employed. A recent and novel theory is that proposed by Holewijn (1990), who suggested that skin pressure could be the limiting factor of load carriage. Holewijn conducted a novel study employing a pressure transducer to measure pressure under shoulder straps of rucksacks. Four young male participants took part in the study. Pressure was recorded at 15 individual points over the shoulder, and measurements were recorded via small pressure transducers (8mm x 4mm x 1mm). Two different backpack designs were assessed: standard (Dutch) military pack and a custom designed pack.

Pressure was recorded whilst the participant was standing still and whilst carrying a load in each of the packs. Two loads were carried: 5.4kg and 10.4kg. The maximal pressure recorded during load carriage (with 10.4kg load) showed highly significant results. The standard military packs showed maximum pressure of 27 kPa whereas the custom pack maximum was only 2 kPa. A pertinent finding was that when the load in the standard military pack was increased from 5.4kg to 10.4kg, skin pressure showed a 36% increase. However when load was increased in the custom pack, no such increase in pressure was observed. Thus, these results highlight that a well designed rucksack can reduce the effects of carrying heavy loads by effectively distributing pressure.

The results of the pressure recordings were supported by the subjective views of the participants, in that they reported significantly more discomfort when carrying the military rucksack. Holewijn (1990) concluded from this that, whilst carrying loads of up to 10.5kg, the discomfort was caused by the pressure under the shoulder straps and hence the limiting factor of load carriage was the pressure on the skin. Since the work of Holewijn, a number of studies have been performed on interface pressure underneath load carriage equipment. The interest in this arena has lead to the development of new, technologically advanced pressure measurement systems.

Much of this research into pressure under equipment has been carried out by the Ergonomics Research Group at Queen's University Canada (Bryant et al, 1996; Doan et al, 1998 (1); Doan et al, 1998 (2); Johnson et al, 1998). Studies by the group all utilised a load carriage simulator which consisted of a 50$^{th}$ percentile mannequin covered in a compliant 'skin-like' material, cycling vertically to simulate human movement. Interface pressure sensing equipment was also used, manufactured by Tekscan™. This system uses specialised 'pressure sensors' incorporating hundreds of pressure sensitive elements, constructed of pressure sensitive inks mounted on flexible plastic. The pressure sensors are extremely thin (0.18mm) and can be curved to fit the lines of the body. Pressure was measured by placing the sensors underneath different packs, placed on the load carriage simulator.

The studies conducted by Bryant, Doan, Johnson et al found differences in pressure on the body depending on the load location. This is illustrated by the finding of Johnson & colleagues (1998) that a 36kg load placed on the back resulted in a mean pressure of 19.8 kPa whereas, when the load was split between the front and back of the body, the mean pressure was only 17.4 kPa. 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 highlighted the possibility of improving pressure distribution via altering the load location and improving elements of equipment design. The improvement of pressure distribution is very important and will lead to decreased injury and discomfort, together with increased performance and military unit effectiveness.

The use of the Tekscan pressure measurement system was also carried forward by the work of Martin (2001); however this work involved the recording of pressure measurements on human participants, rather than mannequins. This has obvious advantages, as this work was the first real study of its kind to assess pressure on humans carrying military LCS. Via informed selection of sensing equipment and the development of specific experimental protocol Martin was able to assess the pressure under the shoulder-backpack interface. Via combining pressure measurements with simultaneous subjective comfort ratings Martin found that as peak pressure was reduced, subjective comfort increased.

The goal then became to utilise new materials and designs in order to reduce interface pressure at the shoulder-backpack interface. Martin showed that by specifically focusing on the design of the shoulder strap, a significant reduction in pressure and a corresponding increase in subjective comfort could be achieved. Martin assessed many different materials and strap types and found that the most significant improvements were found by adding a plastic layer into the shoulder strap and via the use of new 'Airmesh' material.

The work of Martin illustrated that techniques exist for accurately recording the interface pressure on humans during load carriage. These recordings led to improved comfort via the utilisation of new material and design. However the work only assessed backpacks alone and not a real military LCS (webbing + backpack), assessed only interface pressure at the shoulder (not hip or back) and also employed civilian participants in a laboratory setting. The need to assess the whole LCS, with military personnel, and at each interface point has already been discussed (chapter 1), and the work of this thesis concerns these issues.

## 2.9 Effect of Interface Pressure on Skin

Carrying loads via rucksacks and other load carriage equipment which interface with body surfaces causes pressure (to a greater or lesser extent depending on the load) on the underlying soft tissues and musculature. Load is supported solely by the skeleton and thus intervening soft tissues (at contact interfaces) are pressurised by loading. These tissues are generally unaccustomed to bearing constant mechanical forces, thus in situations where these forces occur for prolonged periods tissue damage may occur. Damage may initially appear as simple skin reddening and, when loading is prolonged, the injury may progress throughout the entire body wall. Several attempts have been made to determine the relationship between applied pressure and subsequent breakdown of tissues. Due to these investigations there now exists a generally accepted relationship between applied pressure and a reduction in blood flow. Research by Daniel & colleagues (1985) showed that high applied pressure will also affect the deep body tissues and, if muscle is trapped against underlying bone whilst pressure is applied, this may result in muscle damage.

A significant amount of research has been performed on the effect of different applied pressures on underlying tissues. An applied pressure of 13 kPa, when sustained for 2 hours, resulted in reduced blood flow to underlying muscles but, when sustained for 6 hours, complete muscle necrosis was the end result (Hussain 1953). Holloway & associates (1976) suggested that applied pressure of 4 kPa can result in a 30% reduction in blood flow to the skin and sub-cutaneous tissue. Dinsdale (1974) examined the effects of different sustained applied pressures from 6 kPa to 195 kPa, for various durations, observing changes in underlying tissues which may lead to the development of pressure ulcers. Research by Stevenson et al recommended a maximum sustained pressure limit at the skin of 14 kPa (Stevenson et al, 1995). Whilst this 14 kPa value is commonly cited, care must be taken as this value was determined from Stevenson's review of literature concerning the effect of pressure on the body on bed-bound patients. The pressure during load carriage is undoubtedly less sustained than that found when bed-bound. It is therefore useful to consider this figure of 14 kPa, but for load carriage perhaps less critical than previously thought.

Kosiak (1961) demonstrated that applied pressure of 9 kPa sustained for 2 hours caused a reduction in blood flow to underlying tissues but applied pressure of 5 kPa sustained for 4 hours did not. These studies illustrate that low to moderate pressures sustained for short to medium duration may cause some tissue damage but this will be reversible for healthy tissues. However, non-reversible tissue damage will be experienced if pressure is sustained for significantly long periods or if the applied pressure is very high.

Further research into the effects of pressure on the skin has lead to the finding that the threshold for injury to skin is lower at thin skin sites over a bony prominence. Sangeorzan & colleagues (1989) assessed the effect of applied pressures (from 0 – 16 kPa) to skin sites which directly cover bone and skin sites covering muscle. A significantly lower pressure (5.6 kPa) caused a reduction of transcutaneous partial pressure of oxygen ($Po_2$) to zero when applied to skin covering bone than to skin covering muscle (9.5 kPa). Sangeorzan & colleagues suggested that this difference is likely to be due to the fact that mechanical stress (when applied to skin sites covering bone) is being concentrated in a smaller amount of connective tissue between the bone and surface (than skin sites covering muscle). This work is highly relevant to military load carriage. Rucksack shoulder straps run across and thus apply pressure to skin sites directly over bone (i.e. the scapula and clavicle) which according to Sangeorzan et al (1989) means that skin in this area will be more susceptible to low $Po_2$. Also, with the additive effect of high temperature and moisture, the skin is under increased risk of pressure induced damage.

It is very important that subjective sensation of the individual carrying loads is not ignored. Sensory receptors present in the skin and underlying tissues detect touch, movement, pain and pressure. These receptors have a specific threshold level below which stimuli are not attended to. However, if this threshold is crossed, the pressure stimulus, if sustained, will cause pain and discomfort. This discomfort maybe due to neural fatigue of skin receptors (due to constant firing) or due to reduced blood flow to the skin and underlying muscles. Thus, moves to reduce pressure under shoulder straps (and any other interface with the body) may reduce discomfort and injury, increase individual performance and subsequently increasing effectiveness of military units.

## 2.10 Summary

Much information is now known about the effect of load carriage on human beings. Suggestions have been proposed to allow the most efficient, injury-free and comfortable load carriage. Many of these conclusions are relevant and applicable to the military. Major conclusions are: (1) load should be carried as close as possible to the centre of mass of the body; (2) load should be carried by the largest muscle groups; (3) physical work rate should be below 50% $VO_{2max}$; and (4) load should be carried as close to the waist as possible to reduce body instability (and gait cycle compensations due to this).

However, there is one recommendation very relevant to civilians who have full control of the weight they carry but which may not readily be applied to the military due to the necessity to carry certain equipment. The suggestions made by researchers concerning the maximum load to be carried are largely inapplicable to the military. The research presented above has been carried out to develop more ergonomically designed load carriage equipment. When prolonged heavy load carriage is performed, high interface pressures are found underneath load carriage equipment. These pressures, in addition to causing discomfort, may (in the extreme) damage the skin and underlying tissues. Further to this, physical performance can be detrimentally affected due to decreased blood flow to the skeletal muscles. A combination of these effects could lead to a reduction in task performance of individuals and subsequently entire military units. The maintenance of performance and avoidance of injury is critical to the military, thus reduction of high pressures through advances in design is important.

There has been limited research concerning interface pressure and, until the work of Martin & Hooper (2000), has been solely concerned with measuring interface pressure on mannequins. Martin & Hooper's work, measuring interface pressure on humans, has lead to increased understanding on how pressure can be more evenly distributed over the contact surfaces via adaptations to equipment design. This consequently led to a reduction in pain and discomfort for the wearer when carrying loads on a treadmill as observed in Martin & Hooper's study.

To conclude: "soldier mobility can be improved by lightening loads, *improving the design and load distribution of LCS*, incorporating physical training regimes and specific techniques at injury prevention. If these factors are taken into account soldiers should be able to complete missions at lower energy costs, with more comfort, with fewer injuries, and with a higher chance of mission success" (Knapik, 2004).

## 2.11 Focus for this thesis

The area of concern for this thesis is *improving the design and load distribution of LCS* and in defining and identifying methods and equipment for evaluating these factors. The first effective assessment of different military backpack designs on the grounds of interface pressure was reported by Martin (2001). This work was laboratory based and was performed on civilian participants. The impetus for this thesis is thus to develop a mobile interface pressure measurement system to assess different LCS designs 'in field' with military participants. The intention is to record interface pressure data from the shoulder and hip regions whilst the participant is moving across various terrain rather than walking on a treadmill in the laboratory.

Another aim is to be able to record pressure data from the end users of the LCS. The objective pressure data, together with subjective ratings should provide in depth assessment of different LCS designs. It is important to test the LCS on the military as their subjective views of pain, discomfort and practicality will have been moulded through their military experience. Hence, if testing LCS designs on civilian participants, their subjective views may be very different from those of military personnel. Also, as the designs are intended for sole use by the military, it is even more important that they are assessed in a military context. Testing prototype LCS designs on the end users should lead to the development of more suitable designs.

Prior to the work of this thesis interface pressure measurement of LCS interfaces has been solely laboratory based, utilising a treadmill. A treadmill will not simulate different terrain, gradients and also obstacles which military personnel in field would obviously come across. For 'in-field' work it is necessary to develop a mobile method of interface pressure measurement. This development is important because if true advances in military LCS design are to be made, the designs must be tested on the actual intended end users, in actual situations in which the equipment will be used and for actual military tasks. The limitations of current military LCSs have led to many negative outcomes (as previously discussed) such as pain, injury, discomfort and reduced movement and performance. Via the use of the new mobile interface pressure measurement system (chapter 4) it is hoped that design drawbacks can be identified and improvements made, leading to increased individual performance, decreased injury and thus increased effectiveness of entire military units.

# Chapter 3: Subjective Views of British military end users on the standard issue Bergen LCS

## 3.1 Introduction

The crux of any ergonomic investigation seeking to improve the comfort for military personnel involved in the carriage of heavy loads is to ensure that subjective feedback is incorporated. Chapter 2 has detailed the short comings of current issued Bergen LCS in terms of scientific research, but it is also vitally important to obtain the views of the end users themselves. These views can then influence or even be incorporated into new designs. One of the main concerns of ergonomics is that an item must not only be comfortable but also provide functionality and ease of use. For example, if an arm chair was fitted into a car, this may well be the most comfortable seat, but it would not allow the driver to use the controls and function safely!

By the same rule there would be no point in redesigning a LCS purely in terms of comfort if it could not be used practically by the military. A balance between what is comfortable and what is functional must be struck with any new design. With this in mind it was important firstly to collect the views of military load carriers on the current issued Bergen LCS. The Bergen LCS has been standard issue since 1990 and much views and experience of its use (both positive and negative) exist and must be considered. The Bergen LCS consists of the Bergen backpack (or '90 Pattern Bergen' given its full military term) and belt webbing (as described in chapter 2). 100 British military personnel were asked to fill out a questionnaire recording their views on the Bergen LCS and also their ideas for design change and improvement. This chapter deals with these subjective views and how they can be applied in the development of new LCS designs and concepts.

## 3.2 Methods

### 3.2.1 Questionnaire and the collection of subjective views

A questionnaire was developed to gather views of current military personnel. Whilst this does not form part of the main experimental work of this thesis and is not subject to any statistical analysis, it was obviously still important to consider design of the questionnaire in order to gather credible information. There are certain key areas to consider: (1) avoid leading questions, (2) ensure clarity of questions, (3) ensure each question is applicable to all, and (4) avoid double-barrelled questions (i.e. questions which could elicit two answers). These key areas of consideration were highlighted by Sinclair's article (1995). These areas were considered when drawing up the questions. Within the questionnaire participants were also asked to provide ratings of comfort on a 5 point ordinal scale. The use of such rating scales is the subject of in depth discussion in chapter 5.5. The questionnaire itself is shown the appendices of this thesis.

The questionnaire was piloted with 10 military participants. The questionnaire was found to elicit responses from all participants, with no indication of confusion or questions answered in incorrect contexts. Thus, the questionnaire was utilised for a larger sample. It is important to understand that the author of this thesis was present whilst the questionnaires were filled out, and a briefing was given before participants were asked to complete the questionnaire. This consisted of an introduction, and highlighted the need to enter as much information as possible, equally considering both positive and negative thoughts of the current LCS, in order that new LCS designs can be better informed. Upon completion of the questionnaire participants were asked if they would like to discuss any areas of relevance to the current LCS or future designs, any discussion was recorded and is presented within the results. Given the context of the aim of the questionnaire (to gather background information and understanding from end users) the questionnaire/discussions provided interesting, valuable and credible findings.

### 3.2.2 Military Participants

A sample of 100 military participants was selected. These participants ranged from having 1 to 20 years experience of load carriage. Personnel with less than 1 years experience were not selected as they would not have completed basic training and would have very limited experience of load carriage. Participants from 6 British Military regiments/units took part. Firstly there were two standard infantry regiments, the Second Royal Regiment of Fusiliers (2RRF) and the Black Watch (BW). Secondly participants from two elite infantry units were selected, these participants carry heavier loads than the standard infantry and for longer periods, they also have more lengthy training and are of higher physical fitness. The two units who took part were 1$^{st}$ Battalion Paratroops (1 Para) and the Royal Marines (RM). Lastly the elite Special Forces also participated namely the Special Air Service (SAS) and the Special Boat Squadron (SBS). Participants from these Special Forces units are the most heavily trained, experienced and arguably the fittest members of the British military.

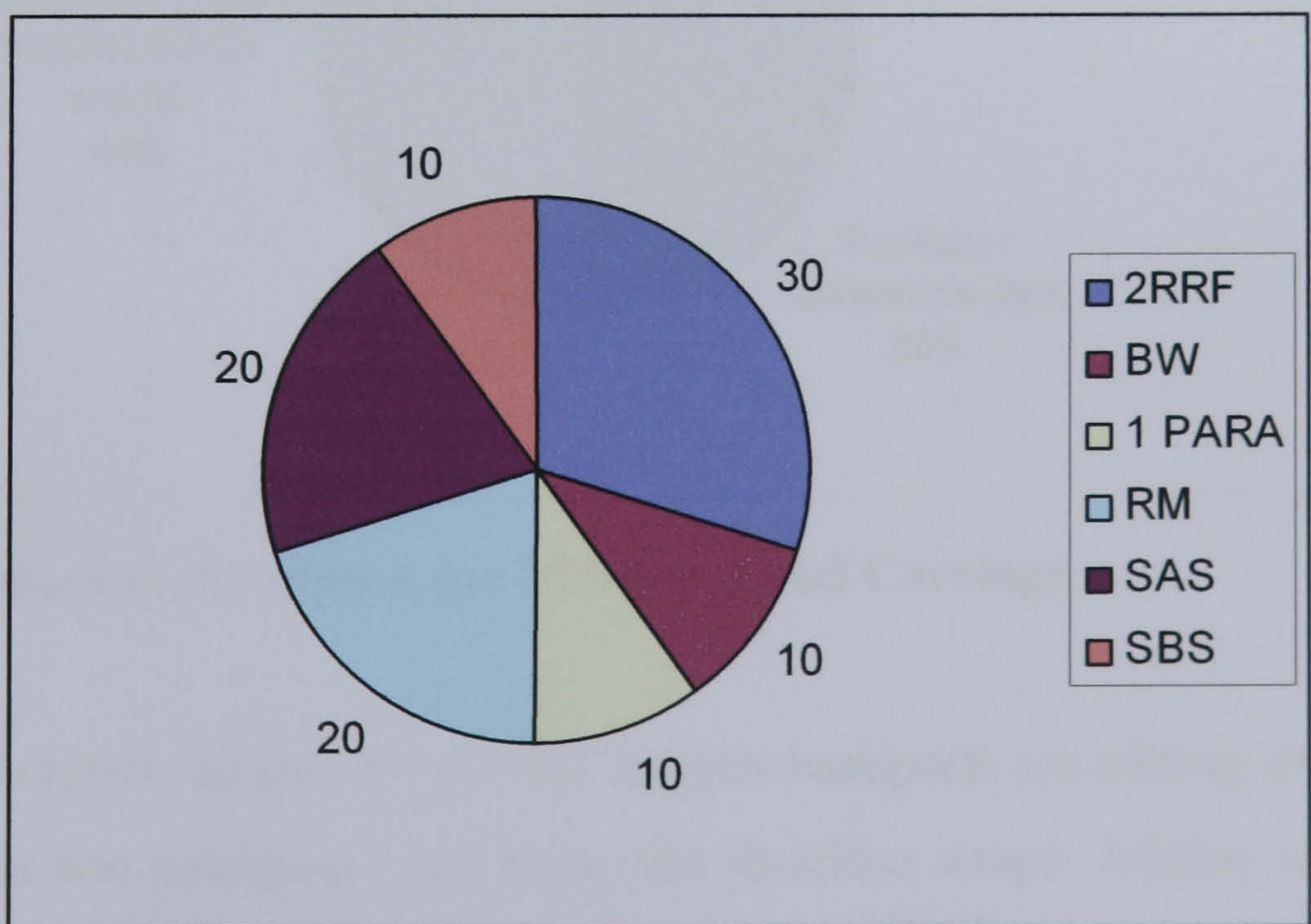



**Figure 3.1 The number of participants from the 6 military units**

It is of importance to have a sample representing the three levels of usage of the LCS. From the basic infantry usage (average 27kg) through to the extreme Special Forces usage (approximate maximum of 70kg, McCraig & Gooderson, 1986). The duration of load carriage also varies with basic infantry units requiring personnel to be able to complete an 8 mile march with 27kg (standard load carriage requirement) through to the Special Forces' requirement of a 30+ mile march with 27kg.

## 3.3 Results from the questionnaire

### 3.3.1 Bergen (backpack)

The Bergen received mixed reviews, with 55% of participants stating they utilised an adapted or alternative pack for load carrying. To have only 45% of troops utilising a standard issue backpack highlights a definite need for new designs.

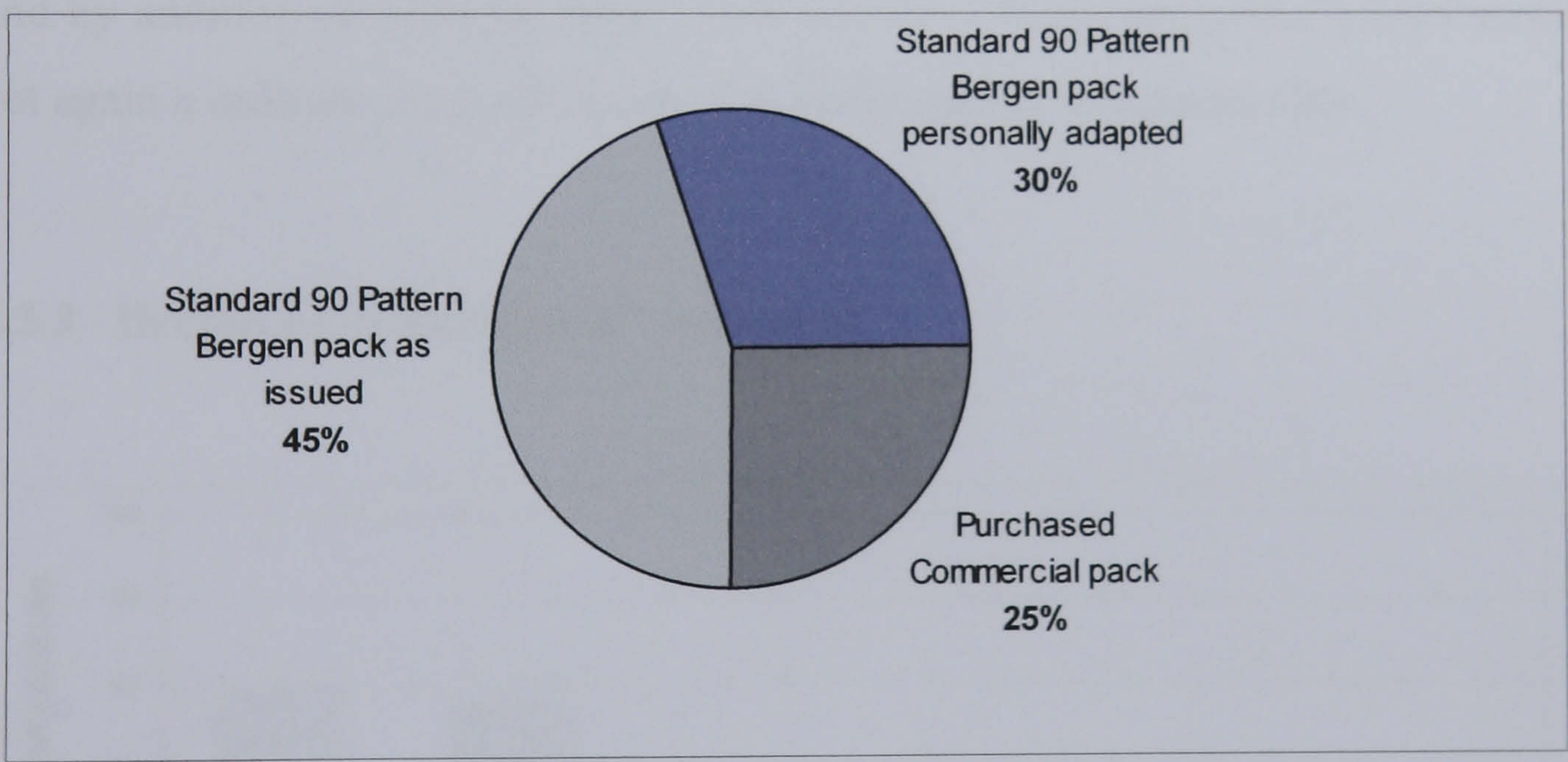



**Figure 3.2 Backpack utilised for Military Load Carriage**

The most common adaptations to the Bergen backpack are adding extra external rear pouches and changing / replacing the shoulder straps. Adding multiple rear pouches adds to the practicality of the Bergen, as the main compartment is sealed and water tight, however if troops have to continually access this for equipment this seal is compromised. If they can operate out of the external pouches for approximately 24 hours, they can then replenish the contents of these from the main compartment when they have time and shelter to do so. The most common changes to the shoulder strap include strapping extra padding on and binding it all together with thick tape to ensure the padding remains in place and provides extra comfort. These adaptations to the shoulder straps may result in greater pressure distribution across the interface, hence the claim of increased comfort.

### 3.3.2 Belt Webbing

During operations the Bergen is never worn alone, it is part of the LCS system the other element being the belt webbing. When asked to comment on belt webbing it received mixed reviews. As belt webbing is worn around the waist not only does it allow for a good range of movement but also easy access to essential items of kit such as ammunition and water. However, 60% found the webbing to cause discomfort and rubbing on the front of their legs and hips during load carriage. It was proposed the webbing could be improved by increased padding and support, and by addition of stronger clips on the pouches. These suggested improvements yet again a indicate the consideration of both comfort and practicality.

### 3.3.3 Bergen LCS (backpack + webbing)

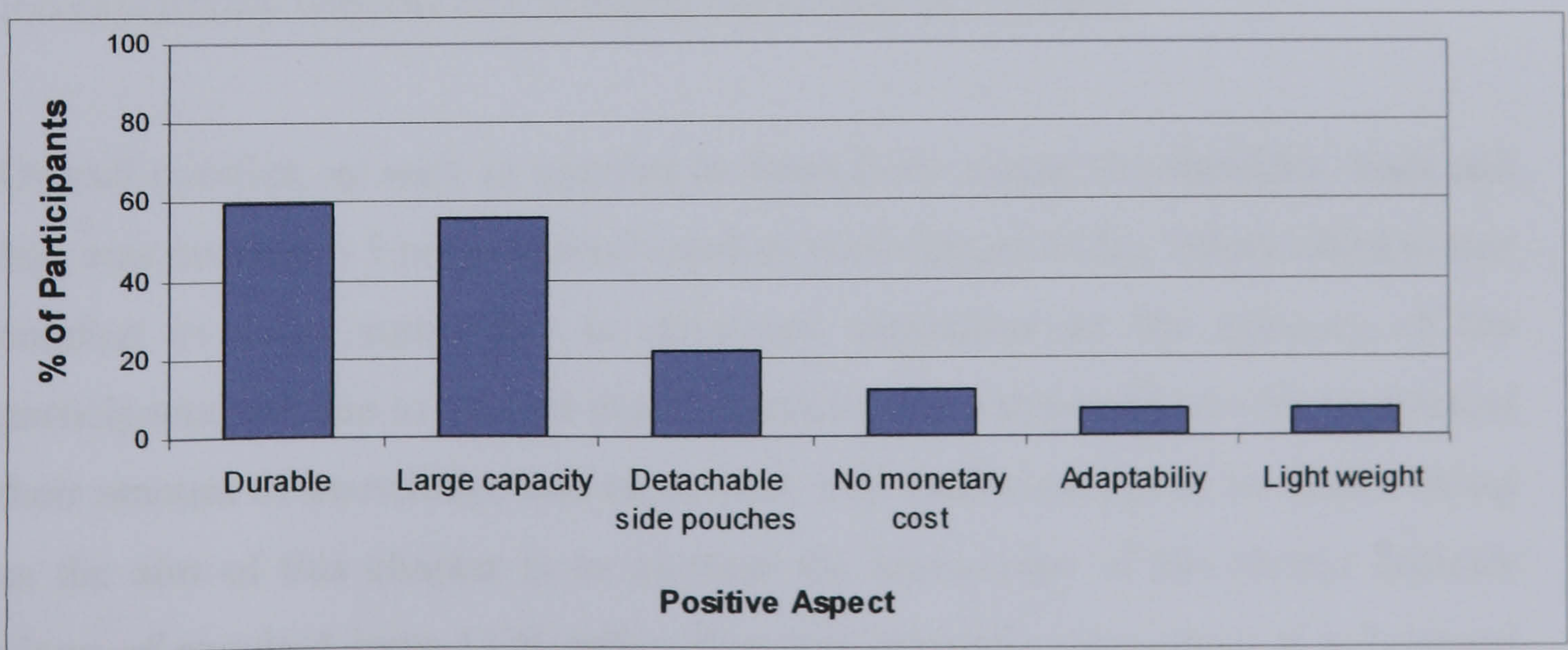



**Figure 3.3 Six commonly discussed positive aspects of Bergen LCS**

The six most positive attributes of the Bergen LCS are displayed in figure 3.3. It is interesting that of the positive aspects none are associated with comfort, all being practical aspects and the fact that it is issued free of charge.

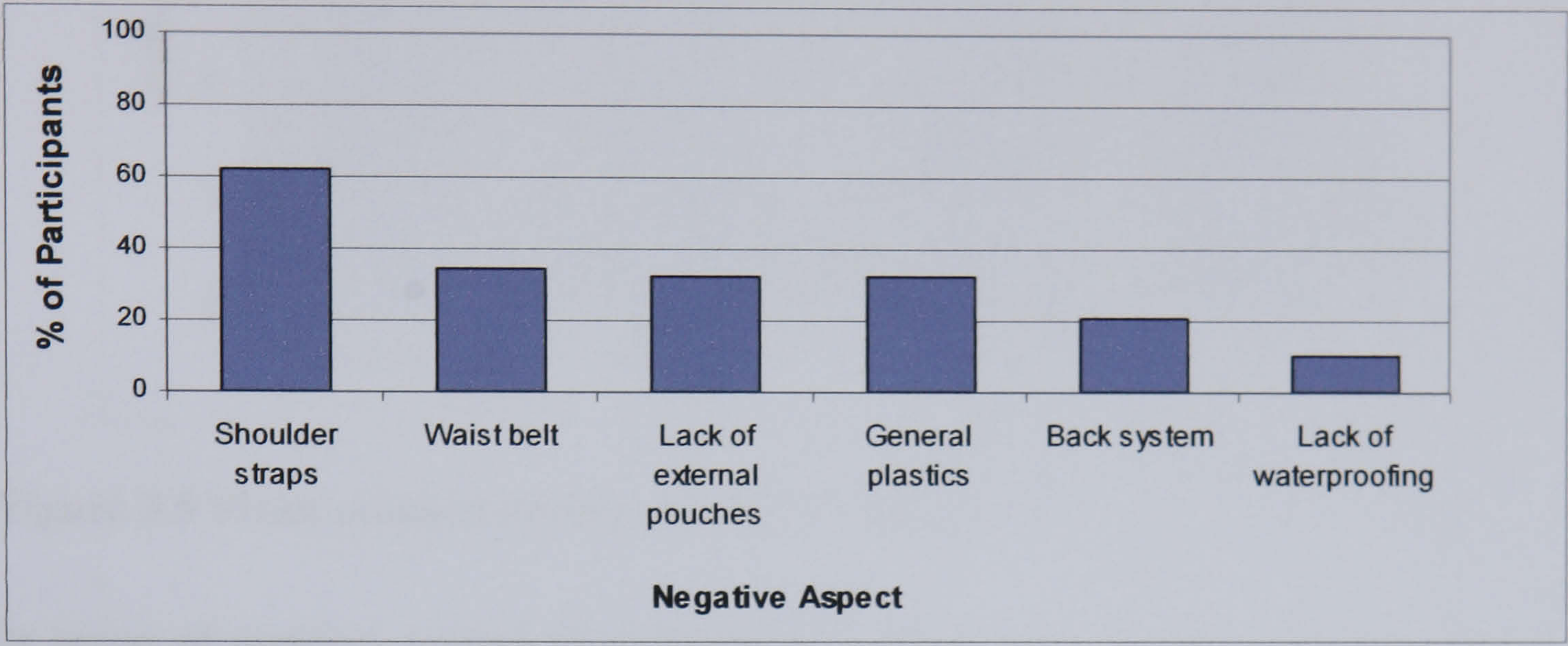



**Figure 3.4 Six most negative aspects of Bergen LCS**

The six most common complaints are displayed in figure 3.4. The shoulder strap is the greatest concern, considered too thin, to contain a lack of padding and to be generally uncomfortable. The waist belt was deemed the second major downfall of the Bergen, mainly due to its lack of function when worn with webbing. This is interesting as opposed to the positive aspects, the two most common negative aspects are those directly related to comfort at the shoulder and hip interfaces. A major criticism of the Bergen as described by 60% of participants is its incompatibility with the belt webbing when worn as a system.

Overall comfort, as well as comfort in three body zones; the shoulder, back and hip, was rated on a 5 point ordinal comfort scale (figure 5.22). When asked to rate comfort in these zones this is obviously dependent on the memory of the participants, but due to the fact that the participants continually use the equipment their amount of knowledge and experience will enable ratings to be made. Being as the aim of this chapter is to increase the knowledge of the current military views of standard issue LCS, rather than any scientific assessment it is believed these ratings will be credible and informative.

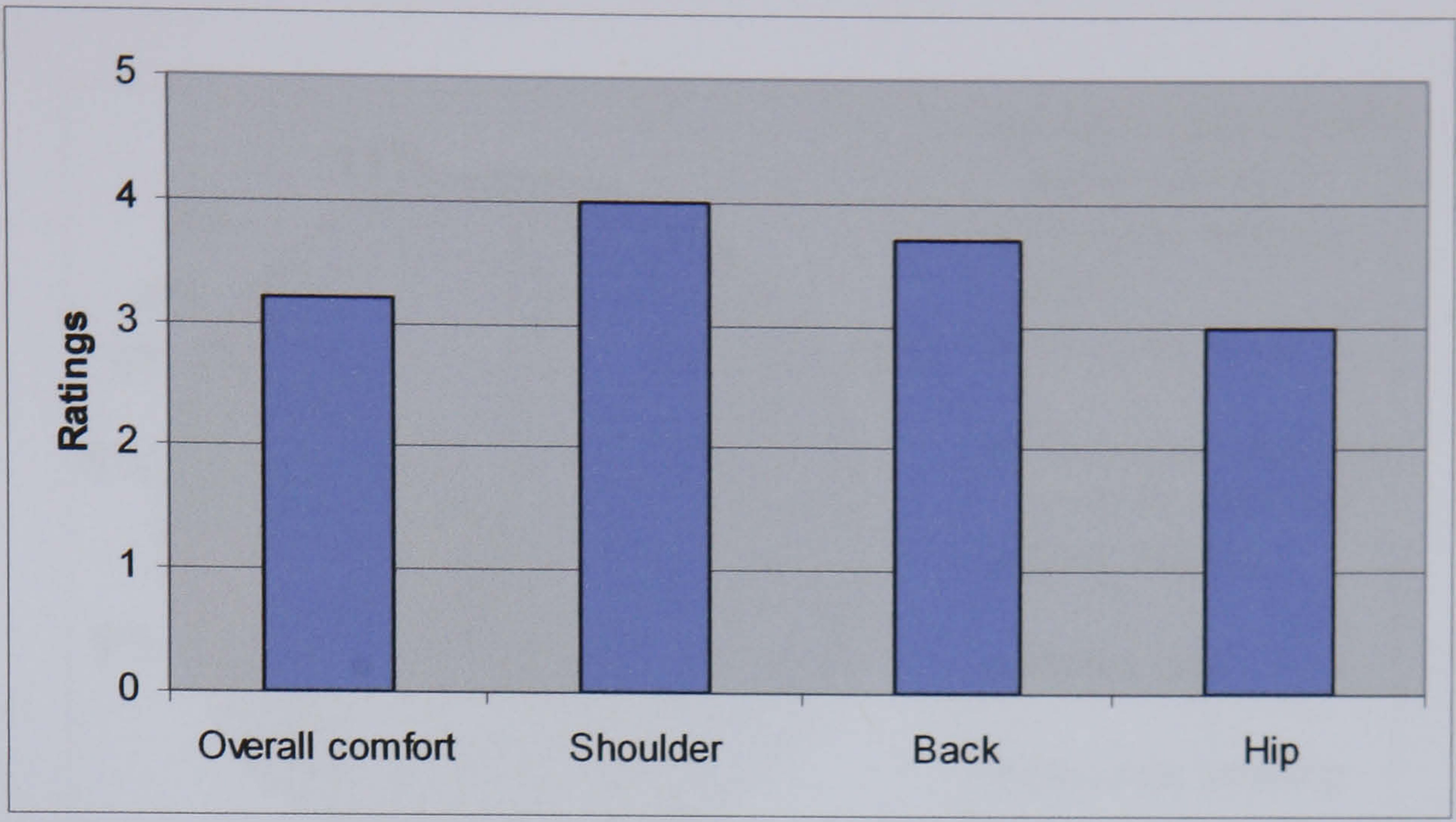



**Figure 3.5 Mean comfort ratings for the Bergen LCS**

In terms of comfort ratings all indicate discomfort with the shoulder and back rated as 'very uncomfortable' and 'uncomfortable' respectively. This supports the findings of zones of injury and discomfort (section 3.3.4) and the participant's suggestions for improvement involving changes to the shoulder straps. These ratings highlight that a need for an improvement in comfort is required, whilst retaining the positive aspects of the system as shown in figure 3.3.

### 3.3.4 Injury and discomfort

The Bergen LCS was associated with an injury or notable discomfort to 73% of the participants; the types of injury experienced are shown in figure 3.6. 73% of participants represents a very high proportion of the sample; one important point to consider though, is whether these injuries are a result of the Bergen LCS design characteristics or due to the heavy loads carried. Logical would suggest this more likely to be due to loading, but when considering the most frequent injuries (i.e. lower/central back rubbing, shoulder rubbing) the effect of the materials at the interfaces and the integration between the Bergen and belt webbing must be important. This highlights the need for design improvement. If injury/discomfort can be reduced via advances in design this would be a major advantage.

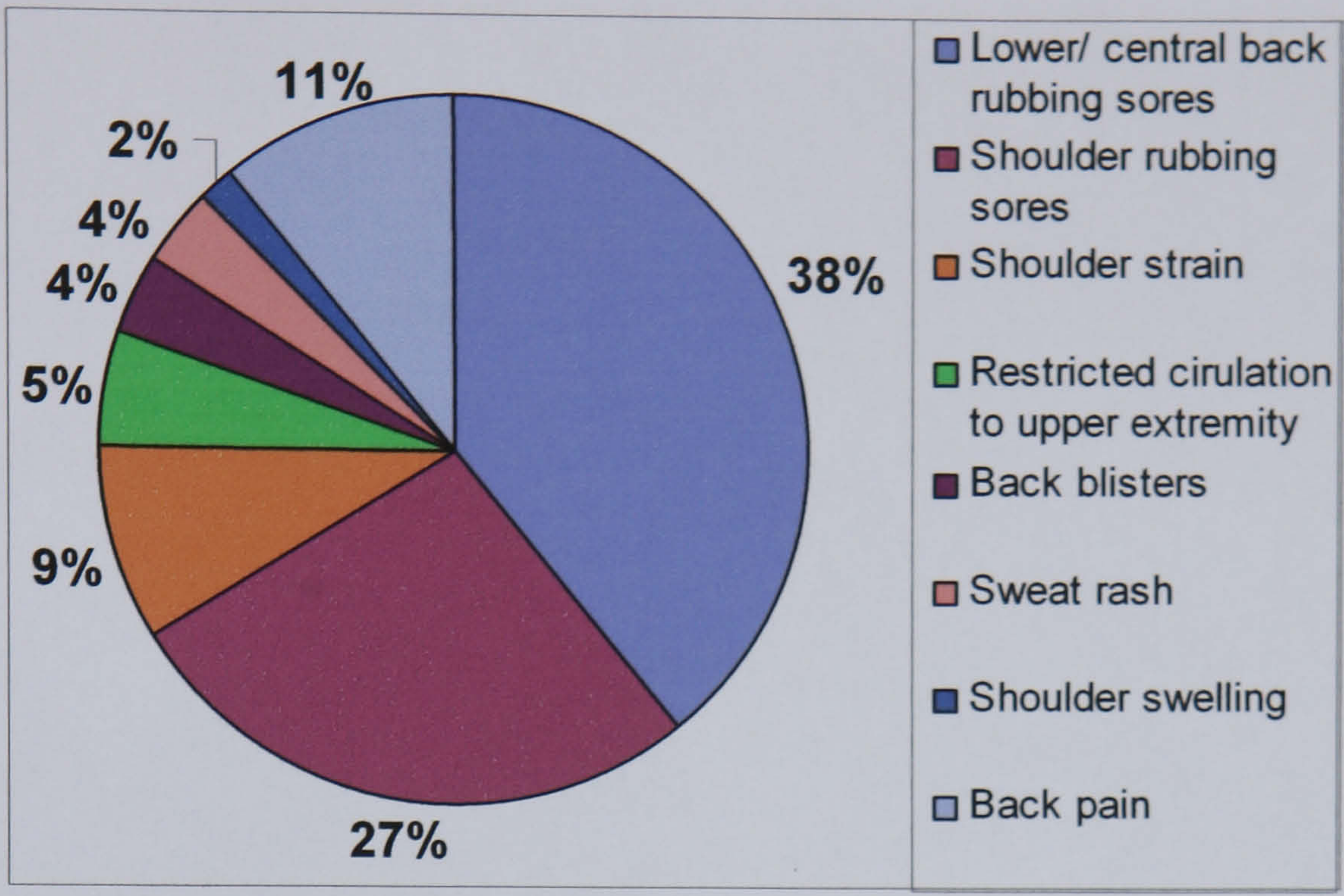



**Figure 3.6 Types of injury occurring when Bergen LCS was worn**

Typical duration of injuries were reported as; back blisters lasted for 1 week, shoulder strain 1 to 2 days, sweat rash cleared up straight after pack was removed and lower back rubbing sores healed after 1 week. It is interesting to note that of the 25% of participants who purchased a commercial backpack, there were no reports of any injury whatsoever. This may indicate that the advanced design and materials creating 'state of the art' straps and also adjustable back systems as found in commercial backpacks have a positive effect on injury. This fact would be supported by Martin (2001) who found that when comparing a standard 90 pattern Bergen with a commercial pack, peak pressure was significantly less at the shoulder interface and subjective comfort ratings were significantly better for the commercial backpack.

**Figure 3.7 Typical abrasions to the lower back after a 20 hour march**

Figure 3.7 illustrates typical 'Bergen burns' as experienced by those carrying heavy loads over long distances (in this case 27kg over a 20 hour march). This may suggest that the inadequate hip belt combined with the hard 1000 denier Cordura material covering the back portion of the Bergen may be linked to these injuries. The really interesting point is that these injuries are still prevalent even when the lower back has been heavily strapped (white residue is glue from the zinc oxide tape used by military to provide protection from rubbing).

**Figure 3.8 Injury to the upper back and scapulae after a 20 hour march. Prominent sores can be seen where the scapulae edges interface with the back of the Bergen.**

Figure 3.8 shows injury to the upper back with large sores present on the scapulae, also sweat rash can be seen in the central mid-back. The sweat rash is caused by a lack of airflow across the back, resulting in a sodden shirt constantly rubbing against damp skin. Whilst the findings suggested the sweat rash is relatively short lived and is alleviated upon removal of the Bergen and drying of the skin, whilst present it can be very uncomfortable. These injury/discomfort findings obviously feed straight into improvements the participants wish to be made to the Bergen. When asked for improvements they wished to see made, the most common ones were; increasing the amount of padding within the shoulder and waist straps, widening the shoulder straps, altering the back system so that ventilation is improved, adding more external pouches to the front of the pack allowing easier access to essential kit items, and introducing on opening at the base of the Bergen for 'lower' kit access. It is important to note the combination of comfort and practicality improvements, linking into Haisman's statement that "the load that a soldier carries will always be a compromise between what is physiologically sound and what is operationally essential" (1988). New LCS designs must incorporate what is practical and what allows increased comfort.

## 3.4 Summary

The subjective findings of this chapter combined with the findings of Martin (2001), Knapik et al (1996) and Wilson (1987) (as highlighted in chapter 2) provide support for the need to improve the current British Military LCS. The findings also highlight the need for continued subjective feedback during any trial of a LCS. Even though it has been shown that interface pressure data can be used to predict subjective comfort (Martin, 2001) what is obviously not gleaned from pressure measurements is what other aspects of the LCS are important. As mentioned in this chapter any advance in LCS must be a compromise between improvements in comfort and what is practical and functional.

An important consideration to include here with regard to any new LCS is the issues surrounding supply and correct use of LCS's within the British Army. Observations made during the collection of subjective views in this chapter highlighted problems with supply of equipment. A distinct lack of supply would appear to exist with the standard infantry units, whereas the Special Forces (with their own equipment budget) are better supplied. It could be argued that supply must be tailored to those groups utilising the equipment the most, but if true advances in injury risk and increase in comfort and performance are the aim, then all end users must have supply of any new issue LCS. Correct use is also important, end users will need to be informed of any new LCS, the reason behind the design changes and the correct method of use. This has particular relevance to the correct fit of shoulder and hip belts, as if fit is not considered the advantages determined during experimental research (where LCS are worn correctly) may not be felt.

## 3.5 Prototype LCS

A new design LCS was created with the thesis sponsors (DLO) by considering issues highlighted by this chapter, the findings on appropriate materials by Martin (2001) and findings from scientific research (chapter 2). This new design termed the 'Airmesh LCS' is the subject of the laboratory and in-field trials (chapter 6 and 7) where it is compared against the standard issue 'Bergen LCS' in-field in terms of interface pressure measurements from the shoulder and hip and also subjective comfort ratings and feedback. The new 'Airmesh LCS' is illustrated and detailed in chapter 5.4.1.

# Chapter 4: Development of the 'In-Field' Pressure Measurement System

## 4.1 Introduction

One of the main aims was to record pressure data from military personnel, carrying military loads and in military scenarios. The 'ideal scenario' being a system which can be 'worn' by the participant, i.e. the pressure sensors, connecting devices and data capture/triggering device can all be placed on or around the person or inside the LCS itself. If this system can be wireless and also provide remote triggering of data capture, then the experimenter would simply be able to follow the participant around a pre-determined field course or military exercise and trigger data capture at set points. The data capture can be synchronised with subjective ratings in order to provide insight into pressure values and also perception of pressure and thus discomfort. This chapter covers the pursuit of this 'ideal scenario' via the identification and fabrication of suitable equipment, and developing appropriate measurement techniques.

## 4.2 Characteristics of the In-Field system

The review of scientific findings (chapter 2) combined with the requirements for making measurements in-field has lead to a list of characteristics which any suitable measurement system must conform to. Firstly the sensing part of the system must be thin enough not to be detected by the participant or to effect the pressure distribution by its own presence. Ferguson-Pell (1980) has specified values for this thickness, recommending that the sensor be no thicker than 0.5mm. Secondly the diameter of individual sensing cells must be small enough to ensure that they follow body contours well and are not affected by the changing body surface. Ferguson-Pell (1980) suggested that these cells be no larger than 14mm in diameter. The sensing cells must be able to conform to the body contours around the shoulder and hips whilst still being able to measure the presence of pressure.

Thirdly the surface area of the whole sensor must be large and malleable enough to provide good coverage of the interface between the shoulder and hips and the corresponding LCS straps. In this respect a 'pressure mat' type of sensor would be most suitable, which is composed of many sensing cells enabling a large surface area for coverage. Ideally the whole of this interface needs to be captured in order for pressure to be assessed most effectively. If the sensor provides coverage for the whole of the interface this will enable the identification of peak pressure zones and even zonal pressure loading throughout the gait cycle.

Fourthly is the importance of how pressure data is captured and whether it can be easily transported to standard software such as Microsoft Excel and SPSS for data extraction and analysis. It is paramount to have a system which provides adequate links for this and does not simply provide a real time indication of pressure. Unfortunately many measurement systems with suitable sensors do exactly this as they are frequently used in a clinical setting to give an indication of in-shoe, prosthetic and seating pressures during consultation with a medical practitioner. Whereas industrial measurement systems do provide very good software packages and cater for data handling, these systems often use unsuitable sensors.

Finally in order for in-field measurements to be made the equipment obviously needs to be (or at least be easily made) portable. The system must be able to be linked to a data logger or portable computer, be powered by battery or direct from a portable computer, be unaffected by changes in attitude, vibration and shock (associated with walking) and be light weight enough to be transported by the participant or possibly the experimenter. The equipment must have a sound and reliable calibration process, or at least be possible for one to be developed and also the system must be capable of sampling at a frequency fast enough to capture pressure change at the interfaces.

## 4.3 Manufacturers of pressure measurement equipment

There are four main manufacturers of interface pressure measurement equipment which may be of use directly or via development for in body-LCS interface pressure measurement. These are 'Tekscan', 'Entran', 'Honeywell' and 'Talley'.

### 4.3.1 Tekscan™

TekScan are an American company based in Boston, Massachusetts. USA. Tekscan actually first began with their *TScan®* Occlusal Analysis System in 1988. This system was designed to be used by Dental practitioners for assessing bite characteristics of patients. Since then Tekscan has advanced on many fronts to improve its basic solution and extend its application to a wide variety of industries. The Queen's University Ergonomics Research Group, Canada has produced several papers where they utilised the Tekscan system for pressure measurement on mannequins dressed in different LCS's (Bryant et al. 1996; Doan et al, 1998 (1); Doan et al, 1998 (2); Johnson et al, 1998). The Tekscan system was also utilised by Martin (2001) for pressure measurement at body-backpack interfaces.

At the heart of each Tekscan system is a patented tactile force sensor. Tekscan manufactures both matrix-based pressure measurement sensors and single element force sensors each being a thin, flexible device utilizing conductive and semi-conductive inks (as shown in figure 4.1). In Tekscan's matrix-based sensors, a matrix of electrically conductive rows and columns are used to form a pressure measurement sensor. By separating the rows and columns with a material that varies its electrical resistance with applied force, each intersection becomes a force sensor or load cell. Each cell is electronically scanned and the change in resistance at each load cell location is measured to determine the magnitude, temporal characteristics and location of forces on its surface.

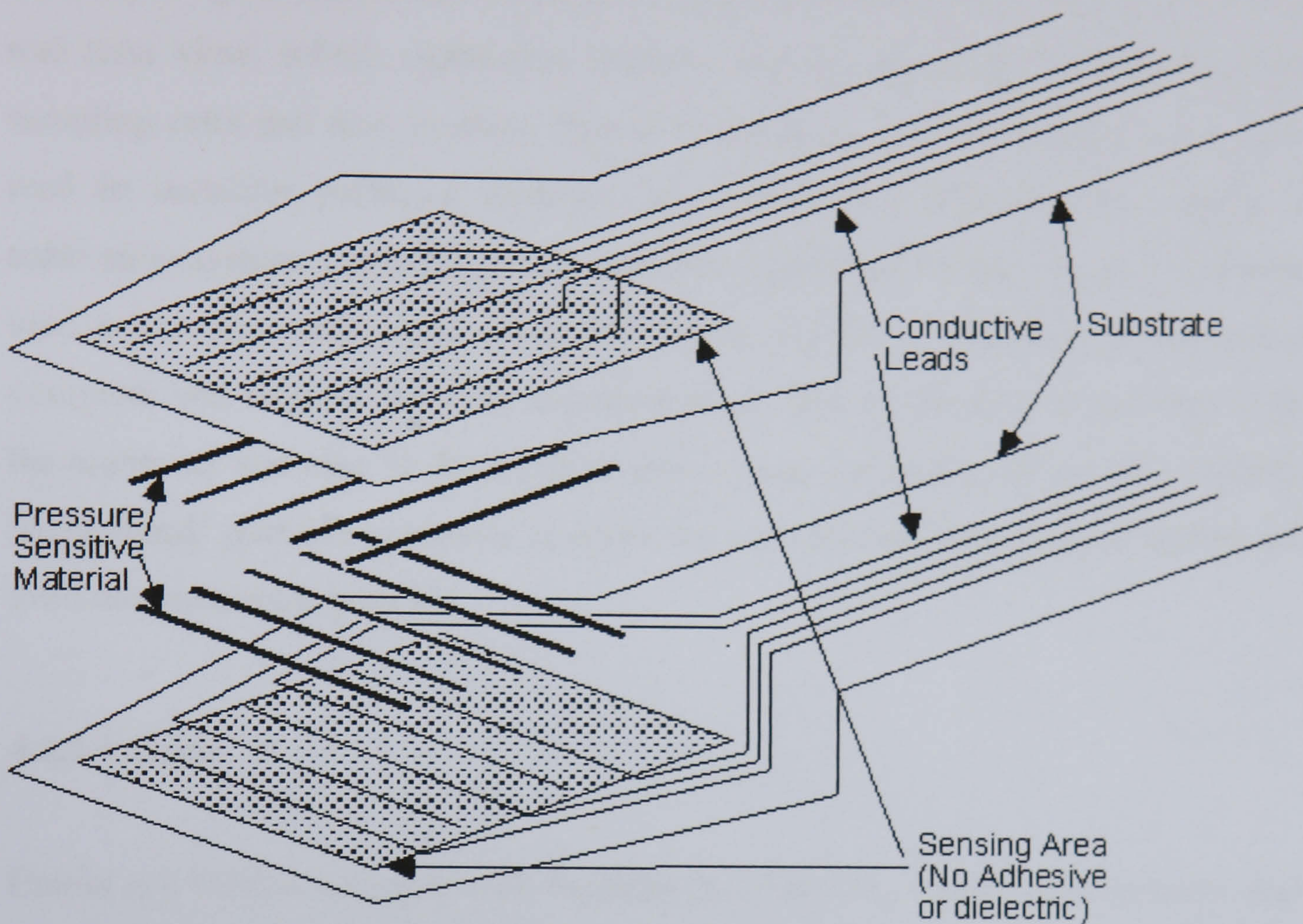



**Figure 4.1 A diagram to illustrate the structure of the Tekscan sensor**

Matrix-based sensing technologies are unique in that they have a separation (electrical isolation) between sensing and non-sensing areas. Knowledge of this spatial dimension allows the system to convert and display the local force data as a pressure profile. Tekscan's sophisticated design capabilities allow for the design and manufacture optimal resolution sensors for individual applications, optimizing the system accuracy for the measurement circumstances. However, this design and manufacture process is extremely costly, and was not utilized by either Martin or the Queen's University Research Group.

The Tekscan technology satisfies all of the requirements for the In-field pressure measurement system. The sensors are very thin (0.1mm) and due to this are extremely malleable and designed specifically to follow body contours. The sensing cells are of a suitable size (according to Ferguson-Pell's recommendation) at 7mm. The surface area provided by the matrix sensors gives good coverage of the body-strap interface. The Tekscan software allows for many options such as a real time view, inbuilt calibration process, remote triggering, sufficiently high sampling rates and also pressure data is exported as ASCII file type and can be read in common packages such as Microsoft Excel. Tekscan also supply a calibration system, consisting of an inflatable calibration bladder to apply uniform load across the sensor and cells. The whole system is designed to run via a computer and requires only the existence of an ISA connection to interface with the computer and also to draw power from. Thus, the identification of a suitable 'ruggedised' portable computer (suitable for in-field use) would make mobile in-field measurements possible.

### 4.3.2 Entran

Entran is a Global company with facilities in USA, UK, France and Germany and specialise in the production of pressure sensing equipment for industry. They have no specific sensor range designed for human assessment. Entran offer two types of sensor; stainless steel and silicon. These sensors are metal transducers of varying shapes and sizes, from industrial and automotive through to sub-miniature. The original Entran stainless steel sensor most closely suits the requirements for the in-field setup with the diameter being 11mm (less that Ferguson-Pell's suggested 14mm limit), however the sensors are thick and at 4.5mm are way above the suggested limit of 0.5mm. Having a solid metal sensor under the shoulder strap would undoubtedly affect the pressure distribution and cause discomfort to the participant.

Also, the Entran sensors are all separate entities. there does not exist a sensor matrix (as with Tekscan) and thus the coverage area is very small. The only way to achieve good coverage of the body-strap interface would be to arrange multiple sensors under the strap but this would further amplify the problems caused by their thickness. The sampling rate of the sensors is more than adequate however and although there is no specific software provided, data can be extracted in a meaningful form compatible with most analysis software and calibration can be achieved through fabrication of a device to apply known loads on the sensor. Data collection for the Entran system is via short range radio telemetry from the sensor itself to a compatible computer. Whether this computer could be carried by the participant and whether remote triggering can be employed would be subject to in depth development work and writing specific software and thus may be costly, complex and time consuming.

### 4.3.3 Honeywell

Again as with the Entran products, Honeywell provide stainless steel and silicon sensors and are mostly concerned with industrial applications. They do however have sensors for use in the medical industry such as sensors specifically designed for use with respiration, dialysis and infusion pump equipment. But obviously these sensors are concerned with monitoring the function of medical devices, not for making measurements on humans themselves. There are only two types of sensor which Honeywell provide which match any of the in-field requirements; these are termed 'CPC' and 'CPX'. Whilst the diameter size is suitable (10mm) their thickness (3mm) is beyond the recommended limit. Again as with the Entran sensors Honeywell do not offer a sensor matrix and thus multiple individual sensors would need to be utilised. A further negative of the Honeywell equipment is that they are more of a part, rather than a systems supplier. Thus, a whole system for connecting, controlling and capturing data from the sensors would need to be fabricated, this fact on top of the other downfalls as highlighted in this section more or less rule out the Honeywell equipment as a viable measurement tool for the in-field work.

### 4.3.4 Talley

The Talley pressure measurement system has been rated highly by the literature. Ferguson-Pell & Cardi (1991) performed an evaluation of systems designed to measure pressure at body interfaces and they concluded that the Talley system produced the most accurate and reliable results, being especially resistant to data drift and thermal sensitivity. The Talley system utilises a different technique to that of Tekscan and also Entran and Honeywell. The Talley system works via pneumatics consisting of an air cushion/sensor connected to an air reservoir, the theory behind this being that changes in applied pressure to the air cushion/sensor will lead to a change in pressure inside the air reservoir. This pressure change inside the reservoir is measured and the interface pressure calculated from this. The Talley system was originally designed to assess the pressures in seating, and has been utilised heavily by the car seat design industry.

However in terms of suitability for the in-field system, the Talley sensor diameter (20mm) is larger than that recommended by Ferguson-Pell (1980) for peak pressure analysis. Also, whilst the Talley system does utilise a matrix of cells within the sensor, the distance between these cells are between 80-100mm and thus any peak pressures within this distance will not be directly detected. Whilst the sensor could be moulded around the shoulder and hip interfaces a major proportion of the interface would not be measured. Also a significant issue with the system is that if the sensor is moulded around these interfaces the bending of the sensor would register as pressure (due to the air setup) when it was not even present. The Talley system does not employ a specific software package to collect and control measurement, instead pressure measurements are shown real time with a reading displayed on the air reservoir. Finally the Talley system was designed for static loading assessments and has a low sampling rate, making it unsuitable for dynamic assessments.

### 4.3.5 Conclusion on suitability of available measurement systems

The only available equipment to match closely the needs of the in-field system is that supplied by Tekscan; the reasons for this being clearly highlighted over the previous pages. The fact that Tekscan has been utilised before to make similar measurements both on humans (Martin, 2001) and on mannequins (Bryant et al, 1996; Doan et al, 1998 (1); Doan et al, 1998 (2); Johnson et al. 1998) provides further support for adoption of the Tekscan measurement system.

## 4.4 Tekscan specification

Tekscan were approached with the requirements for the in-field system and asked to provide an equipment solution. Tekscan identified the need for software and hardware. Firstly, Tekscan provided an ISA type interface card which could be connected to any computer with ISA slots. This ISA card controls the intermediary units (connected via cable, which in turn receive data from the pressure sensors) and provides the interface with the computer and Tekscan software. Secondly, to drive the ISA interface and also provide additional functionality a Tekscan software package named 'IScan' was required. The IScan programme can be configured to allow external triggering (this fact is referred to in section 4.4.2). This remote triggering is catered for by a feature called 'ASR' Automatic Sequence Recording. ASR functions to start recording, saves all data to the hard disc drive and then primes the software for the next recording. This enables the in-field system to be truly mobile, otherwise the experimenter would need constant access to the computer in order to manually trigger and save each pressure recording.

### 4.4.1 Identification of a 'ruggedised' portable computer

The Tekscan software and hardware provide for the requirements of the in-field system, allowing remote triggering and are capable of measuring pressure during in-field conditions. However, to make the system mobile a 'ruggedised' portable computer is required to control Tekscan and collect data. The 'ruggedised' machine has to be able to function normally when exposed to shock during walking over uneven surfaces, (i.e. a field course) has to be resistant to knocks and accidental dropping, needs to be dust and waterproof, to have the facility for an ISA card connection and have sufficient battery power to last a days testing without the need for recharging. A search was performed on these grounds in order to identify a suitable device and two companies appeared to offer a machine to suit, 'Dolch' and 'Terralogic'. The two machines in question were the Dolch NotePAC II and the Terralogic ToughNote Series III (shown in figure 4.2 & 4.3).

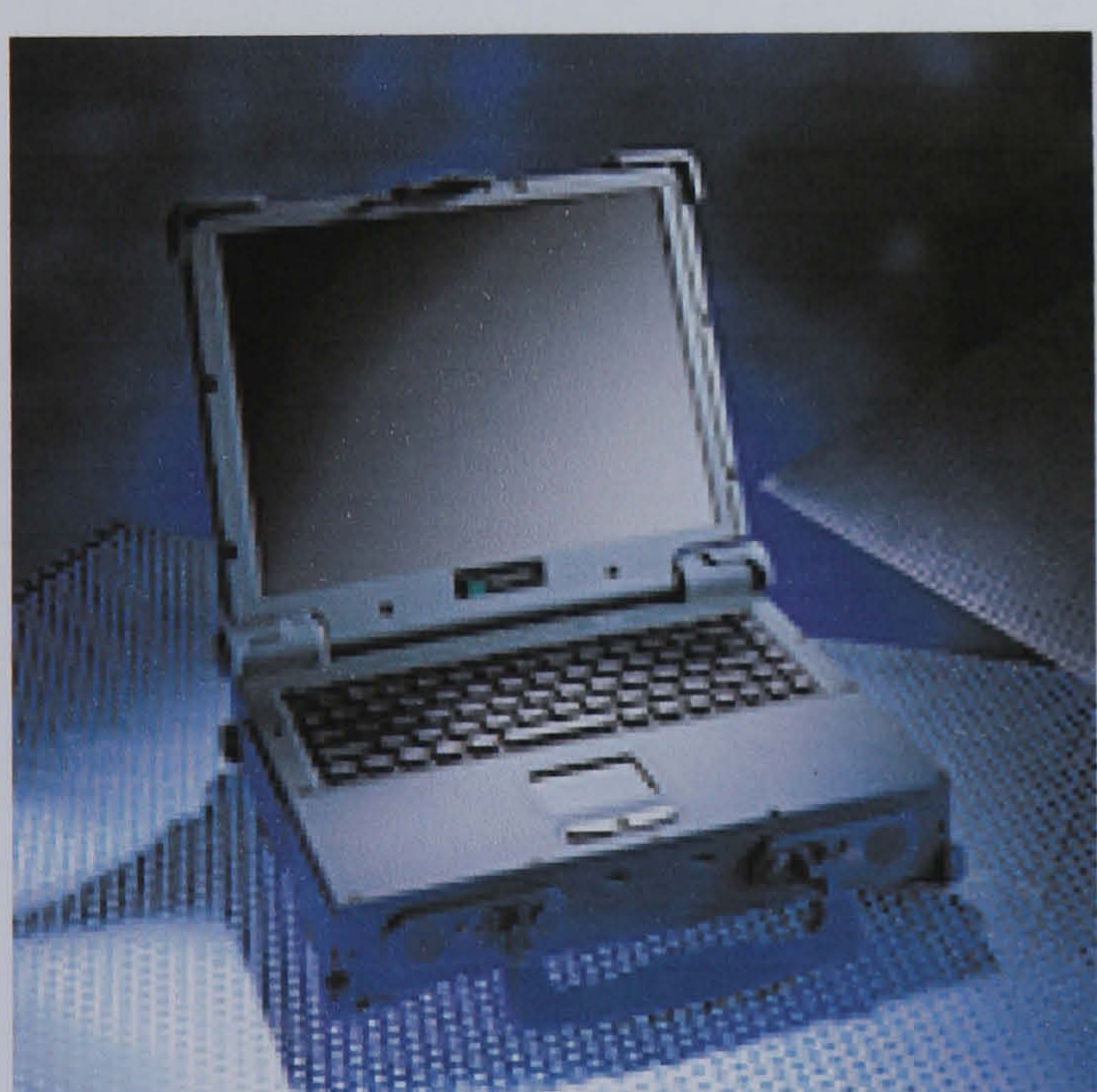


**Figure 4.2 The NotePAC II**

**Figure 4.3 The Toughnote Series III**

Both of the machines offer the same aluminium case construction, rubber side protection mouldings, hard disc drives mounted in a shock absorbent sealed cartridge, and the option for multiple batteries. Subsequently Dolch and Terralogic were approached to provide a solution and quote for the specific requirements of the in-field system. Both companies replied with similar costing, but only the

Dolch NotePAC II had the facility for ISA card connection. Being as this factor was paramount the Dolch machine was investigated further. The manufacturers claimed that it is completely sealed from intrusion by water, salt laden air, and blowing dust and dirt and that its high-strength case and shock mounted components form a portable platform that can withstand a 15g operating shock load and a 50g non-operating shock load. It is stated that the machine can withstand a 3 foot drop onto concrete and still write to the hard disc drive.

In order to test these claims and the machines suitability a demonstration unit was provided. A simple initial test was then undertaken. The machine was connected to the Tekscan equipment and the software was set to continuously record pressure. The machine was then placed inside a backpack with a pressure sensor placed under the shoulder strap. A participant then donned the backpack (with a 15kg load) and carried out a 30 minute walk over varying terrain (asphalt, grass, mud and sand). During this time stationary, walking and sprinting phases were carried out, also climbing under and over obstacles (walls, gates, fences and railings). Three participants took part, thus totally 90 minutes of recording time. Upon returning back to the laboratory it was found that during the 90 minutes there was no data loss at all. Pressure was recorded throughout. Subsequently a number of drop tests were then carried out, including the infamous 3 foot drop onto concrete! Again the machine performed impeccably with continuous data recording and no errors with the hardware or software. Subsequently the Dolch NotePAC II was purchased.

### 4.4.2 Fabrication of the external 'trigger'

The requirements for the in-field system specify a need for an external trigger in order that participants are unhindered and so that data collection can be timed to specific points around a field course or exercise. As mentioned earlier the IScan software has a facility to enable triggering of recordings (ASR) via the serial port on the computer. The aim was to manufacture a small radio telemetry trigger system, consisting of a receiver (connected to the serial port of the ruggedised computer) and a transmitter (carried by the experimenter). Radio telemetry was the desired means of communication as this enables the experimenter to be a sufficient distance away from the participant and allows the computer to be placed inside the backpack. If infra-red communication was utilised this would obviously require a 'line of sight' between the transmitter and receiver and thus the experimenter would have to be very close to the participant with the IR port on the computer exposed. The radio telemetry trigger was manufactured. The device consisted of a receiver which could be placed inside the backpack and a small aerial to receive signals from the transmitter. The aerial was fixed to an extending arm which allows the receiver box to be inside the backpack, with the aerial being outside of the pack. The transmitter was a simple 'remote car key type' fob which the experimenter could easily carry around in the palm of the hand. Figure 4.4 illustrates the trigger and associated in-field equipment.

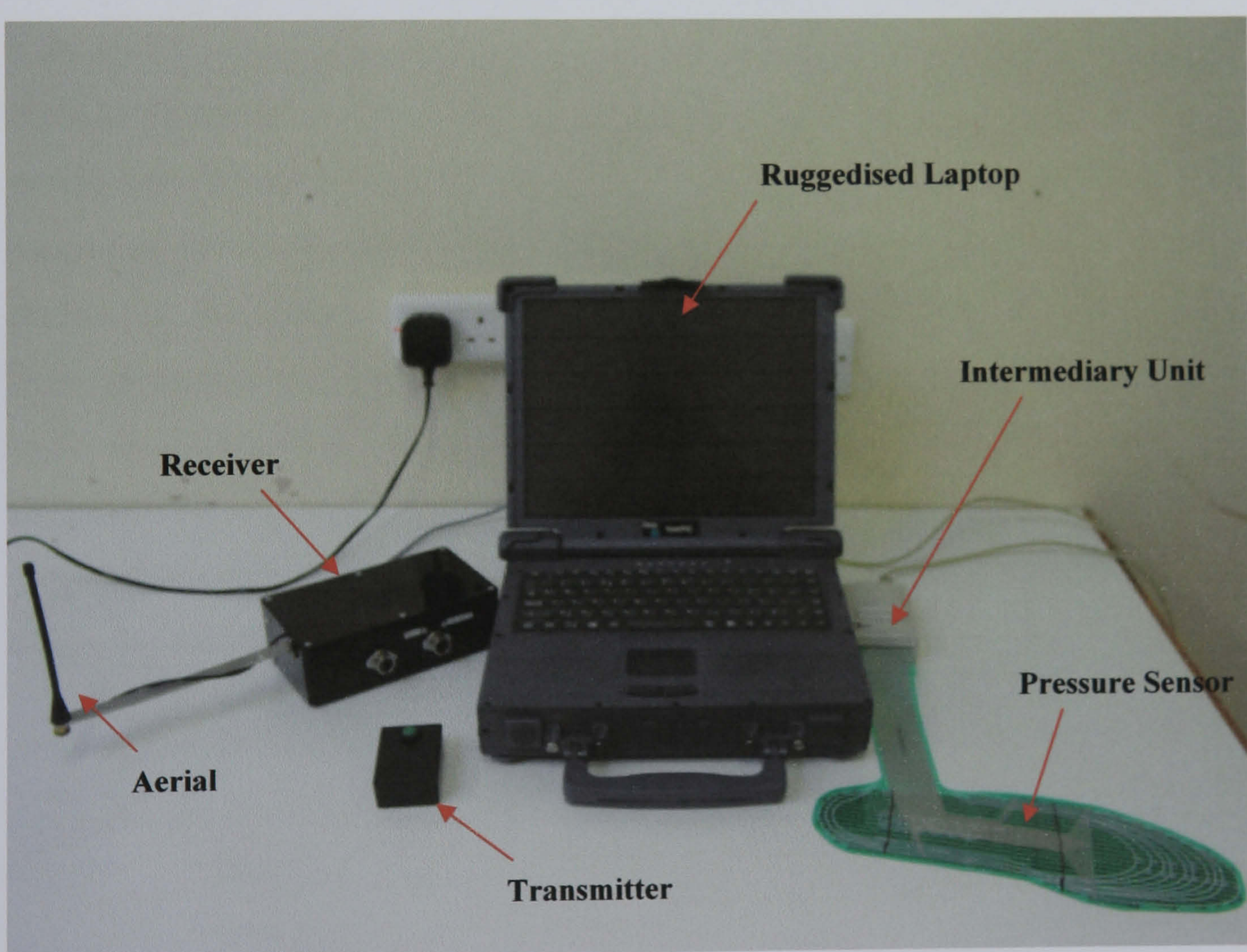



**Figure 4.4 The remote trigger and associated field equipment**

The parameters for the triggered pressure recordings are set up within the software before trialing commences. Options include: (1) one touch to record - one touch to stop; (2) one touch triggers a recording for a set duration; and (3) push and hold the key fob button and then release to cease recording. For the in-field system it was of paramount importance to make sure that all the recordings where of the same duration and triggered at the same points during the field course. Thus, the 'one touch to record for a set duration option' was chosen.

When the fabrication of the triggering system was complete it was trialed on the same course as was the Dolch computer, again three participants completed the course carrying a load of 15kg in a backpack. This 30 minute course included differing terrain, gradients, walking speeds and obstacles as found in a typical military field course. This time however set points were marked throughout the course and the triggering option was set to record for 1 second upon receiving input to the serial port from the experimenter pushing the transmitter. A 1 second period was chosen as this captured at least one full gait cycle (chapter 5.6.6). The triggering points throughout the course included all the different elements of the course (i.e. flat/inclined/declined walk and run, climbing over and jumping down from obstacles, and the differing terrains) to ensure that the system performed under in all situations, including those of high and low shock and vibration. The triggering system was found to work without error throughout. Recordings were triggered and timed correctly throughout the course and all data was captured. The triggering system was therefore accepted, ready to use for field trials (chapter 7).

**Figure 4.5 and 4.6 The trigger receiver connected to the computer (inside the backpack). The aerial can be seen prior to placement in the backpack (4.5) and in situ (4.6).**

### 4.4.3 Sensor choice

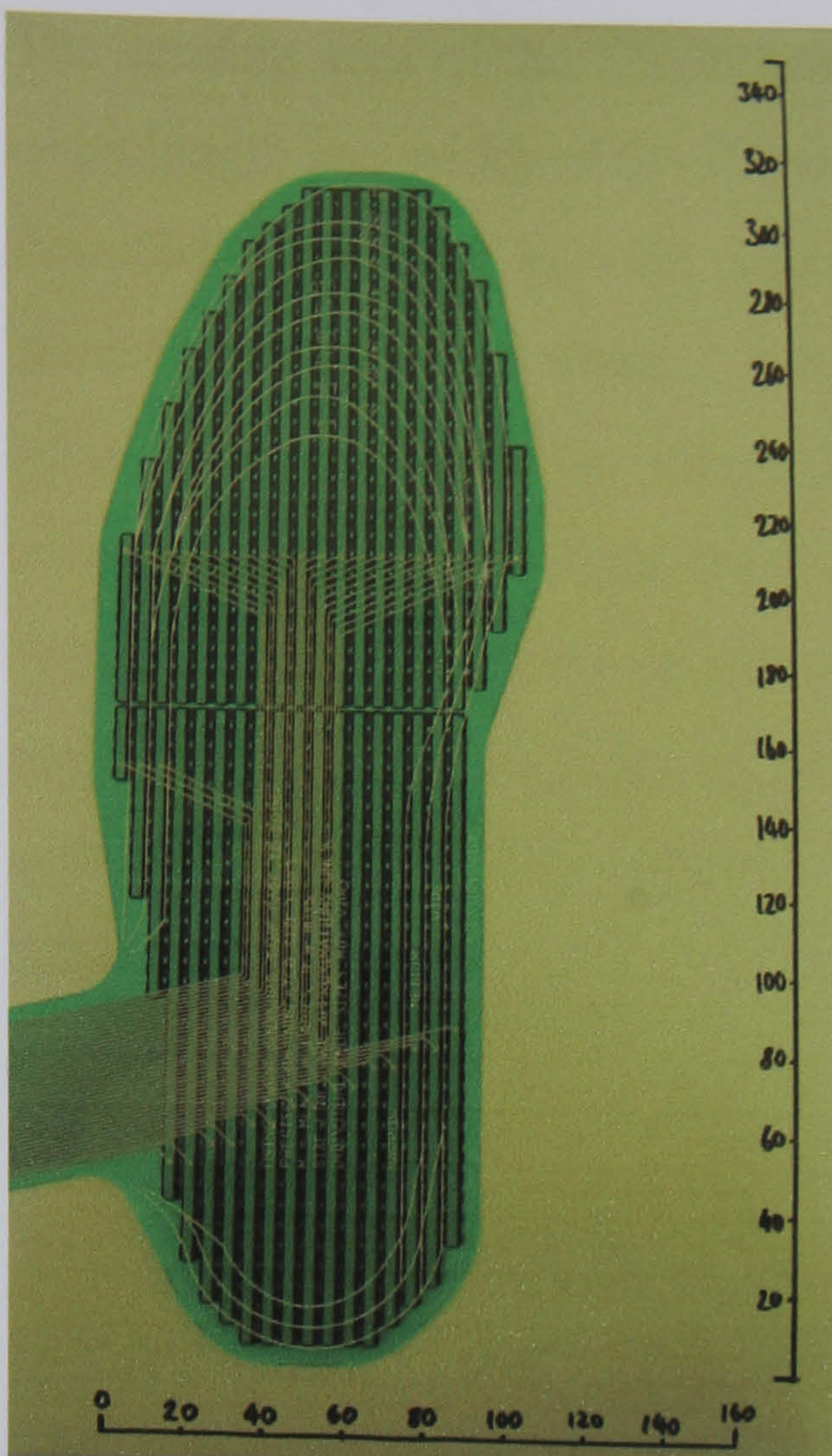
The final part of the initial development of the in-field system was the selection of the correct Tekscan sensor. Tekscan provides two different sensor types suitable for measuring interface pressure on human body surfaces. The two sensor types are termed 'FScan', and '9811'. The requirements for the in-field system highlight the key areas for the pressure sensor as thickness, cell diameter and overall surface area. Being as both sensors are of the same thickness (0.1mm) a decision was made on the two remaining factors. Also of great importance to consider is that the two sensor types are engineered to respond to a specific range of pressures and the most suitable range must be chosen.

**FScan Sensors**

The FScan sensor was specifically designed for assessing the biomechanics of physical disorders and also the effect of prostheses on human gait. A photo of an FScan sensor can be seen in figure 4.7, where the sensor's foot shape is shown. The sensor contains 954 individual pressure cells, giving a cell resolution of 3.88 cells per $cm^2$. The width of the sensing area is 35mm at the 'heel' and 105mm at the 'toe' and the length is 300mm. The maximum pressure which the FScan sensor will detect is 345 kPa and the optimum sensing range is 23 - 345 kPa.

**9811 Sensors.**

The 9811 pressure sensor is a rectangular shape (figure 4.8) and was developed primarily for assessment of pressure under handgrips. The 9811 sensor has larger cells (96 cells per sensor) and thus a significantly smaller cell resolution (0.62 cells per $cm^2$) than the FScan sensor. The sensing area is also smaller, with the length of this area being 205mm and the width 75mm. The maximal pressure detected is 517 kPa, with a sensing range of 35 – 517 kPa.



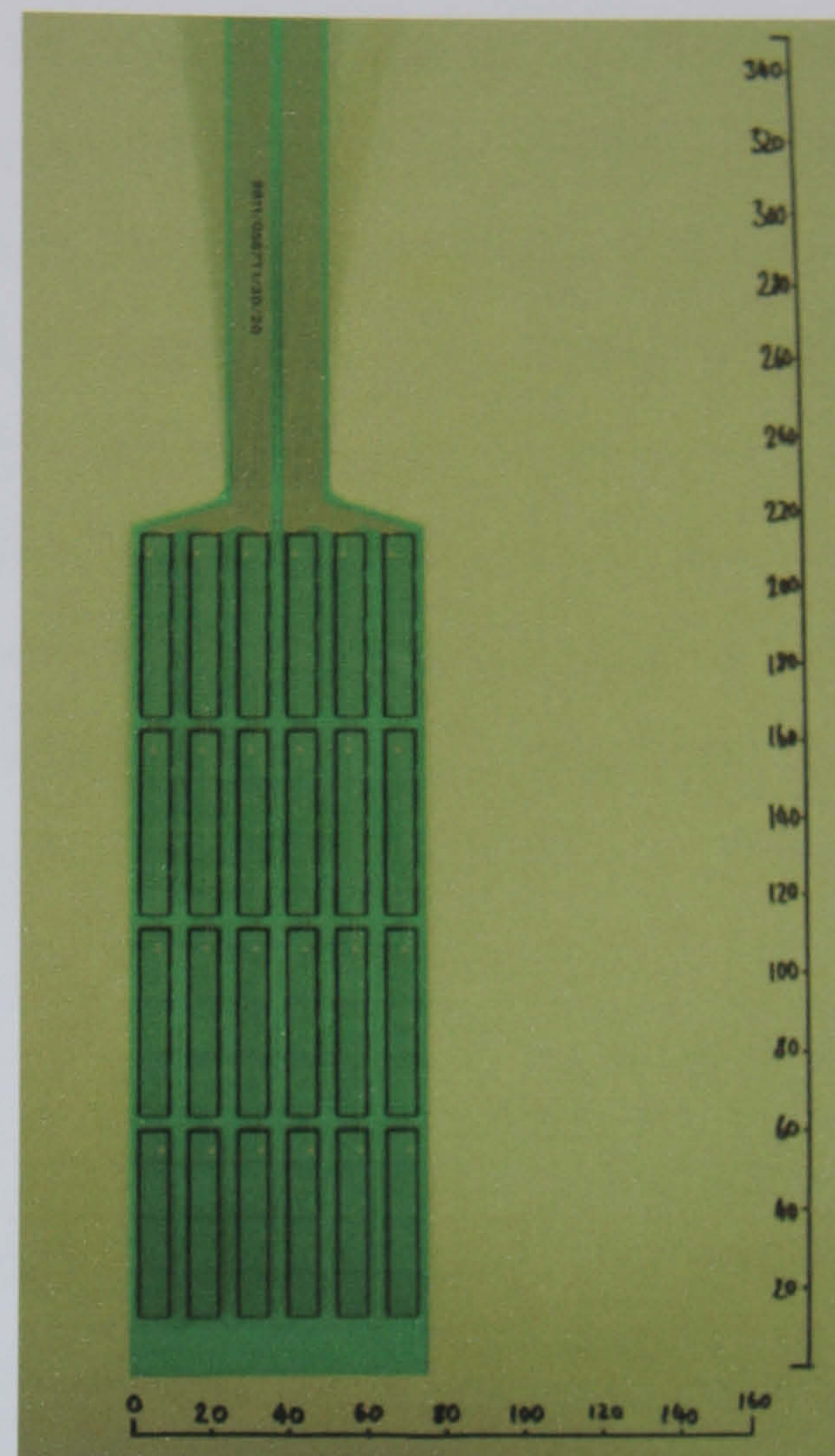




**Figure 4.7 and 4.8 The FScan and the 9811 Pressure Sensors (with mm scale).**

**Choosing the Sensor for the in-field system.**

Previous studies on human load carriage have identified an upper limit of 200 kPa under military load carriage equipment (Holewijn, 1990; Bryant et al, 1996; Doan et al, 1998(1); Doan et al, 1998 (2)). In reality most of the pressures recorded under the LCS were around a tenth of the maximum. Thus, given the pressure ranges and maximal threshold, the FScan sensor would be most suited as its maximal value exceeds the 200 kPa limit and also the sensor is more sensitive to lower pressures (23 kPa lower value compared to 35 kPa for 9811). It is important that the lower threshold be suitable otherwise much of the pressure data may not be accurately recorded.

The sensing area of the FScan sensor is an advantage over that of the 9811. The extra length and width of the FScan sensor means that more of the interface can be assessed. The 9811 is wide enough to match the area covered by a standard shoulder strap (width 60mm), but it is not wide enough to cover that of the hip strap (width 100mm). The FScan sensor is wide enough to cover the hip strap and also its added length means that the pressure across whole of the shoulder and hip interface can be captured. If the pressures across the width of the strap interfaces are not captured (due to the sensor being too thin) this obviously means that the interface may not be accurately measured. This gives support for the FScan sensor.

The final point to consider is the cell resolution. The FScan sensor has a higher resolution than the 9811, and approximately ten times the number of cells. This means that the cells are small and tightly packed together providing extremely good coverage of the interface with cell spacing being kept to the minimum (1mm maximum gap between cells). The 9811 sensor with its larger and more spaced out cells (6mm maximum gap between cells) means it is more susceptible to poor coverage and may also be affected greatly by curvature (curvature issues are described in chapter 5.3.3).

The areas discussed in this section provide support for the use of the FScan sensors with the in-field system. They provide the most suitable pressure range, the largest coverage area and the greatest cell resolution. Also, the fact that Martin (2001) also utilised FScan sensors and found them to be reliable and glean valuable data provides further support for their use here. The elements of the in-field system are now all together, the next chapter discusses the validation of this system for a full scale in-field military trial.

# Chapter 5: Experimental Methodology

## 5.1 Introduction

There are three parts to this chapter. Part I details a number of baseline studies with the Tekscan equipment looking at reliability, validity and suitability for in-field measurement. Part II describes the experimental equipment utilised, from backpacks and LCS's, to weights and loading devices. Part III then details the final chosen methodologies for both objective and subjective measures. Due to the fact that Martin (2001) was the first to develop the Tekscan system for interface pressure measurement of military LCS's, a wealth of background research concerning the accuracy, reliability and validity of this approach has already been undertaken. The aim of this chapter was not to 're-invent the wheel' via the replication of already conclusive research, but to consider areas associated with in-field measurement. Martin's background research is frequently referenced however, as it forms part of the basic understanding for this chapter.

## PART I - Baseline studies

In order to develop suitable experimental methodology for in-field interface pressure measurement, a number of baseline studies with the Tekscan equipment and the in-field system were performed.

## 5.2 Calibration and Equilibration

With all purchases of the TekScan equipment a calibration box and equilibration software are supplied. TekScan highlight the need to prepare the sensors correctly in order to capture meaningful data from pressure recordings. This preparation phase involves two processes – Equilibration and Calibration. Equilibration is carried out first, followed by calibration of the sensor via known pressure values applied to the sensor by the calibration box.

### 5.2.1 Equilibration

TekScan recommend the equilibration of sensors before each usage in order that any differences between the pressure cells are controlled for. These differences in cell pressure sensitivity are due to the method of manufacturing, the use of conductive and semi-conductive inks, and also variations in pressure exposure. It is therefore paramount that all cells are equilibrated (set zero) and then calibrated in order that pressure data recorded be accurate. Equilibration is achieved by placing a sensor inside the calibration box. This device consists of an air bladder sandwiched between two pieces of 4cm thick wood, inside a metal framework (figure 5.1). This provides a rigid casing around the air bladder ensuring that when inflated a uniform pressure is applied across each cell on the pressure sensor.

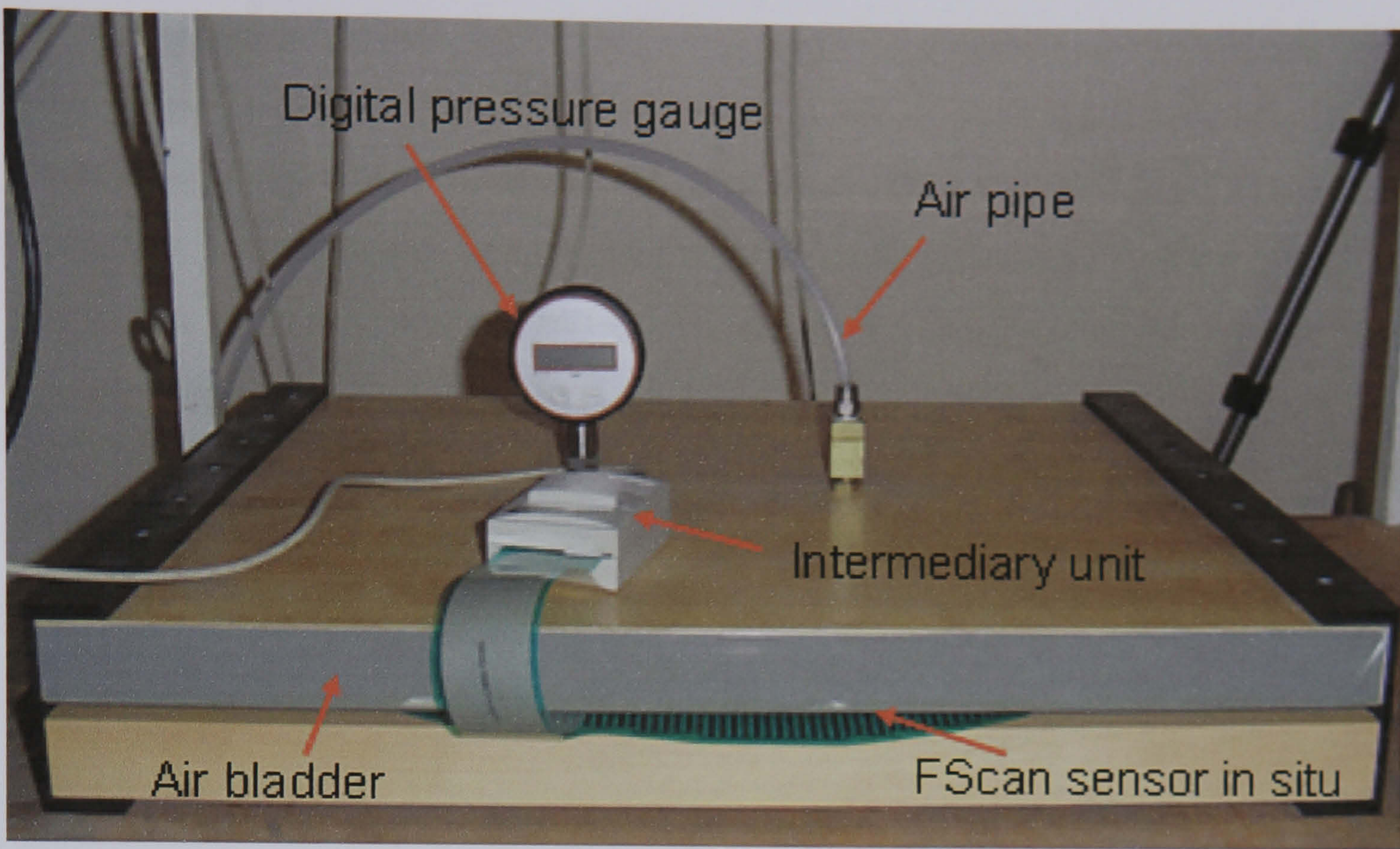



**Figure 5.1 The TekScan calibration device.**

When the pressure is applied the TekScan software detects feedback from each of the cells on the sensor, these cells are then 'zeroed' within the software so that they are all showing equal output. Equilibration is also an important mechanism as it detects faulty cells. Cells which are non-responsive are highlighted by the software. If the presence of faulty cells is apparent a new sensor can be selected.

### 5.2.2 Calibration

Tekscan include calibration equipment with the FScan system. This equipment consists of the calibration box (figure 5.1) and software inbuilt into the FScan program. Calibration is achieved by firstly equilibrating the sensors (section 5.2.1) and then applying a known pressure across the sensor. The calibration software is then run; the calibration line is plotted based on the known applied pressure and the output without any applied pressure. The software then converts the raw data coming from each cell in standard units of pressure (i.e. kPa, psi, etc). The Tekscan calibration system has been found to be both accurate and reliable with the FScan sensors maintaining calibration values (<1% error) for up to 3 hours of sustained pressure (Martin, 2001). The accuracy of calibration over time by test-retest methods at three known pressures was assessed. Five brand new FScan sensors were used, all being equilibrated and calibrated via the Tekscan equipment. The calibration box was then used to apply pressure at 34.5, 68.9 and 103.5 kPa. The test was performed for six hours duration. taking pressure measurements at 5, 30, 60, 180 and 360 minutes. The results (mean pressures ± SD) from this study are shown below;

| | 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 |

**Table 5.1 Results from calibration study (taken from Martin, 2001).**

As the table shows pressure readings were both accurate and constant up until the 3 hour mark, with measurement error equating to less than 1%. Subsequent statistical analysis (via repeated measures ANOVA) found the difference in measurement to be non-significant. When considering accuracy over the 3 hour mark, an increase in error from <1% - 7% occurred, resulting in significant differences (as indicated by ANOVA). In conclusion, the FScan sensors measured pressure with less than 1% error at three different known values, and maintained this reliably for up to 3 hours with a single Tekscan calibration. Hence, measurements over the 3 hour period should not be made without recalibration of the sensors.

One important consideration to make with regard to calibration is how closely the calibration condition matches the measurement condition. The materials used to construct the calibration box (wood, metal and plastic) obviously differ greatly from the material of the human body at the interfaces where pressure measurements will be made. There is also a difference in terms of the calibration box being a flat surface, whereas body surfaces show curvature. However, due to a lack of an accurate on-body calibration system, the calibration box represents the most suitable device available. There may be an issue here surrounding the absolute accuracy of pressure measurement, i.e. it could be argued that sensors calibrated off the human body may not make accurate measurements when recording pressure on the human body. However, the work of this thesis is involved with comparisons between different load carriage equipment, rather than seeking to define absolute pressure values at the interfaces. Therefore, if the reliability of the pressure measurement is high (section 5.8) and this issue is considered in interpretation of results this should not affect any conclusions made.

Being as the experimental work of this thesis shall not extend beyond 30 minutes duration the findings on the accuracy of the calibration process provide strong evidence for utilising the Tekscan calibration process. Tekscan recommend calibrating the sensors toward the maximal end of the range of pressure values expected to be recorded. This maximal value process was utilised by Martin and found to produce accurate readings (2001). In conclusion, for the experimental work of this thesis, given the highly conclusive findings from previous research, and considering the issue surrounding measurement accuracy, the Tekscan calibration process was adopted and used throughout.

## 5.3 Sensor Methodology

There are a number of issues with regard to the use and functioning of the FScan sensors which need to be considered before the experimental methodology can be defined. This section details these issues and considerations.

### 5.3.1. Temperature sensitivity

In addition to the equilibration and calibration processes TekScan also recommend that each sensor is conditioned before pressure measurements are made. 'Conditioning' refers to applying a load across the sensor (in the calibration box or 'in-situ' for non calibrated clinical research) which is similar to the load the sensor shall be exposed to during the actual pressure measurements. Tekscan state that the conditioning process 'raises the temperature of the conductive ink inside each cell' and this primes the sensor for optimum performance. Tekscan suggest this conditioning period should last for 10 minutes. This fact maybe true for in-shoe measurements where temperature varies only very slightly, but whether temperature changes greater than that found in-shoe effect the sensor performance has not yet been studied. This is of great importance with regard to experimental work carried out in-field where temperatures may differ greatly from the constant temperature found in-shoe.

Previous work utilising the Tekscan sensors for pressure measurement with different LCS's has been carried out solely in the laboratory obviously offering a fixed room temperature (Bryant et al, 1996; Doan et al, 1998 (1); Doan et al, 1998 (2); Johnson et al, 1998 and Martin, 2001). For the work of this thesis it was necessary to assess whether the sensors are affected by more extremes of temperature as found in-field.

*Temperature sensitivity study:*

Two studies were performed to assess this issue.

*Study I*

The aim of this study was to determine whether the performance of FScan sensors was affected by temperature change. Three brand new FScan sensors were used, calibrated in the calibration box via the Tekscan method (section 5.2.2). The sensors were 'conditioned' at 25 kPa for 10 minutes prior to use. A specially constructed calibration device was made, consisting of an adaptation to the calibration box. The adaptation involved a replacement bottom (wood) section which had a channel hollowed out in which fitted an aluminium plate (40cm x 30cm). This plate could be cooled or warmed and pressure was applied across the sensor via the calibration bladder. A thermocouple was attached to the under side of the pressure sensor next to the aluminium plate. Three sensors were used, whether they were heated or cooled first was varied. A pressure of 25 kPa was applied to the sensors in the calibration box and pressure recordings were made at

2.5°C intervals, from 5.5°C to 43°C (or vice versa, depending on start point). The results from each of the three sensors are shown in figure 5.2.

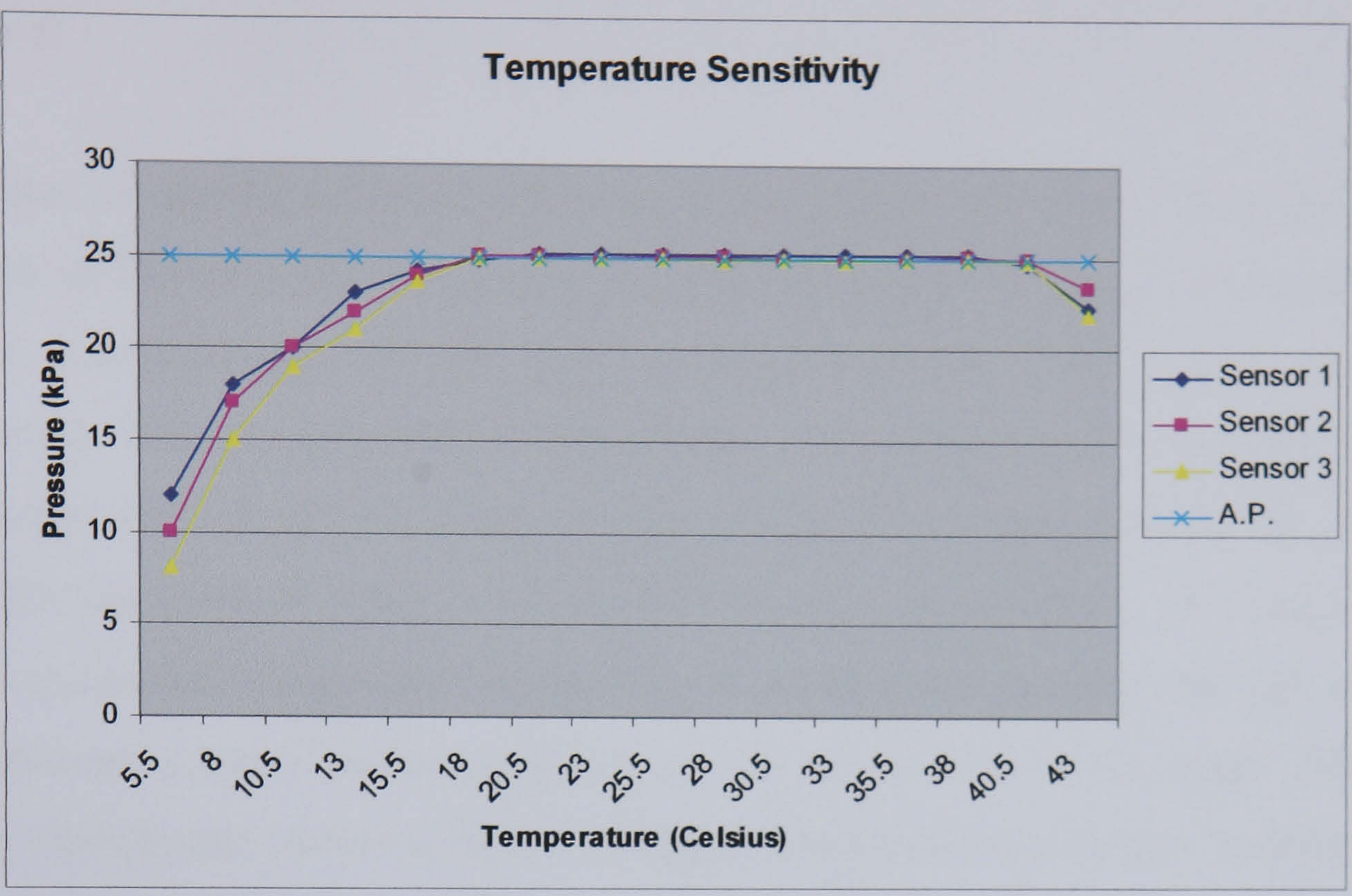



**Figure 5.2 Temperature sensitivity of FScan sensors**

The line on the graph marked 'A.P' is the applied pressure (25 kPa). As the results show the pressure sensors do indeed appear to be affected by changes in temperature, but only in the extreme. From 18°C through to 40.5°C pressure readings from all three sensors were constant, given slight differences between sensors (25 ± 0.2 kPa). Above and below these temperatures data appears to show reduced pressure sensitivity of the sensors. This would most likely to be due to the temperature of the semi-conductive inks, where a physical change in conductivity may occur with extremes of temperature.

This study would support Tekscan's recommendation of FScan sensors for use in-shoe and on the body. The 'safe' range fits well within the limits expected to be found with sensor placed next to the body. The higher limit (40.5) should not be breached due to this being higher than core body temperature, with the lower limit (18) falling below normal skin temperature. From the data it can be concluded that measurements below 18°C or above 40.5°C should be avoided in order to control for any change in sensor performance. The next step was to identify what temperatures are typically found under the shoulder and hip straps.

*Study II*

Whether or not the extremes affecting sensor performance are of relevance and worthy of further study in this context is dependent upon whether the temperature found underneath the shoulder and hip straps fall into/or on the edge of these extremes. This study involved taking temperature measurements on participants under the shoulder and hip straps. Three participants took part in the study; (Mean ± SD) age 24±1.8 years, weight 79.7±8.3 kg, and stature 177.2±6.3 cm. Participants had temperature measurements made at the shoulder and hip, with a thermocouple taped on the underside of the sensor next to the upper clothing layer. Participants carried a load of 23.5kg in a standard issue Bergen backpack.

Participants walked for 30 minutes, with temperature measurements recorded every minute. The first measurement was the external temperature, then the sensor (with thermocouple attached) was placed at the interface, the backpack donned and walking began. The shoulder temperature measurement was made above the trapezius muscle with the hip measurement made above the iliac crest. Participant 1 walked a 30 minute field course at a temperature of 10°C. Participant 2 and 3 walked for 30 minutes on a treadmill ($6km/hr^{-1}$, 0% grade) at a room temperature of 15°C and 20°C respectively. The reason for the differing conditions was to gain an accurate view of temperatures found under the straps when participants walk in the laboratory and also out in the field.

The figures below show the temperatures recorded every minute for the three participants. Figure 5.3 shows the temperatures recorded from the shoulder and figure 5.4 shows temperatures from the hip.

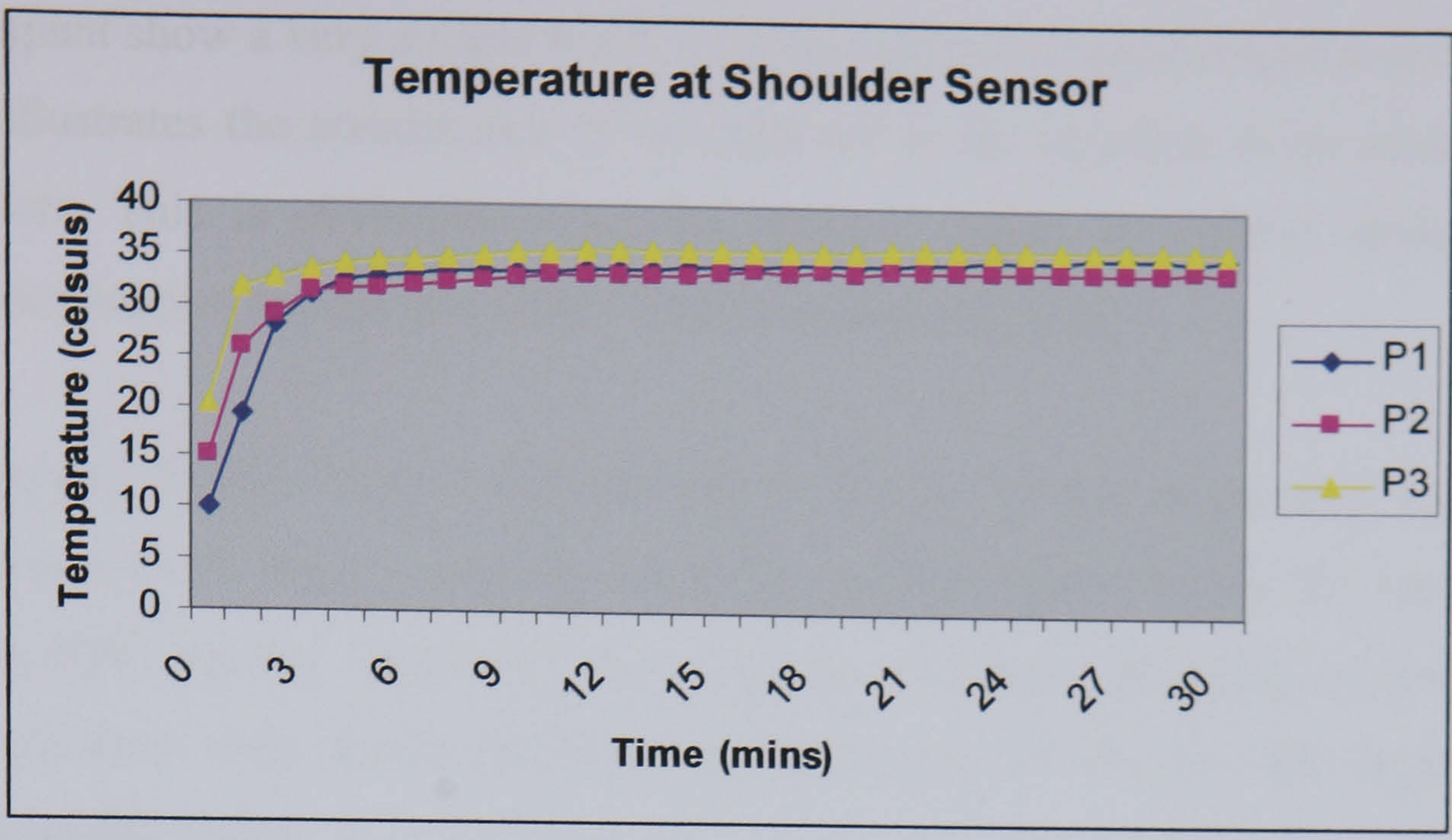



**Figure 5.3 Temperature recorded at the shoulder interface**

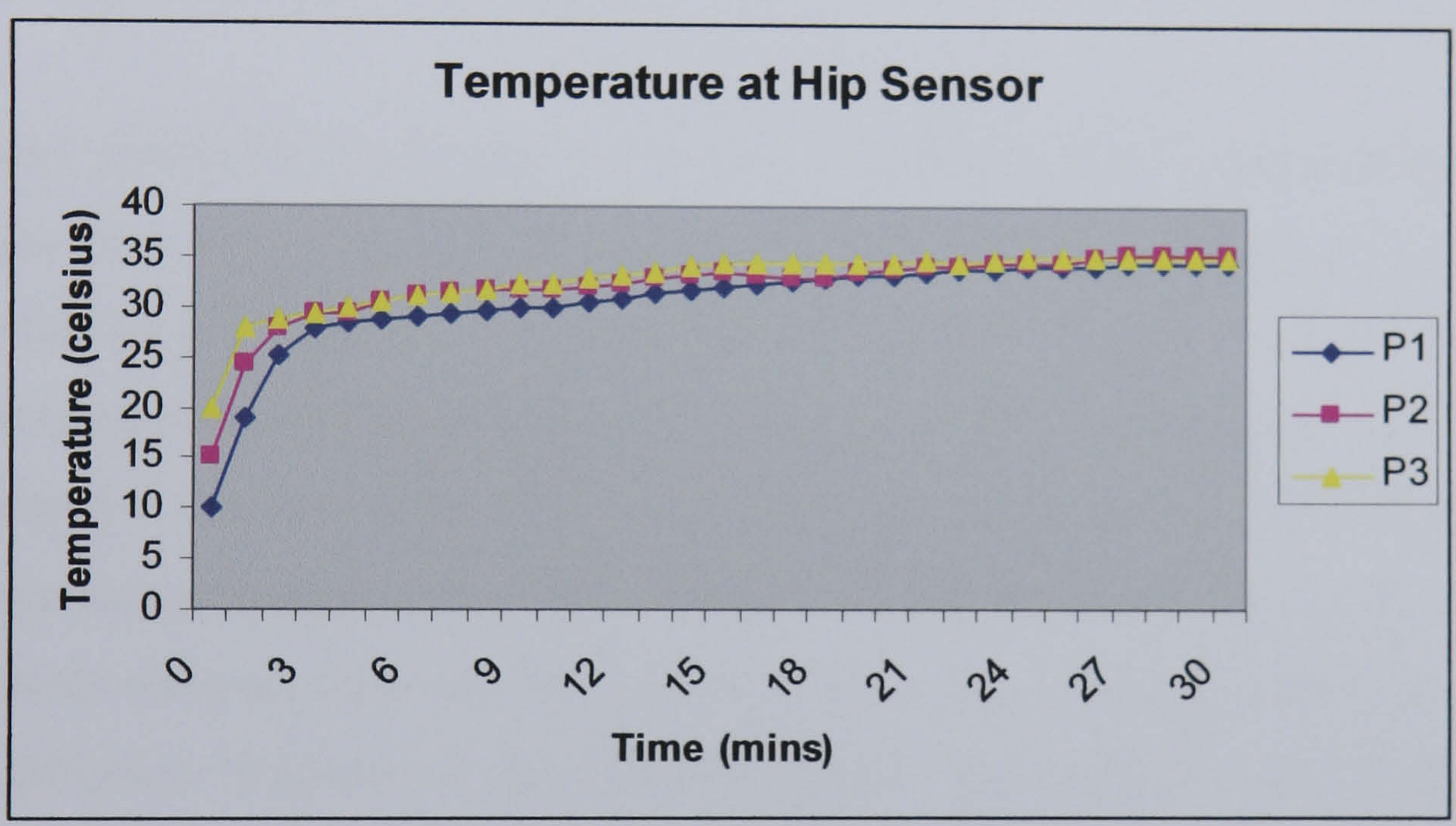



**Figure 5.4 Temperature recorded at the hip interface**

From figure 5.3 and 5.4 it is clear that temperature at the shoulder and hip interfaces (and thus temperature of the shoulder and hip sensors) remain within the limits identified by Study I. It is interesting to note that at the 1st minute the sensors are above the minimum limit for sensor sensitivity (18°C) and then rise to level off at approximately 35°C. The shoulder interface appears to 'warm up' and level out faster than the hip. This is mostly likely due to the larger area of muscle (trapezius) at the shoulder than the hips (iliac crest) which with its increased blood flow will raise the temperature of the interface quicker. The findings from each participant show a very similar trend, even though the external temperature varies. This illustrates the consistency of temperature at the interface even when worn outdoors. This is obviously important when it comes to in-field studies and provides support for the use of the Tekscan sensors in field.

In summary Studies I and II indicate that the FScan sensors are suitable for use at the temperatures found under the shoulder and hip straps in both the laboratory and in-field. Sensor sensitivity falls into the optimum performance zone (18-40.5°C) when worn at the shoulder and hip and the studies provide support for FScan sensor usage.

### 5.3.2. Sensor usage

TekScan developed the FScan sensors for use with in-shoe measurements and stipulate that they will capture pressure data accurately for between 1-7 uses. After this period TekScan recommend that sensors are replaced in order that any deformation to the sensor or individual cell damage does not manifest itself within the recorded pressure data. This '1-7 uses' figure was identified from in-shoe pressure measurements and is interesting as the shoulder and hip are associated with body contours as is the foot, however the range of force vectors would be very different. Tekscan do not actually define what constitutes a single use, whether this is 1 minute, 10 minutes or 10 hours, this is not described. What is clear is that the critical factor for determining that a sensor is unusable is 'cell degradation'. This is when pressure cells become either non-responsive or constantly register maximal pressure.

Martin found that the FScan sensors produce reliable and accurate data given a specific approach is adopted (2001). This approach meant that for each participant a new sensor was used at the beginning of each test and that this sensor was checked pre and post test to identify any cells illustrating cell degradation. If cell degradation (or calibration drift, detailed in section 5.2.2) occurred then data from that participant were rejected, they were fully debriefed and free to leave. Due to the fact that the same sensor type (FScan) was utilised along with Tekscan software this provides support to adopt the conservative approach for this thesis.

A different technique could be employed where data from degraded cells could be removed during the analysis phase, however whether only single cells are affected or whether they are indicative of a decline in whole sensor functioning is unclear and thus for all experimental work a 'conservative approach' was defined where a new sensor was used for each participant and any sensor showing cell degradation was rejected. Whether this degradation occurred pre test (i.e. a new sensor) or during test (identified via recalibration at the end of testing phase, explained further in section 5.4.2) rejection was always the result. The approach may result in rejection of participants and the associated data sets, but this is considered the best approach where accuracy of pressure measurement could come into question. If data rejection occurred, a replacement participant was recruited and a new sensor was assigned to this person.

### 5.3.3. Sensor Curvature

In chapter 4 where the choice of sensor type was described, one of the main requirements for the pressure sensors was that the individual pressure cells were small enough and of high enough resolution in order that the cells do not register pressure due to curvature alone. When placed at the shoulder and hip interfaces the pressure sensors are obviously exposed to curvature to greater or lesser extents. A person who is particularly thin may have pronounced bony areas (such as the clavicle at the shoulder and iliac crest at the hip); these areas will result in higher curvature than someone with more muscle or fat coverage over the bones. One main consideration when it comes to data analysis is that any difference in curvature due to differences in participant anatomy must be controlled for. If curvature does cause pressure to be detected when it is not present, and inter participant analysis is undertaken, it is possible that the error due to curvature may confound the results.

Martin (2001) undertook a study assessing the effect of curvature on FScan sensors. Three participants took part in the study, where pressure sensors were placed at the shoulder (right and left shoulder) and hip (right and left hip) interfaces. The pressure sensors were taped over the shoulder and hip so that the sensors closely followed body curvature, no backpack was worn, nor load applied. Pressure due to curvature was detected with this erroneous pressure being greater at the shoulder interface than the hip (due to increased bony areas and curvature around the shoulder itself). Whilst erroneous pressure readings were detected the magnitude of this was small. Erroneous readings amounted to mean pressure at the shoulder ranging from 0.22-0.31 kPa and at the hip this was lower at 0.02-0.05 kPa. So, given that curvature does effect the sensors but causes such a small error value (<1% error assuming an overall mean pressure of 25 kPa when wearing a 20kg backpack), Martin defined this error as 'small enough to disregard' if comparative methodology is employed.

As comparative methodology was indeed employed by this thesis (described in section 5.6.5), the effect of curvature can essentially be discounted. The error is even less of a concern when using repeated measures experimental design, as the data analysed is gleaned from the same participant and the error will be present when recordings are taken from each backpack/LCS, thus this error should essentially cancel itself out. This issue of curvature provides more support for the conservative approach to methodology where only a comparative analysis shall be made. Curvature effects also further highlight the caution required when interpreting the results in terms of absolute pressure as the error (even though small enough to be discounted with a conservative method) may confound any conclusions made concerning absolute pressure values.

### 5.3.4. Conclusion

The results of the studies and references in this section illustrate that factors that may confound measurement on body surfaces can be controlled and accurate measurements can be made. The potential errors identified are very small and can be further controlled for by using a conservative approach to methodology. These considerations are all taken into account when defining the methodology (part III).

## PART II – Experimental Equipment

### 5.4.1 Developing the prototype Airmesh LCS

An additional aim of this thesis was to develop a prototype LCS focussing on increasing the compatibility between the backpack and webbing parts of the LCS. If compatibility can be increased (to allow effective use of the backpack hip belt) this should allow for increased subjective comfort, and possibly increased performance and reduction in injury risk. Martin (2001) identified several design improvements over the standard issue Bergen shoulder straps, namely by the introduction of plastic inserts and 'Airmesh' monofilament material. These changes were found to lead to increased subjective comfort and decreased peak pressures at the interface when carrying an 18.5kg load in a backpack. These improvements were thus adopted for the prototype LCS. Both the shoulder and hip straps incorporated the material changes and addition of the plastic frame.

The hip strap was also made to be more substantial, following those found on commercial backpacks, the idea behind this being that more effective loading at the hips will reduce loading at the shoulder and thus peak pressure and discomfort. The hip belt on the Bergen backpack essentially consists of two flaps fixed to the outer edges of the Bergen with an interconnecting strap, whereas the Airmesh hip belt extends across the whole width of the pack. It is hypothesised that this (combined with the plastic frame and airmesh material) shall allow for increased transmission of pressure across the hip interface, as was identified by Martin (2001) at the shoulder interface.

Particular attention was also made to the compatibility of the backpack and webbing parts of the LCS. As described in chapter 2, both of these parts remain essential and have to be able to be worn separately in order that when in contact with the enemy the soldier can remove the backpack and go forward fighting with essentials items contained inside the webbing. For this reason it was obvious that a different type of webbing was required to allow greater compatibility. Several different types of webbing exist, some made by commercial companies, some made by the MoD but only issued to certain specialist groups. Two types of webbing exist giving clearance at the back, due to the pouches being arranged on the front and side of the body rather than at the rear, this clearance will allow the backpack to be fitted better to the body and also most importantly the hip belt can be utilised.

The two types of webbing are termed 'vest webbing' and 'chest rig'. Chest rigs are used specifically for arctic climates. Vest webbing was created recently in order to be more suitable for use in military vehicles (due to back clearance allowing the soldier to sit down on the seats properly, thus enabling the soldier to drive safely and also sit comfortably). The continued increase in mechanisation of the British army means that vest webbing is likely to become more and more popular. Unfortunately the chest rig does not have enough pouches on it to contain the essential equipment for all environments (only arctic) and thus is not a viable option. Thus, it was decided to utilise the vest webbing for the prototype LCS.

Finally, and of great importance is the consideration of the issues and opinions of the 100 soldiers who filled out the load carriage questionnaire as detailed in Chapter 3. It has been suggested that "the load that a soldier carries will always be a compromise between what is physiologically sound and what is operationally essential" (Haisman, 1988). Any new prototype system must not just take into account advances in design to improve comfort, physical performance and to reduce injury, but also provide the soldier with the practicalities which are so essential to enable him to carry out his role. The importance of including enough pockets/pouches in the correct places, adjustability of the system to fit varying body sizes and other practical issues is critical. Chapter 3 details the most common negative aspects of the Bergen LCS being the poor shoulder straps and hip belt, but also shows the positive aspects of durability and large capacity. It is important that positive aspects are incorporated into the prototype. The prototype Airmesh backpack can be seen in figure 5.5. It is constructed of the same 1000 denier Cordura material as the standard issue Bergen (durability). The load capacity is also the same as the standard Bergen at 80 litres (capacity). The shoulder and hip straps were obviously changed, incorporating Martins's suggested Airmesh monofilament material and plastic frames. Internally both backpacks utilise an aluminium frame, the only difference being that the Airmesh backpack frame has five arms (rather than the Bergen's three). This is to provide extra support to the pack and help to transfer load to the hip belt.

**Figure 5.5 and 5.6 Anterior views of the Airmesh and Bergen backpacks**

Externally the Airmesh backpack differs slightly in the arrangement, size and location of pouches. The Bergen backpack has two large side pouches which can be a hindrance as the whole pouch must be emptied to retrieve an item from the bottom. Thus, a new arrangement of multiple smaller pouches was chosen for the Airmesh backpack (same storage volume as the Bergen side pouches). Finally the Airmesh backpack top lid was made to be movable, rather than being stitched (where it hinges to open) there is some degree of adjustment which means that when the pack is particularly packed full the top lid can be moved in order that it does not reside right behind the head, limiting head clearance.

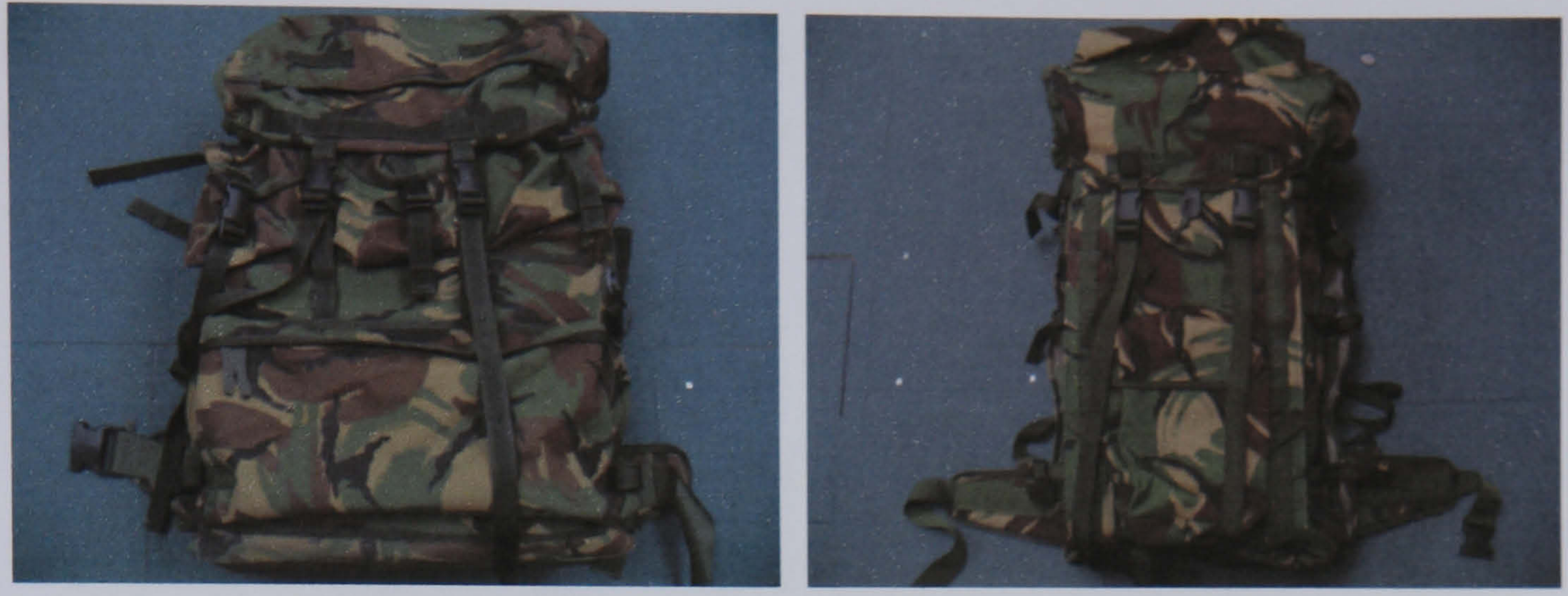


**Figure 5.7 and 5.8 Posterior views of the Airmesh and Bergen backpacks**

Figures 5.7 and 5.8 show the external design differences between the two backpacks. The Bergen hip belt (figure 5.8) can not be utilised when worn as part of the whole LCS. In terms of experimental validity, during the trials (chapters 6 and 7) the external design features of the new Airmesh pack were concealed via a 'Bergen cover' - a large elasticated camouflaged cloth which covered the whole of the outside of the backpacks. This was carried out in order to prevent any bias in the subjective ratings (discussed in Part III and chapter 8).

**Figures 5.9 and 5.10 Anterior view of belt webbing (Bergen LCS) and vest webbing (Airmesh LCS)**

Figure 5.9 and 5.10 illustrate the difference in location of pouches on the webbing items. The Vest webbing pouches are on the front (above the chest and abdomen) and side of the body compared to the belt pouches on the side and rear (around the waist).

**Figures 5.11 and 5.12 Posterior views of belt webbing and vest webbing**

Figures 5.11 and 5.12 show clearly how the back of the webbing items differ, the large pouches on the rear of the belt webbing conflict with the Bergen backpack where it sits on top of them and is pushed higher up the body. The Vest webbing in contrast is clear at the back allowing increased fit and utilisation of the Airmesh backpack hip belt. Another important fact to acknowledge here is the difference in the way the pouches are suspended from the body. The belt webbing has a yoke, consisting of two shoulder straps which connect to a hip belt, around which the pouches are fixed. The Vest webbing (as its name suggests) consists of pouches fixed onto a vest which is then worn like a waistcoat.

**Figures 5.13 and 5.14  Anterior views of Bergen and Airmesh LCS's**

Figures 5.13 and 5.14 show the anterior view of the two LCS's. Increased utility is seen with the vest webbing as all the pockets are accessible even when the Airmesh backpack is worn. The rear pouches of the belt webbing however can not be accessed due to the Bergen backpack residing on top of them.

**Figures 5.15 and 5.16 Posterior views of Bergen and Airmesh LCS's**

Figures 5.15 and 5.16 show how the Bergen sits higher on the body when compared to the Airmesh (due to lack on integration with the belt kit, sitting on top of pockets), possibly having an effect on centre of mass and posture (discussed further in chapters 7 and 8).

**Figures 5.17 and 5.18 Side views of Bergen and Airmesh LCS's**

It is interesting to note the difference in posture (as illustrated in figures 5.17 and 5.18) between the Bergen and Airmesh LCS's. In these photos both LCS's are loaded to 36.4kg and they are worn by an experienced British soldier. Whilst this is by no means an assessment of posture a clear difference can be seen with increased forward lean associated with the Bergen LCS despite of the fact that the backpack sits higher (if wearing backpack alone forward lean would be decreased if pack height was raised). This posture issue is discussed further and in detail in chapter 8. Figure 5.17 also indicates the incompatibility of the Bergen and belt webbing of the Bergen LCS, the hip belt of the Bergen can be seen left undone and hanging over the belt webbing pouches. Because the Airmesh LCS has a frontal loading element to it (via the Vest webbing pouches) this can be linked to the work of Datta & Ramanathan (1976) and also Legg & Mahanty (1985) who found that this type of pack (double pack) was associated with less energy cost and greater subjective comfort than a traditional backpack (like the Bergen LCS, where all load resides on the back).

### 5.4.2 Weight Block

After the two LCS's for the comparative trials were defined the next step was to construct equipment to allow identical loading of the LCS's for trial. A weight block was constructed consisting of a custom made bag which houses a rigid foam block; within this block are holes which allow mild steel rounds of various diameters to be fitted. These rounds are of uniform weight and thus allow the backpack to be loaded at different weights, depending on the measurement condition. Loading weights were achieved by adding more or less steel rounds. For fine adjustment of the load sand was used which when placed in bags could be used to gain exact weighting. The rounds were always placed nearest to the participants back and always the exact same weight (accurate to 1 gram) was used for loading the two LCS's. When fine tuning of the total weight was required the sand was placed in a standard position, the same for each LCS.

**Figure 5.19 and 5.20 The weight block and the webbing weights (1kg).**

For webbing loading (both vest and belt) 1kg mild steel rounds were created. This fitted neatly inside the webbing pouches, the pouches being filled with foam also to prevent movements of the weights. Again fine tuning of the webbing load was made with sand. Total webbing weight was stringently checked (as was the backpack) and total load was accurate to 1 gram. Figures 5.19 and 5.20 show the weight block inside its bag and the 1kg steel round weight protruding from the top pouch of the vest webbing.

The rest of the experimental equipment (i.e. the in-field Tekscan system) was described in detail in chapter 4. This together with the LCS's and weight blocks constitutes the experimental equipment. The final part of this chapter describes the subjective and objective methodologies for the thesis experimental work.

## PART III – Experimental Protocol

The two main aims of this thesis were (1) to develop a mobile in-field method of measuring and quantifying interface pressure at the body-LCS interfaces using objective and subjective methods. (2) to evaluate and compare LCS designs in-field and to provide human factor requirements for design improvements. Chapter 4 detailed the equipment specification to enable mobile measurement, and this section is concerned with defining suitable objective and subjective methodologies. The purposes of the comparative trials presented in this thesis (chapter 6 and 7) were to: (1) compare the standard issue Bergen LCS against the prototype Airmesh LCS in terms of pressure and comfort outcomes; (2) to increase the understanding of the properties of the interfaces; (3) assess the relationship between loading at the shoulder and hip; and (4) to identify whether other ergonomic issues are also important to consider. By assessing these 4 areas human factors requirements for design can then be determined (chapter 9).

## 5.5 Subjective Ratings

### 5.5.1. Introduction

***Comfort*** – "a pleasant state or feeling of physiological/psycho-physiological harmony" – Slater (1985). ***Discomfort*** – "associated with biomechanical changes at joints, muscles or due to pressure which produces feelings of pain, soreness and/or stiffness" – Kee & Karwowski, 2003.

Up until the work of Bryant et al (1996), Johnson et al (1998) and Martin (2001) there were no significant studies performed studying interface pressure at LCS-body interfaces. The main method of assessing LCS designs up to this point for both the military and for civilian manufacturers was from subjective ratings of experienced end-users. The aims of the work of Bryant, Johnson, Martin and of this thesis were to develop advanced methodologies for providing objective assessment of LCS's. However, these objective methods were not intended to replace subjective data, merely to add to them to provide a quantitative approach. Shackel et al (1969) suggested that subjective measures were the ultimate criterion for comfort and that these measures can be used to validate objective data.

Subjective ratings are an invaluable tool for research attempting to assess comfort/discomfort as not only can they be utilised to validate objective work, but they can also illustrate how effective design/material changes are. Peak pressure can be reduced by the utilisation of advanced materials and designs (Martin, 2001), but the extent to which this improves comfort can only be identified with suitable subjective comfort ratings. Martin identified a correlation between interface pressure measurements and subjective ratings. However, this research was performed with civilian participants, with reduced loads (compared to the military), in a laboratory setting and only assessing the backpack (Bergen) alone. Whether the increased comfort and decreased peak pressures are replicated when the whole LCS is assessed in the military context is the one of the aims of this thesis. The importance of the continued use and correct selection of appropriate subjective methods is therefore critical to investigating this aim.

Guilford (1954), Winsmann & Goldman (1976) and Corlett & Bishop (1976) describe in great detail the numerous different types of subjective measures and their uses, drawbacks and advantages. A description of this kind is not undertaken here; only suitable methods for this context are identified and discussed. There are four main methods to gather subjective ratings in this context; Rating Scales, Questionnaires, Interviews and Paired Comparisons. The main requirement for the experimental work of this thesis is that subjective data should be collected simultaneously with pressure measurement. This will enable the identification of any synonymous changes in pressure and comfort.

Questionnaires and interviews are methods which can be utilised pre and post trial but are not suitable for use during a trial, especially a military field trial with obstacles where participants must concentrate in order to avoid injury. These techniques can also be difficult to set up and to analyse, with many potential pitfalls to control for (e.g. leading questions, non responses, etc); however they can provide high quality information and detail not gleaned from ranking or rating variables. Paired comparisons are a post trial technique used when the experimenter wants to glean subjective views on a comparison of two variables. Participants are asked to rank the two variables in first and second place in terms of different factors. These comparisons can be quite powerful as ranking into first and second obviously indicates a preference very clearly; however the reason behind this ranking needs to be assessed. Ratings scales can be used both during and post trial, and are commonly adopted by ergonomists due to ease of use and the fact that ratings can be given at the time of experience and are not subject to memory or 'a simple change of mind'. The fact that they can be synchronised with objective measures is very useful as previously described.

For the subjective protocol of this thesis a combined method approach was chosen. One of the aims of the military trial was to compare two LCS's – the standard Bergen LCS versus the prototype Airmesh LCS. Rating scale and paired comparison were chosen. The rating scale was to be used during trials, made simultaneously with pressure measurement. This captures subjective feedback at the time of experience and gives an insight into pressure measurement. The rating scale was then also used post-trial with participants asked to rate each LCS/backpack in terms of three comfort zones, shoulder, back and hip. Finally paired comparisons were then utilised, where participants were asked to rank the two backpacks/LCS's in terms of overall comfort. Additionally participants were asked if they would like to make any comments or give any reasoning behind their ratings. Any comments would also be recorded by the experimenter. With these basic choices made it was necessary to define the type of ratings scale to be used.

### 5.5.2 Choice of Rating Scale

As previously mentioned a number of different rating scales exist and are described in detail by Guilford (1954), Winsmann & Goldman (1976) and Corlett & Bishop (1976). For the aims of this thesis, three types of scale would appear suitable; (1) Interval scales; (2) Ordinal scales and (3) Visual Analogue (VAS) scales.

**Interval scale.**

Historically research into the effects of LCS's on the human body (Winsmann & Goldman, 1976; Legg & Mahanty, 1985 and Kirk & Schneider, 1992) commonly adopted Borg's RPE (rating of perceived exertion) scale which was developed to gather subjective ratings of exertion during exercise. The RPE scale required participants to define their exertion by matching their perceived effort to a number on a pre-defined list. This type of rating is referred to as 'numerical scaling', where a list of numbers have a description attached to them such as Borg's RPE scale (1970);

RATE OF PERCEIVED EXERTION

| | |
|---|---|
| 6 | no exertion at all |
| 7 | extremely light |
| 8 | |
| 9 | very light |
| 10 | |
| 11 | light |
| 12 | |
| 13 | somewhat hard |
| 14 | |
| 15 | hard (heavy) |
| 16 | |
| 17 | very hard |
| 18 | |
| 19 | extremely hard |
| 20 | maximal exertion |

**Figure 5.21 Borg's RPE scale (1970)**

Significant reservations have been voiced over Borg's scale when attempting to define subjective comfort. The scale can seem somewhat complicated and where numbers are not assigned to a statement (e.g. points 8, 12, 14, 16, 18) this can produce a lack of continuity for the participant. But secondly (and most importantly) the investigators utilising Borg's scale (Winsmann & Goldman, 1976; Legg & Mahanty, 1985 and Kirk & Schneider, 1992) all reported that the scale was insensitive to small to moderate design changes (such as incorporation of different backpack frames and changes in the sensation of loading at the shoulder and hip interfaces) and only sensitive to large changes (such as double pack versus backpack, where load is moved significantly around the body). This is thought to be due to the fact that Borg's scale (by definition) seeks to quantify changes in exertion and has been validated to rate exercise exertion but not to detect changes in comfort. For the participants involved it is doubtful that a change in rating of exertion would be the result of effects due to changes to backpack shoulder and hip straps or other design changes associated with the work of this thesis. This issue highlights the need for a comfort scale here, and one which is able to detect the effect of small design changes such as different straps and increased fit and stability.

**Ordinal scale.**

Recent research within the field of ergonomics has commonly utilised an ordinal scale (Legg et al, 1997; Martin, 2001). This type of scale involves the use of a number of points (typically 5 or 7) each with a description attached. This scale can either be a two way scale where the neutral condition is marked as '0' and positive and negative points from this indicate comfort or discomfort. The other approach is a simple one way scale. Typically the two way scale is a more popular, but when it comes to terminology with regard to rating 'comfort', it could be argued that 'comfortable' would equal the top of the scale. Whether 'very comfortable' or 'extremely comfortable' are descriptions which can be perceived by a participant could be debated. This consideration was made by Martin, who defined a simple one-way comfort rating scale for recording subjective ratings from backpack load carriage (figure 5.22) It has also been suggested that a one way scale is more preferable as it is continuous with no break in the scale and thus is easier to use for the participant (Guilford, 1954).

1. COMFORTABLE
2. SLIGHTLY UNCOMFORTABLE
3. UNCOMFORTABLE
4. VERY UNCOMFORTABLE
5. EXTREMELY UNCOMFORTABLE

**Figure 5.22 5 point ordinal comfort rating scale (Martin 2001)**

These ordinal scales can be very simple (as Martin's 5 point scale) or somewhat complex like Legg et al's Body Part Discomfort (BPD) scale (figure 5.23). This scale seeks to determine whole body discomfort, gathering discomfort values for each of the 12 body areas. A scale like this (although informative) can not be utilised practically during an in-field trial, the amount of concentration required of the participant could be considered too great (as discussed in section 5.5.3).

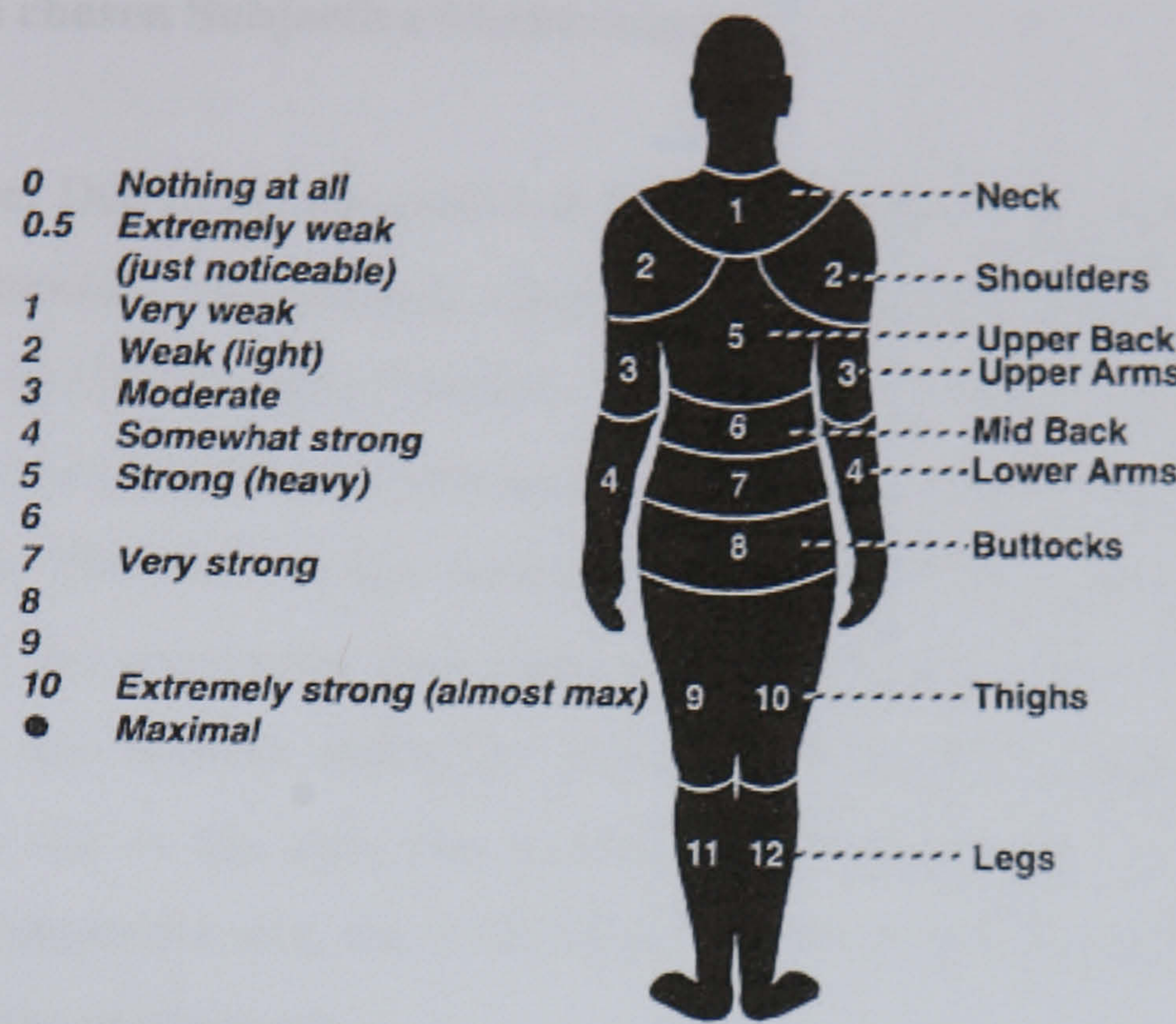



**Figure 5.23 Multi zone body mapping (Legg et al. 1997)**

**Visual Analogue Scale (VAS).**

The VAS consists of a line with minimum and maximum markers, the participant then places a mark on the line to indicate the intensity of the perception. The advantage of VAS's is that they provide continuous data and thus can be analysed quantitatively. VAS's have been utilised in load carriage research (Jacobsen et al, 2003), however this technique can only be used post trial (due to physical input required of the participant), can present difficulty in analysis (no set points as with an ordinal scale), and is subject to inaccuracy of memory if a rating is required after perception of the event. The use of a VAS is therefore thought to be unsuitable for measurements made during load carriage. The limitations of use of a VAS post-trial have also been highlighted.

### 5.5.3. The chosen Subjective Methodology

**Rating scale:** Due to the discussion in the sections above regarding the different types of subjective methodology which could be adopted for use for the thesis trials; it was decided to adopt Martin's 5 point ordinal comfort rating scale (figure 5.22). The reason for this was because the reliability and validity of this scale have already been illustrated in the same context to the experimental work here (a ratings scale for use during load carriage, ran simultaneously with the Tekscan system) and also because neither the interval nor VIS scales would be suitable or practical for use in this area, due to the interval scale being too confusing and potentially insensitive and the VAS being extremely difficult to use whilst the participant was on the move.

One of the salient points to consider here is that comfort ratings shall be recorded whilst the participants walk a field course. This course encompasses many different terrains and gradients. It was decided (upon discussion with the military officers responsible for providing participants) that care must be taken with the ratings scale. If a very complicated multi-zonal comfort ratings scale is used (like Legg et al's body mapping 1997) this could create a health and safety issue with regard to the participants and also effect their pace and rhythm around the course. Annett (2002) highlights the positive aspects of capturing subjective ratings at the time of experience, but also suggested that the subjective measures must not interrupt the testing phase. The suggestions of Annett together with the health and safety issue referring to the concentration required of the participants to focus on a multi-zone sheet carried by the experimenter and give accurate ratings, whilst negotiating mixed terrain, highlighted the need to the adopt a simple method of recording subjective comfort data. It was therefore decided to gather an *overall* comfort rating utilising Martin's 5 point scale during the field course. This rating was recorded in synchrony with each pressure recording.

Corlett & Bishop (1976) were the first to utilise comfort zone ratings in addition to an overall comfort rating. This was in order to gather more detailed information on specific sites of discomfort. Corlett & Bishop concluded that overall comfort ratings combined with additional ratings of comfort zones provides a reliable and robust approach to the collection of subjective data. Martin (2001) utilised the approach as suggested by Corlett & Bishop, and found it to be both reliable and valid. However, Martin's comfort zones were only concerned with comfort at the shoulder and possibly were somewhat confusing due to the gaps between zones.

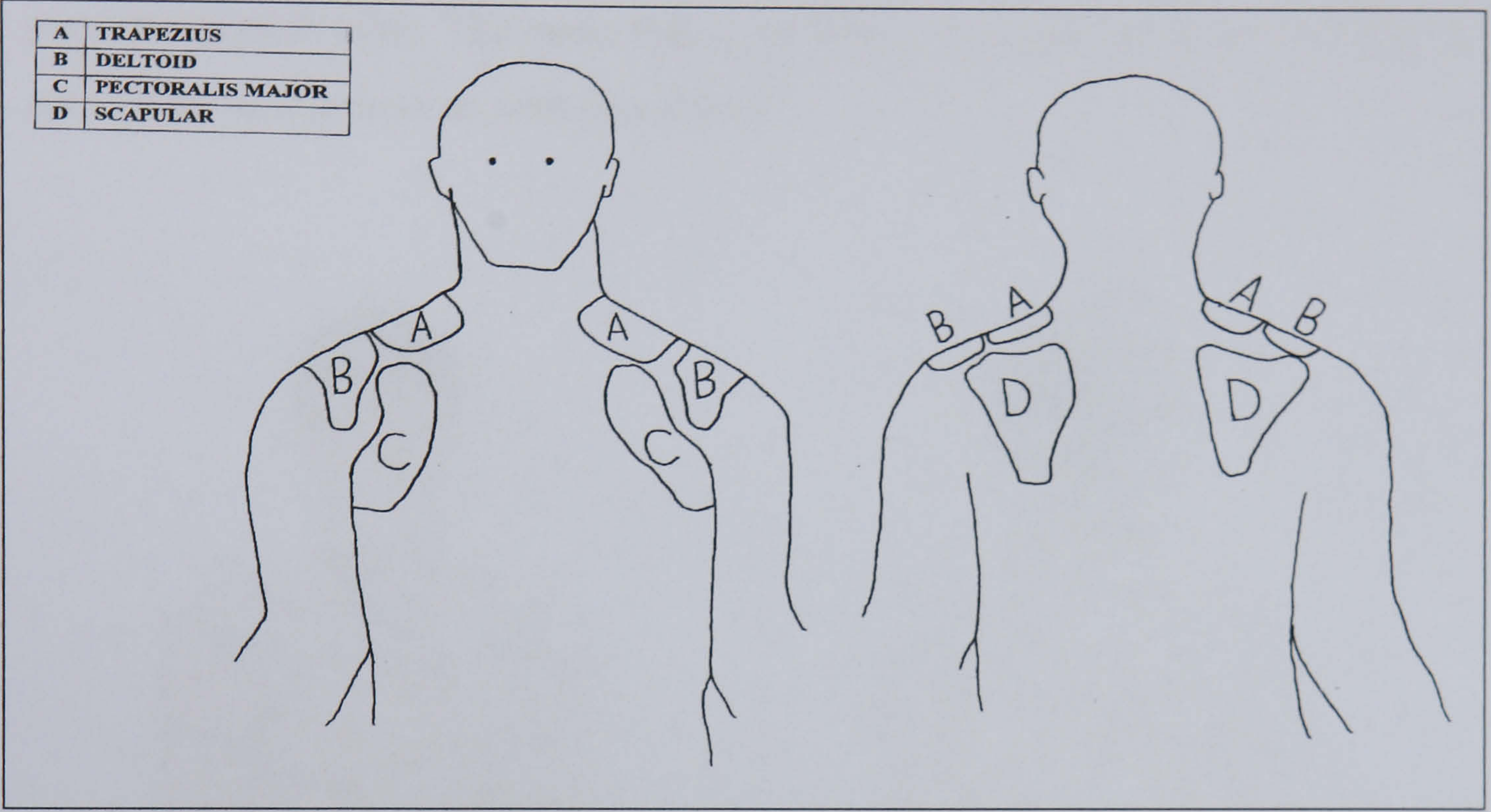



**Figure 5.24 Shoulder Comfort Zones as utilised by Martin (2001)**

Figure 5.24 shows the shoulder comfort zone sheet as utilised by Martin to obtain ratings in four areas of the shoulder. One consideration with regard to these zones is the gaps between each section. This could potentially lead to confusion for participants especially when rating comfort at the clavicle, as it is not clear from the zone sheet where this would fall. For the work of this thesis it was therefore decided to utilise comfort zone ratings but to create a zone sheet with more simple clear comfort zones.

To use a multi zone body map post-walk may lead to a 'time effect' where inaccuracies of memory or confusion may exist as highlighted by Annett (2002) and also by Legg et al (1997). Thus the adoption of a three zone rating was deemed appropriate. This also links in with the location of peak pressures (as discussed in section 5.6) at the interfaces. The relationship between peak pressure location and subjective rating can then be assessed. Whilst pressure measurements were made at the shoulder and hip, subjectively participants were not only asked to rate comfort in these zones but also in the back region. It was hoped that by also considering subjective ratings of the back zone more informed conclusions on the comparisons of the backpacks/LCS's could be made. The comfort zone sheet created for this thesis is shown in figure 5.25. This was presented to the participants upon completion of each walk in order that they could provide ratings accurate to each zone. The same theory of zoning was applied to the hips also to gain zonal ratings here as with the shoulder.

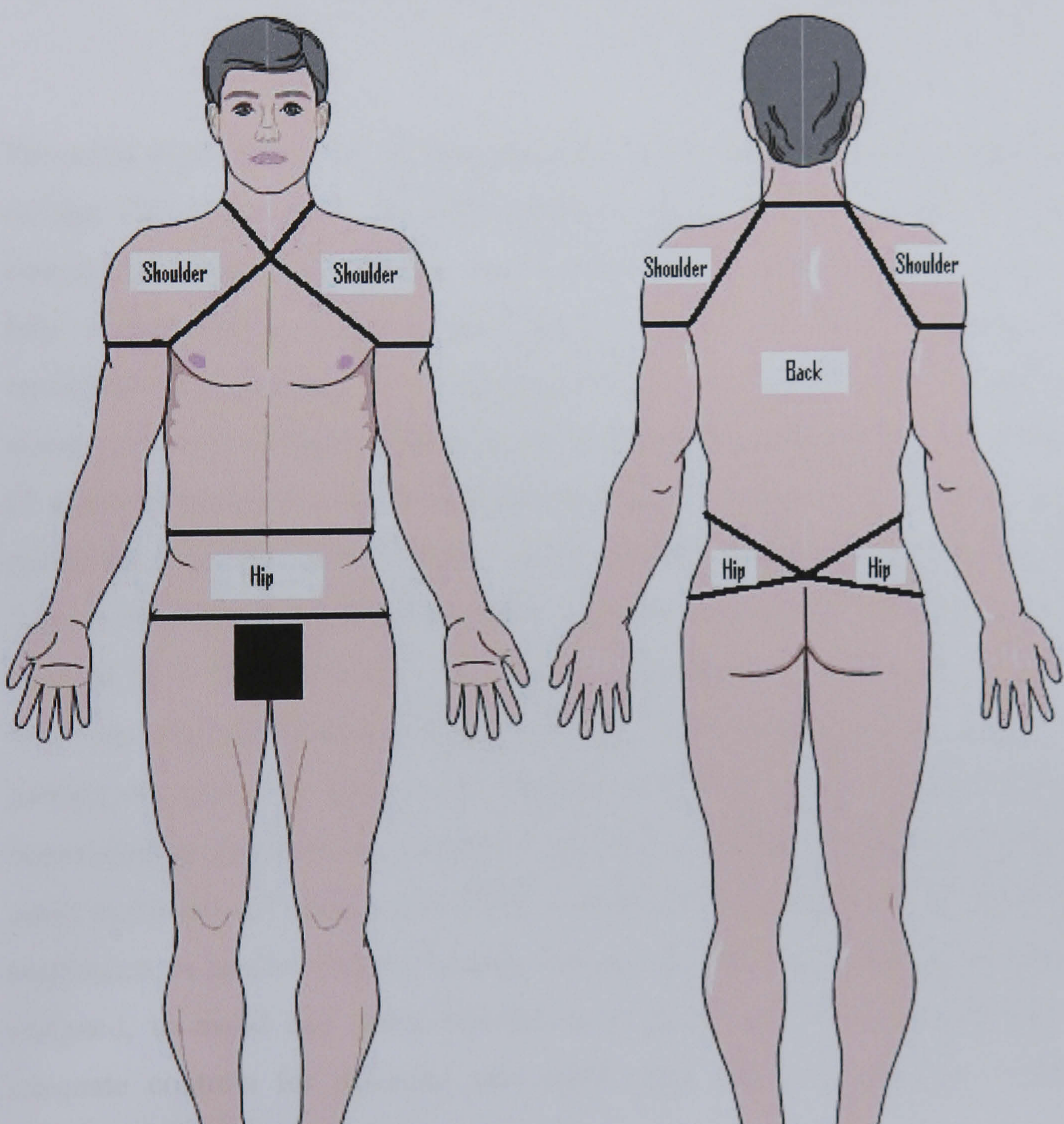



**Figure 5.25 The Comfort Zones Sheet presented to participants**

**Paired Comparison:** The final subjective measure made was to ask participants to rank the backpacks/LCS's into first and second place in terms of overall comfort. Whilst care must be taken when utilising paired comparisons, (i.e. it must be very clear on what grounds the backpacks/LCS's are being assessed) they provide a clear indication for the best performing system. Participants were clearly instructed to rank the backpacks/LCS's in terms of overall comfort only. Upon completion of the treadmill walk or field course the backpacks/LCS's were placed out of sight of the participant in order to reduce any bias which may occur by seeing the aesthetic differences.

**Potential Bias:** This issue of potential bias was controlled for during subjective ratings. This in the main only really applies to the military participants (and when comparing civilian and military results chapter 7, 8 – bias appears to have not been a confounding issue) as only they are aware of what is standard issue equipment and what is a new prototype. Civilian and military participants were simply told they would be comparing two military backpacks/LCS's, no definition of standard equipment and prototype was made in order to ensure their ratings remained impartial. As previously mentioned the backpacks/LCS's were kept from view of the participants as much as possible throughout. The backpacks were covered by a 'Bergen cover' prior to donning the items. When the items were worn the external backpack design changes were obviously not visible to the participant, only the straps and webbing could be seen. It was considered impractical to mask all items and the crux of this work was that actual issued (or ready to be issued) backpacks/LCS's were trialled rather than experimental only equipment. A further control for bias was that the order of testing was randomly assigned, to avoid any order effects occurring. It was therefore believed that adequate controls for potential bias were made. This is discussed further in chapter 8.

**Experimental Protocol:** Three trials were conducted where subjective data was collected alongside pressure measurement (trials 2, 3 and 4 – trials are explained in section 5.7). Trial 2 was a backpack comparison trial, where participants walked for 30 minutes in the laboratory. Trials 3 and 4 were LCS comparative trials, carried out in-field where participants walked a 10 minute field course (reasoning behind the duration of each trial is discussed in detail in section 5.6.5). For all three trials interface pressure recordings and overall comfort ratings were taken simultaneously throughout each walk (experimental details are found in chapters 6 and 7). Upon completing each walk participants gave comfort zone ratings, ranked the two items under comparison into first and second place for overall comfort, and finally were asked for any reasoning behind their choices.

**Data analysis:** Subjective comfort ratings from the final 30th minute (or 10th minute in case of the LCS trials) were used for analysis as this provides the participants with the maximum exposure to inform their subjective ratings. The ratings were expressed as differences in order to show more clearly how each participant rated the two backpacks. Data presented were (1) the differences in comfort rating for each participant, (2) the difference in comfort rating for each comfort zone and (3) the overall ranking expressed as a percentage. For both the $30^{th}$ minute and post-walk subjective data Wilcoxon Signed Ranks tests were used for analysis.

## 5.6 In-Field system methodology

### 5.6.1 Introduction

Following the baseline assessments on the functioning of the TekScan equipment (sections 5.2 and 5.3) certain major rules were defined for objective measurements and a conservative approach to pressure measurement was adopted (as mentioned in section 5.1).

### 5.6.2 Sensors

A new sensor was used for each participant. Calibration was carried out immediately prior to testing and immediately post-test. If cell degradation or calibration drift occurred the participant and was free to leave and the data set disregarded. Pressure measurements were made from the shoulder and the hip interfaces on the right hand side of the body. Martin (2001) performed a study assessing the symmetry of pressure values from each side of the body. Pressure recorded from both the shoulders and both sides of the hips indicated that pressure was not significantly different from one side of the body to the other and thus the adoption of measurements on one side of the body is valid. One important factor to control for here thought is load symmetry, care was taken to ensure that loading was not only exact the same for each LCS/backpack but also that the loading was symmetrical and balanced (use of the weight block described in section 5.4.2 enabled this). To make measurements on one side of the body cuts down the number of walks the participants must make with each LCS and allows for a larger sample size to be studied within the same time frame. Due to practicalities concerning the remote triggering system pressure measurements were made at the right shoulder and hip throughout the experimental work of this thesis.

### 5.6.3 Sensor placement

To enable the collection of valid results a reliable method of sensor placement was required in order that the sensors were placed in the same position for each test and remained so throughout the pressure recordings. Sensors at the shoulder were placed on the body via the 'triangulation method'. This involved firstly locating the participant's clavicle and then matching this with specific points on the FScan sensor. The pressure cell on row 34, column 17 was matched to the superior aspect of the clavicle, 40mm from the sternal end. Then the pressure cell on row 34, column 3 was aligned with the inferior aspect of the clavicle 140mm from the sternal end. The sensor was taped into place around the non-sensing edges of the sensor. The backpack/LCS was then donned and the shoulder strap carefully adjusted. The positioning of the sensor was then again checked and if correct the participant was ready to commence walking and pressure measurements could be taken. This 'triangulation' method was a 'tried and tested' approach and was utilised for shoulder measurements with FScan sensors by Martin (2001).

Sensor placement at the hip differed somewhat from that at the shoulder. A specialised hip sensor pocket was fixed onto the hip belt, which housed the sensor and negated the need to tape the sensor onto the clothing. The reasoning behind this is clearly explained in chapter 6.3. The utilisation of a sensor pocket has advantages as this keeps the pressure sensor in exact position with the hip strap. Also, taping a sensor at the hip is more difficult than the shoulder, and problems frequently occur where the sensor is creased or moved, probably due to the fact the sensor is not secured so firmly by the hip strap. The hip sensor was positioned inside the sensor pocket where it provided 50% coverage across the total length of the hip strap, thus ideally capturing pressure from the mid lumbar region right round to the end of the hip strap at the anterior hip. Due to the fact that the sensor positioning was fixed inside the hip belt, triangulation involved matching the mid sensor point with the iliac crest. Great care was taken to ensure positioning was accurate for each experimental condition, with the hip sensor always being positioned first then the shoulder straps were adjusted.

One additional control made was once the participant had adjusted the shoulder and hip straps for the first walk, these were then marked to ensure that the same positioning and thus tension was present for the second walk and measurement. This was to ensure that the comparisons between pressure distribution at the shoulder and hip were valid and not flawed due to differing strap tensions for the shoulder and hip measurements.

### 5.6.4 Participants

All male participants were recruited for the both the civilian and military trials (chapters 6 and 7). This was because the British Infantry is a male only force. The infantry are the intended end users for the LCS's assessed, as they carry the greatest loads of the regular army regiments. The infantry are the only regiments whose specialism is the carriage of heavy loads on foot and are thus deemed the most appropriate sample to participate in the trials. Another reason for recruiting male only civilian participants is that possible gender effects due to load carriage will not confound the results. Males are typically heavier also which allows higher loads to be carried. The closer the civilian loads are to military loadings and the more similar the civilian participants are to the military participants (i.e. all male and all experienced in load carriage) allows for the most valid comparisons when discussing and comparing the findings from the civilian and military trials.

Civilian participants had to meet the criteria for testing as defined by the Loughborough University Ethical Advisory Committee (LUEAC). The civilian participants were all experienced load carriers, i.e. familiar with carrying heavy loads in a backpack. Participants were fully briefed before participating via the Participant Information Sheet (see appendices) and written consent was required prior to any measurements being taken (for consent form see appendices). Pending satisfactory completion of the health screen questionnaire (appendices) and the absence of injury or illness associated with exercise or carrying load, testing then took place. Throughout participants were free to leave at any time.

The real advantage of this thesis work was that testing was able to take place with military participants, thus allowing real military loading weights and feedback from the actual end users. Military participants were required to give written consent and received the same briefing as the civilian participants. The utilisation of a military sample (especially the infantry) represents a significant move forward in terms of context of experimental work when compared to the civilian laboratory studies of old. One factor which was important to be aware of though was 'bias', and how this may effect subjective ratings, this was discussed in detail in section 5.5.

### 5.6.5 Experimental Protocol

As mentioned in the introduction to part III, comparative trials were undertaken by this thesis to assess the 4 areas of interest. A repeated measures design was adopted for the main experimental trials. This involved all participants completing all of the experimental conditions in each trial. Repeated measures were chosen in order to avoid potentially confounding variables such as the effect of differing participant anatomy on pressure data. Martin's study on the effect of curvature (as mentioned in section 5.1) illustrated how the sensors can be affected when conforming to body contours. This effect was found to be minimal and statistically non-significant, but it was decided to adopt a very conservative approach, in order to reduce possible error to the smallest margins possible. When discussing the absolute pressure values this is even more important. Equally is the data analysis of main experimental trials, by choosing intra-participant analysis this controls for any effect due to differing participant anatomy.

For all of three load carriage trials (civilian backpack, civilian LCS and military LCS) a comparison between two different backpacks or LCS's is undertaken, with each participant carrying each backpack/LCS (carriage order being randomly assigned) with pressure made at both the shoulder and hip interfaces. For the fourth main experimental trial (the assessment of the effect of clothing layers on pressure at the interface) participants are exposed to a number of conditions. The methodologies for each of the four studies are explained in detail where they are presented (chapters 6 and 7).

One important consideration when analysing and presenting pressure data was the effect of material change during the first minutes of load carriage. Previous research has shown that pressure distribution can change up until the tenth minute of load carriage, due to the change in properties of materials when loaded (Martin

& Hooper, 2000). Even though this change in pressure distribution was deemed to be very slight, due to this it was decided that any data presented and utilised for statistical analysis would be from the tenth minute of load carriage onwards. in order to avoid confounding any results/analysis by including data affected by material change and not just the effects of the backpack/LCS alone. For the in-field LCS trials (both civilian and military) a ten minute field course was walked by each participant. Even though data (both objective and subjective) were recorded at 2 minute intervals only the tenth minute are presented and analysed (chapter 7).

This ten minute duration was chosen due to the findings of Martin & Hooper (2000). This was the minimum duration which allowed valid pressure measurements to be made (at tenth minute). The minimum duration was selected in order that the sample size could be as large as possible and to limit the effect of fatigue on participants taking part in multiple walks in one testing session. A sample size of 30 military participants represents a large number when considering most ergonomic research of this kind is usually limited to a maximum of 20 civilian participants at best. To achieve a high number of military participants in-field, carrying military loads in this context has not been achieved before and thus makes this research novel. This 10 minute duration shall be discussed further in chapter 8 and 9.

It is important to note that for trial 1 (the clothing study) this 10 minute duration did not apply. This was because the aim of the trial was to assess whether clothing layers worn between the backpack strap and skin interface affect the transmitted pressure to the skin. This was assessed by having two sensors (one placed on the skin surface and one above the clothing layer/s directly beneath the backpack strap). Thus, the aim was to identify any difference in data recorded from the two sensors. Any slight fluctuations in pressure due to material change would be present for each sensor at the exact same time, thus the 10 minute period did not apply. The exact methodology for the clothing study is described in chapter 6.

### 5.6.6. Tekscan measurement parameters

Each pressure measurement consisted of a recording duration of 1 second and a sample rate of 10 frames per second (a frame constitutes one pressure reading from each cell on the sensor). The duration and rate were chosen in accordance with Martin & Hooper's (2000) research illustrating that interface pressure recorded at this level is adequate to capture the pressure changes throughout the gait cycle. This consideration of pressure change throughout gait cycle is important when it comes to extrapolating data for analysis and presentation. Martin (2001) identified fluctuations in peak pressure which followed the body movements during gait. Maximal pressure was found at heel strike, with cyclical changes in pressure throughout the gait cycle.

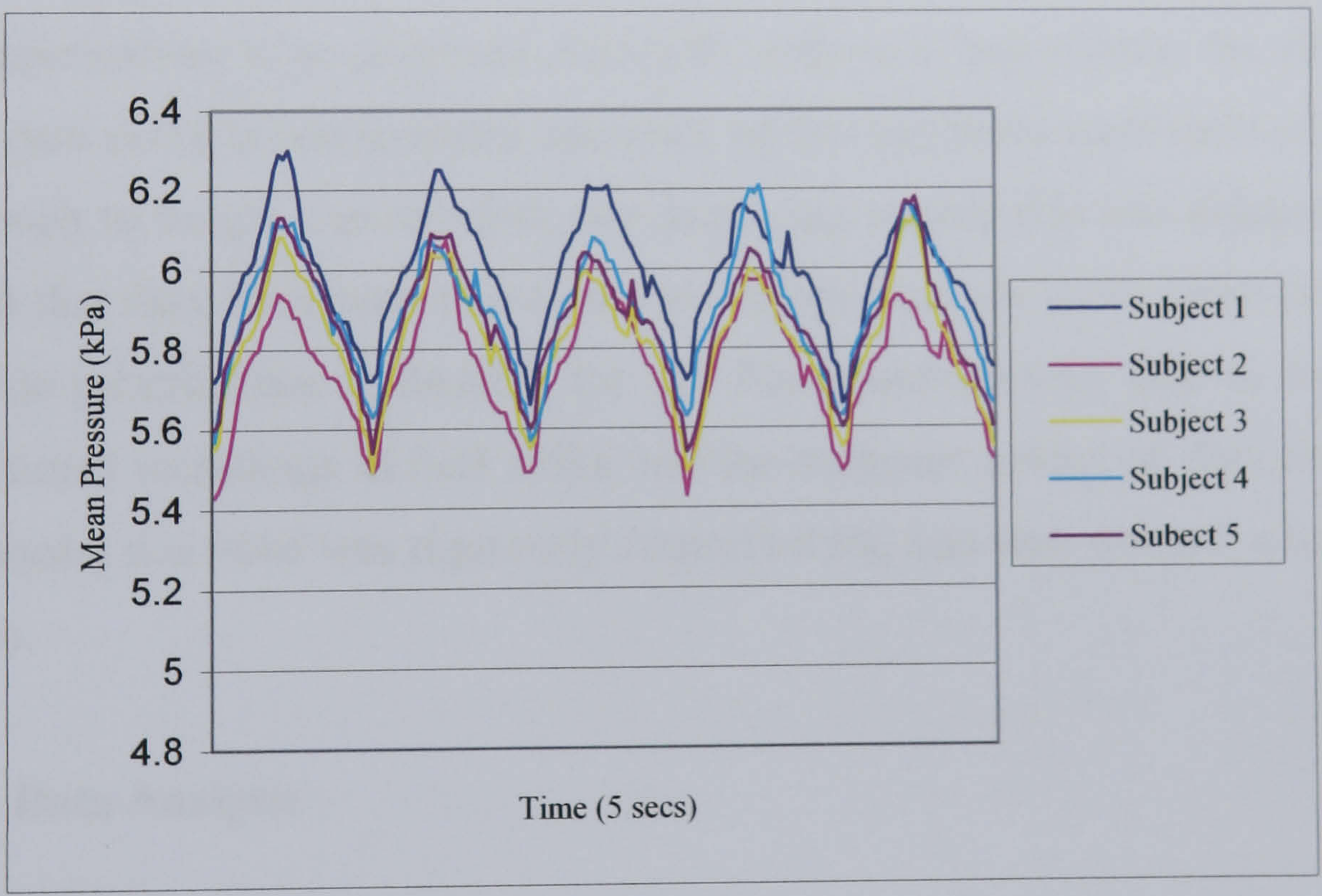



**Figure 5.26 Effect of stride pattern on pressure (taken from Martin, 2001).**

Figure 5.26 is taken from Martin's findings on the effect of the stride pattern on recorded pressure. As can be seen from the graph fluctuations are found in pressure throughout the gait cycle. The highest pressures were associated with heel strike, as this is the point during the gait cycle when the body begins to move upwards in opposition to the LCS which is still moving downwards. The fluctuations identified are small averaging at 0.5 kPa. A fluctuation of this magnitude when compared to the pressures measured at the shoulder and hip (presented in chapters 6 & 7) represents a small proportion of overall pressure. However, if not accounted for this fluctuation could cause error within the data due to the possibility of different sections of the gait cycle being captured for each recording. Therefore, this effect was controlled for in two ways.

Firstly pressure recordings were timed with heel strike. Originally it was hoped to develop a heel switch which could trigger recordings on heel strike. However, the Tekscan software does not cater for such an addition and the cost of a new software programme coupled with linking this switch together with the external trigger proved to be unpractical. Thus, the experimenter timed each recording to heel strike via sight. This is obviously not as accurate as a heel switch, but given that one experimenter was responsible for making measurements throughout no inter-experimenter error occurred. Secondly and most importantly, the first step during data analysis was to select one cycle of the waveform from each recording (i.e. trough to trough was selected, any data lying outside this was deleted). This ensured that data from each recording were taken from the exact same period of the stride pattern, thus controlling for any fluctuation present. Due to the steps taken (timed recordings at heel strike and the stringent control of data extracted for analysis) this issue was rigorously controlled for, and thus was not a cause for concern.

### 5.6.7. Data Analysis

The chosen pressure indices for analysis were the mean and 90$^{th}$ percentile (90%ile) pressures. The mean was chosen as it provides an indication of the average pressures at an interface. This was the mean pressure from the ten frames from each recording (mean pressure calculated from each frame and then the mean of these ten values was presented). Only data from those cells which registered pressure were included. Cells registering zero were assumed to lie beyond the edge of the interface, and were thus discounted. The 90%ile pressure was also calculated across the 10 frames, highlighting the higher pressures found (the 90%ile value was identified for each frame and then the mean of these ten values was presented). It has been found with the FScan sensors that extreme outliers can occur due to 'creasing' of the sensors as they follow body contours (Martin, 2001). If a pressure cell is creased this causes an abnormally large pressure to be displayed due to the compression of the conductive ink through the creasing effect. Great care would always be taken upon placement of sensors to avoid creasing, but to assess peak pressures at the interface without crease artefacts, the 90%ile value was chosen. Also, arguably the most important part of the pressure recordings to consider are the peak pressures, as these cause the most discomfort and lead to possible injury. Hence, 90%ile pressures were calculated. A third index of pressure also chosen to be reported was contact area. This gives an illustration of the degree of pressure distribution across the shoulder and hip straps and was presented as the mean contact area per condition.

Other data presented are the locations of the 90%ile pressures at the shoulder and hip. The shoulder and hip being split into three zones each. The shoulder is divided into the clavicle, trapezius and scapula zones. The hip is divided into the anterior, iliac and lumbar zones (please see appendices for diagrams of these zones). When analysing pressure data the location of the 90%ile pressures was identified at each interface for each participant. The location of these zones is interesting as this represents where the peak pressures are applied to the interface and this may have a link to subjective comfort (i.e. whether or not participants perceive the most discomfort in the same location as the 90%ile pressure - this is discussed further in chapters 6, 7 & 8). Also, whether there are differences in discomfort when peak pressure is applied in different regions of the shoulder and hip will be assessed. If this is found to be true then the most appropriate anatomical regions for loading (at shoulder and hip) can be identified.

The pressure distribution between the shoulder and hip interfaces is also presented, this reflects how well pressure is distributed between the interfaces of the LCS's and backpacks and makes interesting consideration, especially when identifying design differences in regard to loading at the interfaces. Pressure distribution graphs (chapters 6 & 7) depict the mean and 90%ile pressure from the shoulder and hip interfaces for each backpack/LCS. Pressure distribution is discussed further in the results and discussion (chapters 6, 7 & 8).

As discussed previously, due to the conservative nature of the experimental design only data from the same sensor was used for statistical analysis. Paired sample 't' tests were thus the chosen method of objective analysis for the four main experimental trials. This test was the most suitable and powerful given the paired data sets gathered from the pressure recordings.

## 5.7. Experimental Trials

Upon finalisation of the objective and subjective methodologies the four main experimental trials of this thesis were planned.

**Trial 1:** The first trial involved an in depth assessment of the effect of clothing layers on pressure measurements. The question seeking to be answered was "if pressure on the skin is the determinant of comfort and/or injury, then does clothing alleviate peak pressure impact on the skin?" If clothing has no effect then there will be no need to place sensors on the skin and measurements can be made over clothing layers, making in-field trials easier and more realistic. If no effect is identified this would also indicate that specialised padding is required at the interface irrespective of clothing. This trial is described in chapter 6.

**Trial 2:** Also in chapter 6 is the backpack trial. This trial was carried out to assess whether Martin's findings on the effects of the new Airmesh straps were replicated when comparing two backpacks (Bergen and Airmesh). This trial was the first to assess not just shoulder but also hip interface pressure. The relationship between the pressures found at the shoulder and hip was assessed and this gives information about the effectiveness of the whole backpack rather than the shoulder straps alone. The findings from this laboratory study provide a start point for moving on to assess the whole LCS in field, with increased loads and military participants.

**Trial 3:** The third trial was an in-field trial with civilian participants. This trial was novel as it was the first to assess the whole LCS, rather than previous research assessing backpacks alone. A comparison was carried out between the current standard issue Bergen LCS and the prototype Airmesh LCS. A field course was utilised for the first time, rather than a treadmill in a laboratory. Findings indicated how the whole LCS's functioned in terms of pressure distribution between the interfaces and subjective comfort ratings.

**Trial 4:** The final trial was a military field trial, with military participants and loading, the first of its kind to assess the effects of real military loads on pressure and subjective ratings at the interfaces. This trial was also quite large (30 participants) especially when considering other ergonomic research in this field. The findings from this trial provide feedback on the whole LCS when used by the end users themselves and in very similar contexts to 'real life' thus providing a high validity when compared to civilian laboratory trials.

## 5.8. Conclusion

The chosen methodologies for both objective and subjective measurement for this thesis are the same basic methodologies as utilised by Martin (2001) for laboratory measurements of backpack interface pressure and subjective comfort ratings. A wealth of reliability/validity testing has been conducted with highly conclusive results gained regarding both on body pressure measurement via the FScan sensors and subjective ratings via the 5 point ordinal comfort scale. Due to these conclusive results and the fact that the same basic methodologies and equipment are utilised by this thesis, further in depth study into reliability and validity was considered unnecessary here. Thus, the in-field system was now considered ready for use in the main thesis trials. Chapters 6 and 7 detail these trials and the findings.

# Chapter 6: Laboratory Trials

## 6.1 Introduction

Four main experimental trials were performed as part of this thesis. This chapter describes trials 1 and 2, and also the development of the adapted LCSs. The chapter is thus split into three parts. The first trial (part I) assessed the effect of clothing layers at the interface on the transmitted pressure to the skin. If clothing layers worn at the interface have no effect on transmitted pressure, then measurements can be made above clothing allowing participants to wear normal military garments. This would also allow adapted LCSs to be used. These adapted LCSs are discussed in part II. The aim of the second trial (part III) was to assess whether Martin's findings regarding the Airmesh shoulder straps were replicated when comparing the standard issue 'Bergen' backpack and the prototype 'Airmesh' backpack. The basic methodology utilised for all four experimental trials was discussed in detail in chapter 5. Thus, methods are only mentioned in brief, focused on highlighting any methods specific to each trial.

## PART I – Trial 1

## 6.2 The Clothing Study

A crucial (and final) element to the development of the in field equipment was to assess whether pressure measurements recorded over clothing layers placed between the skin and the pressure sensor are a true reflection of skin contact pressure, i.e. is the pressure transmitted through the clothing layers to the skin surface without being distorted. Previous methodology employed by Martin

(2001) involved taping sensors onto a single cotton 'T' shirt layer in relation to anatomical landmarks. This laboratory based work was obviously confined to indoors. One of the main aims of this thesis was to take measurements into the field, and in this case military participants will obviously need to dress according to environmental conditions and task requirements. It would not be a true reflection of military load carrying if participants could only wear a single 'T' shirt layer, hence the importance of this study. If clothing layers are found to have no effect on the transmitted pressure then sensors can be placed above clothing at the shoulder and in specially tailored pockets at the hips (described further in section 6.3).

This section describes the study carried out to assess this question. The findings of this study directly influenced the set up of the in-field pressure system and how trials were carried out in-field. It is an important element of the thesis. The findings of this study have been published in the Applied Ergonomics journal (Jones & Hooper, 2005).

### 6.2.1 Method

Eleven healthy civilian males participated in the study, under conditions approved by the LUEAC. Participant statistics: age 23.5±4.4 yr, weight 75.7±4.3 kg, and stature 177.2±8.2 cm. Participants carried an evenly loaded backpack (23.5 kg) with a stable centre of gravity. A single British military backpack (specifically the Bergen backpack) was used. The shoulder straps are constructed of closed cell polyethylene foam and are 10.4mm thick. Participants walked at 5 $km.hr^{-1}$ on a treadmill, 0% grade, for 3 minutes. During this time pressure was measured at the right shoulder interface.

After each 3 minute spell, participants stopped and changed the clothing combination, necessitating doffing / donning the Bergen. The buckle positions were marked so the shoulder straps were repositioned giving a similar position and tension each time. Sensors were equilibrated and calibrated before and after use by each participant in the Tekscan box calibration box. Any drift (>1%) in calibration value lead to rejection of the data set. Two sensors were used separated by a layer of one or more garments and a no garment condition leaving the sensors in contact as a control. A new pair of sensors was used for each participant. An intra-participant design was employed where only data coming from the same sensor were used for comparison to avoid any inter-participant variability (as discussed in chapter 5.4). The 'skin' sensor was taped onto the skin surface, positioned via the triangulation method (chapter 5.6.3). The 'strap' sensor was taped above the clothing directly under the strap. Alignment between the two sensors was checked via triangulation, with two cells on the skin sensor being matched to the corresponding cells on the strap sensor. Pressure was recorded from the two sensors simultaneously; recordings were made each minute, giving 3 measures. Interface pressure was recorded over a one second period (10 frames per second).

Both individual garments and layered clothing were assessed. The clothing used was standard issue British military clothing consisting of: shirt (cotton), fleece, combat jacket (cotton polyester), raincoat (gortex) and combat body armour (cotton polyester, not including ceramic ballistic protection plate). Garments were tested individually and then layered as would be worn in response to different environmental and task conditions. The order of testing was randomly assigned for each participant. Table 6.1 details the clothing layers assessed.

**Table 6.1 shows the various clothing layer combinations**

| | Individual garments | Garment layers | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| The garments, tested singly and in layers, are shown on the right: | Shirt | X | X | X | X | X |
| | Thick fleece (fl) | | X | X | X | X |
| | Combat jacket (cj) | | | X | X | X |
| | Raincoat (rc) | | | | X | X |
| | Combat body armour (ba) | | | | | X |

After each garment and layer was assessed, the sensors were crossed over (the sensor placed on the skin was now placed on top of the clothing layer/s and vice versa) and all measurements repeated, reversing the sequence of layers and garments. All pressure data used for analysis were a mean of the paired, crossed-over measures to obviate any effect if a degree of sensor offset was present.

### 6.2.2 Results

Mean and 90%ile pressures were calculated (chapter 5.6.7). If a degree of imperfect alignment existed these average pressures may have not been perfectly paired. However, the alignment did ensure the same zones of highest contact pressure were measured by both skin and strap sensors. Consequently the 90%ile pressure recorded should match closely between them. The mean and the 90%ile pressure differences between the skin and strap sensors were calculated for each participant, for each clothing combination.

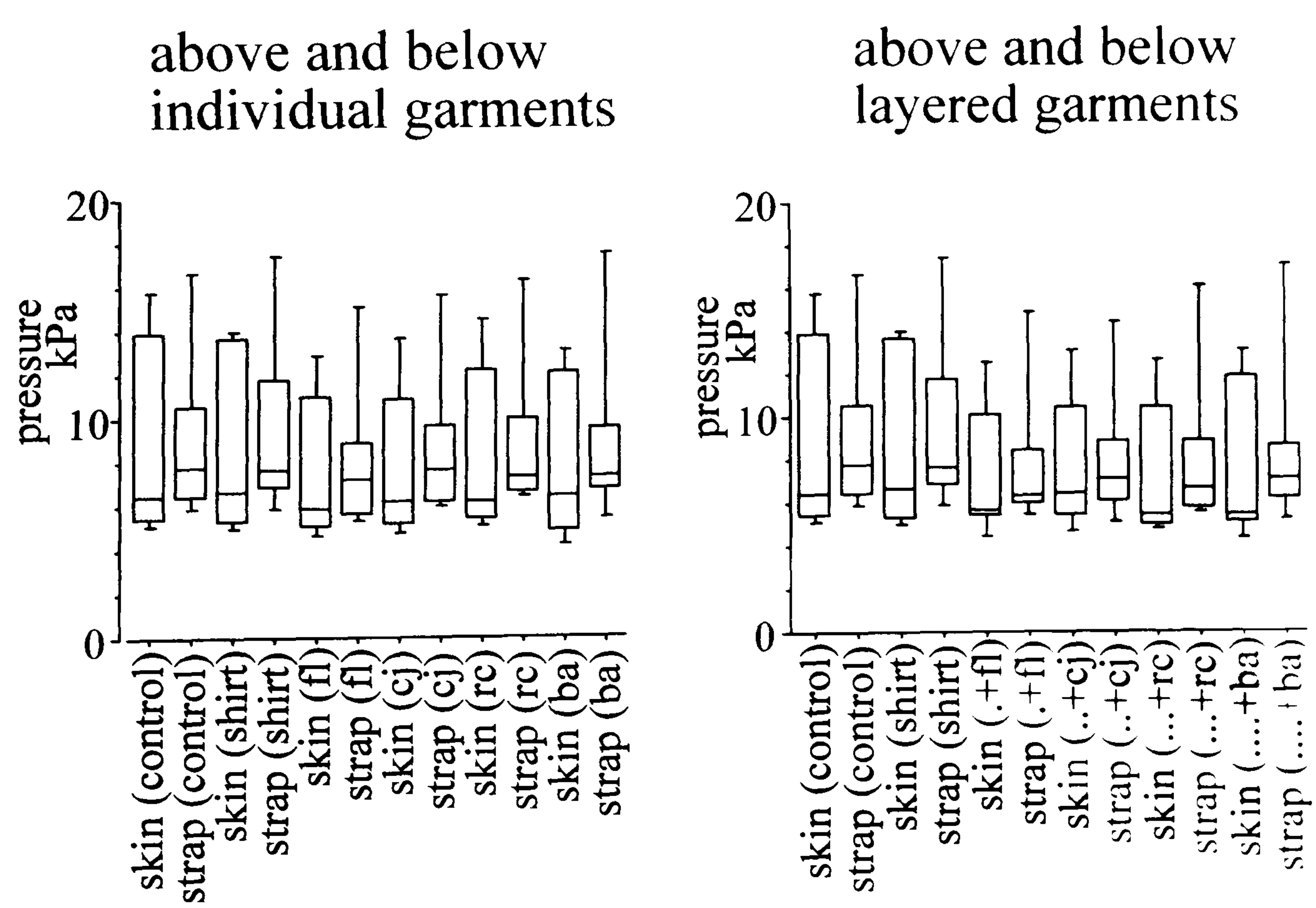



**Figure 6.1 Median pressure from individual and layered garments**

Figure 6.1 shows the range of mean pressures measured by the skin and strap sensors separated by the individual and multiple clothing layers, with the 10th, 25th, the median and the 75th and 90th percentiles shown. As the graph shows the data are very similar for each condition for both sensors. One interesting point to note here is the skew, which shall be considered further in the discussion.

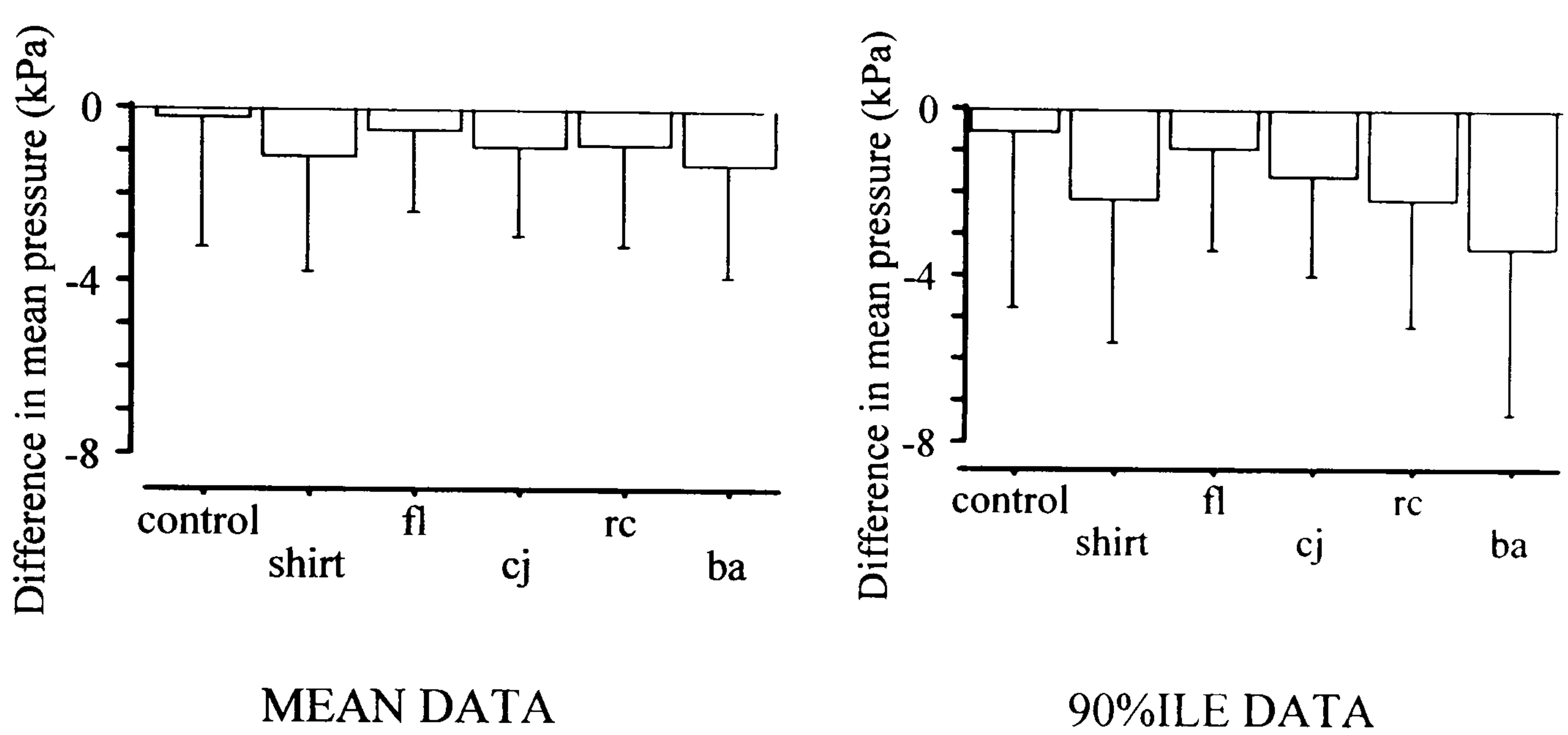



**Figure 6.2 Difference in Mean and 90%ile data from individual layers**

The differences between the skin and strap sensor values were calculated (skin - strap) for the mean and 90%ile data. These are shown in figure 6.2 for the control condition (mean + SD shown on graphs) and for each individual layer. Negative values result when the skin surface sensor returned lower pressure values, being positive if the skin surface sensor returned higher pressure values. When analysed with a One Sample 'T' Test none of the values are significantly different from zero.

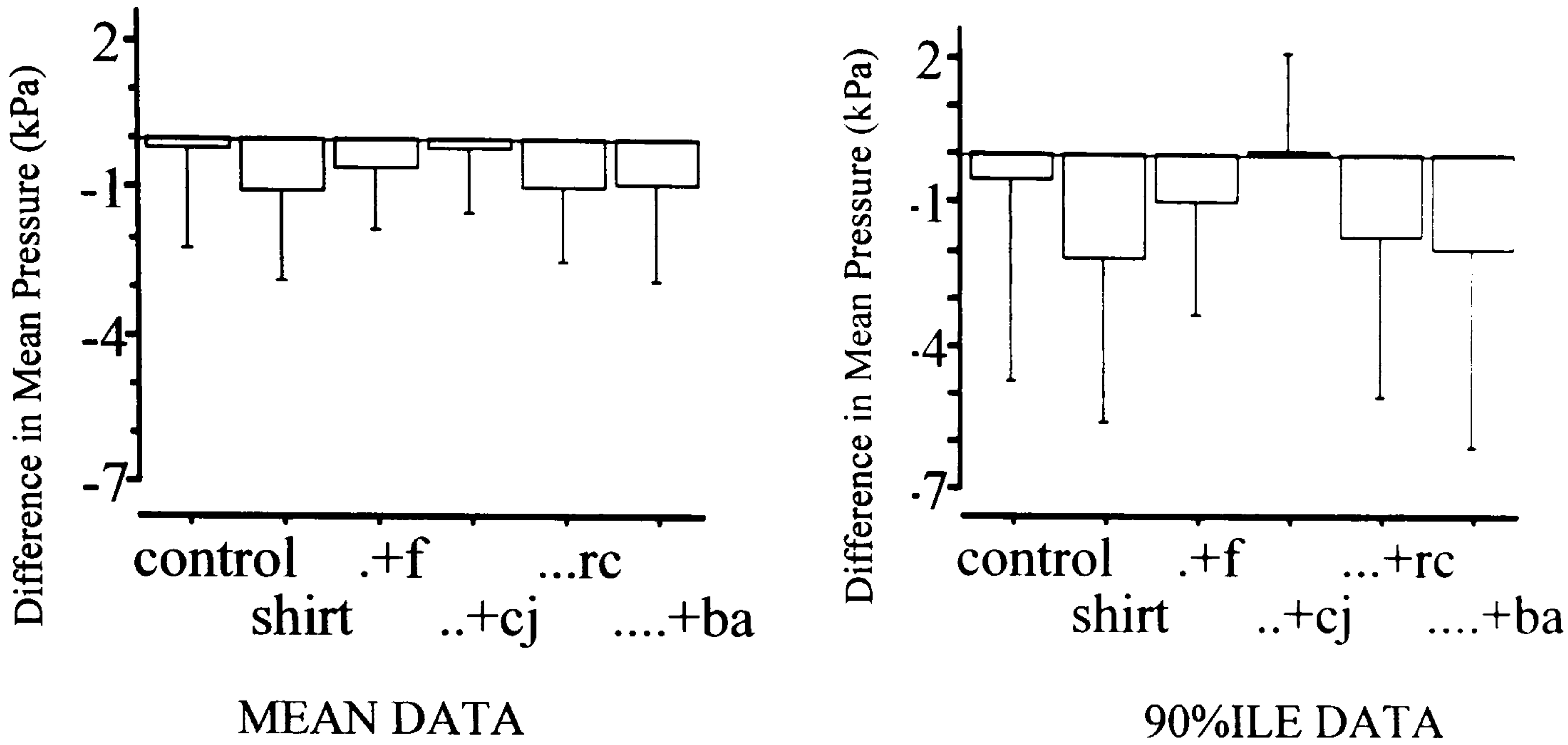



**Figure 6.3 Difference in Mean and 90%ile data from layered garments**

In use, various garments will be layered, depending on environmental and task requirements. The influence of increasing thickness when layering garments is shown in figure 6.3. Again analysis shows that none of the values are significantly different from zero.

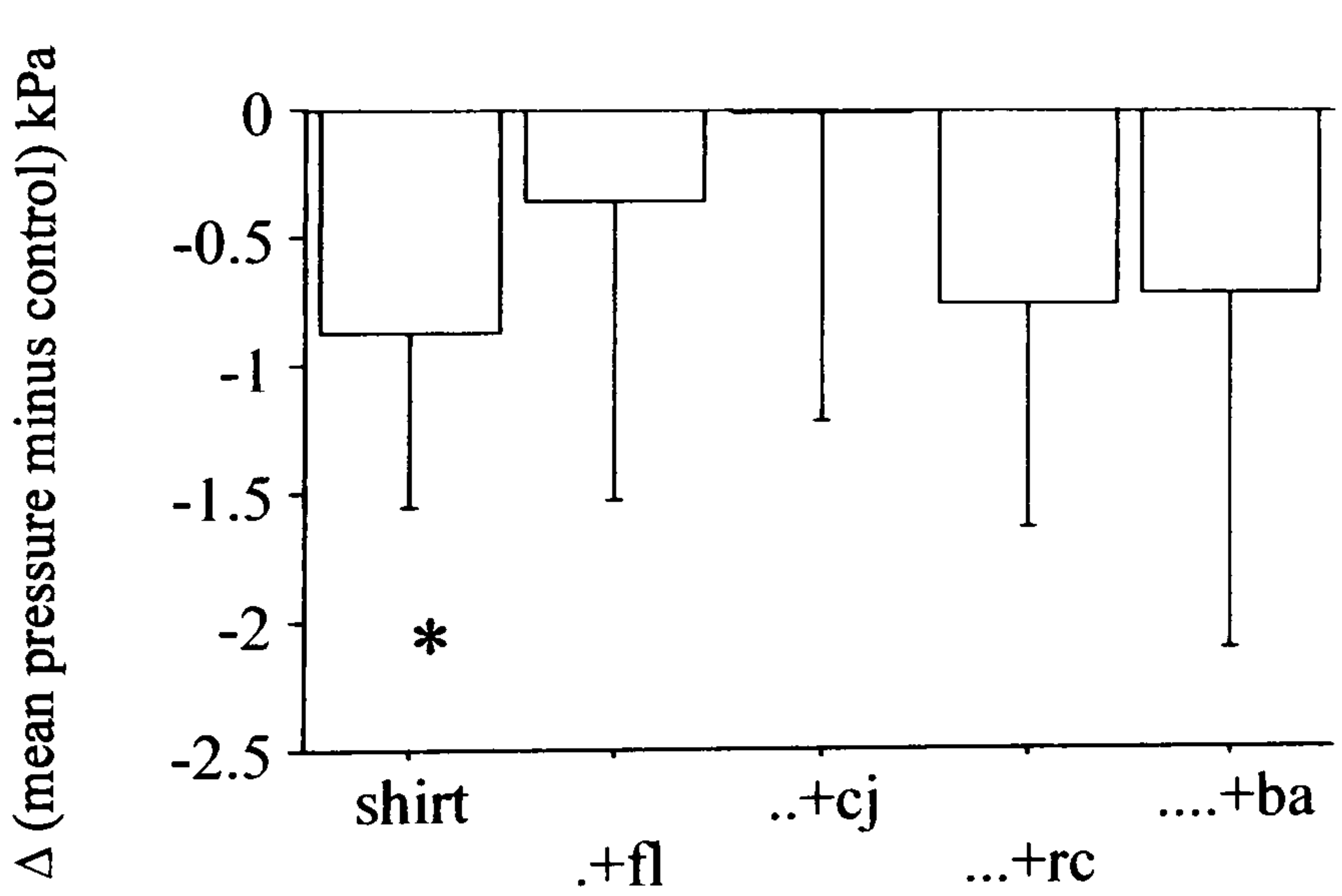



**Figure 6.4 Difference in Mean Pressure minus control condition.**

Unsurprisingly, the control data were not exactly zero. The data were also analysed following subtraction of the control values (fig. 6.4). None of the data were significantly different from zero, except in the presence of the shirt (*) when worn alone.

### 6.2.3. Discussion

The data in figure 6.1 demonstrate the expected detection of pressure, inevitably present under shoulder straps when a backpack is supported wholly or in part by a shoulder harness. The mean pressures shown are the data returned from the activated cells in a sensor placed under the right strap. They are the mean of 3 measures, each being comprised of 10 frames collected over 1 sec. They include pressure measured at all stages of the gait cycle, from a peak following heel strike through to a trough during the single support phase. They include all cells that detected pressure >0 kPa. The 90%ile data are taken from this same data set. These are likely to represent the data measured during the period of highest loading following heel strike in the most loaded zone(s) within the interface.

These data are skewed (fig. 6.1), with pressures above the median showing a larger spread than those below. The cause of skew is not clear. It may be related to variable geometry of participant's shoulders and/or shoulder curvatures possibly causing variation. It may be a user caused skew, the lower pressures being close to the minimum needed to support the load, those higher being dependent on the preferred tension of the straps. The preference would depend on the user's desire for load stability and the ratio between shoulder and other interface zones on the body. Continuous pressure of 14 kPa has been suggested as an upper limit (Stevenson et al, 1995) to avoid tissue damage during sustained load carriage. In the conditions used here, 75% of pressures detected by the sensor lying on the skin were below these limits, whichever garment lay at the interface. This was also the case when layered garments were present at the interface. The 90%ile pressures of course show a higher range. Whether these are sustained higher pressures or whether they tend to be present intermittently during the gait cycle cannot be deduced from these data.

The 90%ile pressures were found either above the clavicle protuberance or at the peak of the mid-shoulder (over the trapezius muscle). The location of the 90%ile pressures remained constant throughout, and thus is most likely to be a product of body contours rather than shoulder strap or clothing characteristics. The small differences in pressure data from the 'skin' and 'strap' sensors maybe due to the nature of the surfaces with which they are in contact. One is in contact with the skin; the other is in contact with the strap. Jointly they are in contact with one another (control condition), or the range of different clothing materials worn. Hence, the 'strap' sensor may perhaps conform to the strap shape, the skin sensor to the shoulder shape. Shear forces or curvature of the sensors could be affected, with the potential to alter the data returned by the sensors. However, differences were not significant and numerically were very small, especially in the control condition. When individual garments or layers separated the sensors, the differences remained insignificant, none being different from zero.

The only significant result found in this study is shown on figure 6.4, for the 'shirt' condition after accounting for the control (sensor to sensor contact). This would account for approx. 1 kPa when taking measurements over a shirt; this is too small to be meaningful. It would be most unlikely to have an effect on the subjective rating or on the risk of tissue damage or fatigue. It is larger differences that appear to be 'felt' by the user and other factors such as fit and stability would arguably be more important here. It is safe to conclude that the effect of individual garments is negligible. The same point also rings true for clothing worn in multiple layers. This in fact refutes the starting supposition that multiple layers will affect the 'footprint' of pressure transmitted from the strap to the shoulder even when multiple garments are worn in layers.

Thus, it would suggest that the soldier will gain no or very little relief from applied pressure by wearing garments, even in layers, when carrying a backpack. It also means that specialised materials are necessary to spread the higher pressure zones at an interface in order to ameliorate pain and the potential for soft tissue injury. In the experimental context, interface pressure may be adequately assessed using a sensor placed above the clothing layer/s rather than at the skin surface.

This will simplify assessment of interface pressure in future studies and opens the practical possibility of instrumenting a pack for 'in-field' interface pressure measurements. In conclusion, the findings from this study suggest that interface pressure measurements are unaffected by layers of clothing. They also show that interface pressures can be measured above clothing layers rather than having to be at the skin surface.

# PART II – Experimental Equipment

## 6.3. Development of the Adapted in-field LCS

The findings of the clothing study add support to the idea of developing an experimental LCS design, comprising of a LCS adapted to house pressure sensors. An extra layer was sewn onto the contact side of the hip straps which could be used as a pocket to hold pressure sensors. The clothing study has already shown that layers have no effect on the transmitted pressure and thus having the extra pocket layer is a valid approach. However, as an extra control for this, the same material shall be used on both adapted LCSs. For the field trials (chapter 7), two LCS designs were assessed – the standard issue Bergen LCS and the prototype Airmesh LCS.

One of the aims of the military field trial was to assess whether the laboratory findings of Martin on the increased comfort and reduced peak pressures associated with the new shoulder straps (as incorporated on the new Airmesh backpack) are replicated in field when the whole LCS is worn, with military loading weights, with military participants, and during military tasks over mixed terrain. To enable this to be assessed in field the Bergen and Airmesh LCSs were adapted to incorporate 'intermediary unit' pockets on the hip and shoulder straps and 'sensor' pockets on the hip straps.

Figure 6.5 shows the hip sensor positioning with the sensor placed inside the specialised pocket placed on the backpack hip belt. 1mm thick cotton mesh material was used to create the sensor pockets (both on the Airmesh and Bergen LCS) on the hip straps. Also shown is the intermediary unit pocket which was sewn onto the outside of the hip strap (1000 denier Cordura) to house this unit. The interface cable can then be seen leading from this unit to the ruggedised laptop (which resides in the backpack for remotely triggered field trial).

**Figure 6.5 and 6.6 Adapted 'Airmesh LCS'.**

Figure 6.6 shows the shoulder sensor positioning. Again the intermediary unit and the interface cable can be seen secured into the intermediary unit pocket on the shoulder strap. However one important difference between the shoulder and hip sensor placement is that the shoulder sensors for both LCSs were placed on top of the outer clothing layer via the triangulation method (as described in chapter 5.6.3) as it was not suitable to place the shoulder sensors in pockets on either the webbing or pack shoulder straps. This was because (unlike the hip) there are two straps interfacing with the shoulder and transmitted pressure from both of these must be captured in order to avoid missing areas of contact. The pressure sensors provide enough coverage for both of the straps as in reality the backpack shoulder strap sits on top of the webbing strap and the FScan sensor is wide enough to provide coverage for the whole of the width of the shoulder where straps interface with the body (as highlighted in chapter 4.4.3). Caution was taken with this issue of shoulder sensor placement however, if for any reason there was any issue surrounding a lack of coverage at the shoulder the participant in question was free to leave and any data (if taken) was disregarded.

Another important factor to note was that the Bergen LCS and the Airmesh LCS differed in terms of the integration between the two elements (webbing and backpack) of the LCS. The Bergen LCS suffers from a lack of integration, preventing the backpack hip belt being utilised, with the backpack sitting on top of the rear webbing pouches. For this reason the sensor pocket was placed on the webbing hip belt on the Bergen LCS (as seen below). The Airmesh LCS had the sensor pocket on the backpack hip belt, as the LCS was designed as a system and thus the incompatibility does not occur.

Figure 6.7 shows the hip sensor positioning (with the belt webbing) for the Bergen LCS. Figure 6.8 shows the shoulder sensor positioning.

**Figure 6.7 and 6.8 Adapted 'Bergen LCS'**

The adaptations to the LCS to include sensor pockets further add to the complete mobility of the in-field system. The findings from the clothing study also confirm that pressure measurements can be taken above clothing layers and thus a major leap forward can be taken, as now measurements can be made on military personnel without the need for any experimental constraints. Participants can wear the LCS in the exact manner in which they would in reality. This obviously further adds to the credibility of data captured, as it truly is in-field and the LCS can be assessed as they would be used for military exercises and operations.

## PART III – Trial 2

## 6.4 The Backpack Study

Martin (2001) found that the Airmesh shoulder straps were associated with reduced peak pressures at the shoulder and improved comfort when compared to the Bergen straps. Following these findings and the subsequent development of the new Airmesh backpack (chapter 5), a study was carried out in the laboratory. This study provides a baseline for further work and identifies whether findings are replicated with the new Airmesh backpack when compared to the standard issue Bergen. An important difference here is that this is an assessment of backpacks not an assessment of straps. Martin used an adapted backpack where the shoulder straps could be interchanged, fastened on via press studs and the pack support strap (figure 6.9). The pack support strap took the whole of the load passing over the shoulder. However, in reality the shoulder straps are stitched on and both the shoulder strap itself and the pack support strap take the load. It is therefore important to assess whether improvements are still found when assessing the backpacks with straps fixed on, otherwise we will not be able to determine whether design advances are still found with end products.


**Figures 6.9 Martin's adapted strap. Figure 6.10 A normal (fixed) strap.**

The same basic experimental design as Martin utilised was carried out here with identical loadings; incline on the treadmill; and objective and subjective data were collected. The duration and speed of the walk did differ however, as infantry units typically walk quicker than 3.5km/hr$^{-1}$, on average around 6km/hr$^{-1}$ during load marching (Knapik, 2004) and also would very rarely walk for more than 30 minutes constantly without a break. Also, in Martin's trial the hip belt (present on both the Bergen and Airmesh packs) was not worn. The reason for this was to isolate the shoulder straps as the only load bearing part, to enable a more effective comparison. However, in reality a hip belt would always play a crucial part in the carriage (either directly by the Airmesh hip belt or indirectly with the Bergen belt webbing taking the load onto the hips) of loads. The hip belt was worn in this trial, with hip pressure measurements taken. Being as the shoulder and hip straps are the main interfaces with the body the relationship between pressures found at the two interfaces can then be assessed.

### 6.4.1 Method

Ten healthy civilian males participated in the study, under conditions approved by the Loughborough University Ethical Advisory Committee (LUEAC). Participant statistics (mean ± SD): age 21.3±2.3 yr, weight 76.4±4.1 kg, and stature 178.5±6.8 cm. Two backpacks were assessed (1) the standard issue Bergen and (2) the prototype Airmesh (see chapter 5.4 for photographs). Participants walked on a treadmill for 30 minutes at 0% grade at a constant speed of 6km/hr$^{-1}$. They carried a load of 18.5kg (in the form of the weight block) which provides even loading throughout the backpack. Participants walked twice with each backpack to allow pressure measurements from the shoulder and hip sites. The order of this was randomly assigned and the participants attended testing on two occasions, 2 walks on each occasion.

When making pressure measurements at the shoulder the sensor was positioned via the triangulation method (chapter 5.6.3). When measuring at the hip the sensor was placed inside the modified hip sensor pocket. Pressure measurements and subjective ratings were collected simultaneously at 10, 20 and 30 minutes. Interface pressure was recorded for one second (10 frames per second). As ever calibration was performed throughout to control for cell degradation or calibration drift. At each recording point, participants were asked to give a rating of their overall comfort on the 1 to 5 comfort rating scale (figure 5.22). Participants were also asked to fill out a post-walk form asking them to rate each LCS for comfort in three different body zones (figure 5.25). Finally they were asked to rank the LCS in terms of overall comfort.

### 6.4.2 Results

The final 30 minute values were used for both objective and subjective analysis as this provides the participants with the maximum exposure to inform their subjective ratings. Subjective ratings are expressed as differences in order to show more clearly how each participant rated the two backpacks. The post-walk ratings for each comfort zone are also shown. Mean and 90%ile pressures were calculated (chapter 5.6.7).

Figure 6.11 shows the mean and 90%ile pressures (± S.E.M) for the shoulder interface. Figure 6.12 shows the mean and 90%ile pressures (± S.E.M) for the hip interface

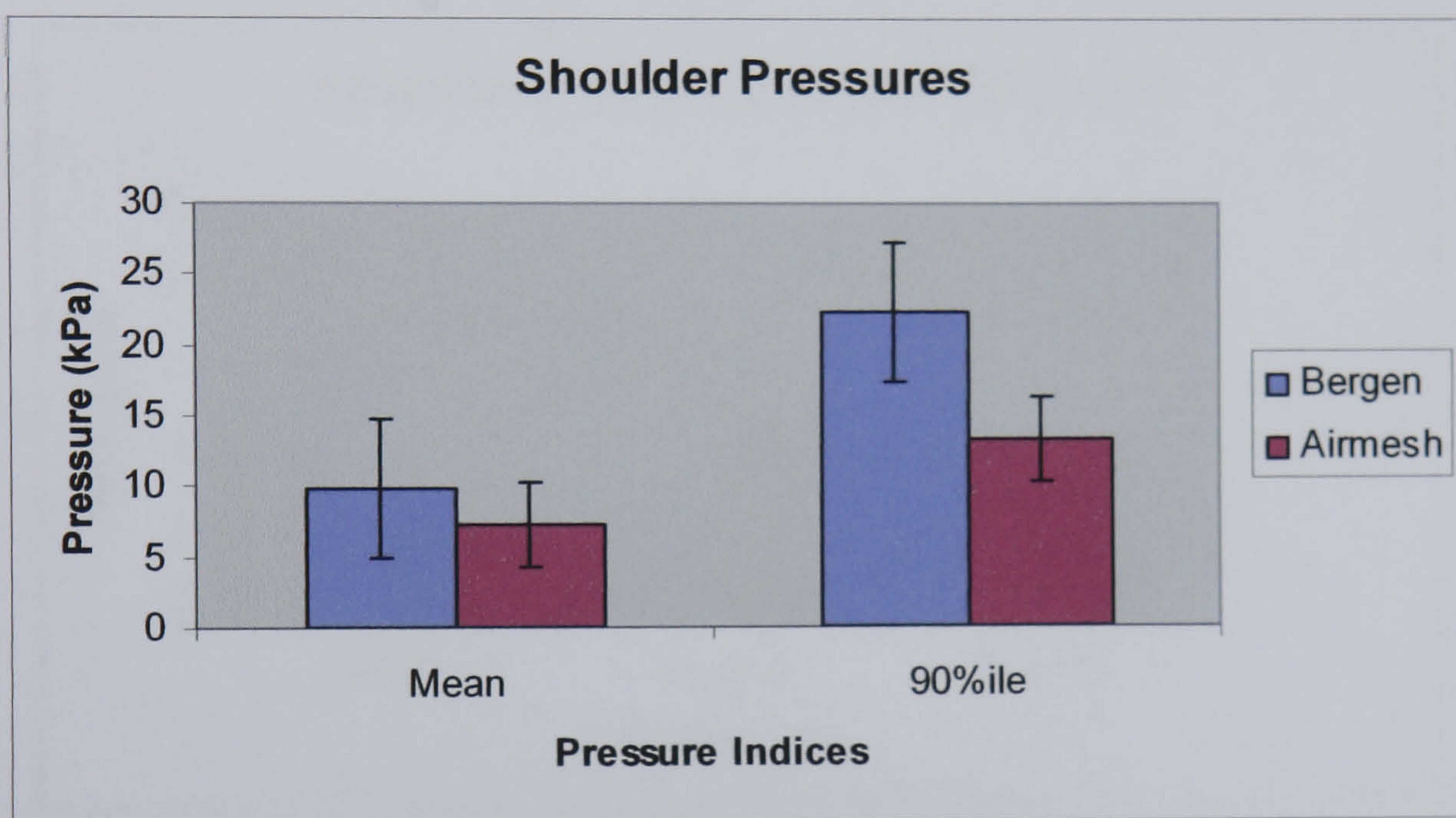



**Figure 6.11 Mean and 90%ile shoulder pressures.**

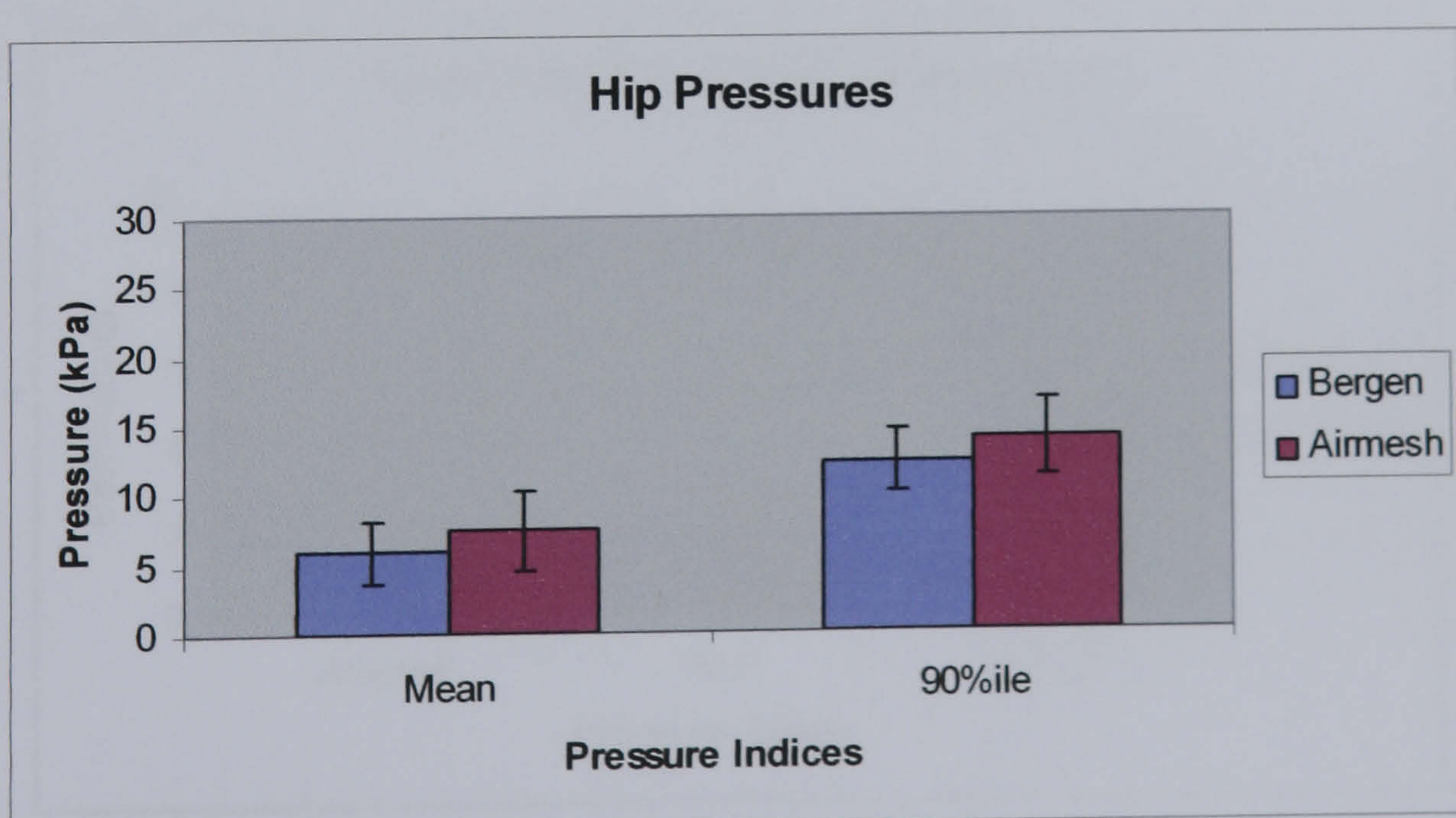



**Figure 6.12 Mean and 90%ile hip pressures.**

For both the shoulder and hip pressure data, paired sample T tests were carried out to analyze differences between the data from the Bergen and the Airmesh backpacks. All the data pairs (Bergen mean + Airmesh mean for shoulder, Bergen mean + Airmesh mean and Bergen 90%ile + Airmesh 90%ile for hip) were found to be non-significant ($P = >0.05$). However the 90%ile shoulder values were found to be highly significant, with the Bergen showing higher pressures ($P = <0.05$).

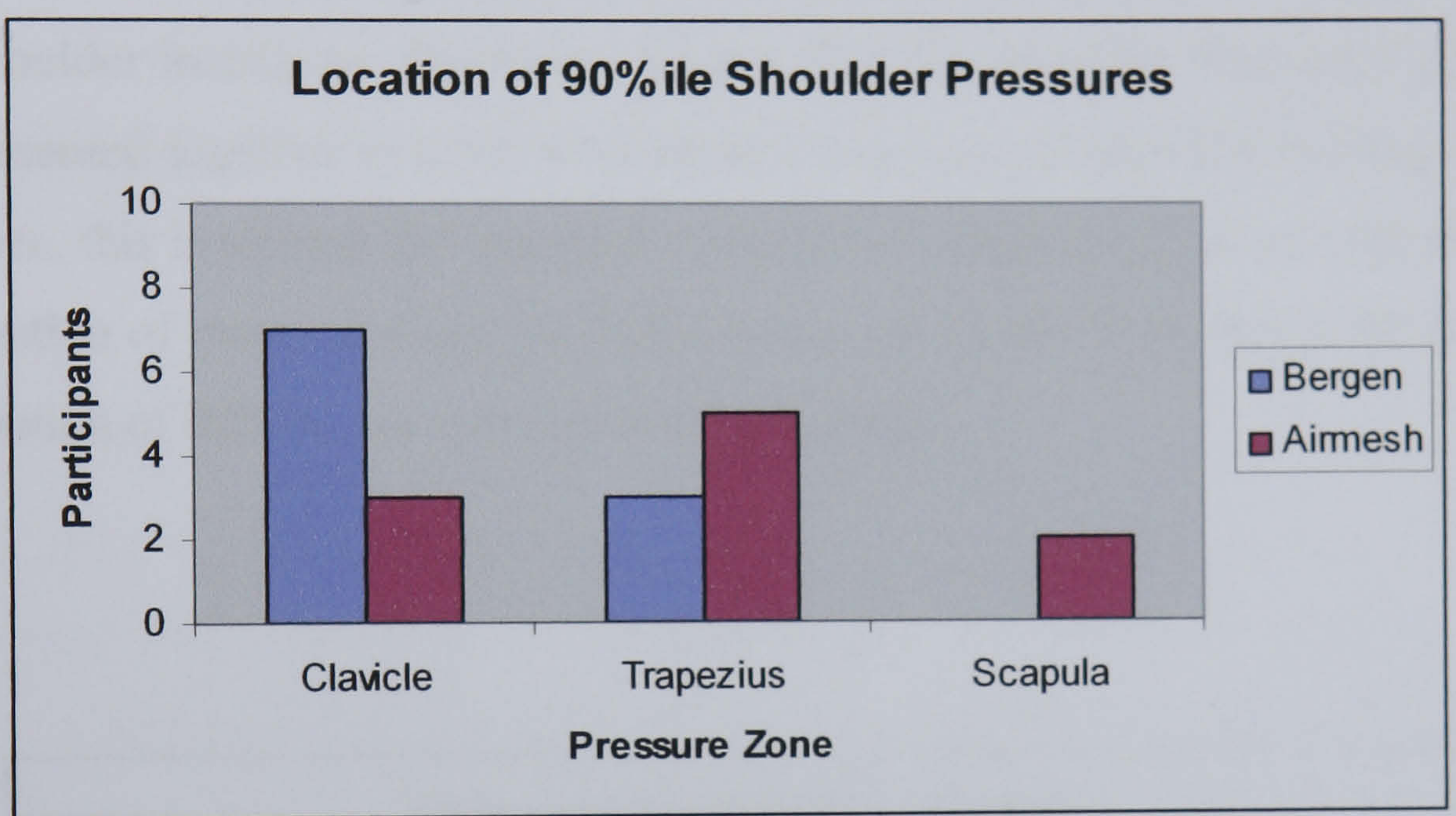



**Figure 6.13 Location of 90%ile shoulder pressures.**

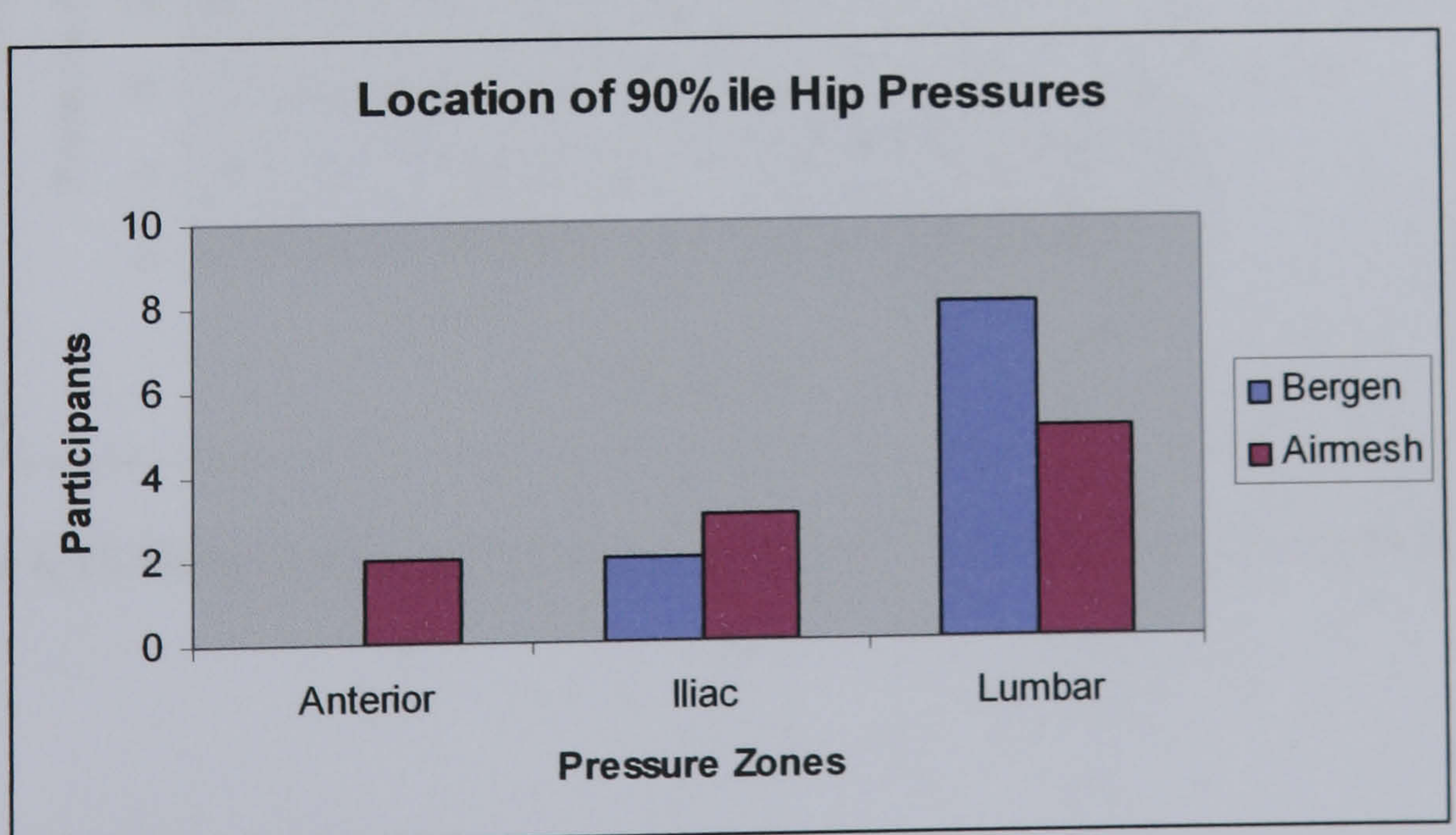



**Figure 6.14 Location of 90%ile hip pressures.**

Figures 6.13 and 6.14 show the location of the 90%ile pressures for each participant for the shoulder and hip regions respectively. For both the shoulder and hip regions the 90%ile pressures occur in two regions for the Bergen, but across all three regions with the Airmesh. Perhaps this is due to the plastic inserts aiding the transmission of pressure across the whole strap; however this shall be considered further in the discussion (section 6.4.3).

This is the first study of its kind to assess pressure measurements at both the hip and shoulder interfaces. Pressures (mean + 90%ile) recorded from each interface are presented together in order to provide comparison of pressure loading at each interface, this is termed the 'pressure distribution'. Figure 6.15 shows the pressure distribution of mean pressure for both backpacks. Figure 6.16 shows the pressure distribution of 90%ile pressure for both backpacks.

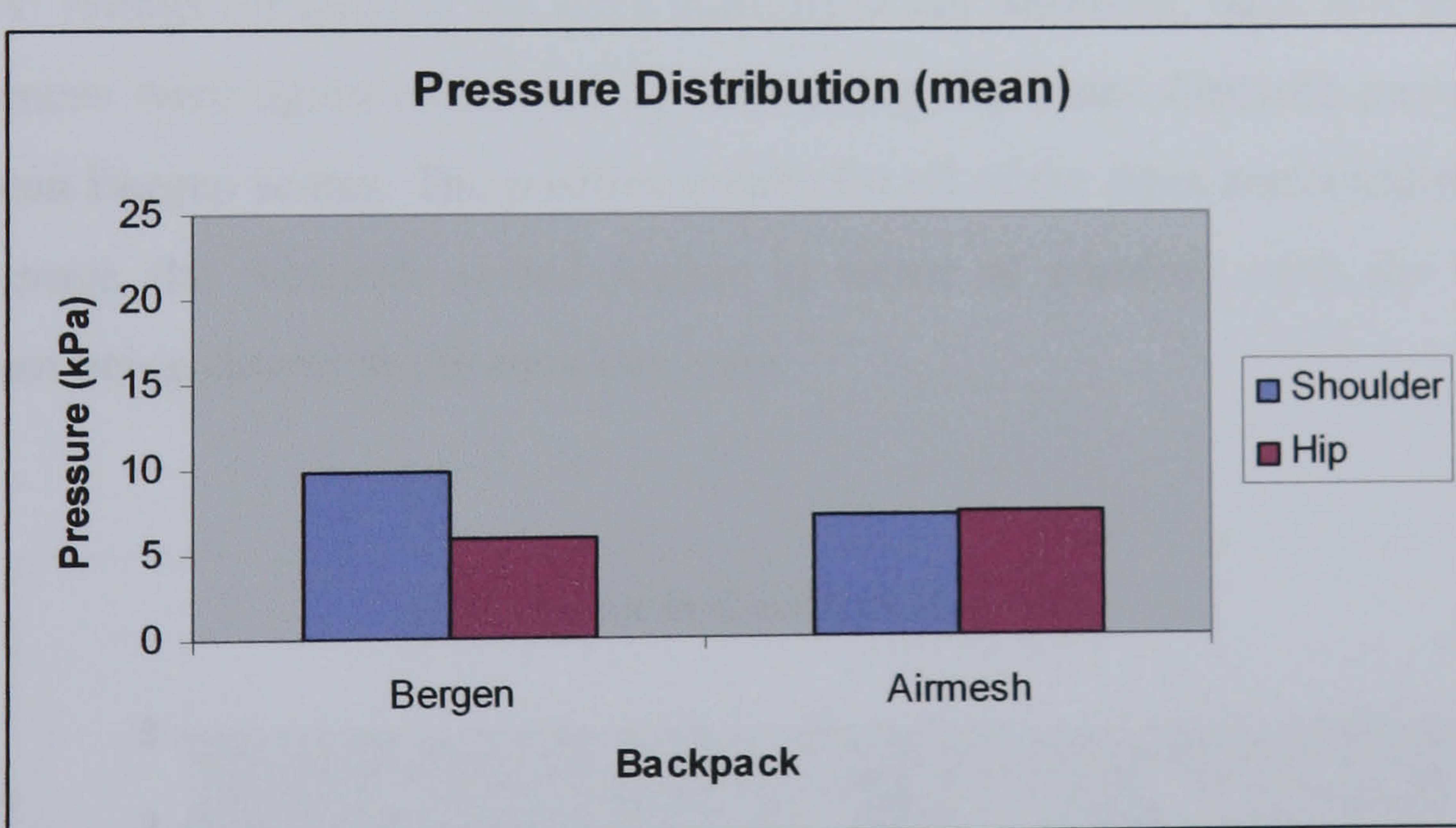



**Figure 6.15 Distribution of Mean pressure between the shoulder and hip.**

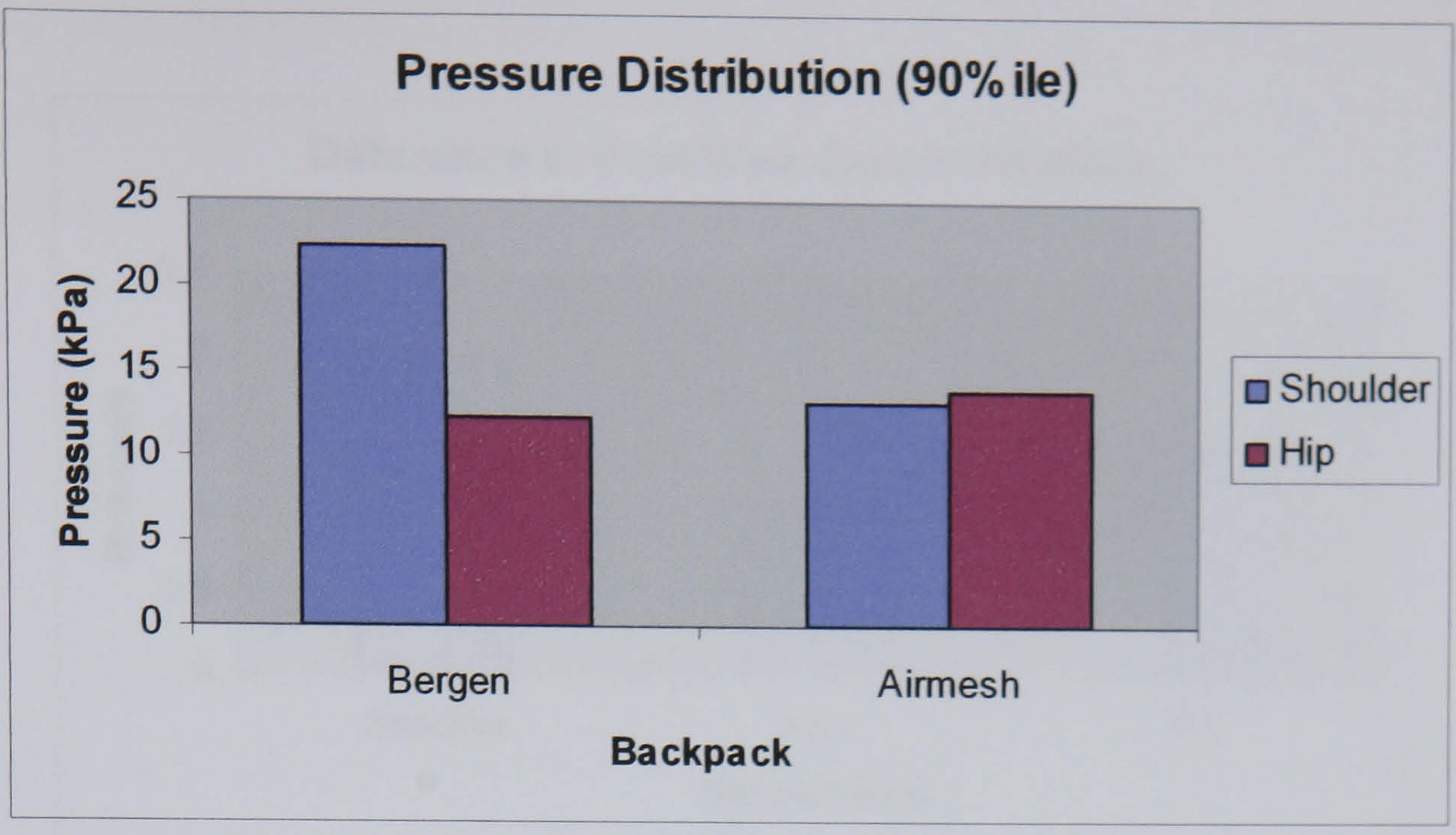



**Figure 6.16 Distribution of 90%ile pressure between the shoulder and hip.**

Figure 6.17 shows the difference in comfort ratings between the two backpacks, calculated by subtracting the Airmesh scores from the Bergen scores. Positive ratings show a preference for the Airmesh, and negative ratings a preference for the Bergen. Figure 6.18 shows the difference in the mean post-walk subjective comfort ratings for each of the three comfort zones (shoulder, back and hip). The differences were again calculated by subtracting the mean Airmesh scores from the mean Bergen scores. The positive results for all of the three zones indicate that on average the Airmesh scored higher in terms of comfort, with the biggest different being shown in the shoulder zone.

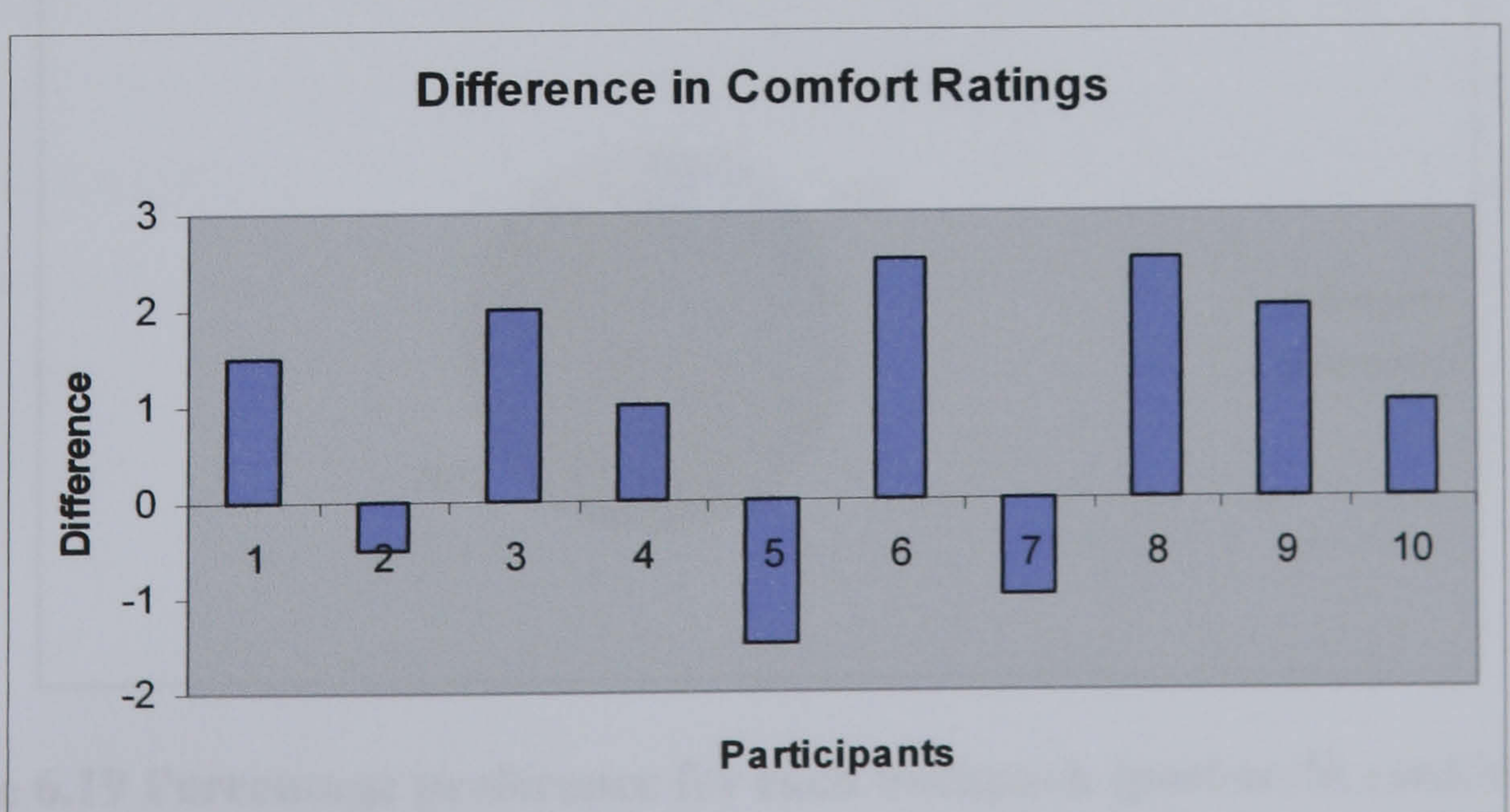



**Figure 6.17 Difference in overall comfort ratings (30th minute).**

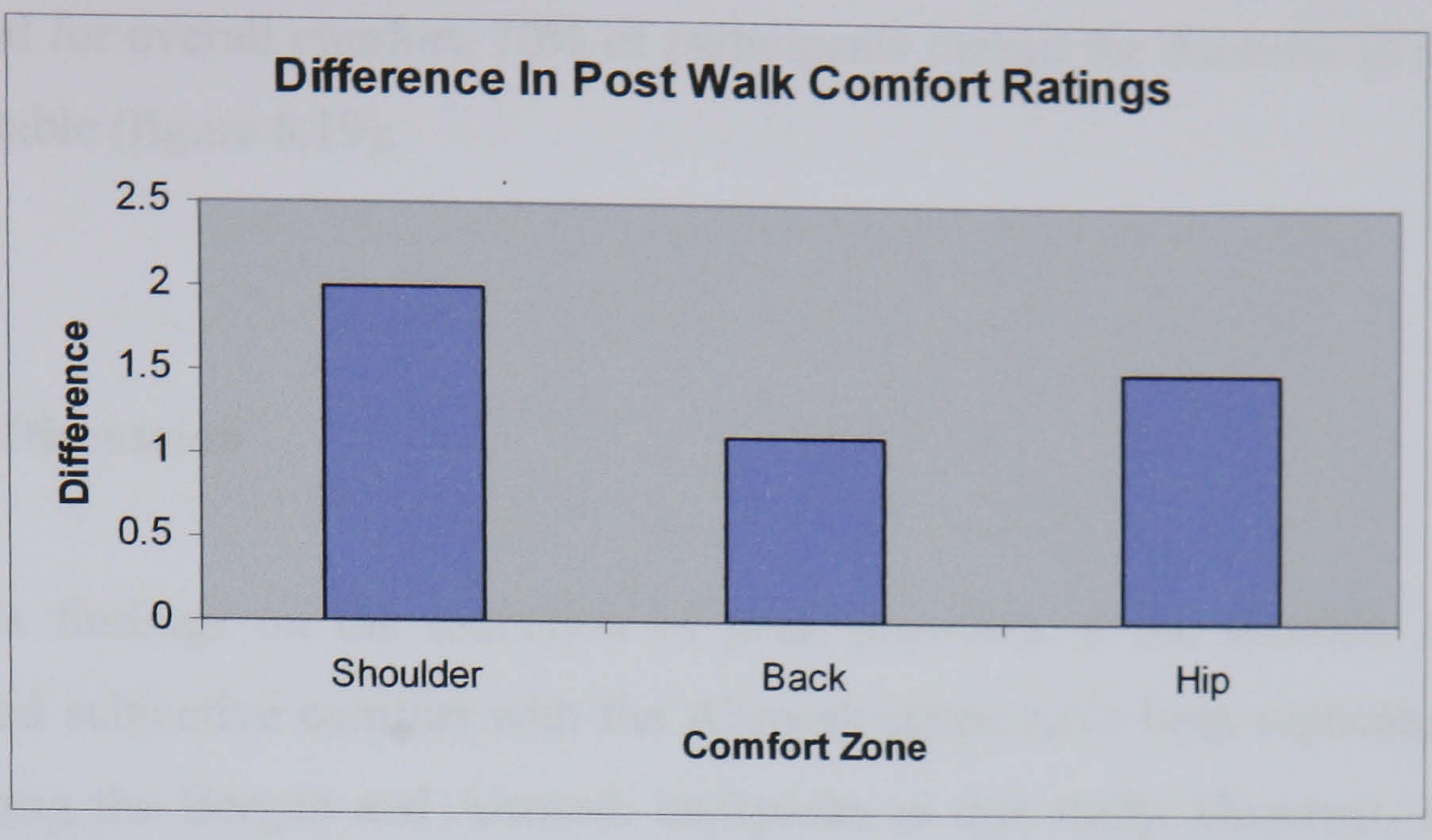



**Figure 6.18 Difference in mean post-walk comfort ratings.**

For both the 30th minute and post-walk subjective data Wilcoxon Signed Ranks tests were used for analysis. For the 30th minute data, highly significant differences were found between the two backpacks, with the Airmesh backpack showing increased comfort over the Bergen backpack ($P = <0.05$). Also, for the post-walk ratings significant differences were identified, for all of the comfort zones, with the shoulder zone showing the largest difference.

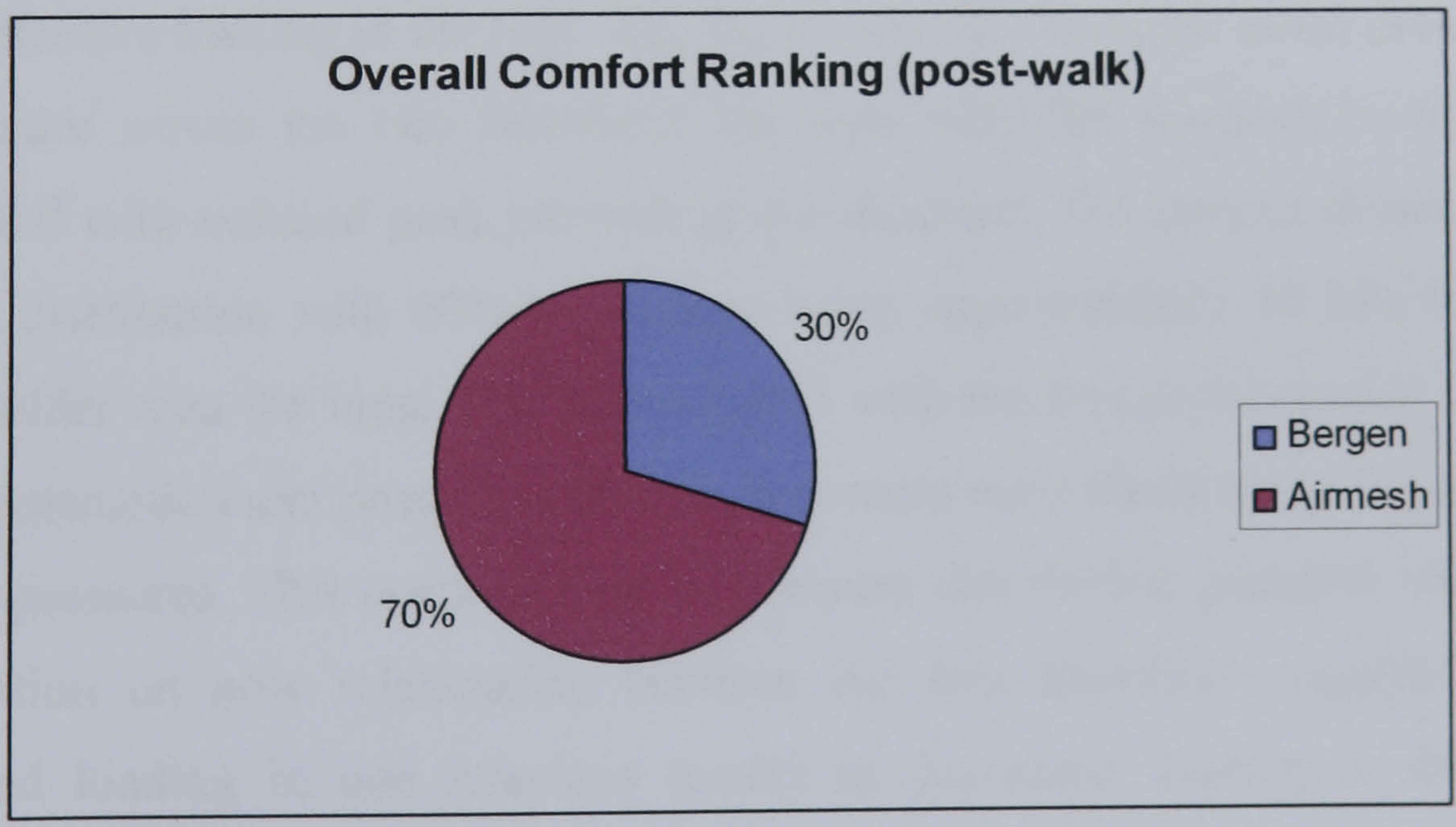



**Figure 6.19 Percentage preference for each backpack (post-walk ranking).**

For the post-walk rankings, where participants had to rank which backpack they preferred for overall comfort, 70% of participants ranked the Airmesh as the most comfortable (figure 6.19).

### 6.4.3 Discussion

Martin's findings on the reduction of peak pressures at the shoulder and the increased subjective comfort with the Airmesh straps have been replicated when comparing the Bergen and Airmesh backpacks in this study. However, highly a non significant difference between the mean shoulder pressures was found. An important difference between the two studies was that the hip belt was not worn by Martin's participants. This meant that the total load of the pack was supported via the shoulder straps. This study assessed the hip pressures and when compared to the shoulder pressures very interesting findings are seen. The hips are the natural anatomical load bearing region of the body and research and commercial backpack manufacturers have always placed much emphasis on using the hips to carry as much of the load as possible, to reduce loading at the shoulder. Until now this has not been quantified in terms of interface pressure.

Figure 6.16 illustrates how peak pressure at the shoulders may be reduced via more effective loading at the hips. The figure clearly shows the more even spread of pressure across the two interfaces (as seen with the Airmesh backpack) is associated with reduced peak pressure at the shoulder. The Bergen shows a more uneven distribution with 90%ile pressure being approximately 10 kPa higher at the shoulder than the hips. This fact coupled with the less sophisticated shoulder strap construction and possibly a change in posture most likely result in the higher 90%ile pressures. This consideration of pressure distribution provides interesting information on how relationship between the two interfaces, suggesting that increased loading in one interface results in decreased loading in the other. Perhaps the key is to design the interfaces to allow an equal pressure loading at the shoulder and hip. This shall be assessed further in the field trials and discussion (chapter 8).

With the uneven spread of load and the fact that the location of the 90%ile pressure is most frequent over the clavicle may indicate a postural effect also. Namely an increase in forward lean, where the participant increases lean to combat loading at the shoulder. This has the potential to cause injury not only at the shoulder but also the lower back. The fact that the shoulder zone showed the highest significant difference when it came to the subjective post-walk comfort ratings is thus no surprise. The location of the 90%ile pressures indicates a more even spread across the three comfort zones when the Airmesh is worn.

The most frequent zone of 90%ile pressures was the trapezius. The trapezius is a less bony region of the body than the clavicle and as Martin suggested it is associated with increased comfort when applied with the same pressure as the clavicle (Martin, 2001). If forward lean was less when wearing the Airmesh backpack this may describe the difference in location of 90%ile pressures. If the participant is more upright then increased contact with the trapezius zone will occur. This point is further supported by the fact that no 90%ile pressures were recorded in the scapula zone with the Bergen, but were with the Airmesh. The design improvements to the shoulder straps may also be a factor here, with increased pressure distribution (due to the plastic frames and different materials).

Contact area is also an important consideration (table 6.2). Both the Airmesh shoulder and hip straps showed significantly higher contact area when compared to the Bergen (paired sample T tests, P = < 0.05).

**Table 6.2 Contact Area of the two backpacks**

| **Mean Contact Area ($cm^2$)** | Bergen Straps | Airmesh Straps |
|---|---|---|
| Shoulder | 39.4 | 61.2 |
| Hip | 66.2 | 82.7 |

The Airmesh hip belt is more substantial than the Bergen hip belt and when combined with the plastic frame and different material this provides a larger contact area. The Airmesh shoulder strap is of the same dimensions as the Bergen shoulder strap, but the structural changes allow for increased contact area. If contact area can be improved this obviously would allow for reduced peak pressures via greater distribution of the applied load.

The fact that significant differences in the pressure indices were not found for the hips may be due to other physical forces at the interface. The slightly higher pressures recorded from the Airmesh hip interface may indicate that the more rigid, substantial belt actually transmits pressure more effectively in a region in which many forces are occurring. Or this could be due to the fact that Airmesh backpack allows for increased hip loading and thus enabling a reduction in peak shoulder pressure. What is very interesting to note is that subjective comfort ratings still indicate increased comfort for the Airmesh hip belt. This could be due to increased pressure (due to a more rigid better fitting hip belt) being deemed more comfort than a belt with less pressure/decreased fit. The overall comfort ratings may have indicated a strong preference for the Airmesh backpack due to more effective loading at the hip reducing the load applied to the shoulder.

The main discussion of the findings from both experimental chapters (6 and 7) shall take place in the discussion chapter (8) and lead onto conclusions, summary and human factors recommendations in chapter 9.

### 6.4.4 Conclusion.

In conclusion, the findings from this study support the design and material characteristics of the Airmesh backpack. The backpack showed significantly lower 90%ile pressures, was rated significantly more comfortable and was ranked as the most comfortable backpack by 70% of participants. However, what remains is to assess this backpack as part of the whole load carriage system. Only if these findings are replicated can the Airmesh LCS (or rather its characteristics) be truly recommended to the military. The next chapter discusses the subsequent in-field trials, comparing the Airmesh LCS against the Bergen LCS.

# Chapter 7: Field Trials

## 7.1 Introduction

This chapter is split into parts I and II and discusses two in-field trials. The first trial was carried out with civilian participants utilising the new mobile interface pressure measurement system. The second trial used the same system but took part on a military base, with military participants, loadings and activities. Both of the in-field trials compare two LCSs; the Bergen LCS and the prototype Airmesh LCS. These two trials are the first of their kind to assess LCSs objectively whilst out in the field. Also, these studies are the first to assess the whole LCS rather than just the backpack alone. By assessing what is actually worn in reality (i.e. the whole LCS) during military activities (in the field) this greatly increases the value of experimental findings and offers more accurate and informed human factors requirements for design.

Experimental methodology for the field trials has been discussed in detail in chapter 5; hence methods within this chapter are brief and only concerned with methodological differences specific to each trial.

# PART I – Trial 3

## 7.2 The Civilian Field Study

With the completion of the clothing study and development of the adapted LCSs (chapter 6) the first real trial utilising the mobile in-field pressure measurement system was undertaken. This trial utilises a field course of the same duration as the military trial (section 7.3) but as civilian participants took part the loading weights are less, this provides an interesting comparison and shall be discussed further in the discussion (chapter 8).

### 7.2.1 Method

10 healthy male participants took part in the trial under conditions approved by the LUEAC. Participant statistics were; age 23.1±3.8 yr, weight 76.4±4.6 kg, and stature 178.2±7.5 cm. Participants carried a total load of 23.5kg split between the webbing (5.9kg) and the backpack (17.6kg) parts of the LCS. A 75/25 split of load was employed as this reflects the distribution of loading as outlined by the British Infantry for exercise scenarios. A field course was marked out which encompassed various terrains (asphalt, grass, mud) and gradients. This field course took ten minutes to walk around. Participants wore standard military clothing, boots and helmet and carried a weapon (standard issue SA80 rifle) throughout each walk. Throughout the course markers were laid, when the participants reached these markers data collection was triggered remotely by the experimenter. Both interface pressure and subjective comfort ratings were collected simultaneously. The participants walked the course four times, twice with each LCS (1x shoulder measurement, 1 x hip measurement); the order of this was randomly assigned.

The Bergen LCS.

The Airmesh LCS.

**Figures 7.1 and 7.2 The Bergen LCS and the Airmesh LCS.**

Two LCSs were assessed (figure 7.1 & 7.2), the Bergen LCS and the prototype Airmesh LCS (as described in chapter 5.4). It is important to reiterate the difference between the two LCSs here. The increased compatibility within the Airmesh LCS enables the backpack to fit around the Vest webbing and the backpack hip belt can be used as normal. The Bergen LCS however, with the conflict between the backpack and webbing, results in the backpack hip belt being unusable, with the backpack resting on top of the rear webbing pouches.

Pressure sensors were prepared for measurement in the Tekscan calibration box, a new sensor being used for each participant. The shoulder sensor was placed over the outer layer of clothing via the triangulation method (chapter 5.4.2), with the hip sensor placed in a modified pocket under the hip strap of the webbing (or in case of the Airmesh LCS, placed in a pocket on the rucksack hip strap – please see chapter 6.3 for full description of the adapted LCSs). Each pressure recording was triggered via a radio telemetry signal sent by the experimenter when the participant reached the recording points along the course. Interface pressure was recorded for one second (10 frames per second).

When the participant reached each recording point, they were asked to give a rating of their overall comfort on the 1 to 5 scale (chapter 5.22). Participants were also asked to fill out a post-walk form asking them to rate each LCS for comfort in three different body zones (figure 5.25). Finally they were asked to rank the LCS in terms of overall comfort.

### 7.2.2 Results

Mean and 90%ile pressures (for both shoulder and hip interfaces) from the final ($10^{th}$) minute recordings were calculated. The subjective comfort rating differences from the $10^{th}$ minute are also reported.

Figure 7.3 shows the mean and 90%ile pressures (± S.E.M) for the shoulder interface. Figure 7.4 shows the mean and 90%ile pressures (± S.E.M) for the hip interface

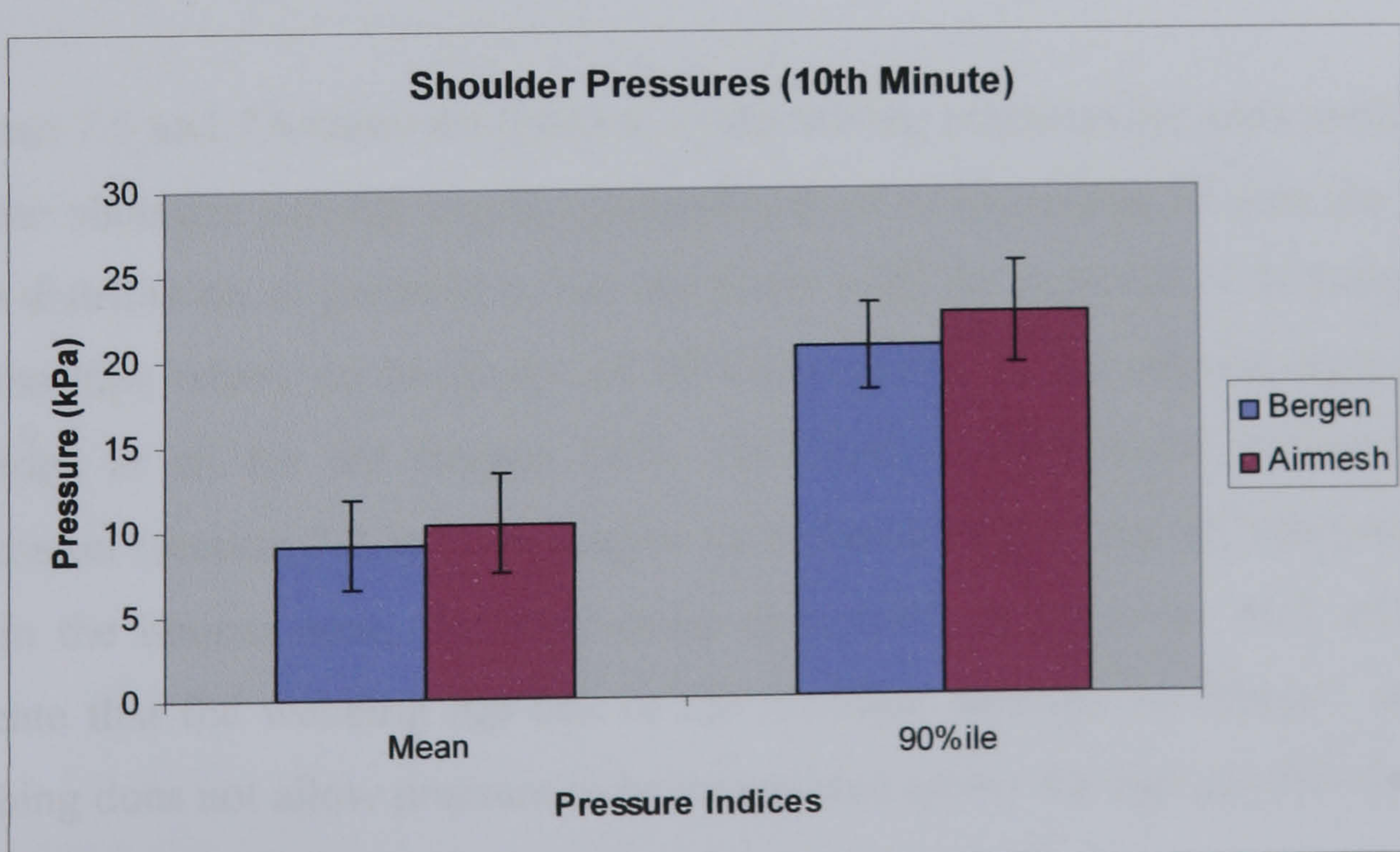



**Figure 7.3 Mean and 90%ile shoulder pressures.**

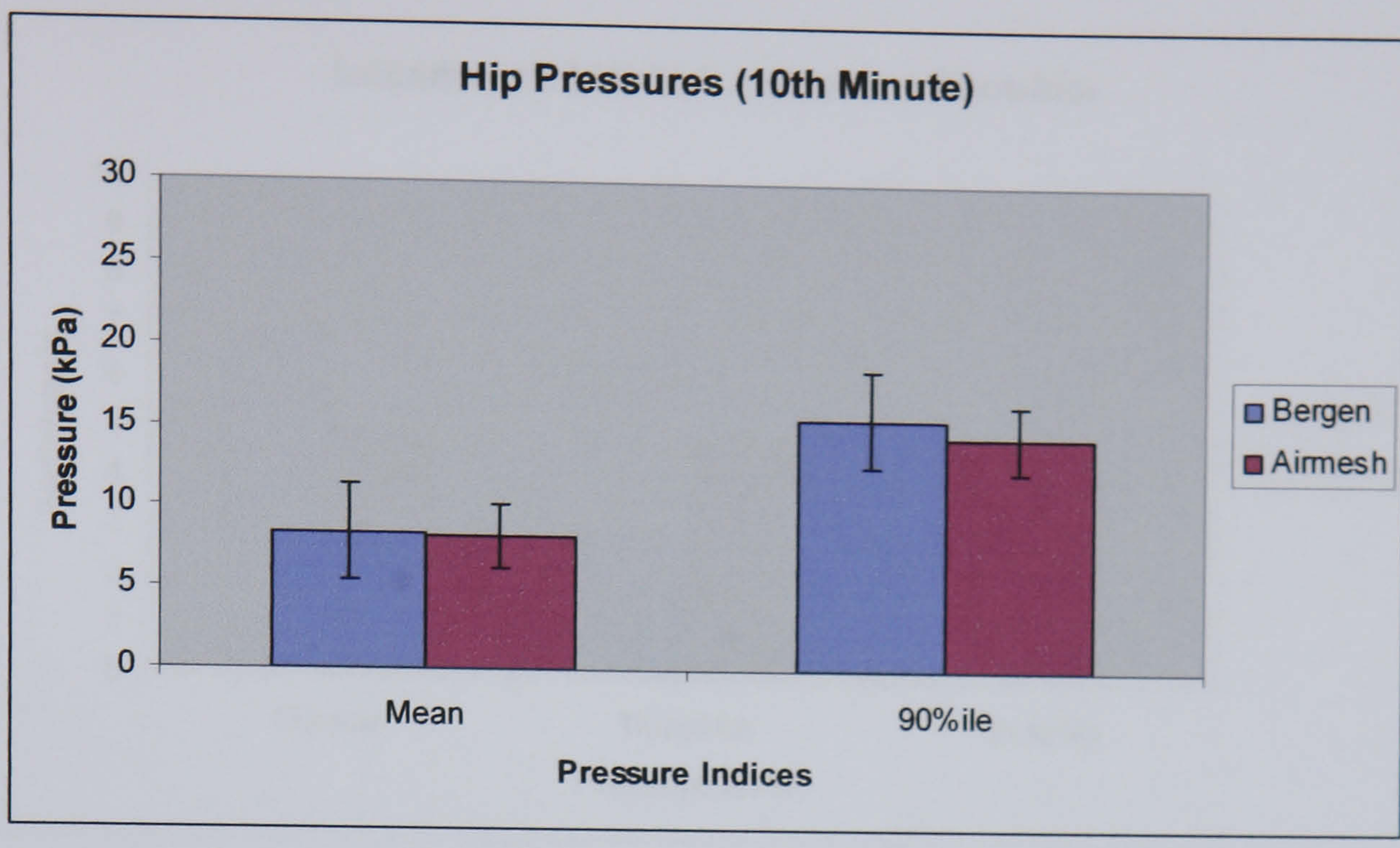



**Figure 7.4 Mean and 90%ile hip pressures.**

For both the shoulder and hip pressure data paired sample T tests were carried out to analyze differences between the data from the Bergen LCS and the Airmesh LCS. All the data pairs (Bergen mean + Airmesh mean for shoulder, Bergen 90%ile + Airmesh 90%ile, Bergen mean + Airmesh mean and Bergen 90%ile + Airmesh 90%ile for hip) were found to be non-significant (P = >0.05).

Figures 7.5 and 7.6 show the location of the 90%ile pressures for each participant for the shoulder and hip regions respectively. It is interesting to note the more even distribution of pressure across the zones with the Airmesh LCS. Especially for the hips where no incidence of 90%ile pressure in the anterior region was recorded at all for the Bergen LCS. This shall be considered further in the discussion (section 7.2.3). The Bergen LCS shows 90% of the 90%ile pressures fall in the lumbar zone, this may cause discomfort at the lower back and may indicate that the webbing hip belt or the interface between the Bergen and the webbing does not allow pressure to be transmitted across the hips effectively. This shall be considered further in the discussion (section 7.2.3).

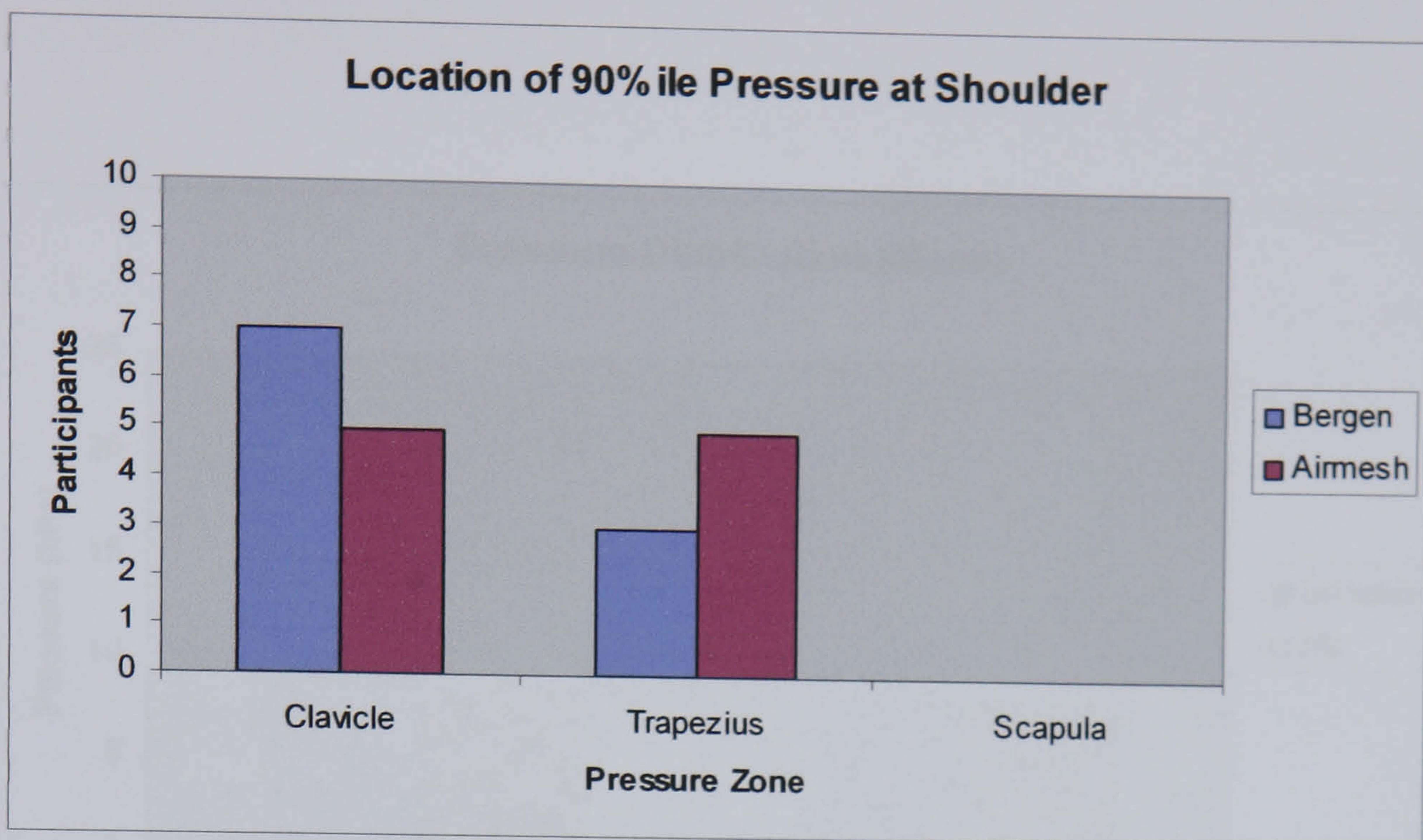



**Figure 7.5 Location of 90%ile shoulder pressures.**

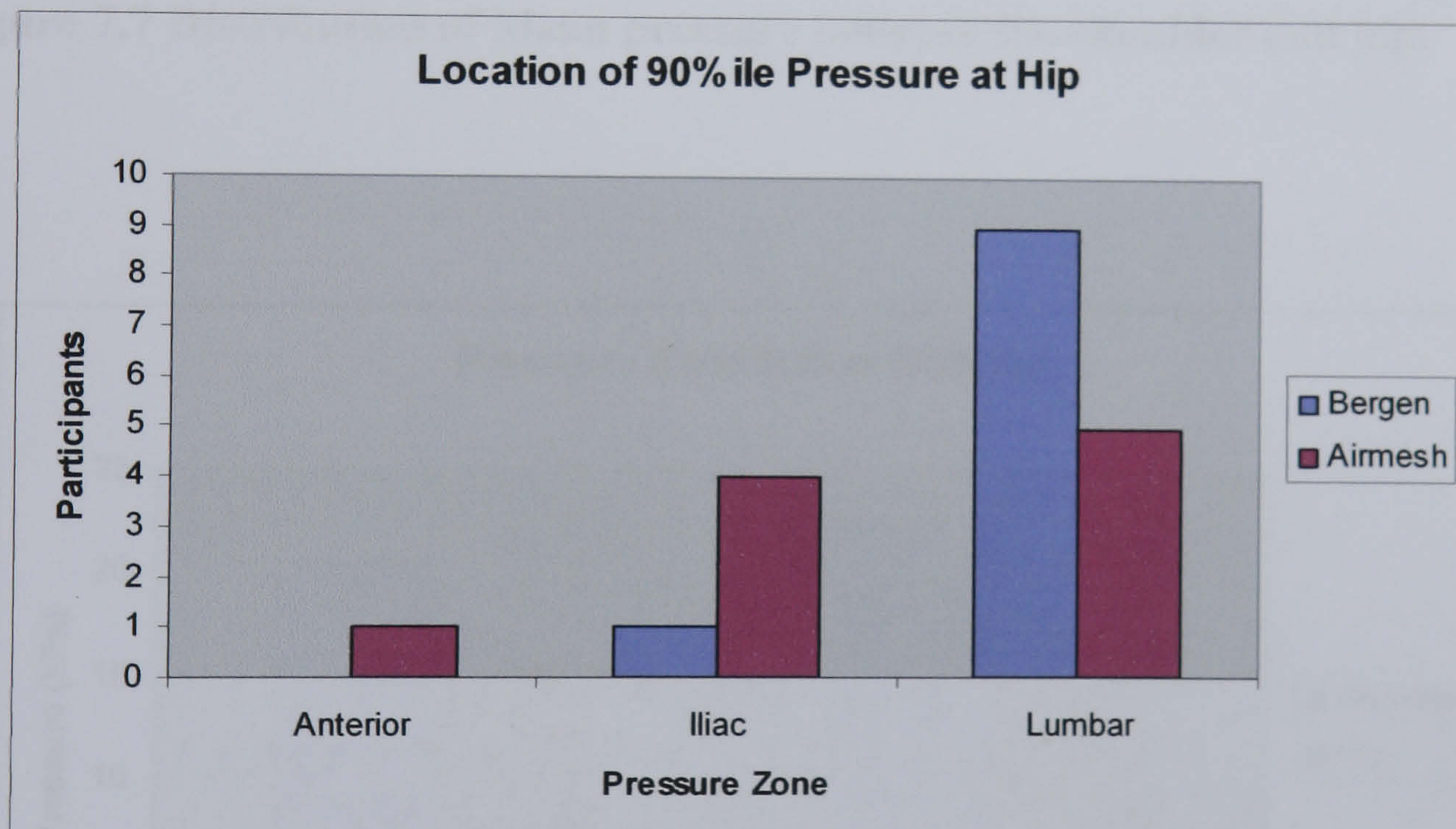



**Figure 7.6 Location of 90%ile hip pressures.**

The pressure distribution between the hip and shoulder interfaces is presented. Figure 7.7 shows the pressure distribution of mean pressure for both LCSs. Figure 7.8 shows the pressure distribution of 90%ile pressure for both LCSs. The distribution of pressure was similar for both LCSs, and do not show the same differences as found in the backpack study (chapter 6.4.2).

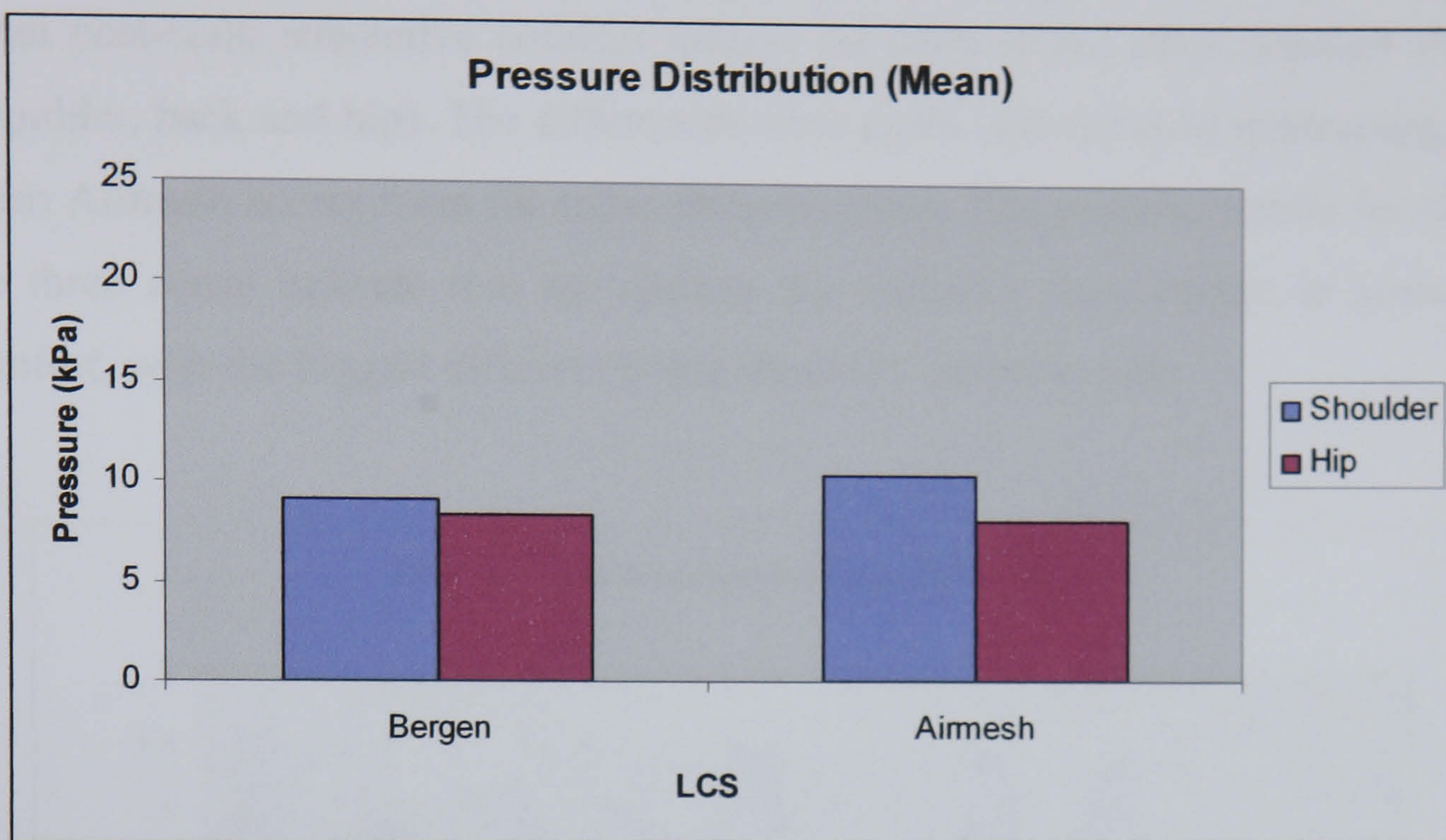



**Figure 7.7 Distribution of Mean pressure between the shoulder and hip.**

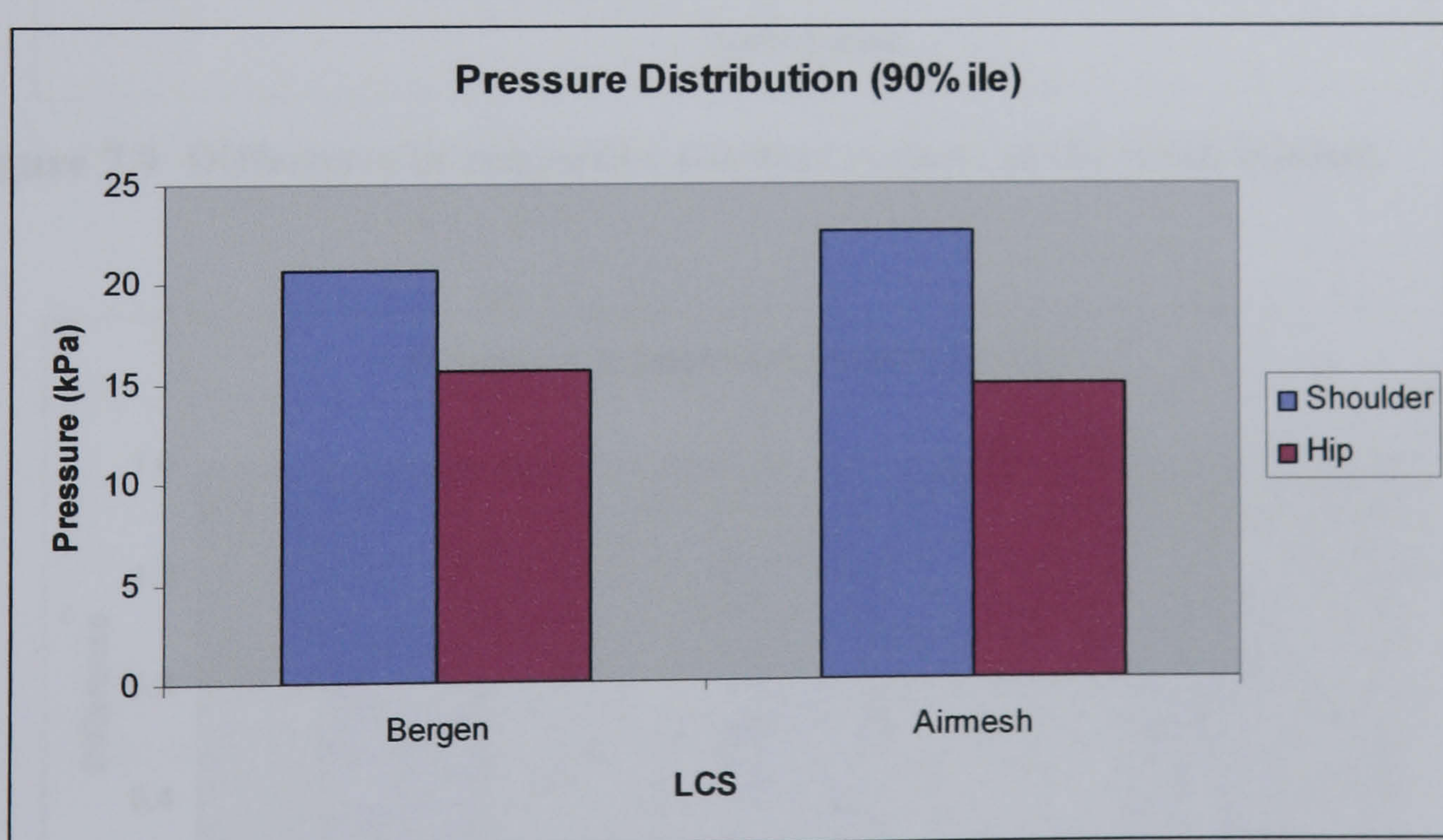



**Figure 7.8 Distribution of 90%ile pressure between the shoulder and hip.**

Figure 7.9 shows the difference in comfort ratings between the two LCS, calculated by subtracting the Airmesh scores from the Bergen scores. Positive ratings show a preference for the Airmesh LCS and negative ratings where the Bergen was deemed more comfortable. Figure 7.10 shows the difference in the mean post-walk subjective comfort ratings for each of the three comfort zones (shoulder, back and hip). The differences were again calculated by subtracting the mean Airmesh scores from the mean Bergen scores. The positive results for all of the three zones indicate that on average the Airmesh score higher in terms of comfort, with the biggest different being shown in the back zone.

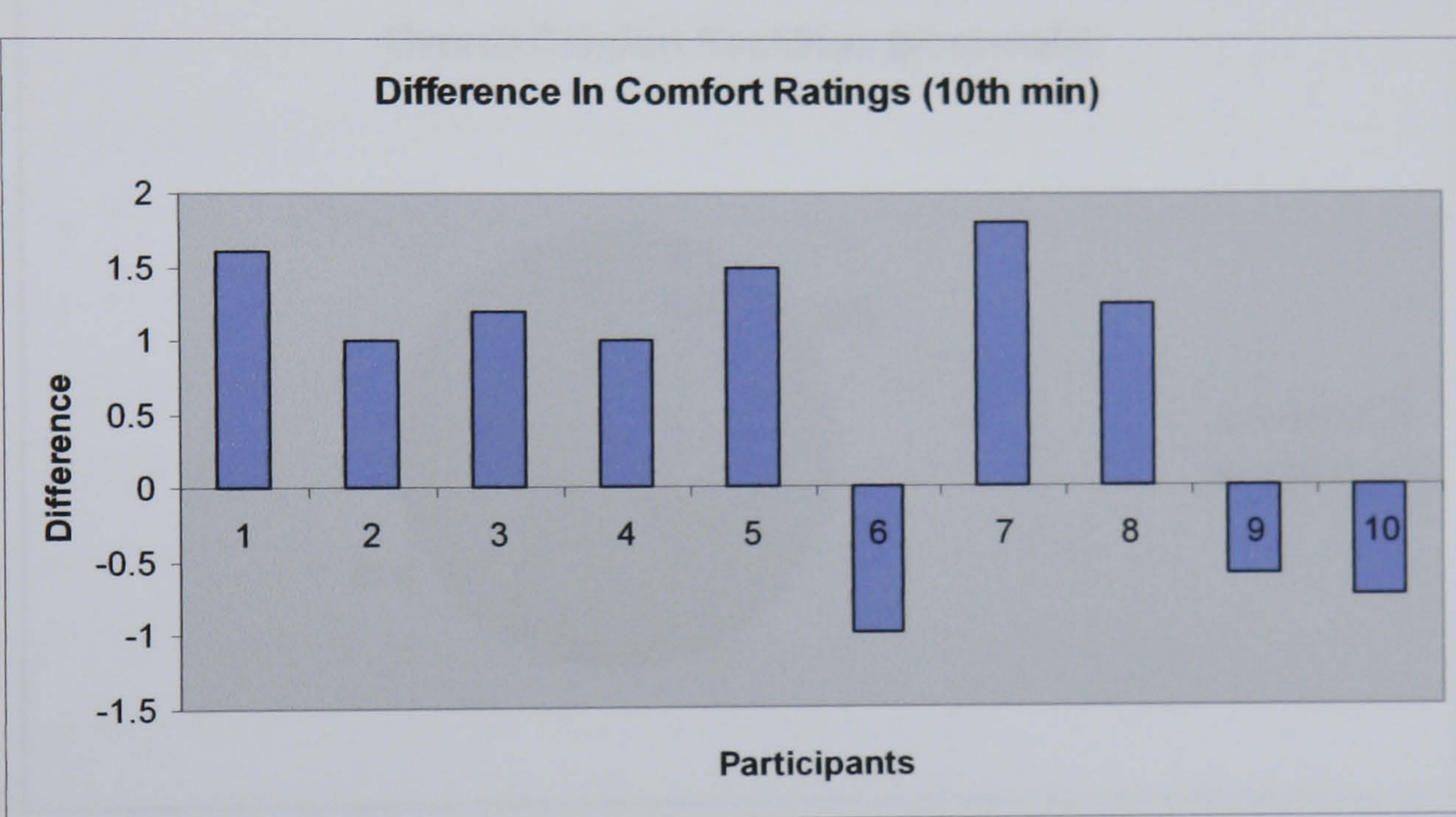



**Figure 7.9 Difference in subjective comfort ratings at the tenth minute.**

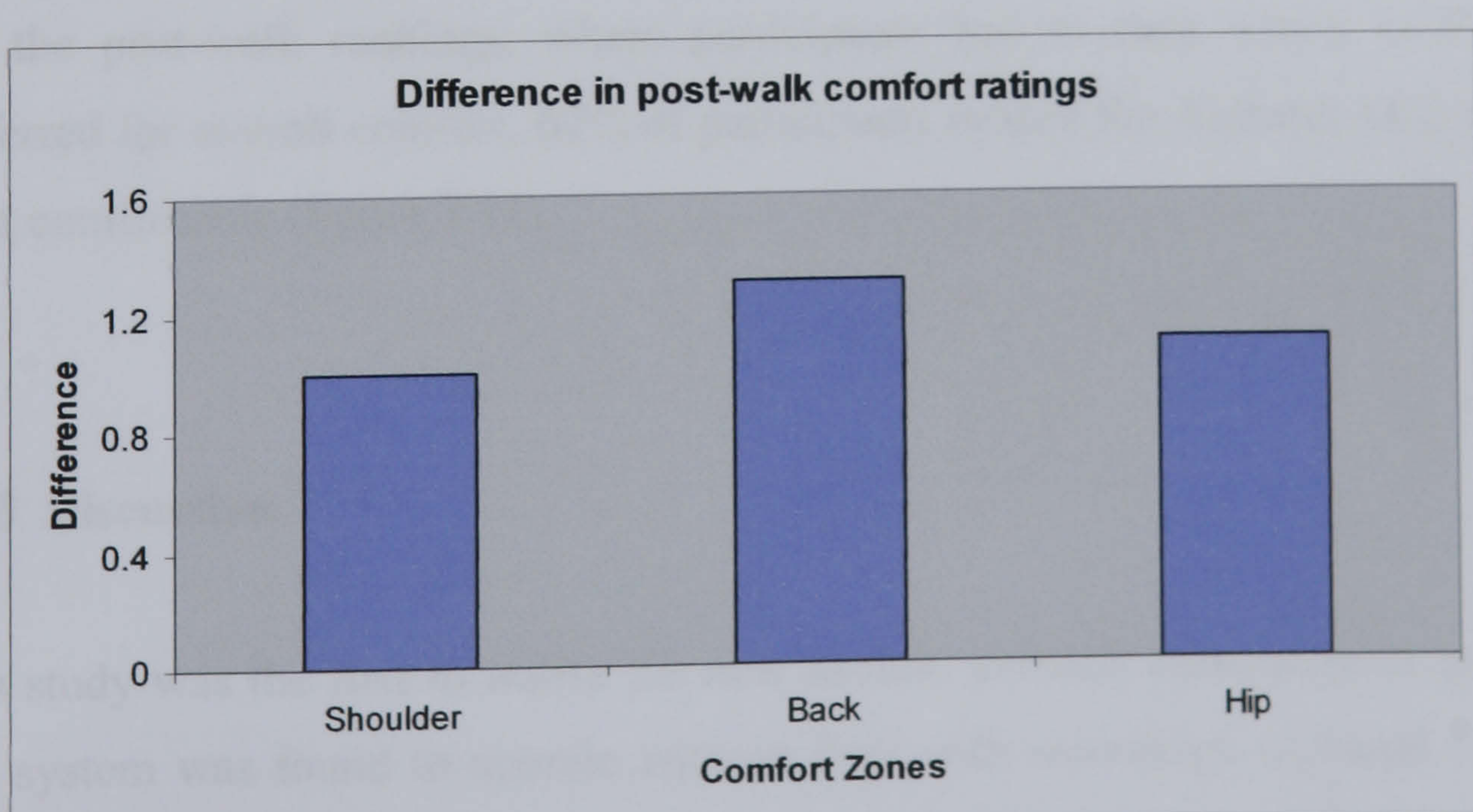



**Figure 7.10 Difference in post-walk mean comfort ratings.**

For both the tenth minute and the post-walk subjective data Wilcoxon Signed Ranks tests were used for analysis. For the tenth minute data, significant differences were found between the two LCS, with the Airmesh LCS showing increased comfort over the Bergen LCS (P = <0.05). Also, for the post-walk ratings significant differences were identified, for all of the comfort zones, with the back zone showing the most significant difference (P = <0.05).

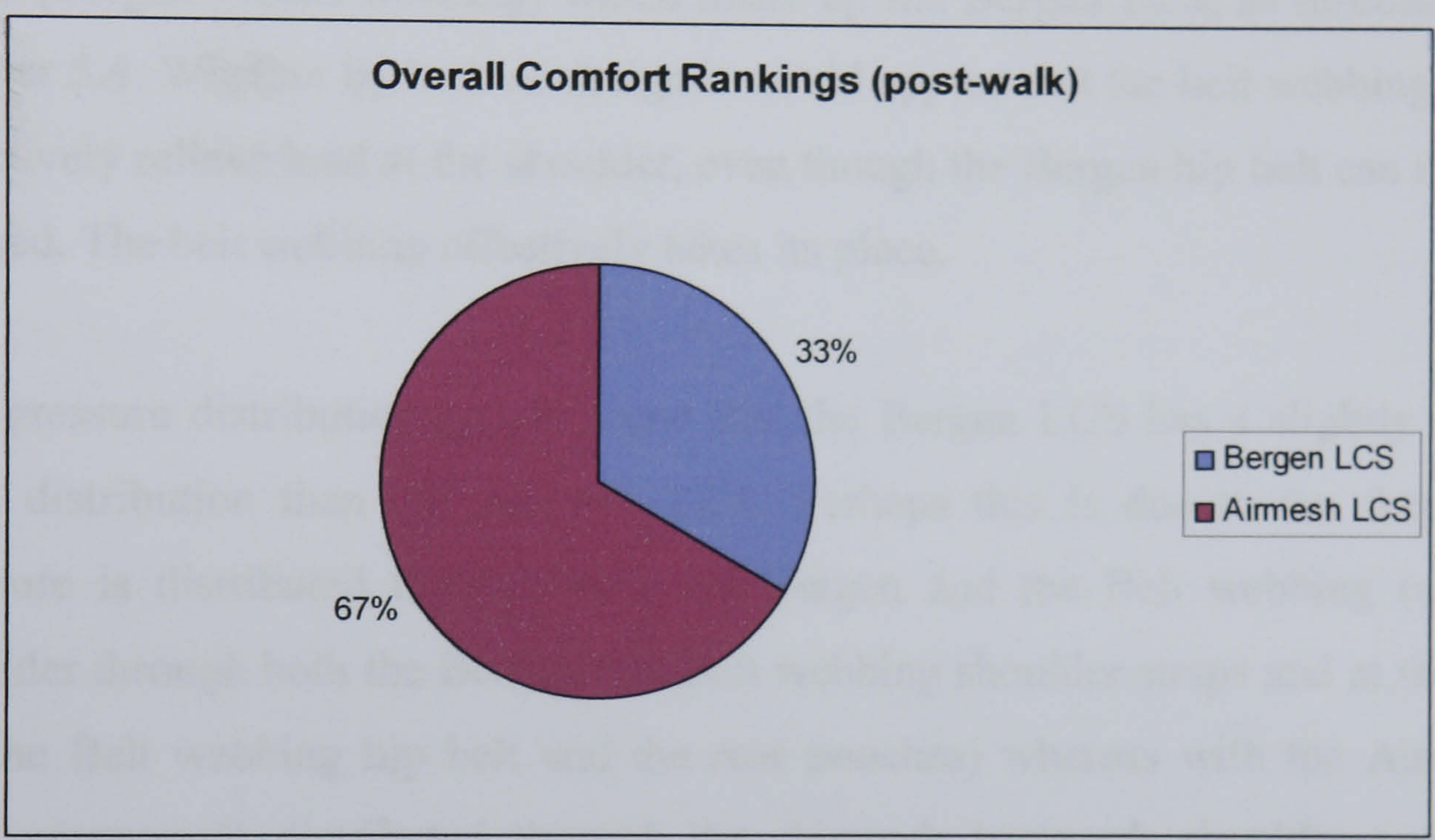



**Figure 7.11 Percentage preference for each LCS (post-walk rankings).**

For the post-walk rankings, where participants had to rank which LCS they preferred for overall comfort, 67% of participants ranked the Airmesh LCS as the most comfortable (figure 7.11).

### 7.2.3 Discussion.

This study was the first to utilise the new in-field pressure measurement system. The system was found to operate without fault with recordings captured via the remote triggering system at a success rate of 100% (i.e. Automatic Sequence Record functioned perfectly). These findings combined with the wealth of background research into the Tekscan devices (chapter 5) provide support for the continued use of the in-field system. The system was used for the military in-field trial as detailed in part II of this chapter.

The findings concerning pressure measurements from trial 2 (laboratory backpack study – chapter 6.4) have not been found when the whole LCSs were compared in-field. In fact the Bergen LCS actually appears to perform better (in terms of interface pressure) as a system than when the Bergen is worn alone. This was contrary to what was believed to be the case due to the incompatibility of the two items (Bergen + Belt webbing) which make up the Bergen LCS, as discussed in chapter 5.4. Whether by luck or design it would appear that the belt webbing does effectively relieve load at the shoulder, even though the Bergen hip belt can not be utilised. The belt webbing effectively takes its place.

The pressure distribution graphs show that the Bergen LCS has a slightly more even distribution than the Airmesh LCS. Perhaps this is due to the fact that pressure is distributed through both the Bergen and the Belt webbing (at the shoulder through both the Bergen and Belt webbing shoulder straps and at the hip via the Belt webbing hip belt and the rear pouches) whereas with the Airmesh LCS pressure is distributed through the Airmesh backpack shoulder and hip straps, as the Airmesh backpack and Vest webbing do not interact (in terms of sharing the applied load).

The contact areas for the shoulder and hip straps for the two LCSs are no longer significantly different (as was found with backpack trial). Non significant differences (paired sample T tests, P = > 0.05) in contact area were found (table 7.1)

**Table 7.1 Contact area of the two LCSs**

| **Mean Contact Area ($cm^2$)** | Bergen LCS Straps | Airmesh LCS Straps |
|---|---|---|
| Shoulder | 53.4 | 55.7 |
| Hip | 88.9 | 90.3 |

Another factor which may be a very important influence is that the carried load was heavier than the Backpack trial. The extra 5kg in total load carried may reduce the positive effects of the material changes to the shoulder and hip straps as seen with the Airmesh in the backpack trial. This factor shall be studied further in the military in-field trial (section 7.3) where loading is increased again up to 36.4kg total load (backpack trial = 18.5kg, civilian in-field trial = 23.5kg).

Even though on the grounds of interface pressure alone there would seem to be no distinction between the two LCSs, subjectively the Airmesh LCS received significantly higher comfort ratings throughout. The overall ranking fell by 3% to 67% who preferred the Airmesh (which may indicate the improvement of the Bergen when worn as a system) but a 3% reduction where no significant differences were found in interface pressures would seem a very small reduction. Perhaps the incidence of peak pressure is not the sole indicator for comfort, other physical forces such as shear and friction could play an equally vital role. The fact that subjective ratings can distinguish between LCSs when objective data does not adds further support for the continued use of subjective ratings during research of this type, and also correlates with Martin's work which too identified no significant differences in objective data for certain parameters, but did find that subjective ratings were still able to make a distinction (2001).

What may be of great importance with regard to subjective comfort (as mentioned in the Backpack trial discussion) is posture. The change in pressure distribution from the hip showing higher 90%ile pressures (Airmesh Backpack) to the shoulder showing higher 90%ile pressures (Airmesh LCS) must have a bearing on posture and may account for the 3% reduction in overall comfort rankings for the Airmesh LCS.

With regard to the hips, the locations of the 90%ile pressures show that for the Bergen LCS a 90% incidence of peak (90%ile) pressures was found within one area of the hips – the lumbar zone. The Airmesh LCS shows a more even spread across the lumbar (50%) and iliac (40%) zones also with some incidence (10%) in the anterior zone. The shoulders also tell a similar story with the Bergen LCS showing a 70% incidence of 90%ile pressure in the clavicle zone with 30% in the trapezius zone, whereas the Airmesh LCS showed a 50/50 split between the two. This point was discussed in the backpack trial discussion (chapter 6.4.3).

One very interesting point for the locations of 90%ile pressure is that (unlike the Airmesh backpack) the Airmesh LCS shows no incidence of 90%ile pressure in the scapula zone – this may well add support to the postural effect, where increased forward lean would result in reduced pressure loading in the scapula zone, hence the increase in incidence of 90%ile pressure found at the clavicle. The contact point for peak pressure appears to shift forward as forward lean increases. This would appear to explain why when considering the Airmesh backpack the highest incidence was found in the trapezius zone, whereas with the Airmesh LCS this changed to a 50/50 split of incidence between the clavicle and trapezius zones. It could be argued that this is the opposite of what would be expected, with increased forward lean expected to cause peak pressure over the scapula. This shall be discussed further in the discussion (chapter 8).

These findings from this study may provide support for the idea of a change in posture influencing pressure loading. It is however, somewhat of a 'chicken and the egg' situation, i.e. does unequal pressure distribution between the shoulder and hip cause a postural change or vice versa. The postural consideration can be linked to Datta & Ramanthan (1971) and Legg & Mahanty (1985) who suggested that the 'double pack' (a pack where load was distributed between the front and rear of the body, like the Airmesh LCS) resulted in a more normal upright posture which lead to increased comfort when compared to the traditional backpack (Bergen LCS – weight is predominantly at the rear of the body).

### 7.2.4. Conclusion.

In conclusion, from the findings of the trials 2 and 3 it would appear that the equal distribution of pressure between the shoulder and hip is a critical factor in the performance of LCSs. This together with adequate contact area and material advances should allow for increased user comfort. However, what remains to be assessed is whether a LCS which enables greater loading at the hip than the shoulder performs better than an LCS with an equal distribution; this could be assessed with further work.

At this loading weight (23.5kg) the importance of peak pressure may be reduced in the face of factors such as postural change. Perhaps a threshold loading value exists (somewhere above 18.5kg) where a reduction in peak pressure through design and material advances ceases to occur. This shall be discussed further in chapter 8 when the results from the military field trial can be considered also. When carrying 23.5kg in-field this study would suggest that there is no difference in interface pressure at either the shoulder or the hip interfaces when comparing the Bergen and Airmesh LCSs. However, subjective ratings still show a clear preference for the Airmesh LCS, the reason for this may be due to some of the factors discussed. The next section (part II) discusses the military in-field trial and what was found when loading was increased to 36.4kg (standard British infantry load).

# PART II – Trial 4

## 7.3 The Military Field Study

The purpose of this trial was to assess two different LCS in a military context, with military personnel, and with military loads. The trial involved the 2nd Royal Regiment of Fusiliers (2RRF) based in Rutland, UK. This is an infantry regiment of the British Army, and thus specialises in the carriage of heavy loads over long distances. A field course was defined encompassing varying terrain and gradients, similar to that found on a cross country march in temperate environments. The Bergen and Airmesh LCSs were assessed in terms of interface pressure under the shoulder and hip straps, and subjective comfort ratings. This experimental work was presented to the International Ergonomics Association (IEA) conference 2003 and published in the conference proceedings (Jones & Hooper, 2003).

### 7.3.1 Method

Thirty male infantry soldiers participated in the study. Participants military load carriage experience ranged from 6 months to 16 years. The participant's ranks ranged from Private through to Major. The Age range was 17-35 years, mean weight 74.2±9.4kg, mean stature 177.3±8.3cm. Two LCS designs were assessed (1) standard Bergen LCS and (2) Airmesh LCS. Participants carried a total load of 36.4kg (80lb). The load was split between the webbing (9.1kg/20lb) and the rucksack (27.3kg/60lb). Participants walked around a field course at self-selected pace encompassing differing terrain (tarmac, grass, mud, gravel, inclines and declines (25% gradients), and small obstacles). Participants wore standard military clothing, boots and helmet and carried the standard issue SA80 rifle throughout each walk. The course took approximately 10 minutes to walk, during which time interface pressure measurements were recorded from the shoulder and hip interfaces. The participants walked the course four times (twice with each LCS). During each walk interface pressure was recorded from the shoulder or the hip.

Pressure data and subjective comfort ratings were recorded simultaneously at specific points along the course.

Sensors were prepared for measurement via the calibration process. The shoulder sensors were placed on the outer clothing layer (via the triangulation method), with the hip sensors being placed in modified pockets under the hip strap of the webbing (or in case of the Airmesh LCS, placed under the rucksack hip strap). Each pressure recording was triggered via a radio telemetry signal sent by the experimenter when the participant reached the recording points along the course. Interface pressure was recorded for one second (10 frames over 1 second). When the participant reached each recording point, they were asked to give a rating of their overall comfort on the 1 to 5 scale (figure 5.5.2). Participants were asked to fill out a post-walk form asking them to rate each LCS for comfort in three different body zones (figure 5.5.4). They also ranked the LCS in terms of overall comfort.

### 7.3.2 Results

As with the laboratory and civilian field trials the data from each pressure recording were presented in two ways – mean and 90%ile. Also, only the tenth minute data were used for analysis. As with the pressure data, subjective comfort ratings are reported for the tenth minute. Also, the post-walk ratings for comfort zones and the overall ranking are shown.

Figure 7.12 shows the mean and 90%ile pressures (± S.E.M) for the shoulder interface. Figure 7.13 shows the mean and 90%ile pressures (± S.E.M) for the hip interface

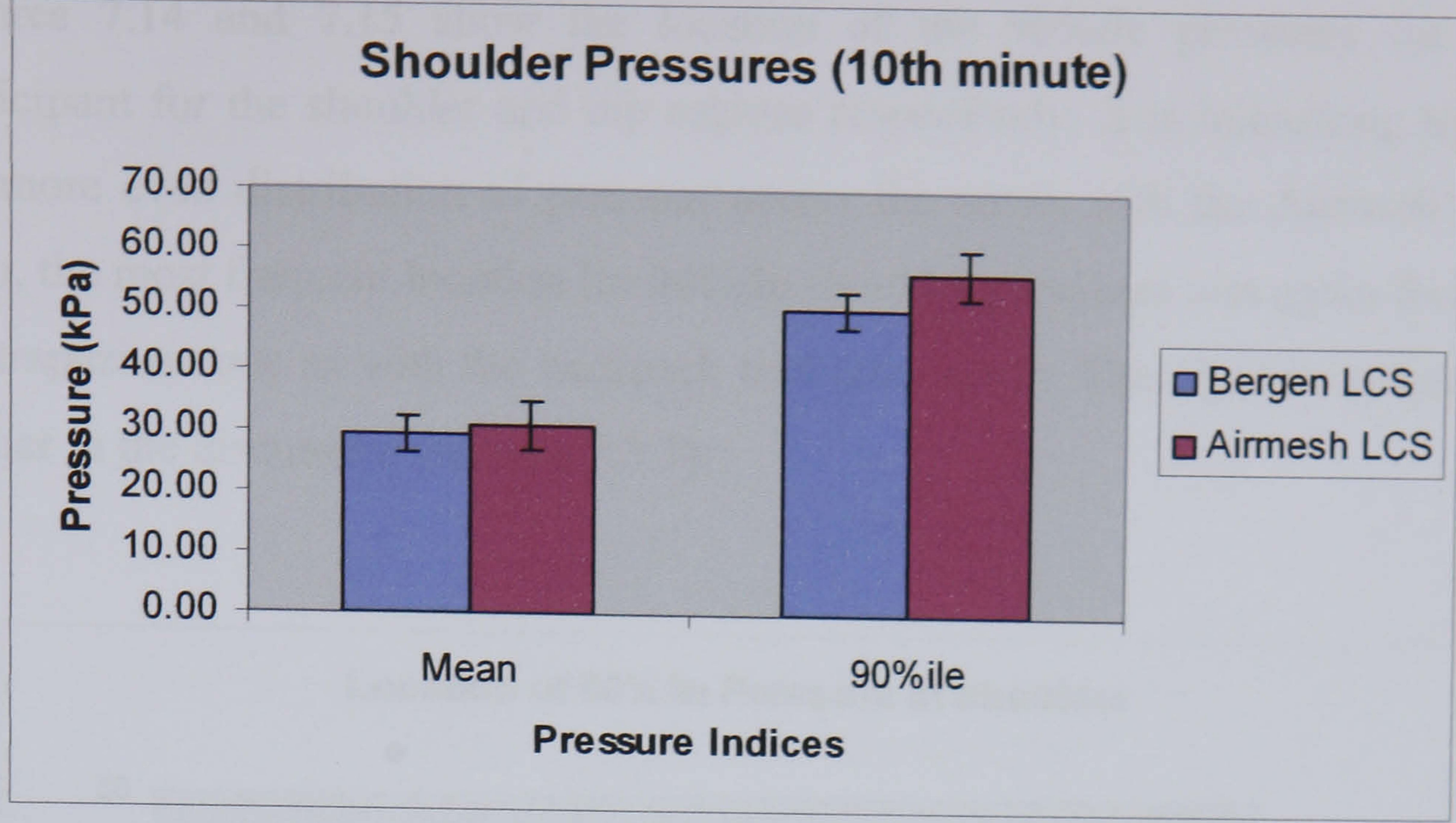



**Figure 7.12 Mean and 90%ile shoulder pressures.**

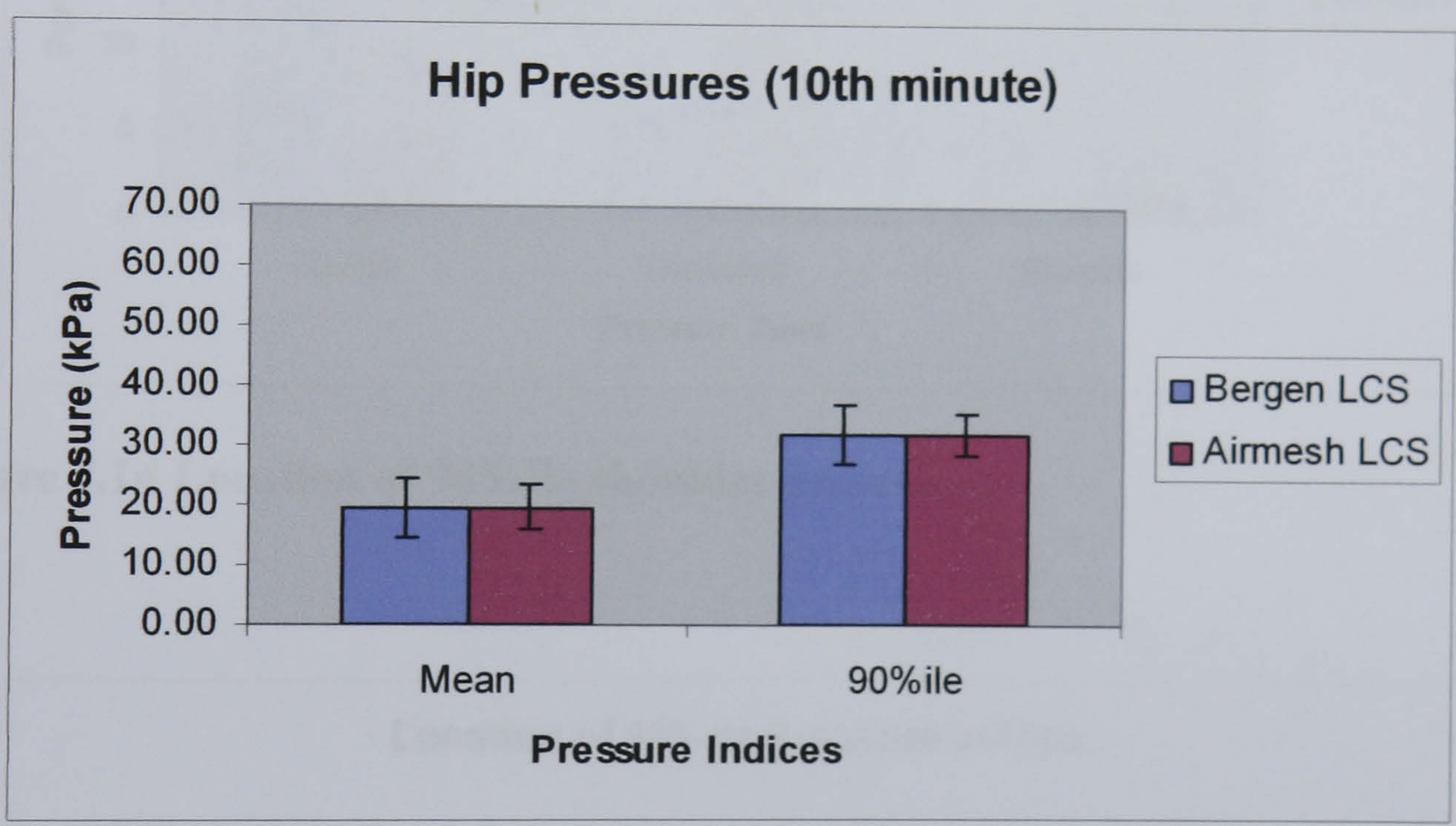



**Figure 7.13 Mean and 90%ile hip pressures.**

For both the shoulder and hip pressure data paired sample T tests were carried out to analyze differences between the data from the Bergen LCS and the Airmesh LCS. All the data pairs (Bergen mean + Airmesh mean for shoulder, Bergen mean + Airmesh mean and Bergen 90%ile + Airmesh 90%ile for hip) except Bergen 90%ile + Airmesh 90%ile for the shoulder were found to be non-significant (P = >0.05). However, significant differences were found for the shoulder 90%ile values, with the Airmesh LCS showing higher pressures (P = <0.05).

Figures 7.14 and 7.15 show the location of the 90%ile pressures for each participant for the shoulder and hip regions respectively. It is interesting to note the more even distribution of pressure across the zones with the Airmesh LCS. Also, the most frequent location for 90%ile shoulder pressures was again found in the trapezius zone as with the backpack trial (chapter 6). This shall be considered further in the discussion (section 7.3.3).

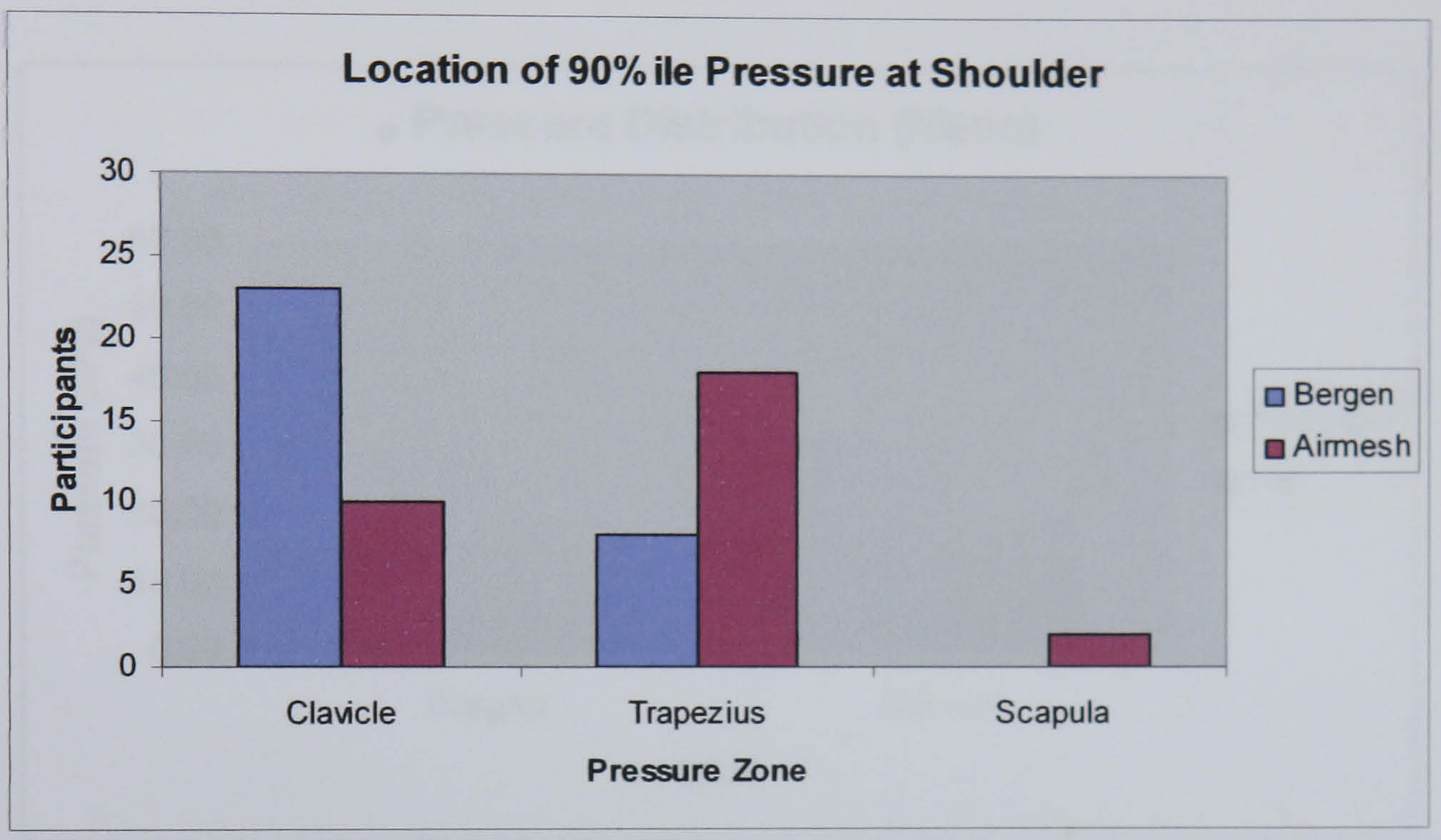



**Figure 7.14 Location of 90%ile shoulder pressures.**

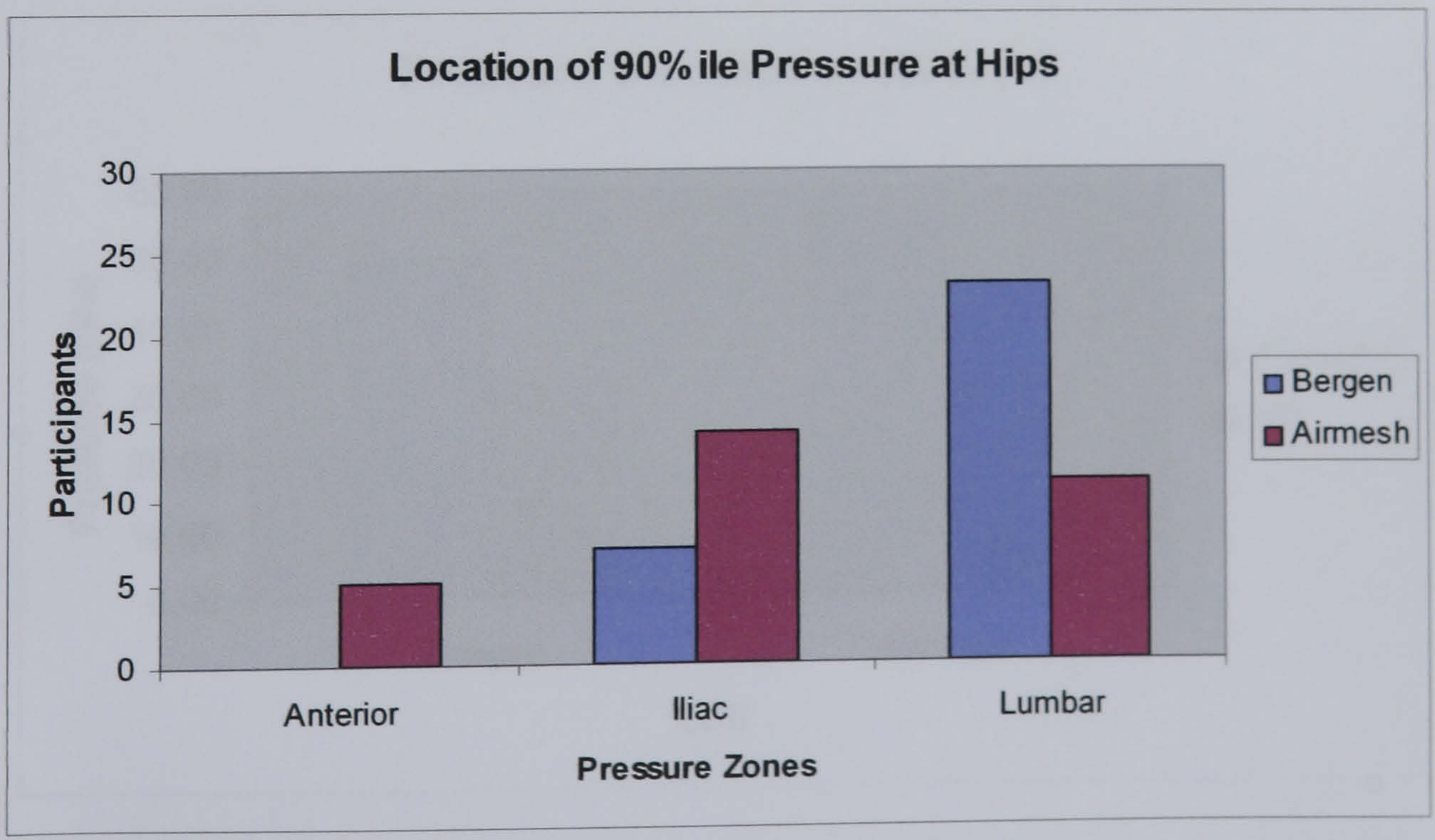



**Figure 7.15 Location of 90%ile hip pressures.**

Figure 7.16 shows the pressure distribution of mean pressure for both backpacks. Figure 7.17 shows the pressure distribution of 90%ile pressure for both backpacks. Again as with the civilian in-field trial the distribution of pressure was similar for both LCSs and do not show the same differences as found in the backpack study (chapter 6.4.2).

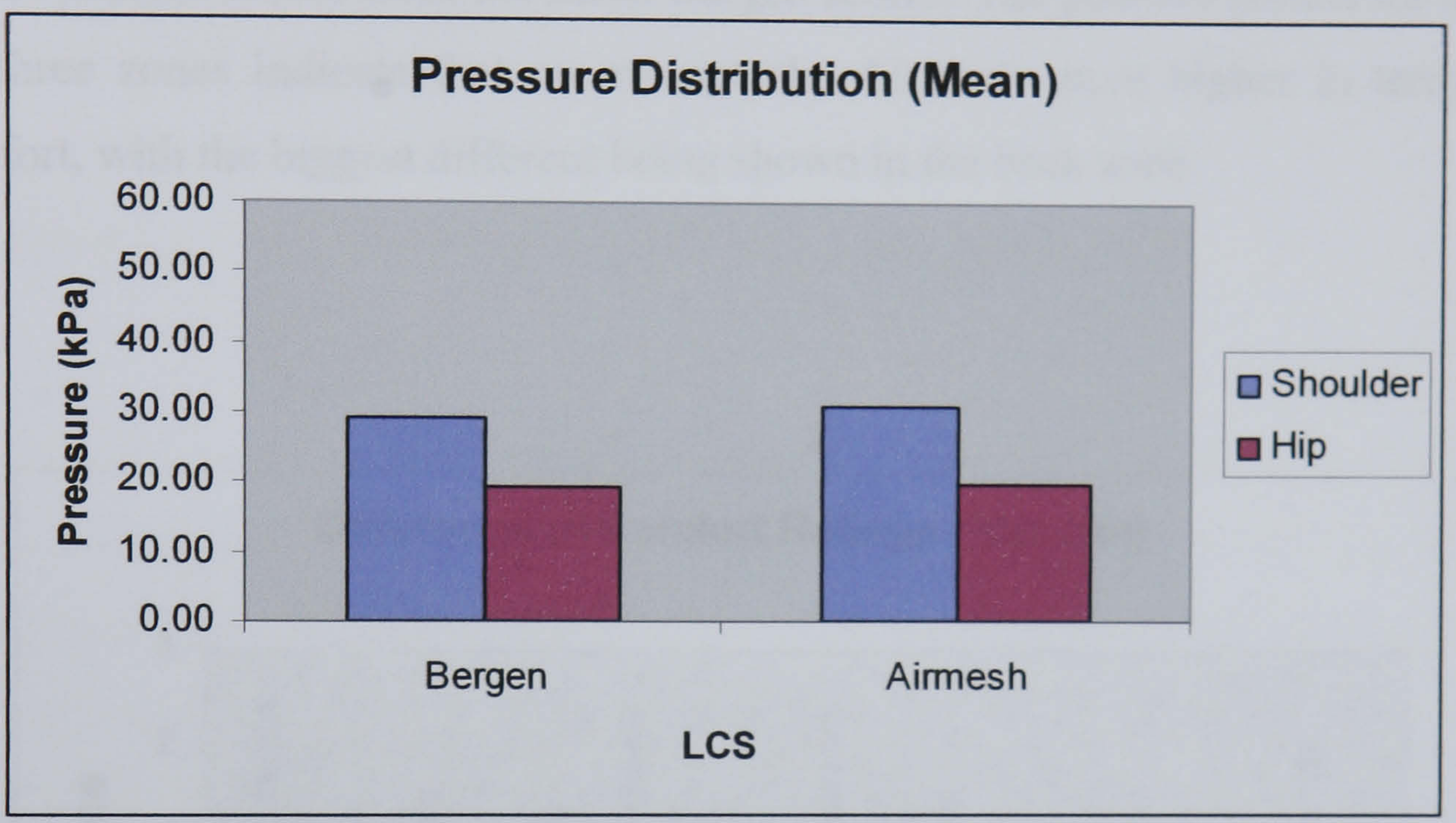



**Figure 7.16 Distribution of Mean pressure between the shoulder and hip.**

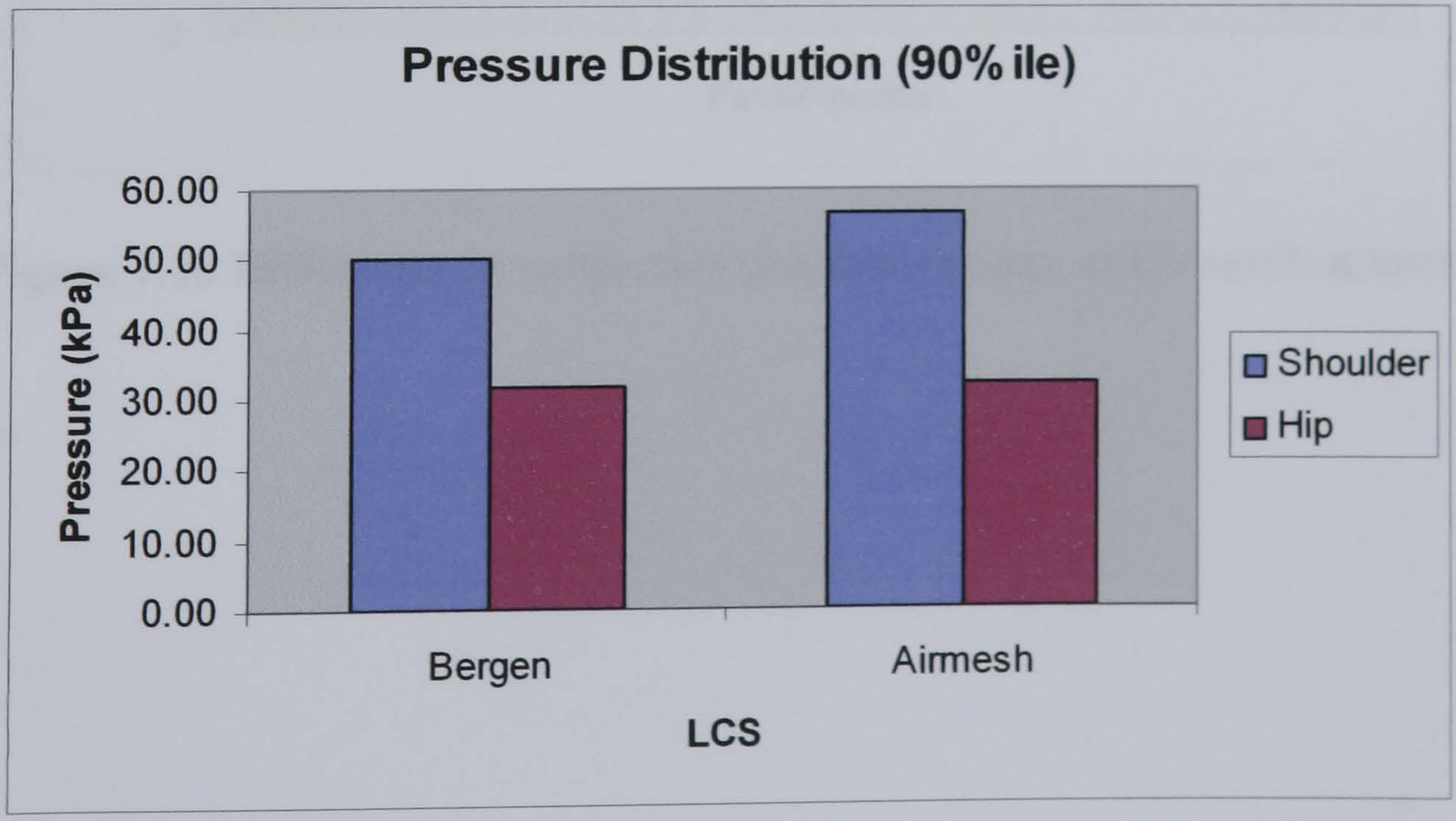



**Figure 7.17 Distribution of 90%ile pressure between the shoulder and hip.**

Figure 7.18 shows the difference in comfort ratings between the two LCS, calculated by subtracting the Airmesh scores from the Bergen scores. Positive ratings show a preference for the Airmesh LCS and negative ratings where the Bergen was deemed more comfortable. Figure 7.19 shows the difference in the mean post-walk subjective comfort ratings for each of the three comfort zones (shoulder, back and hip). The differences were again calculated by subtracting the mean Airmesh scores from the mean Bergen scores. The positive results for all of the three zones indicate that on average the Airmesh score higher in terms of comfort, with the biggest different being shown in the back zone.

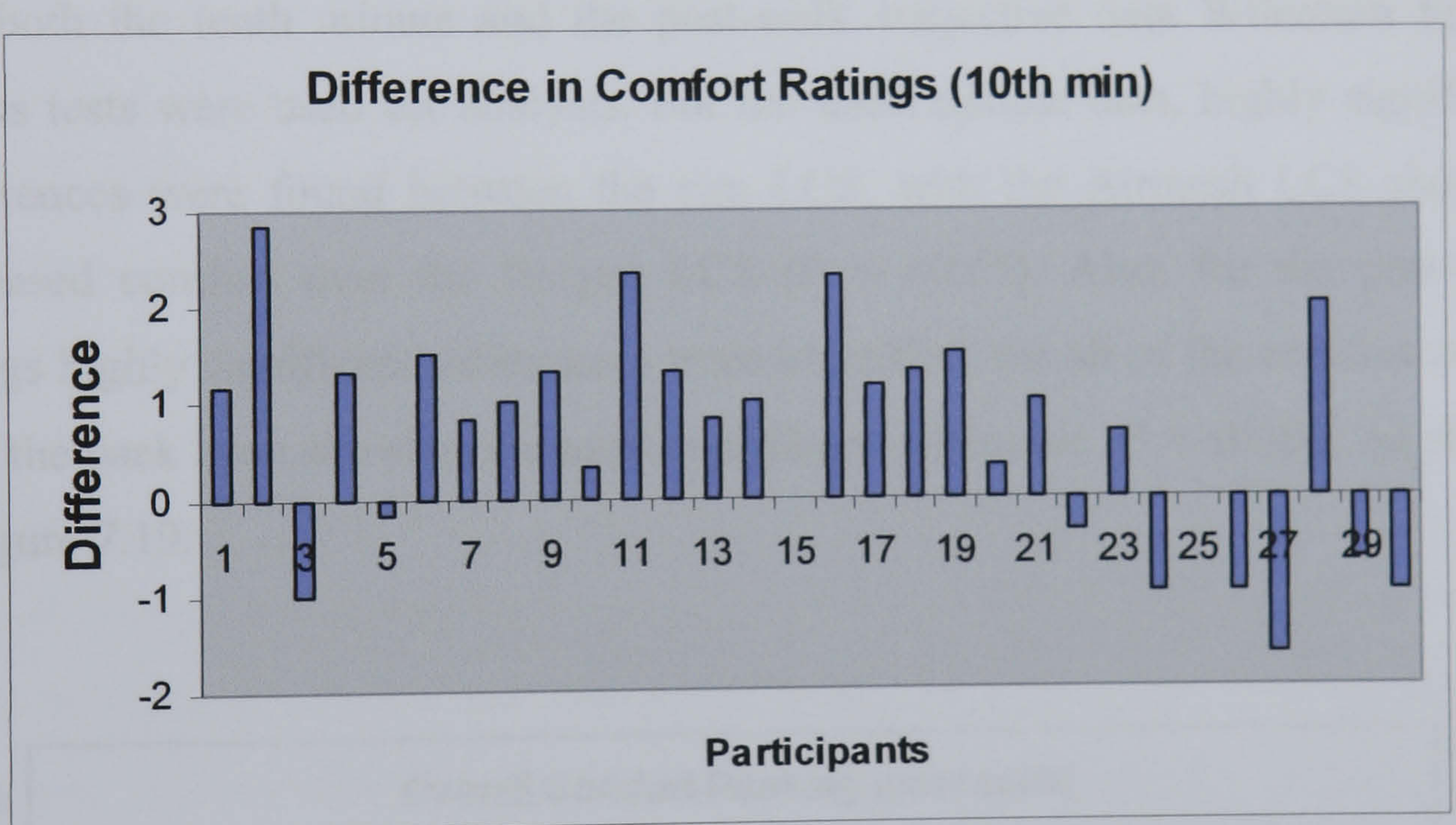



**Figure 7.18 Difference in subjective comfort ratings at the tenth minute.**

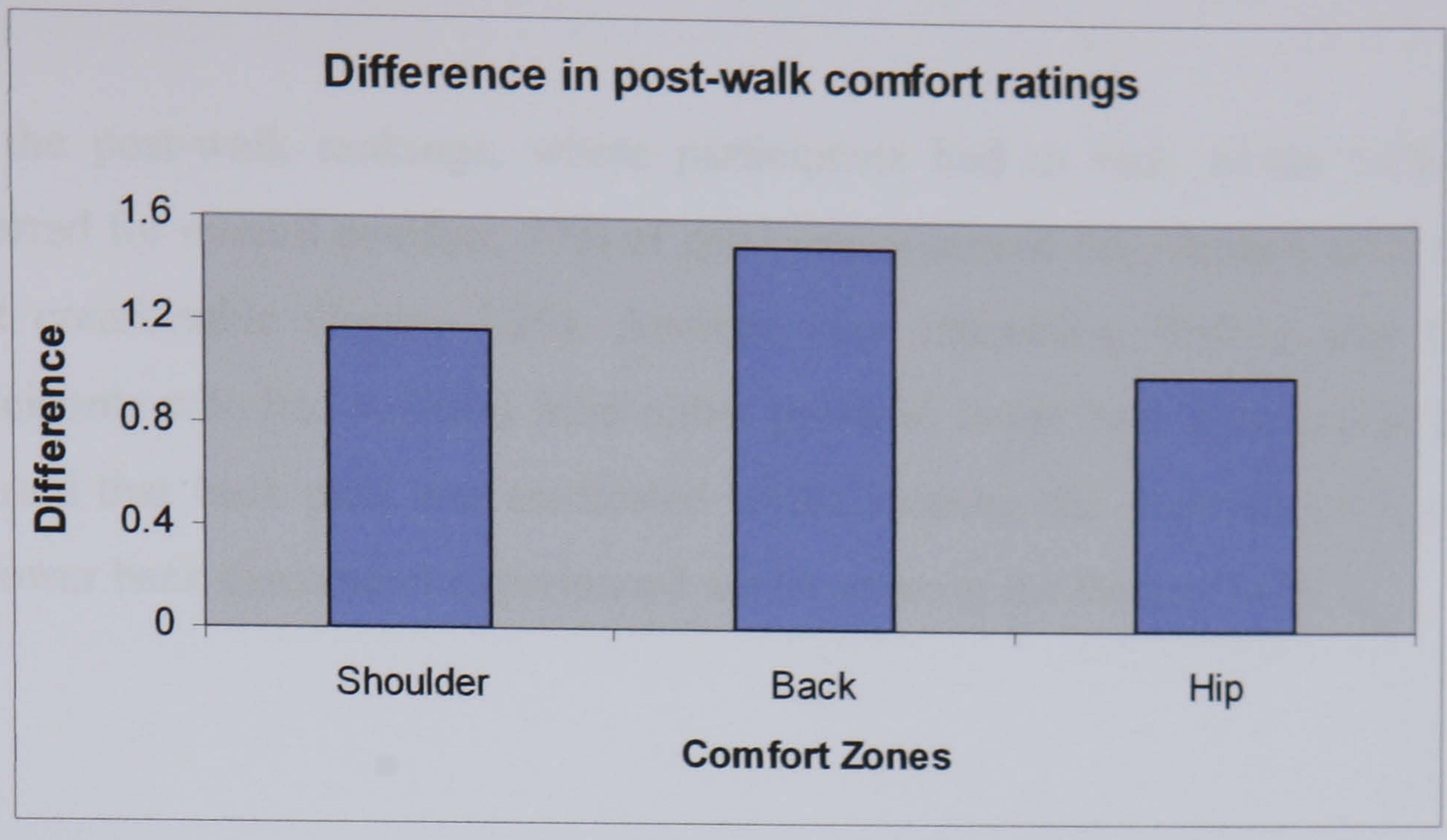



**Figure 7.19 Difference in post-walk mean comfort ratings.**

For both the tenth minute and the post-walk subjective data Wilcoxon Signed Ranks tests were used for analysis. For the tenth minute data, highly significant differences were found between the two LCS, with the Airmesh LCS showing increased comfort over the Bergen LCS (P = <0.05). Also, for the post-walk ratings highly significant differences were identified, for all of the comfort zones, with the back zone showing the most significant difference (P = <0.05). As shown in figure 7.19.

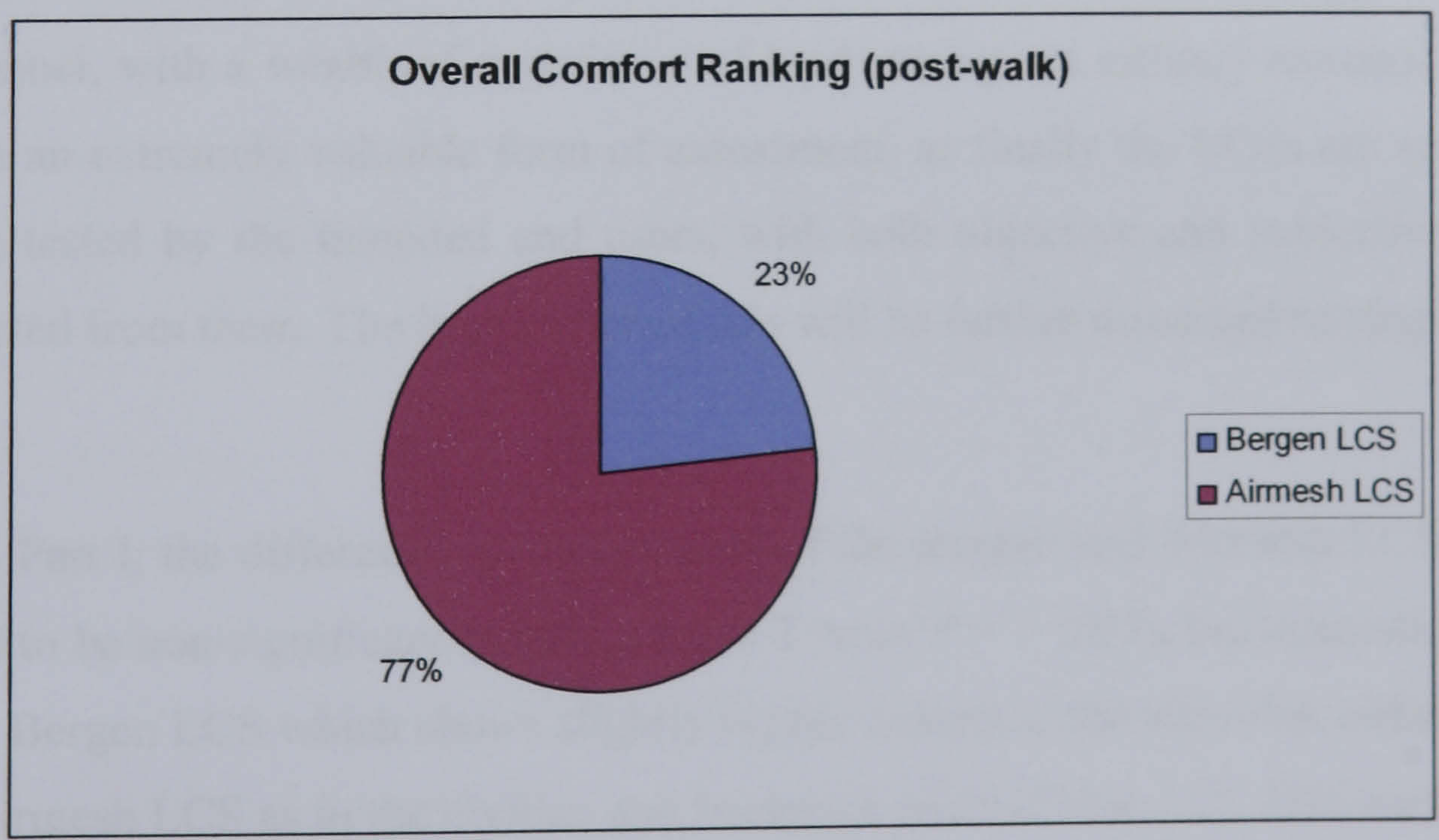



**Figure 7.20 Percentage preference for each LCS (post-walk rankings).**

For the post-walk rankings, where participants had to rank which LCS they preferred for overall comfort, 77% of participants ranked the Airmesh LCS as the most comfortable (figure 7.20). Another very interesting finding was that 7 participants who had suffered from either previous lower back pain and/or injury reported that back pain was eradicated whilst wearing the Airmesh LCS, unlike the lower back discomfort experienced whilst wearing the Bergen LCS.

### 7.3.3 Discussion

Very little difference was identified between the two LCS in terms of interface pressures at the shoulder and hip, apart from one exception (90%ile shoulder). Pressure was measured exactly perpendicular to the interface, and thus no measure of shear or friction forces which may have been present could be made. It is interesting to note however that the subjective ratings and rankings indicate less discomfort and an overall preference for the Airmesh LCS. As suggested in Part I the difference between findings from the objective and subjective data may arise from the forces not measured or some other feature of the LCS. One of the salient points to consider is that this trial was carried out with actual serving military personnel, with a wealth of experience of load carriage in military contexts. This offers an extremely valuable form of assessment, as finally the LCSs are actually being tested by the intended end users, with both objective and subjective data collected from them. The importance of this will be further discussed in chapter 8.

As in Part I, the difference in contact area of the Bergen and Airmesh LCSs was found to be non-significant (paired sample T tests, P = > 0.05), but interestingly it is the Bergen LCS which shows slightly higher contact at the shoulder, rather than the Airmesh LCS as in the civilian and backpack trials (Table 7.2). This may have some influence on the higher 90%ile pressures found here with the Airmesh system.

**Table 7.2 Contact Area of the two LCSs**

| **Mean Contact Area ($cm^2$)** | Bergen LCS Straps | Airmesh LCS Straps |
|---|---|---|
| Shoulder | 62.3 | 61.2 |
| Hip | 91.3 | 92.7 |

The subjective reports from the seven participants who found that lower back pain was eradicated whilst wearing the Airmesh LCS, may provide support for the hip belt, but not in the way it was hypothesized. Instead of relieving pressure at the shoulders it appears to have increased comfort in the lower back region, maybe due to a change in posture. This change may have led to the higher 90%ile values found at the shoulder interface if pressure here is greater due to posture change. However the fact that 77% ranked the Airmesh LCS as most comfortable may indicate the importance of lower back comfort for LCS design. Another possible reason for increased back comfort may be the increased distribution across the interfaces as found with the Airmesh hip belt. If the load is shifted from the lumbar and onto the iliac crest, this would potentially improve comfort in the lower back.

This point is further supported by the post-walk comfort zone ratings which showed the most significant difference (i.e. greatest increase in comfort) for the back zone when wearing the Airmesh LCS. Interestingly even though higher 90%ile pressures are found for the shoulder interface when wearing the Airmesh LCS, this is not reflected in the post-walk comfort ratings. The shoulder zone was rated significantly higher indicating less discomfort than the Bergen LCS. Again (as suggested in section 7.2.3) it is possible that the 90%ile pressure alone may not be the sole indicator for comfort. This could be further investigated and leads onto recommendations for further work (chapter 9).

As was found with the civilian in-field trial, the Bergen LCS appears to perform better (in terms of interface pressure) as a system than when the Bergen is worn alone. The findings from this study provide further evidence to suggest that the belt webbing does effectively relieve load at the shoulder, even though the Bergen hip belt cannot be utilised. The pressure distribution graphs show that the Bergen LCS and Airmesh LCS show near identical distribution, with exception of the 90%ile with the Airmesh LCS showing slightly more loading at the shoulder than the Bergen LCS. This may indicate why 90%ile pressure was found to be higher for the Airmesh LCS.

Another factor which may be a very important influence is the weight of the load carried. An extra 12.9kg was carried compared to the civilian in-field trial. This may have further reduced the positive effects of the material changes to the shoulder and hip straps as seen with the Airmesh in the backpack trial, due to the higher 90%ile values at the shoulder. Even though the Airmesh LCS shows higher 90%ile shoulder pressure it still received significantly higher comfort ratings throughout. When compared to trial 3 the overall ranking actually rose by 10% to 77% of participants preferring the Airmesh, this was a higher ranking than even the Airmesh backpack and provides strong support for its characteristics. The fact that the subjective ratings show the greatest significant difference of all three trials, even when Airmesh 90%ile pressure was significantly higher strongly suggests that the incidence of peak pressure may not be the sole indicator for comfort. However findings relating to the location of 90%ile pressures and also how effective straps are at distributing pressure across interfaces were interesting and are worthy of further investigation. Also, other factors such as shear, friction and posture must play a role in subjective feelings of comfort/discomfort.

### 7.3.4 Summary of experimental trials

When carrying 18.5kg loads in the laboratory a reduction in peak pressure (90%ile) was found with the Airmesh backpack when compared to the Bergen backpack (chapter 6.4). This finding has not been replicated in this study. This was also found to be the case with the civilian in-field trial. Perhaps when above

23.5kg it is the magnitude of the load itself rather than material properties that influences the transmitted pressure the most. Throughout the 3 trials, only two significant differences were found with interface pressure, in the backpack trial 90%ile shoulder pressure was significantly higher for the Bergen and in this trial the opposite was true, with the Airmesh LCS showing higher 90%ile shoulder pressure. Whilst throughout the subjective comfort ratings and rankings have shown a clear preference for the Airmesh backpack and the Airmesh LCS. At the heavy loads (23.5kg and 36.4kg) perhaps interface pressure values alone are not enough to predict subjective comfort, and Martin's theory of this relationship between the two factors does not ring true.

However, from the findings of the three trials, the location of the 90%ile pressures appear to be the strongest indicators (associated with pressure) of subjective ratings. It is suggested that these are the important factors to consider rather than differences in actual pressure values. Throughout the 3 trials the Airmesh backpack and Airmesh LCS have been rated significantly more comfortable by subjective ratings, and without exception these subjective ratings have been matched to the backpack and system which showed the greatest spread of locations of 90%ile pressure across the shoulder and hip zones (namely the Airmesh and the Airmesh LCS). This may well provide support for the material and design changes found within the shoulder and hip straps.

Linked to the location of 90%ile pressures is the issue of 'fit'. The Airmesh shoulder and hips straps may provide improved fit to the body when compared to the Bergen LCS straps, resulting in 90%ile pressures being transmitted across all of the pressure zones. Due to the anatomical differences between humans it may be that participants would naturally support loads in different areas of the shoulder and hip, and thus when this is restricted (as with the Bergen LCS straps) this may result in discomfort for the individual. This consideration of fit can be linked to Martin's work, where the Airmesh foam and plastic frame combination was found conform to body contours better than the standard Bergen straps. This shall be discussed further in chapter 8.

At heavier loads there may well be a need to incorporate other objective measurements in order to accurately predict subjective comfort and thus, make effective advances in design. Physical forces such as shear and friction and biomechanical considerations such as postural effects and also 'fit' may well need to be accounted for also. These considerations are discussed further in chapter 8, leading to further work and Human Factors recommendations for design in chapter 9.

### 7.3.5 Conclusion

In conclusion, over ten minutes of load carriage interface pressure measurements indicated little significant difference between the two LCS. In contrast, the subjective ratings produced highly significant differences with the Airmesh LCS being clearly preferred. The origins for this difference in preference are unknown but back comfort, posture, 'fit', and/or friction or shear forces at the interface may explain the preference. On this basis the data from the 3 trials (backpack, civilian in-field and military in-field) support the adoption of the characteristics as incorporated in the prototype Airmesh LCS.

# Chapter 8: Discussion of research findings and overall conclusions

## 8.1 Introduction

By utilising the Tekscan pressure measurement system and developing equipment enabling this system to be mobile, the first in-field interface pressure assessment of military load carriage systems has been achieved. The work contained in this thesis was the first to assess not only the shoulder and the hip interfaces together but also the whole LCS, rather than backpack alone. This assessment was carried out with both civilian and military participants. The military trial also assessed LCSs with military loading weights, thus providing greater insight into the effect of material and design change. Issues, observations and theories identified in the main text are considered and expanded upon in this chapter.

## 8.2 Discussion of the main thesis trials

A mobile pressure measurement system was developed enabling in-field research without the experimental constraints associated with laboratory work. This enabled LCSs and backpacks to be assessed in the actual context for which they were originally designed. By using this mobile system interesting findings have been made in relation to pressures recorded at the shoulder and hip interfaces.

When the whole LCSs are worn at loads of 23.5kg and above the findings from trial 2 (backpack) and those of Martin (2001) on the reduced peak pressures at the shoulder interface (with the Airmesh backpack) are no longer prevalent. However, highly significant subjective differences do remain and are constant across all three trials. The Airmesh backpack and Airmesh LCS were rated more comfortable throughout. Several theories for this increased comfort have been discussed in chapters 6 and 7, and are considered further in this section. One important difference for discussion is the difference in walk durations between the backpack and LCS trials. A shorter walk was selected for the in-field trials; this was to enable a greater sample size and to reduce the effects of fatigue when participants were required to walk more than once on the testing occasion.

If the walk duration had have been extended for the field trials an increase in fatigue may have occurred , due to the fact that participants carried each LCS twice on the test day. To have had a 30 minute field course would have meant participants would have been carrying a very heavy load (36.4 kg) for 2 hours, rather than 40 minutes. The possible increased fatigue over this longer period is of great concern and may have confounded the subjective comfort ratings. Discomfort may well have been a factor of body fatigue rather than true sensations of comfort at the interfaces. The reason for the fact that testing had to occur all in one occasion was one of logistics, with the man hours required to attend for testing on four occasions simply being too much for a busy infantry unit. The ten minute duration was chosen on the back of specific scientific research, controlled for fatigue effects and provided data from a large military sample.

**Subjective Bias:**

When considering the possible effect of bias (as discussed in chapter 5.5.3), with particular concern given to the military participants (who would most likely recognise a prototype (Airmesh) against a standard LCS (Bergen)) it would appear from both the civilian and military field trials showed significant differences with the Airmesh LCS being rated more comfortable throughout, reduces the concern of whether results were biased. Support for this view comes from the fact that the civilian participants, who had no previous knowledge of military LCSs, elicited the same trend of ratings as the military sample.

The use of the 'Bergen cover' to conceal the aesthetic differences of the two LCSs, coupled with keeping the LCSs out of view at all times would seem to have enabled adequate control for bias. However, it could be argued that bias may have occurred in both samples, but due to the fact that the Airmesh backpack (during trial 2) was rated more comfortable coupled with Martin's findings (Airmesh straps rated significantly more comfortable and also the wealth of reliability and validity testing of subjective measures) would suggest that subjective ratings can be viewed as conclusive.

The purpose of the in-field trials was to assess LCSs in military contexts and thus to have totally concealed the LCSs or to have used an experimental LCS (similar to Martin, with changeable straps) may have reduced the credibility of the results. These trials produced findings which can be directly fed to the MoD, enabling the recommendation of the characteristics of the Airmesh LCS, with the appreciation of the need for possible further work (chapter 9).

**Webbing interfaces:**

A key difference to discuss between the functioning of the two LCSs was the difference in the interfaces of the webbing sets. The Belt webbing is supported at the shoulder by a yoke and at the hip via a hip belt. The Vest webbing however is supported solely at the shoulders via a waistcoat type fitting (as shown in figure 5.10) with no hip belt. This is in order that the LCS as a whole has greater compatibility. However, the fact that the total load in the webbing is supported by the shoulder may have had an effect on the shoulder pressures recorded. The higher 90%ile pressures recorded at the shoulder with the Airmesh LCS may have in part been to due to the fact that the whole webbing load is applied to the shoulder. However, the fact that subjective ratings indicated a strong preference for the Airmesh LCS may indicate that at heavier loads it is other factors which influence the sensation of comfort more than peak pressure.

**Fit, stability and compatibility:**

One of the issues raised in the in-field trial discussion (chapter 7) was the effect of fit on interface pressure and perception of comfort. The Airmesh LCS straps transmitted pressure over more of the interface (as seen from the locations of 90%ile pressure graphs, figures 7.14 and 7.15), whereas with the Bergen LCS straps the 90%ile pressures were predominantly located within one zone; suggesting Airmesh straps conform better to body contours.

Research has shown that the threshold for discomfort and injury to the skin is lower at thin skin sites over a bony prominence (Sangeorzan et al. 1989). Thus, if the decreased conformity associated with the Bergen LCS straps results in loading over such sites (as is indicated by the 90%ile locations, identifying highest incidence in peak pressures in the clavicle and lumbar zones) this may well increase the discomfort experienced by the participants and may help to explain the significant difference in comfort between the two LCSs.

The incompatibility between the Bergen and Belt webbing at the lower back point (as highlighted in chapter 5, part II) results in the Bergen hip belt being unusable and causes the Bergen to be raised (due to it sitting on top of the rear belt kit pouches) causing a poor fit to be the body. This point is very clear from figure 7.1, where the poor fit is shown at the shoulders with the Bergen LCS shoulder straps showing a distinct lack of contact in the scapula zone. Due to this incompatibility the Bergen LCS may feel unstable, due to the load being forced higher up the body, with no support via the hip belt and poor contact at the shoulders. This instability could lead the participants to increase strap tension in order that the fit of the LCS feels more secure. By increasing the strap tension this may have to ability to cause greater discomfort, especially due to the fact that the 90%ile locations frequently exist over bony thin skin sites. The fact that the Airmesh LCS (by design) has increased compatibility between the backpack and webbing components, allowing for a better fit and increased stability (due to load being lower down the body) may well explain the favourable subjective ratings.

**Material Characteristics:**

An important consideration to assess (which was not carried out in this thesis work) would be to measure the material compression at different loads. The Airmesh material was associated with lower 90%ile pressures at 18.5kgs, but this difference ceased to exist on trials of 23.5kg and above. This may be due to the material specification being inaccurate for loads higher than 18.5kg. Martin's work only assessed the materials at 18.5kg and thus care must be taken to specify appropriate resilience of these materials for use in military LCSs. It is quite possible that at the increased loads assessed by this thesis that the materials essentially 'bottom out'. This may be quite simply remedied by increasing the density of the Airmesh material within the straps. However, this needs to be assessed further in a study particularly aimed at identifying material change as load increases. During the thesis trials the plastic framework built into the Airmesh straps appeared to still allow increased pressure distribution, possibly explaining the greater strap conformity and spread of 90%ile locations with the Airmesh LCS. The possibility remains that if the Airmesh material density is specified to the correct military loading then peak pressures may be the same or possibly even lower than the Bergen LCS values.

**Posture:**

From the findings of the in-field trials (chapter 7) came the consideration of a possible posture effect. When the whole LCS was worn with higher loadings, the differences in interface pressures were found to be non-significant (with one case of significance with the Airmesh LCS shoulder peak pressures being higher) the opposite results to those found from packs alone. But the subjective ratings remained constant across all the trials (2, 3 and 4). This may indicate the importance of other factors such as physical forces (shear and friction) but also posture. When considering the photographs of loaded participants (figures 5.17, 5.18 and 7.1) a difference in posture can be seen, with increased forward lean identified with the Bergen LCS. These photographs are by no means an assessment of posture but indicate the possibility of change which could lead to further research.

A particular mention must be made to research carried out by Attwells et al (2004) where such a postural comparison between the Bergen LCS and the Airmesh LCS was performed. Identical loadings to trial 4 were utilised and posture was assessed using the CODA motion analysis equipment via the measurement of trunk and head angles. The sample size was small (3 participants) and thus no significance was found, however the Bergen LCS elicited increased forward lean when compared to the Airmesh. The interesting point to note is that during a trial with lighter loads (40% of participant body weight) with 10 participants a significant difference was identified with the Bergen LCS showing increased forward lean during the first 50% of stance phase (Attwells et al, 2004).

The fact that research has been carried out assessing the Bergen and Airmesh LCS in terms of postural effects and has identified differences, provides support for the theory as suggested in this thesis that posture is a key consideration to make. The difference in posture whilst wearing the Bergen and Airmesh backpacks alone may not be so pronounced (this remains to be assessed). If so, then it could be proposed that compatibility of the LCS is crucial in the feelings of discomfort. It is proposed that this incompatibility results in a change in posture to compensate for this. This change in posture in turn increases the feelings of discomfort in the lower back and shoulder (as was identified in trial 4).

Another issue linked with posture is the effect on the centre of mass due to the Bergen LCS being associated with a higher load centred on the back of the body. The Airmesh LCS has a 'double pack' configuration where the load is distributed on the front and rear of the body. The Bergen LCS has a traditional 'rucksack' configuration where the load is almost totally applied to the back. Research has shown that the double pack configuration is associated with a lower energy cost and has a smaller effect on the body's centre of mass than a rucksack configuration (Datta & Ramanthan, 1971; Legg & Mahanty, 1985). The greater the change to the centre of mass the greater the need for postural change to counteract this and so that the body remains over the base of support. This effect on centre of mass obviously ties into posture effects (as discussed). Also, it is important to consider that the Bergen LCS maybe associated with a greater energy cost than the Airmesh LCS, although further study with military loadings would be required to confirm this. Higher comfort ratings and possibly reduced energy cost provide strong support for the Airmesh LCS characteristics for military use.

However, before any LCS design is recommended to the military a consideration of other important factors must be made. The thermal effects of carrying the Airmesh LCS must be considered, along with practical functions such as ease of donning and doffing and whether pouches on the front of the body interfere with weapon carriage/firing. A consideration of any increase in the soldiers profile must also be assessed. If any LCS results in a significant increase in profile resulting in ease of targeting by the enemy, this will obviously be a major concern. These are but a few of the practical considerations which must be made before recommending a LCS for military use. This is why great care has been taken throughout to only recommend the characteristics deemed advantageous by the thesis trials and not to recommend that the military adopt the Airmesh LCS as a whole.

**Shear and Friction:**

What also must be assessed in order to complete the picture is the effect of shear and friction at the interfaces. Pressure is obviously not the only force acting on the shoulder and hip. Shear, friction forces and pressure are all present when loads are supported by the body interfaces. It may be that when carrying heavier loads in a LCS, shear and friction forces may have a bearing on the discomfort felt by the user, or equally this may be present throughout. Being as these forces have not been considered by the literature in this context this remains to be studied. Developing a method to measure shear may well be difficult and would possibly involve utilising equipment which would detect its presence rather than give absolute values. Nevertheless by the consideration of these physical forces the potential for increased understanding of the intricate workings of the interfaces exists, and in turn the ability to greater inform design.

**Terrain Effect:**

Whilst walking the field course participants covered many types of terrain (as listed in section 7.3.2). Whilst it was not one of the aims to assess what effect terrain has on interface pressure it is interesting to consider in brief. Obviously in terms of the military it would not be possible to select or avoid a particular type of terrain; troops must cover whatever terrain lay in front of them (especially when engaging the enemy). However, if considering the effects of terrain highlights an improvement which could be incorporated into new designs this would be valuable.

The reason for not presenting any data linked to different terrain in the results chapters was that recordings were made before the 10$^{th}$ minute and therefore any variation between readings over different terrain maybe confounded by the effects of material change with load (Martin & Hooper, 2000). Being as an assessment of terrain was not one of the aims of this thesis, this is not a failing of the results. Nevertheless a consideration of terrain effects may prove valuable, not just in terms of interface pressures and comfort but also for injury risk. If an assessment of interface pressure and comfort can be made over differing terrain this may highlight important facts to consider which could affect future designs. For example, if when climbing inclines peak pressure increases significantly with a subsequent change in subjective comfort, this could highlight the need to incorporate a movable back system (as utilised by commercial manufacturers). Uneven ground is another area to consider as this may have a greater effect on the fluctuations in peak pressure as a result of stride pattern. There are a plethora of assessments and considerations to be made when it comes to terrain and is open to further research.

**Absolute Pressure:**

Whilst care must be taken when discussing absolute pressures (as highlighted in chapter 5) it is interesting to relate the mean and peak pressures identified from the military trial (as these represent the most extreme pressures across the trials) with those discussed in the literature. Pressure recorded at the shoulder and hip when loaded to military weights were all above the recommended maximum for sustained pressure of 14 kPa (Stevenson et al, 1995). However, pressure recorded at the body-LCS interface has been shown to be unsustained, where cyclic variations in pressure are seen in response to load increasing and decreasing throughout the stride pattern (chapter 5.6.6).

In physiological terms these fluctuations, though small may actually aid blood flow across the interfaces, acting like a muscle pump (if tissue pressure falls sufficiently to permit an inflow of arterial blood). It is important to consider that much research into the effect of pressure has been carried with invalids, bed-bound in hospitals where pressure really is constant. At the interfaces during load carriage this is not so and is worthy of investigation. The loads that the military have to carry are not likely to be reduced in the near future and thus any research attempting to define pressure or load limits, must define these on the body whilst carrying load. If limits are to be applied in a military context great care must be taken in order to make sure they are accurate and realistic.

**Importance of military views:**

Chapter 3 was concerned with the subjective views of current military personnel on the current standard issue LCS (Bergen LCS). The feedback from these personnel provided areas to consider when designing the prototype Airmesh LCS. The importance of durability and storage volume were incorporated in the Airmesh LCS design, however without this consideration, material specification may have been inaccurate and volume too high or low. These are two small factors but they indicate the importance of including subjective data – not just gathered from experiments, but also gathered from experience. If input from current end users is not continually sought then new designs have the potential to have significant failings.

For example if durability was not considered, the 'default setting' in terms of purchasing and cost would be to select the cheapest material. If consequently this material failed, this could have disastrous consequences for the effectiveness of military units. The same rings true for the volume or any other aspects. Also, consideration must be made for the demands from the MoD on such areas as mission requirement, survivability aids, new technologies, etc. These must also be catered for before any design can be put forward for full scale military use. Thus, by careful consideration of the positive aspects of current equipment, and via the incorporation of material and design improvements, real advances in LCS design can be achieved.

## 8.3 Summary

The experimental work contained in this thesis represents the first real in-field assessment of military LCSs in terms of pressure measurement and subjective comfort ratings. When considering the heavy military loads (36.4 kg) interface pressure measurements appear somewhat non-conclusive, however the subjective ratings show a highly significant preference for the Airmesh LCS. Several reasons for the discrepancy between objective and subjective data have been put forward. Most likely is the fact that at extreme loading there are many important processes to consider and peak pressure alone (unlike Martin's suggestion) will not provide an indication of subjective comfort. Consideration of the factors of importance as raised in this chapter will lead to greater understanding of the reasoning behind the subjective ratings. Given the highly conclusive subjective ratings and careful consideration of any potential areas of concern the recommendation from the experimental findings for the MoD is that the design features of the Airmesh LCS are the features of choice.

## 8.4 Overall conclusions from the thesis findings

1. The creation of a mobile interface pressure measurement system (utilising the proven Tekscan equipment) has enabled the assessment of interface pressure in field. In field assessment provides in depth information of how LCSs perform in their arena of intended use. Further research should continue to utilise this system.

2. Both the Airmesh backpack and Airmesh LCS were consistently and significantly rated as more comfortable than the Bergen backpack and Bergen LCS.

3. At loads of 23.5 kg and above the occurrence of peak pressure and discomfort are no longer synonymous. Other factors such as posture, fit, system compatibility and also physical forces present at the interfaces are thought to be critical here.

4. What is interesting to note from the pressure data is the importance of pressure distribution across the interfaces. The Airmesh backpack and LCS showed increased pressure distribution with 90%ile pressures found across the shoulder and hip interfaces; as suggested in the text this may be related to subjective comfort. Further work is warranted here to assess this, and the value of interface pressure measurement must not be overlooked.

5. The continued importance of gathering subjective data alongside objective measurement has been highlighted and is critical in order for an accurate assessment of LCSs.

6. Any new LCS design must account for; evidence of comfort and/or objective data; subjective feedback regarding not only comfort but also practical aspects of the system; demands from the MoD on system requirements.

7. Finally, LCS designers must consider compatibility between the backpack and webbing elements, as (on the whole) this would appear to be the most important influence on user comfort. LCS design must be performed as a whole process, not a series of individual parts.

# Chapter 9: Summary and future work

## 9.1 Introduction

This chapter gives a succinct summary, lists possible further research outcomes, gives Human Factors requirements for design and includes a final comment.

## 9.2 Summary

The aims of this thesis have been met.

(1) The development of a mobile 'in-field' method of measuring and quantifying interface pressure at the body-LCS interfaces (shoulder and hip) using objective and subjective methods was achieved

(2) The evaluation and comparison of LCS designs in-field and the production of human factors requirements for design were achieved.

An additional (minor) aim was to develop a new prototype LCS with a greater degree of compatibility between the components (backpack and webbing), incorporation of material advances, and a consideration for fit and posture. This was also achieved.

## 9.3 Future work

Below is a list of future research ideas leading on from the findings of this thesis.

1. An analysis of posture when wearing the Bergen and Airmesh LCSs should be undertaken in order to confirm or dispute the conclusions found in this thesis.

2. A method for measuring shear, friction and other physical forces at the interfaces needs to be defined. This would allow for greater understanding of the interfaces, providing more objective measurements which can be considered during design.

3. Further consideration of interface pressure could also be made. By conducting field trials over a longer period, this would identify any difference in pressure (and subjective ratings) when the LCSs/participants are exposed to loading for longer.

4. A worthwhile assessment would be to assess the effect of differing load on pressure and subjective variables. The possibility of a load limit for the reduction of peak pressures has been discussed in this thesis. To detect whether such a limit is present would greatly inform further research into this area. This may also identify an optimum load range within which interface pressure can be reduced and comfort increased. If military loading is always above this limit – different approaches (such as those mentioned in 1 and 2) need to be adopted.

5. To assess the effect of terrain (described in chapter 8) on interface pressure measurement and subjective comfort would be an interesting study. It is unlikely that the military will be able to avoid certain terrains (if associated with increased peak pressure and/or discomfort) but this may inform

design, and at the least lead to greater understanding of 'risk' for military commanders.

6. Commercial backpack manufacturers currently adopt many different adjustable back systems and 'fine tuning' elements to their designs to improve fit for the individual. This consideration of fit and stability has been highlighted. Further work seeking to assess the possibility of incorporating such design advances into military equipment may highlight factors which could be included and thus improve the lot for military users.

7. Work remains to be carried out to assess the functionality of the design changes (other than the straps) to the new Airmesh LCS. Namely the change of pouches, additional of movable top lid, etc. This work could be carried out via subjective trial – i.e. issue the Airmesh LCS to a trial group, closely follow them and their activities and then glean subjective feedback.

8. A further element of interest which would be interesting would be the assessment of a third backpack type. One which is able to transfer more than 50% of the pressure loading onto the hips. This could be linked with the backpack trial and indicate whether subjective comfort is increased further by continued reduction in loading at the shoulder.

## 9.4 Human Factors requirements

1. Compatibility between the backpack and webbing components of a military LCS **must** exist. Future designs must adopt a system approach, rather than designing individual components and presuming they will integrate effectively.

2. The load carried within a military LCS must be effectively distributed between the shoulder and hip interfaces. This should allow a more natural posture to be taken and thus it is hypothesised this will result in increased user comfort.

3. If truly valid findings are required regarding the assessment of military LCSs (or indeed any product) trials must be carried out with end users, in realistic contexts.

4. The importance of combining subjective measures with objective research still remains. If further research continues to identify objective measurements which provide greater understanding of the interfaces then this is obviously an advantage. However, whether objective measurements can truly negate the need for subjective ratings remains to be seen. For the moment the utilisation of subjective measures alongside objective measurement is strongly recommended.

5. The characteristics of the Airmesh LCS are recommended to the British Military at this stage as it represents a significant improvement in comfort for the soldier when compared to the standard issue equipment (Bergen LCS). However, further research seeking to assess the physical properties at work at the interface, combined with a detailed assessment of posture should be made.

6. When designing LCSs the load should be supported as close to the body as possible, preferably distributed between the front and back of the body (as with the Airmesh LCS) rather than all on the back, as this has negative effects on energy cost, and possibly posture and discomfort (as discussed in chapter 8).

## 9.5 Final Comment

The work of this thesis has highlighted the need to consider the whole LCS, to conduct trials with end users and to utilise accurate loadings. If the further research put forward is taken up it must continue to trial equipment in a manor similar to that set out by this thesis, if valid and meaningful results are to be gained. These results can then influence design and the possibility to improve the comfort, performance and also reduce injury risk of entire military units will exist.

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## Load Carriage Questionnaire

### Part 1.

Please fill out this questionnaire, relating to your current load carriage system (LCS), your experience with the standard issue system (Bergen + Belt webbing) and any ideas/requirements you would like to suggest for future design.

1. Please state the 3 most positive and 3 most negative aspects in your opinion of the standard issue Bergen LCS.

   Positive:

   (1)

   (2)

   (3)

   Negative:

   (1)

   (2)

   (3)

2. Have you adapted your current load carriage system in any way? (please circle)

Yes

No

2a. If you have adapted your current system, please detail the changes made.

3. Have you purchased any commercial load carriage equipment? (please circle)

Yes

No

3a. If you have purchased any commercial equipment please describe it.

4. Have you experienced any injury or discomfort whilst wearing the standard Bergen LCS? (please circle)

Yes

No

4a. If any injury or discomfort was experienced please give details and duration.

5. Have you experienced any injury or discomfort whilst wearing any commercial equipment you have purchased? (please circle)

Yes

No

5a. If any injury or discomfort was experienced please give details and duration.

6. Is there any specific design change (or changes) you would like to see made to the standard Bergen LCS? (please circle)

Yes

No

6a. If there is any change (or changes) you would like to see made please give details and reasoning for these changes.

7. How well do you find the standard issue Bergen and Belt webbing integrate? Please circle.

Very well

Well

Neutral

Poorly

Very poorly

8. Please give any other comments you would like to make in any aspect concerning military load carriage equipment.

## Part 2.

This section of the questionnaire requires you to rate certain aspects of the standard Bergen LCS on a 5 point scale.

| |
|---|
| 1. COMFORTABLE |
| 2. SLIGHTLY UNCOMFORTABLE |
| 3. UNCOMFORTABLE |
| 4. VERY UNCOMFORTABLE |
| 5. EXTREMELY UNCOMFORTABLE |

Using the scale shown above please rate the standard Bergen LCS in terms of overall comfort, and comfort in three body zones: shoulder, back and hip (please circle the rating of your choice).

Overall Comfort

| | | | | |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |

Shoulder Comfort

| | | | | |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |

Back Comfort

| | | | | |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |

Hip Comfort

| | | | | |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |

Please give your name, rank and unit.

Name:

Rank:

Unit:

**Thank you for your time.**

## 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
   - (e) Heart problems ........................................................... Yes    No
   - (f) Problems with bones or joints ................................. Yes    No
   - (g) Discomfort of the back ...................................... Yes    No
   - (g) Disturbance of balance/coordination .......................... Yes    No
   - (h) Numbness in hands or feet ......................................... Yes    No

4. **Has any,** otherwise healthy, member of your family under the age of 35 died suddenly during or soon after exercise? ..... Yes    No

**If YES to any question, please describe briefly if you wish (eg to confirm problem was/is short-lived, insignificant or well controlled.)**

..............................................................................................................................

..............................................................................................................................

..............................................................................................................................

Please fill in the table below relating to your current exercise level.

| Type of exercise | How often each week | Approx. how long each time |
|---|---|---|
| | | |
| | | |
| | | |

**Thank you for your cooperation!**

**Load Carriage Study – participant information sheet**

This study aims to understand the way in which individuals are affected by the carriage of loads, to increase the understanding of the dynamics of load carriage and the distribution of load on the body. To improve the comfort and ease of load carriage by design of relevant carrying equipment, such as backpacks and webbing.

You will be asked to carry loads in a backpack or military Load Carriage System. You will be asked to walk either on a treadmill for 30 minutes, or to walk a 10 minute field course (as explained by the investigator). A constant walking pace shall be kept throughout. During the walk interface pressure measurements shall be made at the shoulder and hip. Also, throughout the walk you shall be asked to give comfort ratings based on your feelings of discomfort at each point (a rating scale for this shall be shown and explained by the investigator).

To ensure there are no risks from the load carriage, you will be asked to complete a health screen questionnaire. If you have lower back discomfort or pain, gait, joint or muscular discomfort or disease, with diagnosed respiratory, circulatory or blood pressure difficulties, you will not be permitted to participate (the exclusion includes a history of such difficulties and will apply if you are receiving medication acutely or profilactically).

Any load carriage may include some discomfort at the interface between the pack and the body. This is the subject of the work. So, there is the possibility of discomfort. It should not be great but you are free to withdraw at any time if you wish to do so, without having to provide a reason.

## Participant consent form

I ...................................... have read the information sheet concerning the load carriage experiment and been given the opportunity to ask for clarification and further details. I understand the conditions I shall experience in the trials and what is required of me.

I freely give my consent to take part in this study. I understand I am free to withdraw at any time, without explanation if I prefer.

Signed : .................................................. Date : .....................

Print name : ..............................................

# Pressure Zones for 90%ile Locations