Investigation into elastic performance and functionality of fabrics for medical pressure garments

A thesis submitted in fulfillment of the requirements for the degree of M.Tech (Textiles)

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DECLARATION

I, Leah Di Bartolomeo, certify that:

a. Except where due acknowledgement has been made, the work is that of the candidate alone;

b. The work has not been submitted previously, in whole or in part, to qualify for any other academic award;

c. The content of the thesis is the result of work, which has been carried out in the School of Fashion and Textiles, RMIT University between March 2008 and February 2014.

d. Any editorial work, paid or unpaid, carried out by a third party is acknowledged.

e. Ethics procedures and guidelines have been followed.

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February, 2014

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DEDICATION

This work is dedicated to my family.

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ABSTRACT

The aim of this study was to evaluate and compare the elastomeric performance and comfort-related attributes of knitted fabrics used in garments for scar management and venous insufficiencies. Pressure garments used for scar management and venous insufficiencies need to provide sustainable pressure to the underlying limb from the time the garment is donned by the wearer to assist in recovery. In addition, fabrics used in the construction of pressure garments must be able to transport heat, vapour and moisture from the human body to the environment, leaving the wearer dry and comfortable. By adding a fabric assembly (two separate pieces of fabric layered on top of one another) to the pressure garment, pressure generating and comfort properties of the garment are expected to be enhanced. Six commercial knitted fabric samples were studied. Their selection was based on a representative sample of fabrics currently used for pressure garments, for scar management and venous diseases.

Pressure garments have been comprehensively studied for their material composition, construction, pressure delivery and physiological benefits as single layers in the past, while the amount of research carried out on fabric assemblies is limited. All fabrics were tested in both single layers and as fabric assemblies to compare their elastic performance and comfort attributes. Fabrics' physical parameters and structural properties were analysed for mass per unit area, thickness, stitch density, optical porosity and air permeability. The elastic characteristics of the six fabrics were tested at 25%, 40% and 60% strain to determine their properties relevant to pressure generation. In addition, the fabrics were tested for tension decay. The fabrics were also assessed for thermal resistance (R_{ct}) and water vapour resistance (R_{et}). Additionally, selected fabrics were tested for moisture management properties.

It was found that fabric assemblies influenced and enhanced the overall elastic and comfort properties of the single layer fabrics. For elastic characteristics it was found that the most powerful fabrics are the powernet fabrics in both warp and weft direction as single layers. The powernet fabrics are able to generate the most pressure on the underlying limb of the patient wearing a garment made from these, in comparison with the lining fabrics. When a second fabric was introduced as a second layer in a fabric assembly, the power also increased in the warp and weft direction for powernets. For moisture management capabilities, single layer brushed-back powernet had better moisture management characteristics. However, as a fabric assembly the non-brushed powernet paired with the lining fabrics had better moisture management capabilities. Also, a fabric assembly, lining on the inside next to skin, facilitates the removal of sweat from the skin and the evaporation into the environment better compared with powernet when next to skin. For thermal and water vapour resistance non-brushed powernet had the lowest thermal and water-vapour resistance as the next to skin side of the fabric is not brushed and doesn't entrap air which acts as an insulator. Also, as a fabric assembly, the non-brushed powernet next to skin has the lowest thermal and water vapour resistance compared

with the lining next to skin and powernet outside. For thermal and water vapour resistance in garment form different segments of the body had different thermal and water vapour resistance, which have to be taken into account at all stages of garment design and engineering.

CHAPTER 1: BACKGROUND

1.1 Introduction

Medical, healthcare and hygiene products represent an important and growing sector of the technical textiles industry. The expanding field of medical textiles includes all textile products that contribute to improving human health and wellbeing, protecting against infection and disease, providing external support for injured limbs, promoting the healing of wounds and replacing injured and diseased tissues and organs. The number and complexity of applications has continued to increase as research and development produces improvements and innovations in both textile technology and medical procedures.

Pressure garments have been used to exert pressure on human limbs for scar management, venous and lymphatic problems, bone and muscle injuries and post-cosmetic surgery. These garments are produced from knitted elastic fabrics, which on wearing extend and remain in an extended state while worn, thereby exerting pressure on the wearers body. Since pressure garments are worn next to the skin in intimate contact with the body, their comfort properties are of immense importance. As the skin of the wearer is often extremely sensitive in the affected area, the comfort characteristics of pressure garment fabrics play a critical role in patient compliance and healing. Therefore, the design of pressure garments must simultaneously enhance their direct medical functions and improve the wearer's comfort by transporting heat, moisture and water-vapour from the body.

For the design of pressure garments a comprehensive knowledge needs to be established to improve their performance and wearing comfort. An understanding needs to be obtained by identifying the functioning of pressure garments by carrying out experimental investigations, which involves information on the physical properties of pressure garments, performance attributes testing with emphasis on elastic characteristics, physiology of the human body and vapour and moisture transmission through pressure garment fabric.

In this study, the design and engineering of fabrics used for pressure garments are evaluated and compared, in regard to their elastomeric performance and comfort attributes in both single layers and as fabric assemblies.

1.2 Pressure garments for medical application

Pressure garments play a very important role in burn rehabilitation by helping prevent or reduce the formation of hypertrophic scars (Ripper et al. 2009). Also, by applying uniform or graduated pressure, garments with different degrees of compression assist in the process of blood flow for venous disorders such as lymphoedema and deep vein thrombosis (Lymphoedema Framework 2006).

Pressure garments are tight fitting and are intended to exert pressure on the underlying limb of the wearer. Garments are constructed using a variety of fabrics usually having an elastic component that exerts pressure on the body when stretched. The garments are made smaller than the body they are designed to fit (negative fit). Different compression rates are produced by selecting different kinds of elastic fabric and by adjusting pattern size to achieve different levels of negative fit. The average life expectancy of a pressure garment is two to three months. The constant stretching and restricting of pressure garments will eventually decay the elasticity of the fabric and cause it to lose its ability to exert the correct pressure on the patient, which reduces the garments' effectiveness and practical usefulness. The durability of pressure garments is influenced by many variables such as donning procedures, care, environmental factors, heat, moisture, excessive stretch from constant bending and heavy exercise.

1.2.1 Physiological mechanisms of medical pressure garments for scar management and venous insufficiencies

Scar management

Few humans reach adulthood without experiencing a wound to the skin that results in a scar. A scar is an essential part of the natural healing process of the skin, subsequent to an injury to the dermis or the epidermis. Scars are defined as thick mounds of scar tissue, which are characterised by excessive amounts of collagen deposition and range from fine lines to raised, hard, painful hypertrophic scars (Bloemen et al. 2009).

Hypertrophic scarring following surgical procedures, trauma and especially burns are a great concern for patients and a challenging problem for clinicians. Peacock (1981) defined hypertrophic scarring as a scar raised above the skin level that stays within the confines of the original lesion. Hypertrophic scars usually develop within one to three months after injury. Many factors such as race, age, genetic factors, hormone levels and the immunological responses of the individual patient play a role in the formation of hypertrophic scars (Ripper et al. 2009). Hypertrophic scars may cause significant functional and cosmetic impairments and pain that are responsible for a decrease in quality of life. Hypertrophic scars result from a general failure of the normal wound healing process. The time to heal is the most important factor in hypertrophic scar formation and is closely related to the depth and size of the wound (Macintyre 2007).

The skin's attempts to achieve wound closure trigger important mechanisms with regard to healing, contraction and rapid growth of connective tissue. When a normal wound heals, the body produces new collagen fibres at a rate that balances the breakdown of old collagen fibres. Hypertrophic scars occur due to excessive collagen synthesis coupled with limited collagen degradation during the remodelling phase of wound healing. The result is the formation of thick collagen bundles consisting of fibroblasts and fibrocytes (Ripper et al. 2009). The healing process of wounds starts with the constriction of blood vessels that form clots to minimise blood loss. To repair the damage, the body has to accumulate new collagen fibres, a naturally occurring protein which is produced by the body. An increased blood supply in the maturing scar tissues enforces the growth of excessive cells. A scar requires two years or longer too completely mature. During that time the scar is active and contracting, which can result in deformity and immobility in the affected areas (Ripper et al. 2009).

While the clinical effectiveness of pressure therapy in scar reduction has never been scientifically proven, a large body of dermatological, histological, clinical, anecdotal and case study evidence supports its use (Ng, SF, Parkinson & Schofield 1999; Wienert 2003). It is widely believed that the pressure excreted by pressure garments on underlying limbs controls collagen synthesis by limiting the supply of blood, oxygen and nutrients to the scar tissue, thus reducing collagen production to the levels found in normal scar tissue more rapidly than the natural maturation process (Macintyre 2004). The pressure exerted on underlying tissues encourages realignment of collagen bundles already present and restricts the availability of oxygen in the affected region. It is assumed that the lack of oxygen accelerates the maturation of the scar. Without the constant pressure of the garment, the collagen fibres of the scar tissue grow unsystematically, whereas, the inner structure of a scar matured under constant pressure resembles more the natural patterns of fibres in healthy skin (Ripper et al. 2009). These uses of pressure garments may hasten scar maturation and reduce the incidence of contractions and the need for surgical intervention. Also, it is accepted that application of pressure commonly alleviates the itchiness and pain associated with active hypertrophic scars (Macintyre 2004).

One of the main aims of rehabilitation after a major burn is to recover the best possible functioning of the affected body areas; this normally involves a long period of recuperation and numerous corrective surgical interventions (Ripper et al. 2009). A hypertrophic scar after a burn requires a special approach as the scars are often not linear but widespread and a shortcoming of pressure garments is difficulty of use with scars in anatomical flexures and areas of high movement. Pressure garments provide constant and equal compression over the burn, which minimises scar development and scarring deformity. The use of persistent external pressure applied by pressure garments is well accepted as one of the best, non-invasive means of preventing and controlling hypertrophic scaring after burn injury. As soon as the wound has healed the wearing of pressure garments may commence; they are worn continuously night and day, except for short periods of personal hygiene, until the scar is mature. The length of time required for wearing the garment varies from several weeks up to more than two years, depending on the severity of the injury (Ripper et al. 2009).

Due to patients wearing garments for a prolonged period of time, garments must not abrade the developing scar or adjacent skin, which is either covered by or in contact with the pressure garment. Also, comfort factors are of immense importance, garments should not cause physiological discomfort due to excess warmth or sweat production (Yildiz 2007). The introduction of a fabric assembly in the garment can improve patient compliance due to enhanced comfort properties of thermo-regulation and smooth surface on the inside of the garment next to the skin (Macintyre 2004). Additionally, especially for children, introducing a second layer of fabric on the outside of the garment can enable manufactures to add embellishments, such as printing on the garment.

Patients are normally fitted with pressure garments as soon as the wound is fully closed and able to tolerate pressure. Garments are designed to exert a pressure of approximately 25mmHg on the underlying tissue; pressure should be more than 24mmHg in order to exceed the inherent capillary pressure. This design pressure has varied over the years and has never been scientifically established (Macintyre 2007).

Venous insufficiencies

Mechanical interventions like compression garments have found wide application in the treatment of venous insufficiency of the lower extremities (Agu, Barker & Seifalian 2004). Compression exerted on lower limbs is effective to prevent and manage various venous diseases, such as lymphoedema, varicose veins, oedema and deep vein thrombosis (Lymphoedema Framework 2006). When pressure garments are applied the soft tissue of limbs is radially this is a prerequisite for the compression garment to mechanically increase blood flow (Perrey 2008).

Knowledge of the anatomy and physiology of the human circulatory system is essential for the understanding of how compression garments work and how they perform their medical functions. In the human body, four types of vessels form the vascular system of the lower extremities: arteries, veins, capillaries and lymphatics. The arteries carry oxygenated blood from the heart to the capillary bed; the veins return deoxygenated blood to the heart; the lymphatic network returns interstitial fluid and other plasma constituents such as protein molecules back into the systematic circulation (Rong 2006).

The leg veins are at a greater risk of developing disorders than any other part of the circulatory system due to the distance from to heart. Blood flows from the heart to the legs through arteries taking oxygen and nutrients to the muscles, skin and other tissues. Blood then flows back to the heart carrying away waste products through veins. The valves in the veins are unidirectional, which means that they allow the venous blood to flow in an upward direction only. If the valves do not work properly or there is not enough pressure in the veins to push back the venous blood towards the heart, blood pools in the veins and this leads to higher pressure in the skin.

The power to drive the venous blood back to the heart from the lower limbs is provided by the calf muscle pump, which on walking contracts and relaxes in a regular movement. This increases the resistance to the return of blood through the venous system and exerts increased pressure on the valves of the perforating and superficial veins. The contraction of the calf muscle helps to push the blood upwards through the veins; the valves prevent backflow. Relaxation of the calf muscle allows the empty segment of deep vein to refill with blood from the superficial veins and thus blood circulation is repeated. Lack of movement when standing leads to the leg muscles exerting prolonged, unvaried pressure on the deep veins.

The working mechanisms of compression are a result of the pressure exerted on the leg, through which the veins become narrower, the insufficient perforating veins become closed and the retrograde bloodstream will diminish. The use of physical pressure garments is a conservative measure that in no way cures venous insufficiency but aims to prevent venous deterioration. The venous blood volume will diminish as well and calf muscle pumps can work better; thus resulting in higher tissue oxygenation and better microcirculation (Perrey 2008).

Pressure garments can be designed to apply uniform or graduated compression. Uniform pressure garments are engineered to exert even pressure over the limb, as usually used in scar management. Graduated compression refers to the application of varying degrees of constant compression to different segments of the leg, with pressure being greatest at the ankle and gradually decreasing proximally up the thigh. Graduated compression is commonly used for venous problems. To achieve maximum increase in deep venous velocity with a decrease in pooling of blood in the calf veins, external static compression should exert a gradient pressure, highest in the ankle region and lowest in the upper thigh, therefore avoiding the relative tourniquet effect produced by applying equal pressure throughout the lower limb (Perrey 2008). Many researchers have shown that pressure garments are effective in reducing venous symptoms when the external compression is graduated, this facilitates the flow of blood through the deep veins back towards the heart.

Lawrence and Kakkar (1980) concluded that an optimal pressure gradient of 18mmHg at the ankle, 14mmHg at the calf, 8mmHg at the knee, 10mmHg at the lower thigh and 8mmHg at the upper thigh would generate the fastest venous flow. Previous studies suggested that compression of the limb below the knee contributes most to the increased velocity of blood in the femoral side (Lymphoedema Framework 2006). Present recommendations are that compression garments should exert a pressure of 30mmHg at the ankle decreasing linearly up the leg to 6mmHg at below the knee (Perry 2008). The beneficial effects of this design are that the graduated compression can reduce the hydrostatic pressure and redress the balance between the deep and superficial veins; it can help the veins to contact without muscle activity and to pump blood up toward the heart, increasing flow velocity (Lawrence and Kakkar 1980).

The practices of layering pressure garments produces higher pressure on the limb and is usually done in severe cases of lymphoedema (Lymphoedema Framework 2006). A second layer typically adds about 70% to the pressure applied in a single layer (Lymphoedema Framework 2006). Also, in severe cases of lymphoedema and oedema, bandaging or wrapping is used to provide and maintain constant levels of pressure. Two layers of bandage are thought to exert twice as much pressure as one layer (Nelson 1997), which allows practitioners to deliver greater levels of compression via incrementally increased layers of bandaging. As garments are worn 24 hours a day, they can be engineered from two layer fabric assemblies to give more precise pressure to the underlying limb and increase the comfort properties of the wearer by allowing sweat and moisture to be transferred through the fabric and into the surrounding environment.

Problems associated with pressure garment treatment

Several problems are associated with current pressure garment treatments. Important problems in treatment delivery include lack of scientifically established guidelines on safe and effective pressure. Pressure is difficult to apply evenly, particularly in concave areas of the body. The influence of parameters such as percentage body fat, age, sex and race has not been scientifically determined. Differences in sub dermal pressure delivered using similarly constructed garments are not fully understood; blistering may occur if too much pressure is applied too soon, resulting in treatment suspension. Moreover, applied pressure reduces during the course of the day and the life of the garment, pressure varies with movement and the exact nature of these changes has not been measured. 'Reduction factors' used by therapists are often arrived at in a subjective manner without considering differences in fabric properties, such as stress and strain. The application of pressure garments for scar management places high demand on patents in terms of co-operation because the garment should be worn almost 24 hours a day and the procedure should be continued for a period of 1 year or until the scar matures (Macintyre, Baird & Weedall 2004), therefore, elastic and comfort characteristics of fabrics garments are constructed from are of immense importance.

1.3 Classification, standards and testing of pressure garments for medical applications

There are many existing standards regarding pressure garments: European standards for medical compression hosiery such as British standard for graduate compression hosiery BS 6612: 1985 (BSI 1985), British standard for compression, stiffness and labelling of anti-embolism hosiery BS 7672: 1993 (BSI 1993), British standard for non-prescriptive graduated support hosiery BS 7563: 1999 (BSI 1999), French standard ASQUAL (ASQUL 1999) and German standard RAL-GZ for medical compression hosiery 387:1 (RAL 2008). These standards do not necessarily correspond with each other. There were attempts to produce a European standard for medical compression hosiery EVS-ENV 12718-2002 (EESTI 2001) which was unsuccessful (Clark & Krimmel 2006).

Currently, no international or Australian standard exists for pressure garments or for the fabrics used in their production. In 2003 Standards Australia prepared a draft standard document for public comment based on a draft document developed for the European community but this was withdrawn when the European Standard was not agreed upon (Lymphoedema Framework 2006).

The Hohenstein compression measurement system (HOSY) was developed by Hohenstein Laboratories in order to test the effectiveness of textiles for compression treatment. It consists of a range of tests that are essential if garments are to be labelled and sold in Germany (Lymphoedema Framework 2006). The tester consists of 20 tensile test devices, each with a width of 5cm, which enables the apparatus to examine stockings with a maximum length of 100cm in almost any shape without destroying them. The specimens to be measured are fastened to 20 opposing pairs of clamps. The specimens are then stretched to the desired circumference and the force required for each test clamp pair measured, along with tension and hysteresis.

The UK's Hosiery and Allied Trade Research Association (HATRA) developed the HATRA pressure apparatus, which is considered to significantly increase the reliability of measuring the degree of compressive pressure exerted by a garment (Simmons 2013). The device consists of a prosthetic leg and a measuring head. The garment is loaded onto an adjustable prosthetic leg, simulating the wearing of the garment on a human leg. The measuring head, pressed against the stretched fabric at various points along the length of the leg, displays the circumference tension in the fabric, which is converted to a value for pressure. Garment performance is expressed as a compression value in millimetres of mercury (mmHg); this is derived from the pressure exerted by garments at the ankle and the relative pressure at the calf and thigh, which must gradually decrease up the leg in order to improve blood circulation. It is also required that the garment be capable of exerting at least 85% of its original pressure after having been washed 30 times and this must be taken into account when assigning the compression value (Simmons 2013)

1.4 Design and engineering of pressure garments for medical applications

1.4.1 Pressure garment fibres

Textiles fibres are broadly classified as natural or synthetic. Pressure garments are sometimes constructed from both natural and synthetic fibres; however, synthetic fibres are most commonly used. Most synthetic fibres are hydrophobic, meaning they repel water, whereas hydrophilic fibres attract water. Fibres with low surface energy are considered hydrophobic and fibres with a high surface energy are considered hydrophilic.

Pressure garments are usually fabricated from polyester, polyamide and elastomeric fibres such as elastane. The polyester fibre has poor absorbency with 0.4-0.81% moisture regain (Gioello 1982). Polyester is hydrophobic and its wicking rate is slow compared with that of other synthetic fibres. Also, polyester is strong and does not lose strength when wet. Polyester has good elasticity and very good recovery: 97% recovery at 2% elongation, 80% recovery at 8% elongation (Gioello 1982). Moreover, the polyester fibre is also cheap to manufacture, easy to care for and has excellent washing properties.

The polyamide fibre has a poor absorbency with 4-4.45% moisture regain (Gioello 1982). Polyamide has good elasticity 26-40% elongation at breaking point and 100% recovery at 8% elongation (Spencer 1996) and is an exceptionally strong fibre. Moreover, polyamide fibres such as nylon have higher moisture absorption rates and better wicking ability than polyester but dry more slowly. Polyamide fibres are more expensive to produce than polyester fibres. Several variants of polyamide fibres are available, for example anti-microbial, high-wicking and extra-soft grades.

Elastomeric fibres such as elastane have poor absorbency, are hydrophobic and have 0.75-1.3% moisture regain (Gioello 1982). They have very high elasticity about 440-770% elongation at breaking point and have a 96% recovery at 5% elongation (Spencer 1996). They have poor strength compensate for by high fibre stretch.

Synthetic fibres can be modified during manufacture to improve their properties; for example, fibres can be extruded with different cross sections and can be coated after treatment. One of the most popular modifications made in order to improve properties is the use of superfine fibres or microfibers with the filaments having a linear density below 1 decitex. Some pressure garments employ specially engineered fibres for example, CoolMax® fibres, a three-channel fibre with a cross section that was found to offer improved wicking capability and moisture vapour permeability (Onal & Yildirim 2012).

1.4.2 Pressure garment fabrics

Fabric is the most important element of a pressure garment. It must simultaneously provide elasticity, ease of movement and comfort, while at the same time, it must apply significant pressure to compress the body to the desired level. The fabric should be soft and elastic, cause no irritation to the skin and should fit the body contours like a second skin. Also, fabric should be smooth and cause no abrasion, especially during body movement. The fabric should be easy-care and washable, and its properties should be maintained after multiple washings. To resist daily wear and tear, the fabric and the sewing method selected should be strong enough so the pressure garment can last for a few months (their general life expectancy). Surprisingly, despite anecdotal and clinical evidence for the beneficial effects of pressure therapy for hypertrophic scars and venous deficiency, little scientific data about the mechanical properties of fabrics used in pressure garments exists.

Fabric is a manufactured assembly of fibres or yarn that has substantial surface area in relation to its thickness and sufficient cohesion to give the assembly useful mechanical strength.

Based on the nature of the yarn or fibre arrangement, fabrics are classified as woven, knitted and non-woven. Woven and knitted fabrics are the major materials used for apparel. Most pressure garments are constructed from knitted fabrics. The interlacing of yarn loops forms knitted fabric structures. There are two types of knitted fabric structure weft and warp.

- *Weft-knitted fabrics*- are produced by a system of interlocking loops in the weft direction. The loops are in horizontal courses with each courses built on top of the other and all the stitches in the course are made by one yarn.
- *Warp knitted fabrics*- are produced by a system of interlocking loops in the warp direction. Several parallel yarns that form one stitch for each yarn in each course produce fabric. Each stitch in a course is made of different yarns. Warp-knitted fabrics give different levels of elasticity and strength of the materials giving varying degrees of fabric tension, thus inducing different degrees of pressure on patients.

Elastic fabrics are an important way to achieve fit and comfort with freedom of body movement by way of reducing fabric resistance to body stretching. Simple body movements may extend the skin by about 50% (Senthilkumar et al 2012). Fabric should also respond by stretching with the body's extension and recovering on relaxation. The most sophisticated pressure garments utilise a powernet structure. Powernet is a warp-knitted fabric; its distinctive feature is its extensibility in both the warp and weft directions. The structure may allow a warp extension of 75-85 per cent and a weft extension of 65-75 per cent (Spencer 1996). The structure of the powernet is formed from four half set threaded guide bars on a knitting machine, the front two bars producing a net, the remaining two bars laying in an elastomeric yarn (Spencer 1996). Powernet garments offer firmer pressure to the underlying limb due to the construction. The arrangement of threading in and the lapping movement of all guide bars are illustrate in Figure 1.1 and the loop structure is shown in Figure 1.2.

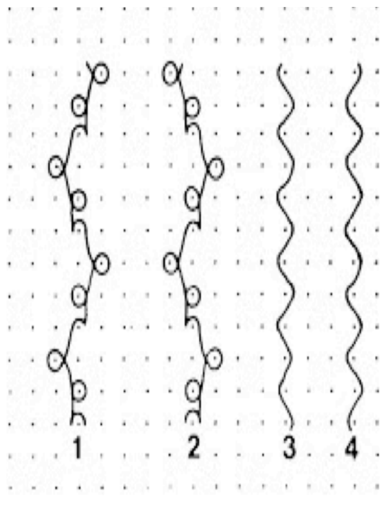


Figure 1.1 Lapping movements and guide bars of power net (Raz 1987)

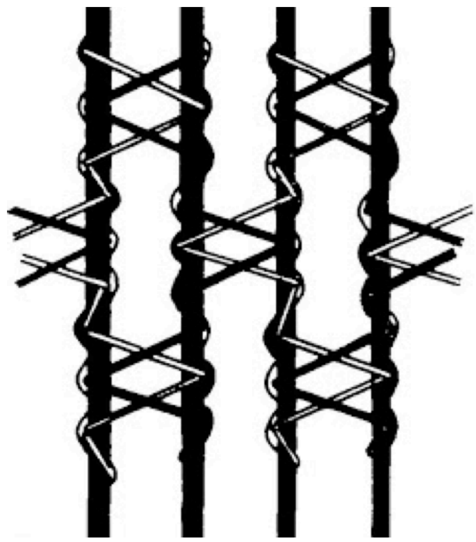


Figure 1.2 Power net loop structure (Raz 1987)

In order to maintain adequate pressure throughout the lifetime of the pressure garment, its fabric must have certain characteristics. They include:

- Tension: the tension of the garment is determined by the amount of force applied to the fabric during application. The ability of the fabric to sustain a particular degree of tension is determined by its elastomeric properties and these in turn are dependent on the composition of the yarns and the method used to construct the fabric.
- Extensibility: the ability of a fabric to respond to an applied force by increasing in length (stretching).
- Power: the amount of force required to cause a specific increase in the length of a fabric is an indicator of power. This characteristic determines the amount of pressure a fabric will produce at a predetermined extension.
- Elasticity: the elasticity of a fabric determines its ability to return to its original length as the tension is reduced.
- Hysteresis: the loss of recovered linear length of an elastic fabric when it returns after exposure to repeated force-extension cycles. A hysteresis curve shows the deformability characteristics of elastic material and the recovery after consecutive force-extension cycles. A fabric never returns completely to its initial length after stretching, an ideal material would be one that undergoes little deformation as possible.
- Modulus- the slope of the initial straight-line portion of a stress-strain curve, which signifies the initial resistance of a fabric to the applied force. In this region, the fabric is elastic; that is, the force absorbed is recovered when the force is removed and no permanent damage or deformation results (Collier & Epps 1998). A steep slope in this preliminary region indicates a higher modulus and a larger resistance to the applied force.

Pressure garments can be manufactured and structured from fabric assemblies, that is, multiple layers of fabric. These fabric assemblies can be used to increase pressure of the underlying limb of the wearer and facilitate fast removal of sweat from the skin and evaporation into the environment. For example, the garment's inner layer (next to skin) can be produced from a synthetic fabric that is hydrophobic while an outer layer can be made of hydrophilic fabric that absorbs wicked moisture and then allows it to evaporate. In this way, on the surface of the skin will be transferred to the outer layer of the fabric and absorbed by the outer surface. When absorptive material is used as an inner layer, skin will have continuous contact with wet fabric and this will irritate the wearer (Ceken 2004).

The human body, especially that of a recovering patient, can easily become contaminated. The body provides the ideal environment for the growth of microorganisms that cause odour, mould and mildew (Holme 2007). An anti-microbial fabric is protected against the growth of bacterial, microbial and fungal colonies. No chemically unaltered natural or synthetic fibres are inherently resistant to these microorganisms; however, differences exist in the persistence and retention of these microorganisms in various types of fibres. Synthetic fibres retain more odour-causing bacteria than do natural fibres; whereas, natural fibres such as, cellulosic fibres, are much more susceptible to attack by mildew and rot producing fungi and algae than are synthetic fibres (Holme 2007). Several anti microbial finishes are now available on the market and can kill bacteria and enable garments to smell fresh for longer.

For pressure garments, it is important that the anti-microbial finish leaves the garment comfortable to wear and safe to handle and use. Anti microbial finishes for pressure garments should be non-toxic and non-irritating. Moisture management finishes promote rapid wicking and evaporating of perspiration, leaving the wearer drier and in a significantly more comfortable state. Moisture management finishes increase moisture absorbency and improve the wetting and wicking properties of fabric.

1.4.3 Construction methods of pressure garments for medical application

Many fabrics and construction methods are used to manufacture pressure garments. However, the two main types of pressure garments are:

- Ready-to-wear garments: warp or weft-knitted garments available 'off the shelf' or from specialist manufacturers.
- Custom-made garments: typically constructed from warp-knitted fabrics by specialist manufacturers and fitted by a trained clinical advisor.

Ready-to-wear pressure garments are available from commercial companies. Garments are usually made from elastic fabrics and are generally used for introductory treatment before custom-made garments can be provided. Ready-to-wear garments are available in a variety of styles and sizes for all body parts; they do not normally fit patients perfectly so adjustments are often required.

Custom-made pressure garments constructed by a specialist manufacturer are generally considered to be the most effective form of pressure therapy (Macintyre 2007). In order to provide each individual patient with correct continuous pressure, garments should be made to measure, allowing them to conform precisely and comfortably to the contours of the patient's body and provide maximum benefit. Patients are supplied with two or three sets of garments so they can wear one while washing the others. Every five to six weeks patients are re-measured by a therapist and the performance of the garment is reassessed in order to maintain the required compression.

In order to fit each patient accurately, the circumference of the limb area is measured, so adequate pressure can be constantly maintained. Garment measurements are taken in short intervals (for example, every 2cm along the limb) by using tape measures to obtain accurate longitudinal and circumferential dimension of affected body parts (Figure 1.3 & 1.4).

Figure 1.3 Example of leg measurements (TSL Australia)

Figure 1.4 Example of arm measurements (TSL Australia)

Most established specialist garment manufacturers have developed their own standard engineering formulae to determine the size of the pattern and create a pressure gradient within a pressure garment constructed from individual patient measurements. Dependent on the characteristics of the elastic fabric, simple patterns are adjusted to allow for stretch in garments in order to produce the required compression. The patients' measurements are reduced by a certain percentage, often around 10% for the first set of pressure garments and 15% or 25% for all subsequent pressure garments, this is referred to as reduction factor (Macintyre & Baird 2006). The reduction factor is not normally changed based on the dimensions of the body part being treated or the specific properties of the fabric. A paper pattern is made from the body part measurements; the pattern is placed on the fabric and cut out.

The choice of fabric is dependent on the therapist evaluation of the patient's requirements and the necessary pressure. Burns patients in differing phases of the healing process need garments that provide different levels of pressure, therefore, fabrics of varying pressure are used. The adjustment of pattern size and fabric type can achieve different degrees of compression for diverse groups of patients and end uses. In general, children or patients with newly healed wounds will be offered garments made of a lower-pressure fabric while higher pressure fabrics are used on adults who require greater compression for their treatment.

Once the pattern is cut, the fabric pieces are sewn together to form the garment. A variety of stitches and seams are used on different parts of the garment for diverse requirements. For example, flat seams are used to reduce the thickness of the seam allowance of two joined edges. The seams are usually located on the outside of the garment to prevent irritation of the skin. Zippers and hook and loop fastener fasten the majority of pressure garments. The fastenings used must be long enough to enable the patient to don and doff the garments easily. Also, the location of the fastenings is important to the design of the garment relative to the wound location. A two-thread zigzag lockstitch is used for sewing fastenings onto the garment and the lockstitch is used mainly for sewing zippers in position. After construction, the garment is fitted on the patient. The fit is normally assessed subjectively based on the experience of the fitter (Macintyre 2006).

The construction of custom-made pressure garments differs slightly depending on the manufacturer. Commercial company patient measurements are usually sent directly to the manufacturer by a hospital or burn clinic, normally using the manufacturer's measuring charts and tapes. Commercial manufacturers often use specialized computer aided design systems that aid the pattern construction process (Macintyre 2006). The pattern pieces are cut out and sewn together by machinist using a variety of stitch types. Finally, garments are sent to the patient at the hospital or burns clinic and their fit is assessed (Macintyre 2006).

1.5 Methods of calculation and evaluation of the pressure generated by garments

Pressure garments currently used for the treatment of scar and venous insufficiencies are made from different fabrics with a wide range of performance parameters such as; tension characteristics. The tension of fabrics depends on the elasticity of the material and the way it is constructed. The pressure a garment exerts on the limb depends on both the tension of the fabric and the radius of the limb.

Some of the methods used for theoretical prediction of pressure generated by pressure garments by researchers are mathematical/numerical modelling using the Finite-Element method (FE method) and approximation of Law of Laplace.

Okss & Lyashenko (1999) studied the distributed forces within elastomeric fabric, engaging various mathematical and physics theories and laws, and the 'geometrical meaning' of the limb (curvature of the surface of the limb). They concluded that the pressure induced over the body from the elastomeric textile/garment depends on 'mechanical parameters' of the fabric (fabric tension) and on the geometry of the limb.

Also, the triangular FE method was applied in modelling the textile material considering various hypotheses; from this model, a technique was derived predicting the pressure induced from pressure garments over a limb. The FE method was also used by Dai et al. (2007), where the pressure was simulated below the knee by modelling both the pressure garment and the 'three-dimensional biomechanical lower limb' having bone and soft tissue; the model revealed that the pressure was not evenly distributed over the limb.

Alternative approach in theoretical prediction of pressure generated by pressure garments is approximation of Law of Laplace. Law of Laplace defines 'the relationship between the pressure across a closed elastic membrane or liquid film and the tension in the membrane or film' (Thomas 2002). Although the human body and its limbs are not truly cylindrical, Laplace's

Law can be applied to give useful information on fabric pressure to assist in the healing of wounds or venous inadequacies. To attain consistently effective and comfortable pressure garments covering various parts of the body, the relationship between garments and body dimensions must be calculated carefully given the elastic properties of the fabric. Laplace's Law states that pressure is inversely proportional to radius for a constant tension; thus, a decrease in the radius will give an increase in pressure. Laplace's Law is mathematically represented in the following equation:

$$P = T/R \tag{1.1}$$

Where
P is the pressure (Pa)
T is the tension (N)
R is the radius (m)

For example, garments are tailored to leg contours so that the circumference increases towards the thigh and tension in the fibres is relatively constant along the length of the leg but since the leg radius decreases at the ankle, the same tension causes pressure to increase. Laplace's Law can be used to design powernet pressure garments that will exert a specific desired pressure on limbs or other near-cylindrical body parts. As a powernet fabric is extended its tension will increase, and this relationship is linear (up to a point) (Saville 1999). Therefore Laplace's Law indicates that making garments from different fabrics and/ or designing them using different reduction factors will change the pressure they exert.

Stress-strain curves are derived from various methods of testing for determination of tensile properties of fabrics. In order to achieve stress-strain curve for a fabric, 'an increasing force is applied gradually to a textiles material' (Saville 1999). Standard methods such as BS4952: 1992 (Macintyre, Baird & Weedall 2004) and BS2907: 1992 (Yildiz 2007) were used for testing fabrics for stress-strain curves. Instruments such as dead weight system (Ghosh, S et al. 2008) or constant rate of extension tensile testing machines such as Instron tensile testing machines (Ng, SF, Parkinson & Schofield 1999; Saville 1999), Nene M5 (Macintyre, Baird & Weedall 2004), Zwick dynamometer (Partsch, Partsch & Braun 2006), and biaxial tensile tester (Lin et. al 2010) have been used by various researchers for determination of tensile properties of fabrics.

1.6 Interaction of textiles comfort, human, clothing and environment

1.6.1 Physiology of clothing and comfort

Clothing has always played an important role in human well-being, protecting from harsh environmental conditions, increasing physiological and psychological comfort and improving the functioning, productivity and health of the wearer. Pressure garments are a cornerstone in care, treatment and rehabilitation of burn scars and venous diseases. Garments are intended to provide recovery of the wearer but they are also intended to provide comfort for patients.

Comfort is one of the most important aspects of clothing but a satisfactory definition is yet to be obtained. Physiological comfort is related to the human body's ability to maintain life by controlling its temperature and psychological comfort refers to the mind's ability to keep the body functioning satisfactorily. According to Kothari and Sanyal (2003), comfort is not easy to define because it covers both quantifiable and subjective considerations. Nevertheless, they suggested that comfort is a situation in which temperature differences between body members are small with low skin humidity and the physiological effort of thermal regulation is reduced to a minimum. Li and Wong (2006) stated that comfort depends on subjective perception of visual, thermal and tactile sensations, psychological processes, body-apparel interaction and external environmental effects. Barker (2002) recognised that comfort is not only a function of the physical properties of materials and clothing variables, but must be interpreted within the entire context of human physiological and psychological responses.

Wearer comfort is a complex phenomenon but in general it can be divided into four main aspects (Bartels 2005). The four basic elements of clothing comfort are:

1. Thermo-physiological comfort: comprises heat and moisture transport through the clothing and directly influences a person's thermoregulation. Human thermo-physiological comfort is associated with the thermal balance of the human body, which is highly dependent on metabolism rate, physical activities, ambient temperature and the thermal and moisture transmission behaviour of the worn clothing. Clothing creates a microclimate between the skin and the environment, which supports the body's thermoregulatory system to keep its temperature within a safe range, even when external environment temperature and humidity changes markedly.
2. Sensorial comfort: the direct contact of the textile with the skin. Sensorial comfort is associated with the direct-skin fabric mechanical interactions such as prickly, scratchy, itchy, rough and static.
3. Ergonomic comfort: the fit of the clothing and ability of a textile to allow freedom of movement. The garment's construction and the elasticity of the materials are the main determinants of ergonomic comfort. The cut of the garment also affects thermo-regulation and the wearer's feeling of comfort; layers of air between the textiles and the

skin and on the garment can be circulated (convection) and exchanged with the surrounding air (ventilation). Convection and ventilation are increased as the wearer moves. Depending on the cut of the garment (width, clothing openings), effective heat and moisture transport process are supported or prevented (Li and Wong 2006).

4. Psychological wearer comfort: subjective perception of clothing to the eye and hand, which contributes to overall feeling of well-being and pleasantness on the part of the wearer. It is affected by fashion, personal preferences and ideology.

1.6.2 Thermo-physiological comfort

One of the fundamental functions of clothing is to maintain its thermal balance and comfort. Thermo-physiological comfort of humans depends on climate, clothing and physical activity (Alagirusamy & Das 2010). Thermal balance of the human body is maintained in hot environments when the heat produced from metabolism and gained from the environment equals the heat lost by conduction, convection, radiation and evaporation (Gavin 2003).

Throughout the course of its biological development, the human body has lost much of its ability to control heat loss and maintain thermal balance. Therefore, clothing is needed to protect the body against climatic influences and to assist its own thermal control functions (constant core body temperature of 37°C) under various combinations of environmental conditions and physical activities. Clothing fabrics should allow moisture into the environment in order to cool the body and to reduce the accumulation of moisture. If the fabric in contact with the skin is not dry, heat flow from the body increases which results in unwanted loss of body heat in cold environments. In hot conditions, the heat loss is beneficial. The heat generated from the body is controlled by varying skin temperatures as well as changing perspiration rates providing evaporative cooling (Fan 2009), and clothing must assist the human thermoregulation system in various conditions, including transmission of heat from the skin and moisture from perspiration and sweating to the outer environment.

During a patient's recovery, the heat the body generates must be dissipated through the pressure garment to prevent overheating. A patient usually wears a pressure garment everyday underneath normal clothing. If perspiration in both the form of vapour (insensible) and liquid (sensible) cannot escape the skin and the garment next to skin, the build-up of moisture on the skin compromises the comfort of the wearer (Fan 2009). The thermo-physiological wear comfort of clothing is evaluated through its moisture management (moisture permeability and liquid-water transport) and thermal and water-vapour resistance.

Many researchers have investigated the thermal transmission characteristics of fabrics. These depend on various factors, including their physical and structural characteristics, the internal structure of the yarn and the characteristics of the fibres.

The fabric thickness has the most significant influence on thermal behaviour, explaining more than 90% of the phenomenon (Alagirusamy & Das 2010); this is due to the fabric volume, which determines fabric insulation. Also, fabric thickness determines the distance that the heat and water-vapour must pass through from one side of the fabric to the other and has been reported as one of the paramount fabric parameters influencing thermal and water-vapour resistance of fabrics by many researchers (Bedek et al. 2011; McCullough 1993; Prahsarn, Barker & Gupta 2005; Cubric et al. 2012). Bedek et al. (2011) observed a positive relationship between thickness and thermal and water-vapour resistance of fabrics.

Most fabrics, particularly knitted fabrics, have air trapped within their structure; thus when analysing the thermo-physiological comfort of fabrics, both systems including the fabric parameters as well as air must be taken into consideration. Air has a lower thermal conductivity (by ten times) than most fibres (Salopek Cubric et al. 2012) and is know to act as a significant insulator (Bhattacharjee & Kothari 2009). Additionally, when clothing consists of layers, each material layer has a still air layer attached to its outer surface and these air layers become important insulators. Hence, the presence of air within a fabric structure has major effect on the thermo-physiological comfort of fabrics.

Fabric stitch density and mass per unit area are strongly correlated; where increase in stitch density, increase the mass per unit area of the fabric. Fabric thickness, mass per unit area and stitch density have inverse and fabric pore size has a direct relationship with fabric air permeability (Karaguzel 2004; Majumdar, Mukhopadhyay & Yadav 2010). High air permeability resulted in better thermal conductivity and heat transfer (Bedek et al. 2011; Huang 2006).

Also, found to be influential on both thermal and vapour resistance and overall moisture management capability (OMMC) of fabrics is fabric porosity, which is, the portion of air volume to the total volume of the fabric (McCullough 1993). Porosity is calculated from mass per unit area of fabric, fabric thickness and fibre density (Skinkle 1940), so it is also affected by stitch density (Dias & Delkumburewatte 2008). Dias & Delkumburewatte (2008) observed that a decrease in stitch density increased the fabric porosity and Hatch (1990) reported that increased porosity led to lower thermal conductivity and higher thermal resistance.

Moreover, large drops of moisture can be diverted by the construction a textile fabric, thereby preventing wetting and unwanted heat loss while considerably smaller water vapour molecules, carrying heat are able to escape through the fabric through extremely fine fibre interstices, pores or molecular interstices (Alagirusamy & Das 2010a). Textiles fabrics are porous materials and their thermal transmission characteristics depend primarily on their porosity.

Thermal insulation is measured for fabrics comprising the garments, and garments themselves separately. The thermal conductivity of textiles depends on various structural parameters of the fibres such as molecular structure, density, crystallisation level, crystal orientation angle and mobility of molecular chains in amorphous regions (Alagirusamy & Das 2010a). Also, the arrangement of fibres within yarns influences the thermal transmission behaviour of textile fabrics. The thermo-physiological properties of fabrics cannot be directly translated into thermo-physiological properties of garments, due to other parameters such as the amount and part of the body covered by the garments (clothing area factor), weight, layers, fit, the resultant air gap between the body and garment, variable temperature on different body parts and body positioning and movement influencing the thermal insulation of garments (Fan 2009; Huang 2006; McCullough 1993).

Pressure garments have a negative fit, there is no air gaps affecting their thermal insulation and water-vapour resistance. However, when a second layer of fabric is introduced to enhance comfort properties or design aesthetic, depending on the properties of the fabric and the amount of the fabric used, the overall thermal insulation of the garment is affected.

Vapour and liquid moisture transmission through textiles has a great influence on the thermo-physiological comfort of the human body. The moisture vapour transmission property of a fabric is governed by inter-yarn or inter-fibre spaces. The vapour diffuses through the air spaces between the fibrous materials. Resistance to moisture vapour diffusion comes in different layers: the evaporating fluid layer (which remains full of water saturated vapour), the confined air layer (between the skin and clothing fabric), the boundary air layer and the ambient air layer (Alagirusamy & Das 2010). If the clothing moisture transfer rate is slow during sweating, the relative and absolute humidity levels of the clothing microclimate will increase suppressing the evaporation of sweat. This will increase skin temperatures, resulting in heat stress. If moisture is accumulated in the inner layer of the fabric system and evaporation of sweat is low the thermal insulation of the clothing will be small and cause unwanted loss of body heat. In hot and cold weather and during normal and high activity levels, moisture transmission through fabrics plays a major role in maintaining the wearer's comfort level.

1.6.3 Comfort measurement and evaluation

Standard method for evaluation of comfort specifically for pressure garments does not exist, yet some manufactures are interested in assessing and evaluating comfort properties of functional pressure garments, to gain a competitive advantage over other manufactures. Researchers are interested to find methods to improve these properties.

Wearer trials with human test subjects in climatic chambers (subjective/objective) and laboratory test (objective) for various aspects of comfort are used for assessment of comfort (Bartels 2011). Laboratory testing equipment is widely used for objective evaluation of various aspects of clothing comfort. For instance, thermal insulation of fabrics can be evaluated with the sweating guarded hot plate or thermal manikin. A sweating guarded hot plate measures the energy required to keep a heated surface covered with fabric at a set temperature. The sweating guarded hot plate is internationally standardized (ISO 11092: 1993(E)). The measuring unit is made of sintered stainless steel. Water, which is supplied by channels beneath the measuring unit, can evaporate through the numerous pores of the membrane, just like sweat from the pores of the skin. The measuring unit is kept at a temperature of 35°C, so heat and moisture transport are comparable to those of the human skin (Bartels 2005). According to Bartels (2005), different wear situations can be simulated with the skin model by setting the machine:

- Normal wear situations: characterised by an insensible perspiration (that is, wearers do not recognise they are sweating). At least 30 grams of water vapour is evaporated through the semi-permeable membrane per hour.
- Heavier sweating: wearers recognise they have started to sweat but are not sweat-wetted yet (for example, while walking up a few flights of stairs).
- Heavy sweating situations with a high amount of liquid sweat on the skin: the buffering capacity against liquid sweat transport is defined as 'moisture permeability'.
- The wear situation directly after exercise: the fabric might be soaked with sweat and lose its thermal insulation.

Yet as mentioned in section 1.6.2, separate analysis of thermal insulation of garments is required which could be carried out on a heated thermal manikin simulating the actual wear conditions of garments, a heat thermal manikin measures the heat loss due to conduction, convection and radiation (Das & Alagirusamy 2010). Thermal manikins are complex instruments used to measure the thermal transmission behaviour of clothing in actual wear conditions and body heat fluxes in complex environments. A human-shaped thermal manikin allows measurement of the heat losses in all directions, over the whole surface of the manikin or defined regions. For instance, the thermal manikin 'Newton' from Measurement Technology Northwest consists of 20 independently controlled thermal zones and complies with International Standards (ASTM F1291, 2010; ASTM F2370, 2010).

A value for the whole body heat loss can be determined by totalling the area-weighted values. For the same exposure conditions, a thermal manikin measures heat losses in relevant, reliable and accurate ways. Recent developments of sweating manikins, as well as breathable and walking manikins, allow even more realistic simulations of human thermal interactions with the environment. According to Holmer (2004), significant performance features of a thermal manikin include:

- Relevant simulation of human body heat exchange with environment
- Whole body and heat fluxes measurements of three- dimensional heat exchange
- Integration of dry heat losses in a close to realistic manner
- Objective measurement of clothing insulation
- Quick, accurate and repeatable measurements
- Cost-effectiveness for comparative measurements and product development.

Both the sweated guarded hot plate and heated thermal manikin are used for objective evaluation of water-vapour resistance of fabrics and garments, respectively, by measuring the evaporative heat loss (Fan 2009).

One method of objective analysis of liquid-water transmission is areal wicking 'spot' test (Fan 2009). There is a number of other existing methods not covered in this background research. To test the liquid water transfer and distribution properties of fabrics, the moisture management tester is used. The principle of the apparatus design is that when moisture transports through a fabric, the contact electrical resistance of the fabric will be changed. The value of the resistance change depends on two factors: the components of the water and the water content in the fabric. When the influence of water components is fixed, the electrical resistance measured is related to the water content in the fabric (Hu, Li & Yeung 2006). The moisture management tester is designed to objectively and accurately measures fabric moisture management properties. The fabric specimen is held flat by a top and bottom sensor and synthetic sweat is pumped onto the top surface of the fabric. Meanwhile, the computer records the resistance change in the fabric between the top and bottom sensors. The sensors act as detectors to identify the fabric-wetted area in order to measure the size of the wetted area and the time it takes for the fabric to become wet. The solution transfers in three directions:

1. Outward on the top surface of the fabric
2. Through the fabric from the top surface to the bottom surface
3. Outwards on the bottom surface of the fabric and than evaporates (Hu, Li & Yeung 2006).

1.7 Summary of Background

Pressure garments are widely used in medical applications and are a cornerstone in care, treatment and rehabilitation of burn scars and other diseases such as lymphoedema, varicose veins and oedema. Pressure garments are tight fitting, have a negative fit and are intended to exert pressure on the underlying limb of the patient. Pressure garments are usually constructed from a single layer of fabric; however, the functionality of the garment can be increased with a fabric assembly, which are two layers of fabric.

Pressure garments have been comprehensively studied for their material, construction, pressure delivery and physiological benefits in single layers, while the amount of research carried out on fabric assemblies and layered bandages is limited. There are a substantial number of existing standards regarding pressure garments, however, there are no worldwide standards in existence for production and quality assurance of fabrics made from them or to layered bandages or layered garments.

Similar to any technical garment, pressure garments benefit from advances in textile technology, in terms of fibre, fabrics, finishes and garment engineering to enhance functionality and comfort of the garment. Pressure garments are usually fabricated from a blend of polyester, polyamide and elastomeric fibres such as elastane. Garments are constructed using a variety of elastomeric fabrics that exert pressure on the body. The garments are made smaller than the body they are designed to fit. The most sophisticated pressure garments utilise a powernet structure. Powernet is a warp-knitted fabric; its distinctive feature is its extensibility in both the wale and course directions. Also, the powernet structure provides a powerful fabric, that is, the amount of force required to cause a specific increase in the length of a fabric. This characteristic of power determines the amount of pressure a fabric will produce at a predetermined extension. Pressure garments currently used for the treatment of scar and venous insufficiencies are made from different fabrics with a wide range of elastic and comfort performance attributes. The elastic behaviour of fabrics depends on the way it is constructed. Different compression rates are produced by selecting different kinds of elastic fabric and by adjusting the garment pattern size. By layering garments, pressure can be increased in severe cases of venous diseases. It would also be possible to better vary and engineer the layers to deliver more precise pressure to underlying limb and a smooth next to skin feeling for the patient. There is little scientific information available on fabric assemblies.

Many fabrics and construction methods are used to manufacture pressure garments. However, the Custom-made pressure garments constructed by a specialist manufacturer are generally considered to be the most effective form of pressure therapy. One of the methods used of theoretical prediction of pressure generated by pressure garments used by researchers is approximation of Law of Laplace. Laplace's Law states that pressure is inversely proportional to radius for a constant tension; thus, a decrease in the radius will give an increase in pressure.

Pressure garments must fulfil their intended use, is to aid in recovery for the wearer as well as physiological function and overall comfort (Bartels 2011). During the wear of a pressure garment, there is a dynamic interaction between the garment and the body, this includes thermo-physiological, tactile, ergonomic and physiological interaction. These are all dependent on various properties of the fabric and garment as well as environmental conditions.

There are many variables found to influence the thermo-physiological comfort of fabrics such as thickness, porosity, presence of air within the fabric structure. Pressure garments can be manufactured and structured from fabric assemblies. These fabric assemblies can be used to facilitate fast removal of sweat from the skin and evaporation into the environment. For example, the garment's inner layer (next to skin) can be produced from a synthetic fabric that is hydrophobic and has good capillary action while an outer layer can be made of hydrophilic fabric that absorbs wicked moisture and then allows it to evaporate. In this way, moisture on the surface of the skin will be transferred to the outer layer of the fabric and absorbed by the outer surface. In addition, recently therapeutic and pressure garment manufacture laboratories are considering utilising a two-layer fabric assembly in these garments (Hu, Li & Yeung 2006).

The options of using a smooth surfaced fabrics next to skin and powernet outside would provide more tactile comfort to the wearer, as well as offering an opportunity for more flexible pressure control.

Furthermore, as current pressure garments look very much as 'medical devices', introducing a second layer on the outside of the garment will offer opportunity for garment embellishments, such as printing, especially for children's garments. Due to this, further investigation into elastic and comfort attributes of multi-layer fabric assemblies suitable for pressure garments is required.

CHAPTER 2: PURPOSE OF THE STUDY

Aim and objectives of the study

The aim of this study is to evaluate and compare relevent functionality attributes of knitted fabrics used in garments for scar management and venous insufficiencies, in terms of their elastomeric performance and comfort attributes in both single layers and as fabric assemblies.

The study will focus on selected pressure garment fabrics that are currently used in the industry.

The principle objectives of the study are:

1. To examine and evaluate the structural parameters of different fabrics used for medical pressure garments.
2. To assess fabrics' elastomeric performance attributes in single layers and as fabric assemblies.
3. To evaluate the elastomeric performance of fabrics used in pressure garments after prolonged garment wear in single layers and as fabric assemblies.
4. To investigate fabrics' thermo-physiological comfort attributes in single layers and as fabric assemblies.
5. To examine a garment's thermo-physiological comfort attributes.

Research questions

The research questions to be addressed in the study are:

1. What are the physical parameters of pressure garment fabrics used for medical applications?
2. What are the elastic characteristics of pressure garment fabrics in regard to extension, recovery and tension decay?
3. What occurs in the elastic characteristics of fabric assemblies if a second layer fabric is introduced?
4. What are the thermo-physiological comfort attributes of pressure garment fabrics?
5. When introducing a second layer of fabric, do the thermo-physiological comfort attributes of pressure garment fabrics change and if yes, how?
6. What are the thermo-physiological comfort attributes of a pressure garment?

Research hypothesis

Pressure garments used for scar management and venous insufficiencies need to provide sustainable pressure to the underlying limbs. Also, fabrics used in the construction of pressure garments must be able to transport heat, vapour and moisture from the human body to the environment, leaving the wearer as comfortable as possible during prolonged wear of the garment.

Fabrics of different physical parameters will have different elastomeric performance attributes that would affect the generated pressure by garments made from them. By adding a second layer of fabric, the elastic properties of the resultant assembly will change for example stretch and recovery properties. In addition, as fabrics have diverse structural and physical parameters, their performance attributes relevant to the thermo-physical comfort will also differ. The introduction of two fabric layers will affect these performance attributes and thus the overall comfort of the resultant garment.

CHAPTER 3: STUDY DESIGN

The chapter discusses the methodology, materials and methods used for the present study. The aim was to create a research design to achieve objectives and answer the research questions stated in the previous chapter.

3.1 Methodology

To achieve the objectives of the study, the following methodology has been adopted.

1. Background literature review:
    - Literature review was carried out to understand the characteristics of pressure garments for medical textiles and to recognize the mechanical and thermo-physiological characteristics of pressure garment fabrics.
2. Selecting commercial experimental fabric samples:
    - Fabric samples were selected based on the fabrics used in the medical textiles industry for scar management and venous insufficiencies.
3. Analyzing experimental fabric samples' physical parameters and structural properties:
    - Fabrics were tested for mass/unit area, thickness, stitch density and optical porosity.
4. Conducting fabric performance attributes testing on selected fabrics with emphasis on their elastic characteristics:
    - Selected fabrics were tested at 25%, 40% and 60% strain to determine their stress/strain properties as single layers and as fabric assemblies. The specified strains were determined by use in the industry.
    - Selected fabrics were tested for tension decay both as single layers and as fabric assemblies.
5. Analysing tests results of selected experimental fabric samples for elastic characteristics
6. Conducting fabrics thermo-physiological comfort testing in a relaxed state:
    - Selected fabrics were tested for moisture management properties as single layers and as fabric assemblies.
    - Selected fabrics were tested for thermal resistance (R_{ct}) as single layers and as fabric assemblies.
    - Selected fabrics were tested for water-vapour resistance (R_{et}) as single layers and as fabric assemblies.
    - Selected garment was tested for thermal resistance (R_{cf}) and water-vapour resistance (R_{ef})
7. Evaluating results of thermo-physiological comfort testing of fabric samples.

3.2 Materials

Six warp knitted commercial fabric samples (Table 3.1) were selected for the study. Fabric samples were obtained from a pressure garment manufacturer. Their selection was based on currently used and new pressure garment fabrics for scar management and venous diseases. In the industry garments are constructed from fabrics PN1 and PN2, these fabrics are used to generate pressure on the underlying limb of the patient. Fabrics T1, L1, L2 and L3 could be used as a lining to enhance comfort characteristics, a smooth next to skin feel for the patient, or outside of the garment as a decorative feature.

All the experimental fabrics were assessed individually and then in two layer assemblies. The study was carried out in the following sequence:

- Two powernet fabrics PN1 and PN2, four lining fabrics T1, L1, L2 and L3 were evaluated as single layers for their physical, elastic characteristics and thermal comfort attributes.
- Fabric assemblies with the combination of powernet fabrics (PN1 and PN2) with lining fabrics were made (T1, L1, L2 and L3) as inside and outside layers of both powernets. This formed twelve 2-layers assemblies as PN1/L1, PN1/L2, PN1/L3, PN2/L1, PN2/L3, PN2/L3, L1/PN1, L2/PN2/ L3/PN1/ L1/PN2, L2/PN2 and L3/PN2.
- Fabric samples are labelled according to single layer or fabric assembly. For example, PN1 and L1 are single layers; PN1/L1 are fabric assemblies with PN1 next to skin and L1 facing the outer environment; L1/PN1 are fabric assemblies with L1 next to skin and P1 facing the outer environment.

Table 3.1 Details of fabric specifications used in the current study

Sample fabric code	Fibre content	Fabric construction
PN1	67% Nylon 33% Elastane	Powernet
PN2	75% Nylon 25% Elastane	Powernet
T1	68% Polyamide 32% Elastane	Tricot
L1	90% Nylon 10% Elastane	Tricot
L2	90% Polyamide 10% Elastane	Tricot
L3	100% Polyester	Mesh

A commercial body suit pressure garment for burns was constructed for the study. The garment was assembled from the measurement of the thermal manikin to fit its form. The fabric used for the garment was PN1 (whole garment) and L3 (underarm and crotch area) as theses fabrics are most commonly used in the industry. A zip was sewn down the front chest/ stomach segment to don and doff the garment. Refer to figures 3.1 and 3.2.

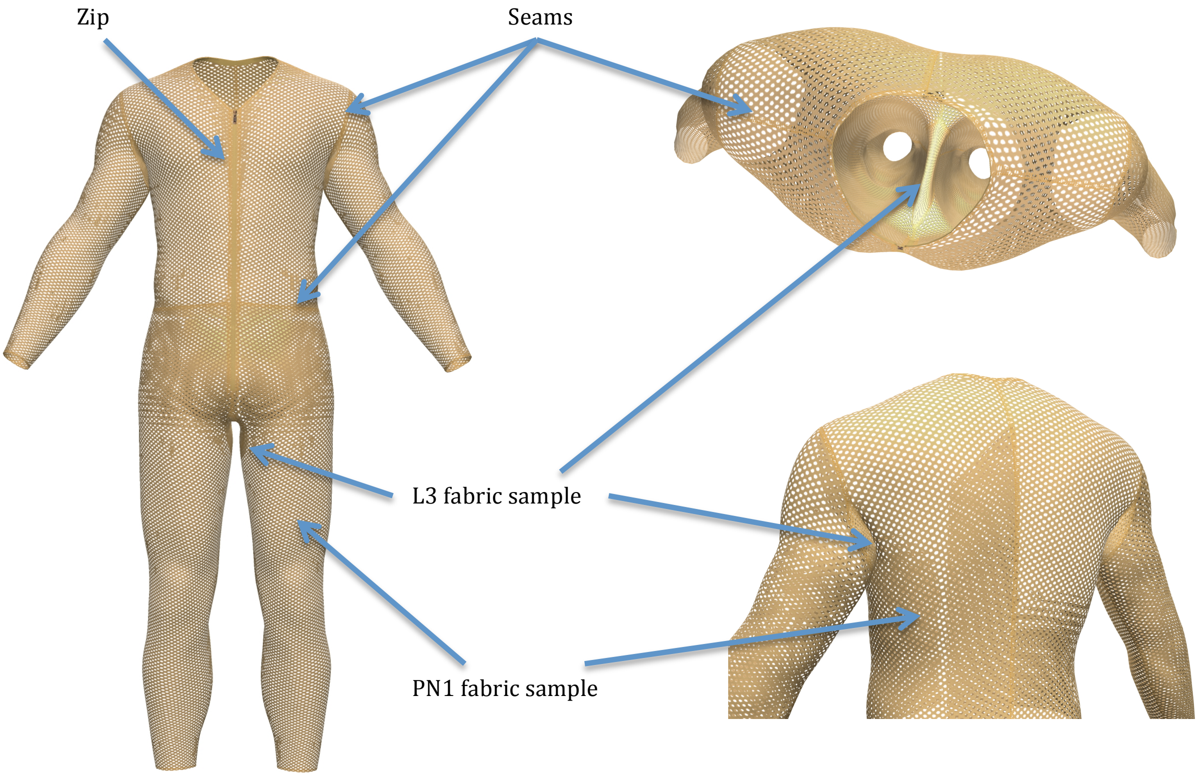


Figure 3.1 Garment view: front, inside and back

The garment was constructed with 25% reduction factor. The software V-Stitcher was used to generate a 2D pattern and a 3D simulation of the garment.

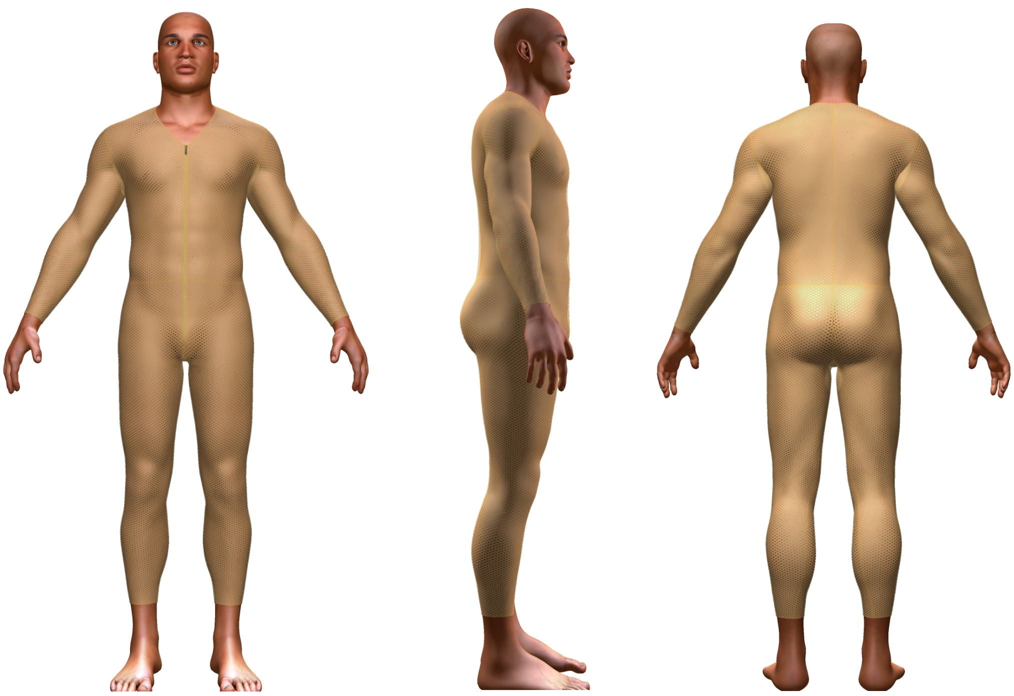


Figure 3.2 Front, side and back view of garment generated by V-Stitcher

3.3 Methods and Instruments

A summary of the test methods and laboratory instruments used are found in Table 3.2.

Table 3.2 Test methods and Instruments used

Relevance	Characteristics and attributes	Test methods	Instruments used
Structural and physical	Mass per unit area	AS 2001.2.13-1987	SARTORIUS BP100 Measuring balance
	Thickness	AS 2001.2.15-1987	John Bull thickness tester
	Stitch density (courses and wales)	AS 2001.2.6–2001	MOTIC Microscope with mounted camera
	Optical porosity	N/A	MOTIC Microscope with mounted camera
	Air permeability	AS 2001.2.34-1990	Air permeability apparatus-SDL ATLAS
Elastic properties	Determination of fabric elastic characteristics at 25%, 40% and 60% strain	Developed method based on BS 4952:1992	Instron 5565A apparatus
	Determination to susceptibility to fatigue	Developed method based on BS 4952:1992	Instron 5565A apparatus
Thermo-physiological comfort	Moisture management	AATCC 195-2009	Moisture management tester (MMT)
	Thermal resistance	ISO 11092:1993(E)	Integrated Chamber Sweating Guarded Hotplate: 431-213
		ASTM F1291, 2010	Sweating thermal manikin-Newton P357
	Water-vapour resistance	ISO 11092:1993(E)	Integrated Chamber Sweating Guarded Hotplate: 431-213
		ASTM F2370, 2010	Sweating thermal manikin-Newton P357

Physical properties of fibres can be affected by their moisture content, therefore before each test commenced the fabrics were conditioned to eliminate the influence of the atmosphere moisture content. Fabric samples were preconditioned to ensure subsequent conditioning in the standard atmosphere commenced from dry state. After that fabric samples were exposed in as open a manner possible to the standard atmosphere in the controlled laboratory until moisture equilibrium had been attained. The standard temperature is 20± 2% and relative humidity of 65%± 2% (AS 2001.1-1995). The standard deviation of the error bars used throughout are ± 1%.

3.3.1 Determination of fabric structural and physical parameters

Determination of fabric mass per unit area

Five specimens (10cm x 10cm) were conditioned and tested in a standard atmosphere. Each of the specimens was weighed with a measuring balance. The mass per unit area was calculated as the mean mass per unit area of the five specimens (AS 2001.2.13-1987). Mass per unit area was calculated using the following formula:

$$M_{ua} = \frac{m}{a} \tag{3.1}$$

Where

M_{ua} is the mass per unit area of the fabric after conditioning in the standard atmosphere of testing (g/m^2)

a is the area of the specimen (m^2)

m is the mass of the specimen (g)

Determination of fabric thickness

The thickness of fabric samples was measured as the distance between the reference plate and parallel presser foot (AS 2001.2.15-1989). After the presser foot was lifted, the fabric sample was positioned on the thickness tester reference plate and then the presser foot was gently lowered to apply pressure to the fabric sample. Ten specimen readings were taken and recorded (AS 2001.2.15-1989).

Determination of fabric stitch density (courses and wales per unit length)

The number of wales and courses in an accurately measured length were counted along a line at right angles to the courses or wales being considered. After sample fabrics were conditioned, each was laid to on a horizontal space and the minimum tension required was supplied to keep the fabric flat. The number of wales and course was counted using a microscope. Determination was made at the point not closer to one tenth of the width of fabric to the edge of the fabric being tested. Five counts in each direction were made; positions evenly spaced along or across the fabric were selected; selvedge was avoided and no count in either direction included the same wales and courses performed (AS 2001.2.6–2001).

Determination of fabric porosity

Fabric porosity is a significant parameter in assessment of clothing comfort and physical properties of textile fabrics. Fabric porosity depends largely on the construction of the fabric and is represented by voids between fibres and yarns. Porosity is the ratio of the total amount of void space in a material to the bulk volume occupied by the material (Elnashar 2005).

Optical porosity is expressed as transmittance (%) of visible light through fabric (Hatch et al. 1990). The light from a microscope is captured through the voids and is converted into white pixels while the yarn that blocked the light is converted into black pixels. A microscopic image of the experimental sample was presented by Motic stereo microscope and image tool software was used to determine optical porosity of obtained images.

Microscope image capture process-

1. Motic Image Plus 2.0 software was launched.

2. The specimen was mounted onto the microscope.
3. The image was display on the screen.
4. The microscope was set to x100 magnification obtain a proper image.
5. The image was captured.
6. The image file was saved.
7. Thirty images of each of the sample fabric were captured.

Optical porosity determination procedure-

1. Image Tool software was launched.
2. The image file was opened.
3. The image was converted into a grey scale.

The grey scale image was threshold by clicking the threshold button in the software window.

1. The software counted the black and white pixels in the image.
2. Optical porosity was determined based on the formula:

$$Optical\ porosity = \frac{white\ pixel}{white\ pixel + black\ pixel} \text{ x } 100\% \qquad (3.2)$$

Determination of fabric air permeability

Air permeability is measured on an apparatus designed to force air through the test specimen. In order to assess the air permeability of medical pressure garment fabrics, the Australian Standard (AS 2001.2.34-1990), 'Determination of Permeability of Fabrics to Air' was followed. A standard testing method is given to test the airflow through a given area of fabric at a constant pressure drop across the fabric 10mm head of water. After ten testing specimens were conditioned, they were clamped over the air inlet of the apparatus using gaskets and air is sucked through it by means of a pump. The air valve is adjusted to give a pressure drop across the fabric and the airflow is then measured using a flow meter. The airflow is measured and the air permeability is calculated by the following formula:

$$L = \frac{V}{A} \qquad (3.3)$$

Where

L is air permeability (cm/sec)

V is rate of airflow (cm^3/sec)

A is the area of fabric under test (cm^2)

3.3.2 Determination of elastic characteristics for experimental fabrics

In order to evaluate the elastic characteristics and susceptibility to tension decay of medical pressure garment fabrics, two groups of experiments were developed based on the British Standard (BS 4952:1992) 'Methods of test for Elastic fabrics'.

1. Determination of fabric elastic characteristics at 25%, 40% and 60% strain
2. Determination of susceptibility to tension decay

Looped test specimens were used to investigate the behaviour of medical pressure garment fabrics for their elastic and tension decay properties. Specimens were prepared as follows. Specimen size was 7.5cm and 25cm, five specimens of each experimental fabric were tested in each direction (wale and course). For single layer specimens, one layer of experimental fabric was used. For fabric assembly specimens, two layers of experimental fabrics were used. To construct the looped specimens, a line was marked 2.5cm from each end of the specimen parallel to the relevant direction of warp or weft and sewn from one end of the line, returning along the same line to form the specimen into a loop. For single layer specimen, one layer of experimental fabric was sewn. For fabric assembly specimen, two layers of experimental fabrics were sewn.

The Instron apparatus 5565A model was used to undertake the fabric elastic characteristics and tension decay testing. The Instron was equipped with loop bars and was capable of cycling between zero strain and a predetermined strain. The Instron maintained a specimen under constant tension or strain. The Instron records the stress of the test specimen and the corresponding strain via the Bluehill software connected to a computer at one-second intervals.

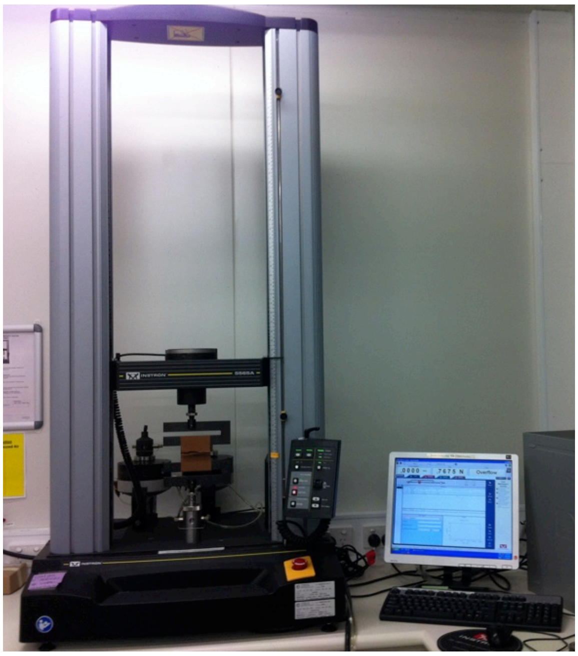


Figure 3.3 Instron apparatus

Determination of fabric elastic characteristics at 25%, 40% and 60% strain

For determination of fabric elastic characteristics the following procedure was undertaken: the gauge length was measured and set to 20cm around the circumference of the looped bars, the specimen was mounted onto the looped bars of the Instron manually under zero load and the positions of the specimen was adjusted around the bar so that the seam lied midway between the bars and the rate of strain and retraction of the specimen was set to 500mm/min and the specimen was cycled twice between zero and the specified strains of 25%, 40% and 60%.

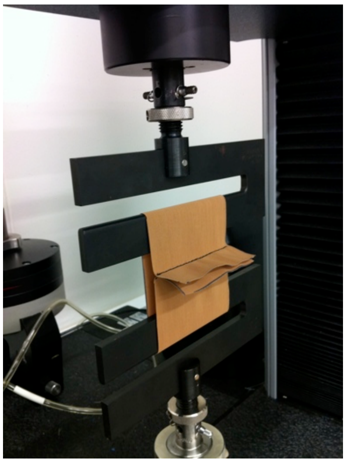


Figure 3.4 Looped fabric sample mounted on Instron

Determination of susceptibility to tension decay

For determination of susceptibility to tension decay the following developed procedure was carried out on selected fabrics: the gauge length was measured and set to 20cm around the circumference of the looped bars (Figure 3.4). The specimen was mounted onto the looped bars of the Instron manually under zero load and its position was adjusted around the bar so that the seam lied midway between the bars. The rate of extension and retraction of the specimen was set to 500mm/min and the specimens were cycled twice between zero and the specified strain of 25%. After cycling twice to 25% strain without a pause, the specimen was extend to 25% strain again and held at that strain for five minutes. The force against time was recorded at one second intervals for a period of 5 minutes. The tension decay was expressed as a percentage of the maximum force after the five minute period. The tension decay was calculated from the equation:

$$Tension\ decay = 100(F_o - Ft^5)/F_o \quad (3.4)$$

Where

F_o is the maximum force (N) at 25% strain

Ft^5 is the force (N) after 5 minutes

In addition, the selected fabrics were tested for tension decay for twelve hours. The principle and procedure was the same as five minutes, however the duration is 12 hours. The tension decay is expressed as a percentage of the maximum force after the twelve-hour period. It is calculated from the equation:

$$Tension\ decay = 100\ (F_o - Ft^{12})/F_o \qquad (3.5)$$

Where

F_o is the maximum force (N) at 25% strain

Ft^{12} is the force (N) after twelve hours

3.3.3 Determination of thermo-physiological comfort properties of experimental fabrics

In order to evaluate the thermo-physiological comfort properties of medical pressure garment fabrics, four groups of experiments were performed.

1. Determination of liquid moisture transport capabilities using the moisture management tester.
2. Determination of thermal resistance of experimental fabrics and assemblies performed on the sweating guarded hotplate.
3. Determination of water-vapour resistance of experimental fabrics and assemblies executed on the sweating guarded hotplate.
4. Determination of thermal resistance capabilities implemented on the sweating thermal manikin.

Determination of liquid moisture transport capabilities

The Moisture Management Tester (MMT) instrument was used to test the liquid moisture transfer of experimental fabrics. The Liquid Moisture Management Properties of Textile Fabrics (AATCC 195-2009) standard was followed. The MMT is designed to sense, measure and record the liquid moisture transport behaviour in multiple directions. The MMT consists of two horizontal sensor rings, upper and lower that determine the liquid content and liquid moisture transfer behaviour on the top and bottom surfaces of the fabric. The principle utilised by the MMT (Li & Wong 2006) is based on the fact that when moisture travels through a fabric, the contact of electrical resistance of the fabric will change. The fabric is in contact with the sensor rings, which determines the liquid content and the liquid moisture transfer behavior on the top and bottom surfaces of the fabric.

The liquid moisture management properties of the experimental fabrics were evaluated by placing an 8cm x 8cm fabric specimen between the upper and lower sensors. Five specimens for each experimental fabric were tested. For single layer specimens, one layer of experimental fabric was used. For fabric assembly specimens, two layers of experimental fabrics were used. All fabric samples were conditioned in a standard laboratory.

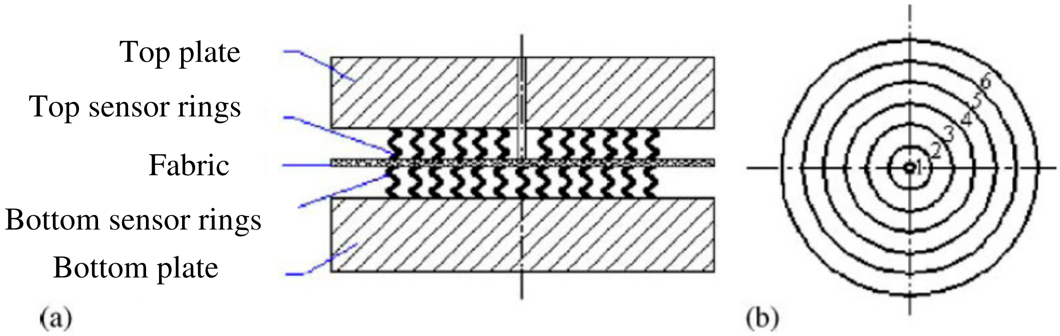


Figure 3.5 Sketch of MMT sensors: a) sensor structure; b) measuring rings (Yao et al. 2006)

The test solution (synthetic sweat) was prepared by dissolving 9g sodium chloride in 1L of distilled water. The synthetic sweat was pumped onto the upper surface of the fabric to simulate a drop of liquid sweat. The synthetic sweat was dropped on the experimental fabric for 20 seconds. The upper surface of fabric is the closest surface to the skin and the bottom surface of the fabric is the closest to the environment. The simulated sweat will than transfer onto the experimental fabric for 120 seconds in three directions:

1. Spreading outward on the top (inner) surface of the fabric.
2. Transferring through the fabric from the top surface to the bottom (outer surface)
3. Spreading outward on the bottom surface of the fabric.

The parameters were recorded via the MMT software connected to a computer. The parameters measured were:

- Wetting time: WTt (top surface) and WTb (bottom surface) are the time in which top and bottom surfaces of the fabric just start to get wet respectively after the test commences.
- Absorption rate: ARt (top surface) and ARb (bottom surface) are the average moisture absorption ability of the fabric top and bottom surface during the rise of water content, respectively.
- Maximum wetted radius: MWRt (top surface) and MWRb (bottom surface) are defined as maximum wetted ring radius at the top and bottom surfaces.
- Spreading speed: SSt (top surface) and SSb (bottom surface) are the accumulative spreading speed from the centre of the fabric sample to the maximum wetted radius.
- Accumulative one-way transport index (AOTI): represents the difference of the accumulative moisture content between the two surfaces of the fabric and determines whether the fabric has good moisture management properties. In terms of comfort, it means the higher the one way transport capacity the quicker and easier the liquid sweat can be transferred from next to the skin to the outer surface of the fabric and keep the skin dry.

- Overall moisture management capacity (OMMC): indicates the overall capability of the fabric to manage the transport of liquid moisture. The larger the OMMC, the higher overall moisture management capability of the fabric.

Determination of thermal and water vapour resistance capabilities

For determination of thermal and water vapour resistance the sweating guarded hot plate instrument was used. The sweating guarded hot plate apparatus (Integrated Chamber Sweating Guarded Hotplate: 431-213) simulates heat and moisture transfer from the body surface through fabric sample to the environment. The software ThermDAC operates the sweating guarded hot plate instrument. The international standard, (ISO 11092:1993(E)) specifies the method for measurement of the thermal and water vapour resistance under steady state conditions. Since the sweating guarded hot plate instrument is not designed to measure thermal and water vapour resistance at the same time, two separate tests were undertaken.

1. Dry test (thermal resistance)
2. Wet test (water vapour resistance)

Dry test

In the dry test condition, the thermal resistance of a fabric is determined by subtracting the thermal resistance of the boundary air layer above the surface of the test apparatus from that of a test specimen plus boundary air layer, both measured under the same conditions. Three fabric specimens to be tested are 27cm x 27cm. The fabric sample is mounted on the porous plate that is heated to a constant temperature that approximates body skin temperature (35˚C). For single layer specimens, one layer of experimental fabric was used. For fabric assembly specimens, two layers of experimental fabrics were used. All fabric specimens were conditioned in a standard laboratory. A test is complete when three consecutive readings are shown for the three test specimens. For the determination of thermal resistance, the heat flux through the experimental test specimen is measured after steady state has been reached.

For the determination of thermal resistance of the sample, the air temperature is set to 20˚C and the relative humidity is controlled at 65%. Air speed is 1+-0.05m/s. after the system reaches steady state; the total thermal resistance of the fabric is governed by:

$$R_{ct} = (A(T_s - T_a) / H) - R_{ct0} \quad (3.6)$$

Where

R_{ct} is the total thermal resistance of the fabric ($(m^2 \cdot {}^\circ C)/W$)

A is the area of the test section (m^2)

R_{ct0} is the thermal resistance of the boundary air layer ($(m^2 \cdot {}^\circ C)/W$)

T_s is the surface temperature of the plate (°C)
T_a is the temperature of ambient air (°C)
H is the electrical power in (W)

Wet test

For determination of water-vapour resistance, a smooth, water vapour permeable but liquid-water impermeable cellophane membrane is fitted to a heated porous plate so that it remains completely free of air bubbles and wrinkles. Water passed to the heated plate evaporates and passes through the membrane as vapour, so that no liquid contacts the test specimen. The water vapour resistance of a fabric is determined by subtracting the water vapour resistance of the boundary air layer above the surface of the test apparatus from that of a test specimen plus boundary air layer, both measured under the same conditions. Three specimens to be tested are 27cm x 27cm. All specimens must be pre-conditioned in the same atmosphere in which it will be tested of 35˚C air temperature and 40% relative humidity, a environmental chamber was used for this study to condition specimens. A 'bare plate' value is calculated first and then the test specimen is placed above the membrane. Air temperature is set at 35˚C and relativity humidity is 40%. The total evaporative resistance of the fabric, after steady state has been reached can be calculated by the following:

$$R_{et} = (A(P_s - P_a)/H) - R_{et0} \qquad (3.7)$$

Where
R_{et} is the total evaporative resistance provided by the liquid barrier, fabric and boundary air layer ($(m^2 \cdot Pa)/W$)
A is the area of the test section (m^2)
P_s is the water vapour pressure at the membrane surface (Pa)
P_a is the water vapour pressure of the air (Pa)
R_{et0} is the total vapour resistance provided by the boundary air layer ($(m^2 \cdot Pa)/W$)
H is the electrical power in (W)

Determination of thermal and evaporative resistance capabilities implemented on the sweating thermal manikin

For the determination of thermal and evaporative resistance capabilities the sweating the thermal manikin 'Newton' from Measurement Technology Northwest was used, to understand the thermal behaviour of clothing systems. The manikin surface is divided into separate sections, each of which has its own has its own sweating, heating and temperature measuring system. Each thermal zone has sweat control through evenly distributed fluid ports on its surface and the operator can control sweating rate. The manikin consists of 20 independently controlled thermal zones. All thermal zones are fitted with heaters to simulate metabolic heat output rates and use distributed wire sensors for measuring skin temperatures. The surface temperatures of all zones were set to 35°C. The surface temperature, heat flux and heat loss were measured continuously at 10s intervals for 90 minutes. The software ThermDAC operates the sweating manikin.

The entire tests were conducted in a controlled laboratory within the acceptable ranges as specified in the International Standards (ASTM F1291, 2010; ASTM F2370, 2010). The air was steady flowing from the roof chamber and was controlled under minimal air velocity at 0.08±0.01 m/s for both dry and wet tests. The manikin is not designed to measure clothing thermal and water vapour resistance at the same time. Consequently, two separate test were required:

1. Dry test (thermal resistance)
2. Wet test (evaporative resistance

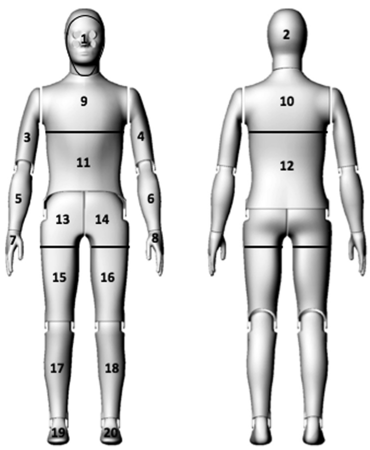


Figure 3.6 Newton sweating manikin segment

Table 3.3 Thermal manikin segment number and name

Segment	Segment name
1	Face
2	Head
3/4	Upper arm
5/6	Forearm
7/8	Hand
9	Chest
10	Shoulders
11	Stomach
12	Back
13/14	Hip
15/16	Thigh
17/18	Calf
19/20	Feet

Dry testing

In the dry test conditions, the testing environment was set at a temperature (T) of 23±0.5°C and a relative humidity (RH) of 50± 5% to simulate the dry conditions. The dry heat loss was measured for the 'naked' test, where no garment is present. The nude manikin was tested at the beginning of each series of clothing tests.

Figure 3.7 Newton sweating manikin dressed with 'skin' suit

The manikin was dressed the in the garment to be tested. The dressed manikin skin temperature and system need to reach a steady state which is the mean skin temperature of the manikin and the power input remain constant ±3%. After the manikin ensemble reaches equilibrium conditions, the manikin's skin temperature and air temperature were recorded every one minute. The average of these measurements taken over a period of 30 minutes will determine the thermal resistance. Three independent replications of the clothing test were conducted. Only one set of garments was being tested, therefore garments was removed and then put back on the manikin for another test. The dry test measurements are used as a reference for the wet test.

The thermal resistance of the clothing system, which is used to define the insulation between the skin surface and the environment under dry conditions, is calculated for each zone by the following equation:

$$R_{ct} = \frac{(T_s - T_a)}{Q/A} \qquad (3.8)$$

Where

R_{ct} is the total thermal resistance (insulation) of the clothing ensemble and surface air layer ((m²·°C)/W)

T_s is the temperature at manikins surface (°C)

T_a is the temperature in the air flowing over the clothing (°C)

Q/A is the area weighted heat flux (W/m²)

Using the clothing factor to calculate the intrinsic thermal resisteance of clothing ensembles is given by:

$$R_{cf} = R_{ct} - (R_{ct0}/f_{cl}) \quad (3.9)$$

Where

R_{cf} is clothing insulation ((m^2·°C)/W)

R_{ct0} is nude resistance ((m^2·°C)/W)

f_{cl} is clothing area factor, which was 1 due to the garment being skin tight.

Wet testing

To measure the evaporative resistance of a garment on the manikin, wet tests were conducted in an isothermal condition, which is the air temperature of the environment is the same as the manikins surface temperature, so no dry heat exchange is occurring between the manikin and the environment. This is the preferred condition for measuring evaporative resistance. The mean skin temperature of the manikin was set to T=35± 0.5°C and the relative humidity was controlled at RH= 40 ± 5%.

The skin suit was pre-wetted by spraying distilled water from a spray bottle over the skin. In addition to this pre-wetting procedure, the wet-naked test was run for 1½ hours with the manikin constantly perspiring. The wet-naked tests were performed before the wet test in order to evenly distribute the moisture over the skin to simulate saturated sweat. During the wet-test, the perspiration rate of the manikin was set to 30gm/minute to keep the manikin surface moist. Measurements were taken for 80 minutes after covering the manikin with garment. The 80-minute duration was set to allow sufficient time for the dressed manikin to reach steady-state condition and at maximum saturation in moisture absorption, if there is any. For testing, only one garment was available therefore the garment had to be removed from the manikin after each test, dried and conditioned. The garment was left in the test chamber to condition for 12 hours, allowing the clothing components to come to equilibrium with the atmosphere in the test chamber.

Figure 3.8 Newton sweating manikin dressed in garment for wet test

When the manikin is sweating, the total evaporative resistance under the wet conditions is calculated for each zone as follows:

$$R_{et} = \frac{P_s - P_a}{\frac{Q}{A}} \qquad (3.10)$$

Where

R_{et} is the total evaporative resistance provided by the liquid barrier, fabric and boundary air layer ((m^2·Pa)/W)

P_s is the water vapour pressure at the manikin's sweating surface (Pa)

P_a is the water vapour pressure in the air flowing over the clothing (Pa)

Q/A is the area weighted heat flux (W/m^2)

Using the clothing factor to calculate intrinsic evaporative resistance of clothing ensembles is given by:

$$R_{ef} = R_{et} - (R_{et0}/f_{cl}) \qquad (3.11)$$

Where

R_{ef} is evaporative resistance ((m^2·Pa)/W)

R_{et0} is nude evaporative resistance ((m^2·Pa)/W)

f_{cl} is the clothing area factor, which was 1 due to the garment being skin tight.

CHAPTER 4: RESULTS & DISCUSSION

This chapter reports and discusses the outcomes of the study according to the experiments carried out. Results covering the structural and physical parameters of fabrics, performance attribute testing with emphasis on elastic characteristics of fabrics and thermo-physiological comfort properties of fabrics are defined in this chapter.

4.1 Fabric structural and physical parameters

The structural and physical parameters of six medical textile experimental fabrics are given in Table 4.1.

Table 4.1 Structural and physical parameters of experimental fabric samples

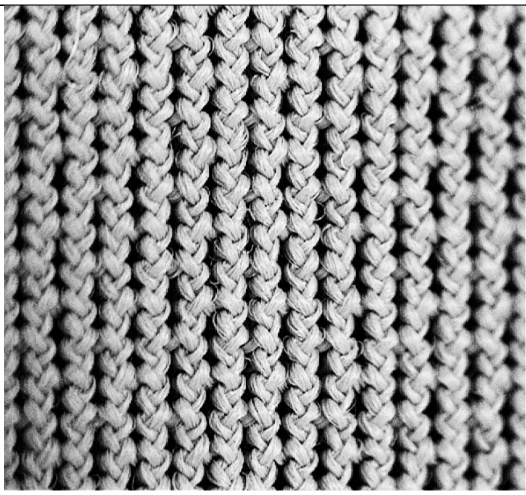
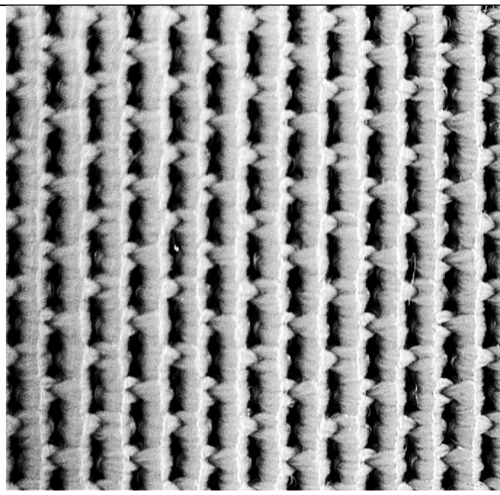
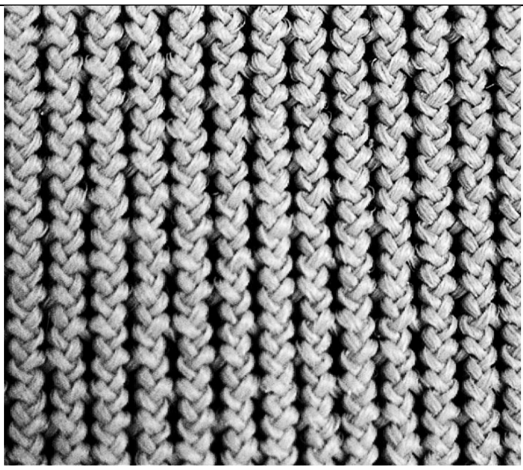
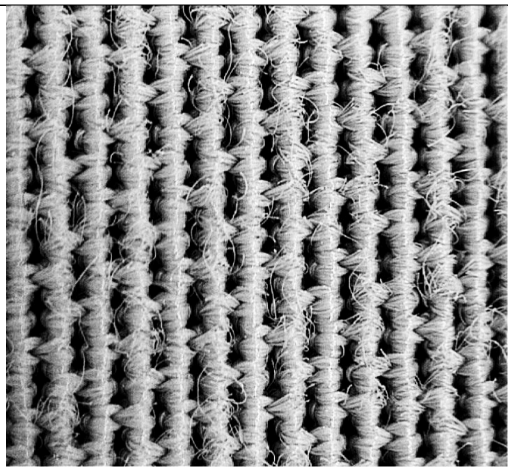
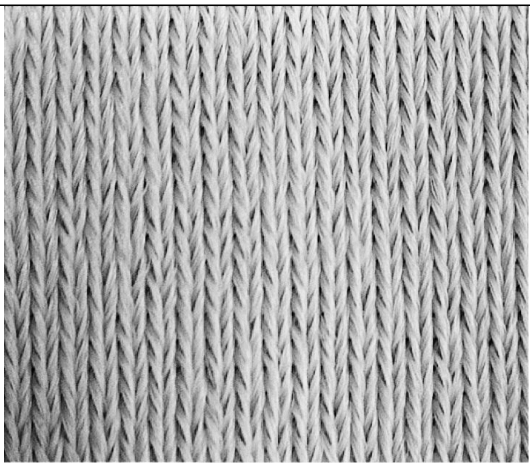
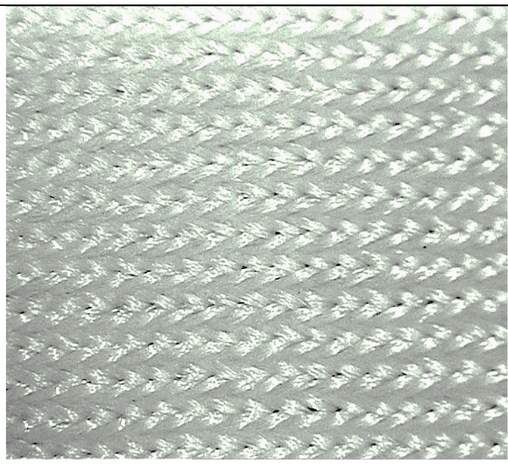
Fabrics	Mass (g/m^2)	Thickness (mm)	Courses /cm	Wales /cm	Optical Porosity (%)
PN1	322	0.52	8	14	18.19
PN2	237	0.51	9	17	7.74
T1	138	0.41	28	23	0.30
L1	141	0.39	30	24	0.10
L2	206	0.67	30	20	0.85
L3	187	0.58	16	14	10.14

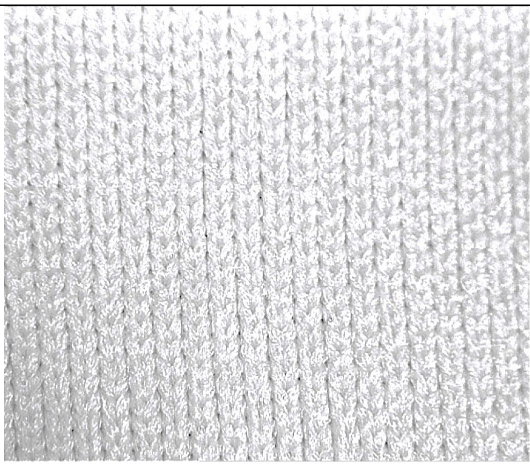
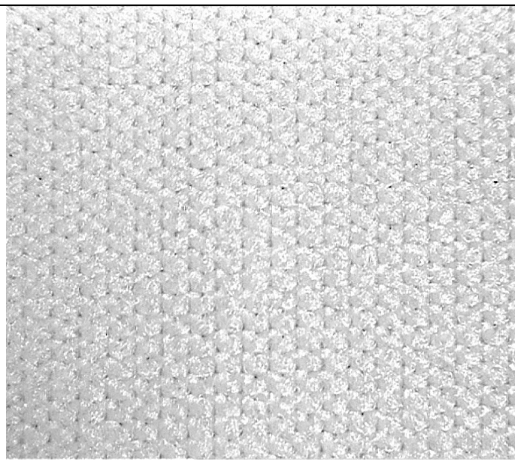
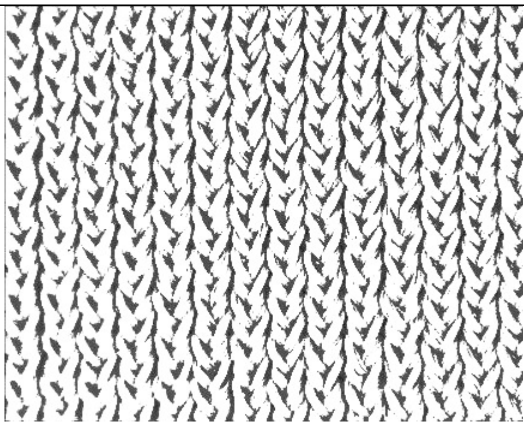
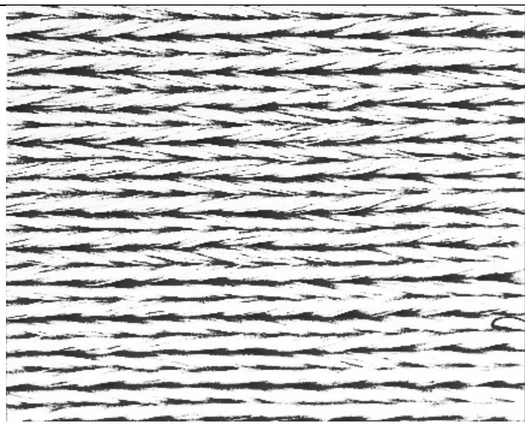
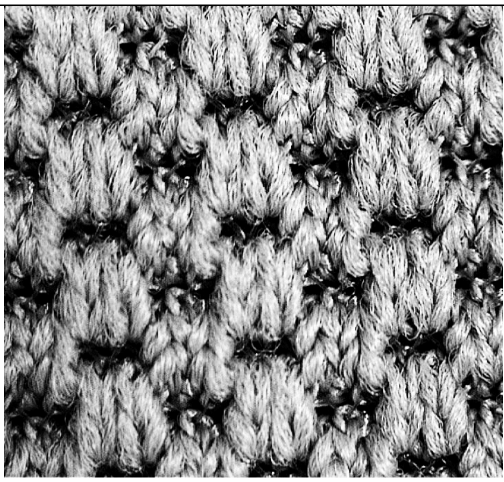
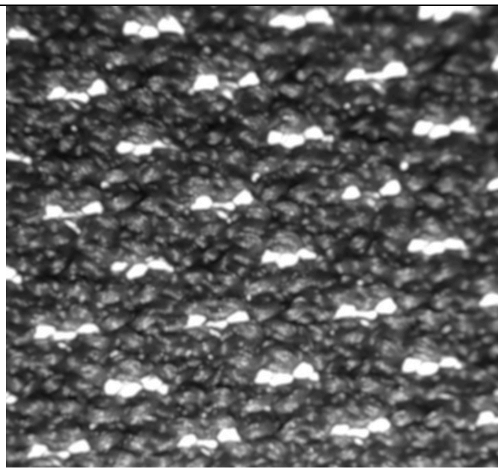
From Table 4.1 it can be seen that, PN1 has a higher weight than PN2 although they have comparable thickness and courses/wales, the only major difference is the optical porosity this is due to structure of PN1 being more open in comparison to PN2 thus enabling more light to pass thought the structure. Also, the next to skin side of PN2 is brushed/raised, consequently not as much light will pass through the fabric structure compared with PN1 hence the lower optical porosity of PN2. Additionally, T1 is lighter, thinner and has a much lower optical porosity compared with PN1 and PN2 due to the stitch density and construction.

Moreover, Table 4.1 determines that L1, L2 and L3 have different weights, thickness, optical porosity and stitch density. Fabric L2 has the highest weight and thickness, whereas L3 has the highest optical porosity due to the fabric construction. From the results in Table 4.1, it can be expected that in the study PN1/PN2 and L1/L2 would have comparable results due to similar structural and physical parameters. Also, it can be anticipated that PN1 will have higher air permeability than PN2 as PN1 has higher optical porosity and the next to skin side is not brushed. The higher optical porosity and air permeability of L3 would reflect higher thermal and water vapour resistance compared with L1 and L2.

Table 4.2 demonstrates the technical face and back of the experimental fabrics under the microscope. The images have been magnified x100 optical lens.

Table 4.2 Technical face and back images of the fabrics under the microscope

Fabric	Technical Face	Technical Back
PN1		
PN2		
T1		

L1		
L2		
L3		

From Table 4.2 it can be seen that the technical face of PN1 and PN2 are the same, both a smooth surface. The technical back of PN1 and PN2 are different. The back of PN1 is smooth however; the back of PN2 is brushed. The brushed fibres can be seen in the image of PN2 back. The images are magnified at x100 optical lens, it can be seen that the structure (knit construction) of PN1 and PN2 are the same thus it would be expected that they would have similar performance parameters, except the brushed back of PN2 could have an influence on the thermo-physiological parameters such as thermal and evaporative resistance. Also, Table 4.2

shows that T1, L1 and L2 have a similar construction, however, L3 has a different structure with more air gaps.

The air permeability of selected fabrics was tested in single layers and fabric assemblies (Figure 4.1).

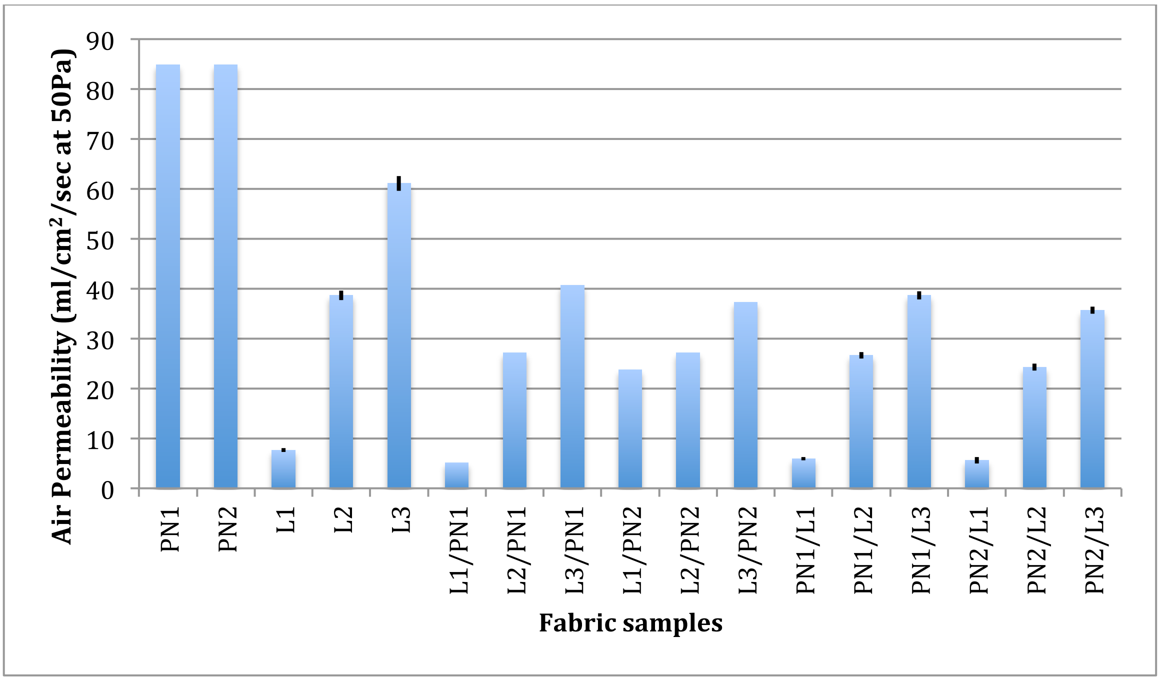


Figure 4.1 Air permeability of fabrics as single layers and fabric assemblies

From Figure 4.1 it can be seen that, PN1 and PN2 had equivalent air permeability. This indicates that both fabrics allow comparable amount of air through their structures. Also, Table 4.1 indicated that PN2 had 57% higher optical porosity compared with PN1 due to the construction of the next to skin surface of PN2. This indicates that the brushed back of PN2 doesn't influence the overall air permeability. Higher air permeable fabrics would be considered most appropriate for the construction of pressure garments.

Additionally, air permeability plays a role in the transporting of moisture vapour from the skin to the outside environment. Moisture vapour diffuses from the side of the fabric next to skin to the outside of the fabric to the environment through spaces in the fabric. In hotter climates, higher air permeability allows more air to circulate around the skin, facilitating the removal of moisture in hot weather and reducing perspiration. Also, Figure 4.1 shows that fabrics L2 and L3 had higher air permeability than L1, indicating that air was able to travel through the fabric structure. Pressure garments lined in L2 and L3 would be more comfortable to wear as heat and moisture vapour can pass through the structure easier in comparison with L1.

Moreover, as fabric assemblies PN1/L1 has the lowest air permeability compared with PN1/L2 and PN1/L3 due to PN1/L1 being less porous and thus not allowing air to pass through the fabric assembly as easy compared with PN1/L2 and PN1/L3. A garment made from fabric assembly PN1/L2 and PN1/L3 would be more comfortable to wear compared with PN1/L1. Additionally, PN2/L1 has a considerably lower air permeability compared with PN2/L2 and PN2/L3 due to PN2/L1 fabric assembly being less porous in comparison to PN2/L2 and PN2/L3. A garment made from PN2/L2 and PN2/L3 would be more comfortable to wear as more air and moisture vapour passes through the structure.

Overall, fabric assemblies containing PN1 are more air permeable compared to fabric assemblies containing PN2, this could be due to air becoming trapped in the fabric assemblies containing PN2. Figure 4.1 shows that PN1/L3 is the most air permeable fabric assembly compared to PN2/L1, which is the least, air permeable.

4.1.1 Summary of fabric structural and physical parameters

It is evident from the structural and physical characteristics of the experimental fabrics that powernet fabrics have the largest mass and thickness compared with lining fabrics. However, the lining fabrics have a higher stitch density that influences the optical porosity and air permeably being lower. Also, the brushed back powernet has significantly lower optical porosity compared with a non-brushed back powernet, which could be due to the fibres protruding on the back and blocking the light from the microscope. Additionally, the brushed back of a powernet doesn't significantly influence the overall air permeability of the fabric as seen in Figure 4.1, this indicated that the brushed powernet fabric only influenced optical porosity and not air permeability.

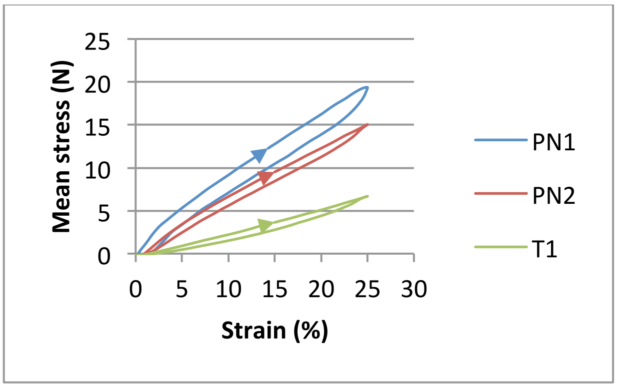
4.2 Fabric elastic behavior for single layer fabrics & their assemblies

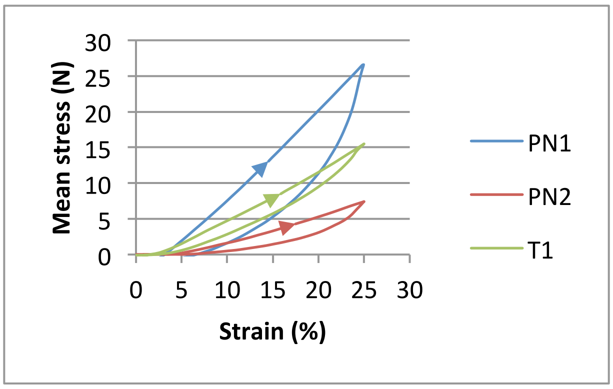
4.2.1 Elastic characteristics of single layers and their assemblies at 25%, 40% and 60% strain

To determine the elastic properties of fabrics, they were tested to 25%, 40% and 60% strain in single layers and also as fabric assemblies. The stress-strain curves used throughout this section are an average of the five samples used.

Single layers at 25% strain

The stress-strain curves of single layer for PN1, PN2 and T1 at 25% strain can be seen in Figure 4.2.





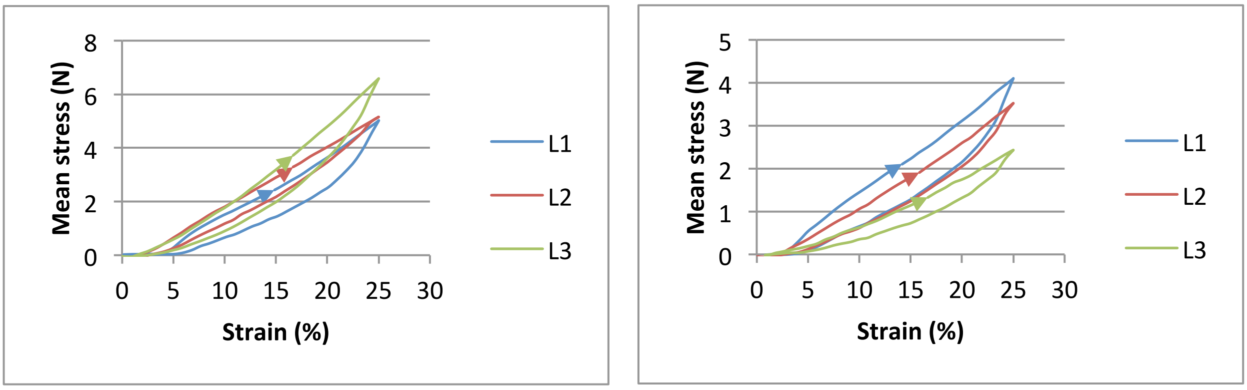
a **b**

Figure 4.2 Elastic behaviour of single layer PN1, PN2 & T1 at 25% strain; a) warp direction b) weft direction

Figure 4.2a demonstrates that PN1 requires most force to be extended to 25% strain in the warp direction, followed by PN2 and T1. The difference of force required to extend PN1 compared to PN2 is 26%. At the same time, the force difference of PN1 and T1 is 68%. This illustrates that PN1 is the most powerful fabric in the warp direction. PN1 will generate most pressure when extended and thus a greater pressure on the underlying limb of the patient wearing a garment of the same size made of this fabric, compared to the other two fabrics. On the other hand, T1 will require considerably higher strain to generate the same amount of pressure to the limb of the same size. It can also be seen from Figure 4.2a, that PN2 and T1 had a smaller hysteresis than PN1, indicating a better ability to recover after extension. For example, at 15% strain the difference in hysteresis between PN1 and PN2 is 75%, whereas the difference between PN1 and T1 is 65%. The steep slope of the curve for PN1 in Figure 4.2a indicates a higher modulus and larger resistance to the force applied of this fabric, while PN2 and T1 had a slight slope, consequently having a smaller resistance to the same amount of force in the warp direction.

Figure 4.2b determines that PN1 requires the highest amount of force to be extended to 25% strain in the weft direction, followed by T1 and PN2. The difference of force required to extend PN1 and PN2 is 73%, whereas the difference of force required to extend PN1 and T1 is 42%. This shows that PN1 also in the weft direction is more powerful and will exert a greater pressure on limbs when a garment made from PN1 is worn. Figure 4.2b shows that PN1 had a larger hysteresis indicating the fabric doesn't recover as well after extension compared with PN2 and T1. For example, the difference of hysteresis at 15% strain between PN1 and PN2 is 84% and the difference of hysteresis between PN1 and T1 is 77%. The steep slope of the curve for PN1 indicates a significantly larger resistance to force in the weft direction, whilst PN2 and T1 had a gentle slope thus having a smaller resistance to force of the same strain.

The stress-strain curves of single layer for L1, L2 and L3 at 25% strain are exhibited in Figure 4.3.



a b

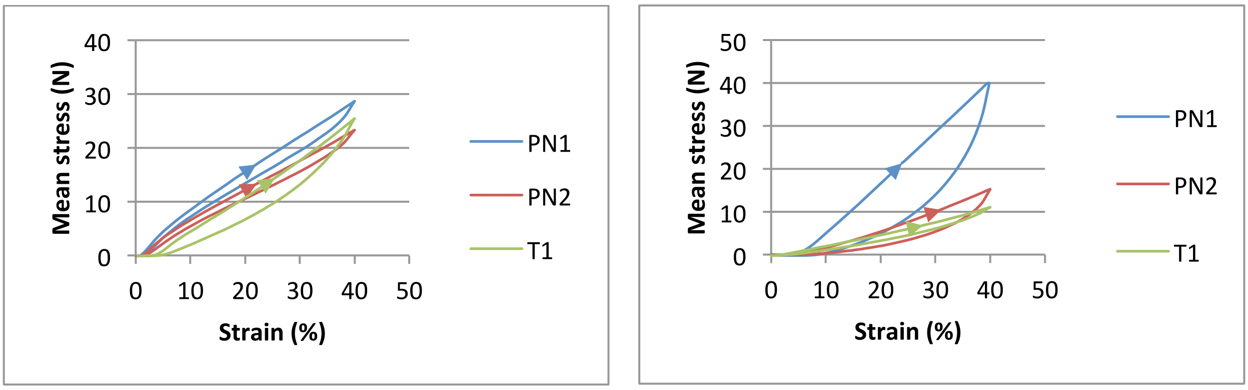
Figure 4.3 Elastic behaviour of single layer L1, L2 & L3 at 25% strain; a) warp direction b) weft direction

Figure 4.3a displays that L3 requires the most force to be extended to 25% strain in the warp direction, followed by L2 and L1. The difference of force required to extend L3 and L1 is 20%, whereas the difference of force between L3 and L2 is 17%. Also, the force is the same for L2 and L1. The power generated by L1, L2 and L3 is quiet minimal therefore, to exert pressure on underlying limbs when a garment is being worn a higher extension is required. However, when these fabrics are used in garments they are not designed to exert pressure, they are used as a lining for comfort performance. From Figure 4.3a it can be seen that, L2 had a smaller hysteresis than L1 and L3 thus recovering better at 25% strain. For example, at 17% strain the difference in hysteresis between L3 and L1 is 50%, while the hysteresis difference between L3 and L2 is 55%. The steep slope of L3 curve indicates a larger resistance to the applied force, whilst L2 and L1 have a slight slope hence having a smaller resistance to the applied force.

Furthermore, Figure 4.3b demonstrates that L1 in the weft direction requires most force to be extended, followed by L2 and L3. The difference of force required to extend L1 and L2 is 13%, compared to the force difference of L1 and L3 that is 42%. This shows that L1 in the weft direction is the most powerful fabric and will generate the most pressure. Figure 4.3b shows that in the weft direction L1 had a larger hysteresis, signifying the fabric doesn't recover as well after extension compared with L2 and L3. At 10% extension for example, the hysteresis difference of L1 and L2 is 62%, compared with L1 and L3 that is 75%. The steep slope of the curve for L1 indicates a larger resistance to the applied force in the weft direction, however the force is very minimal. L2 and L3 have a lesser slope thus having a smaller resistance to the force of the same strain.

Single layers at 40% strain

The stress-strain curves of single layer for PN1, PN2 and T1 at 40% strain are shown in Figure 4.4.



a b

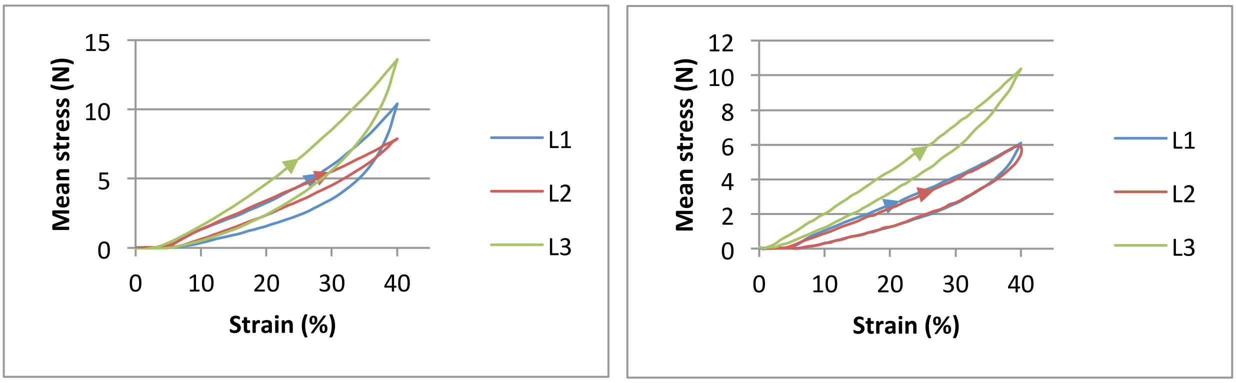
Figure 4.4 Elastic behaviour of single layer PN1, PN2 & T1 at 40% strain; a) warp direction b) weft direction

From Figure 4.4a it can be seen, that PN1 requires more force to be extended to 40% strain in the warp direction, followed by T1 and PN2. The variance of force required to extend PN1 compared to PN2 is 14%. Also, the force variance of PN1 and T1 is 10%. This shows that at 40% strain, PN1 is the most powerful fabric and will generate the most pressure on the underlying limb. PN2 and T1 will require a higher strain to generate the same amount of pressure on the underlying limb. It is event from Figure 4.4a, that T1 had a larger hysteresis indicating less recovery than PN1 and PN2 when extended to 40% strain. For instance, at 20% strain the difference in hysteresis between T1 and PN1 is 60%, compared with the hysteresis difference between T1 and PN2 that is 80%. In Figure 4.4a, the steep slope of the curve for PN1 signifies a higher modulus and a larger resistance to the applied force of this fabric, compared with PN2 and T1 which had a slight slope, thus having a smaller resistance to the same amount of force applied.

Moreover, Figure 4.4b shows that PN1 in the weft direction requires the highest amount of force to be extended to 40% strain, followed by PN2 and T1. The difference of force between PN1 and PN2 is 63%, where as the difference in force between PN1 and T1 is 73%. When a garment made from PN1 in the weft direction is worn, the garment will exert a greater amount of pressure on the underlying limbs compared with a garment made from PN2 and T1. In addition, Figure 4.4b determines that PN1 has a considerably larger hysteresis indicating the fabric doesn't recover as well after extension compared to PN2 and T1. For example, at 40%

strain the difference in hysteresis between PN1 and PN2 is 73% and the difference in hysteresis between PN1 and T1 is 93%. The gentle slope of the curve of PN2 and T1 in the weft direction indicates a smaller resistance to force, whereas PN1 has a steeper slope consequently having a greater resistance to force.

The stress-strain curves of single layer for L1, L2 and L3 at 40% strain can be determined from Figure 4.5.



a b

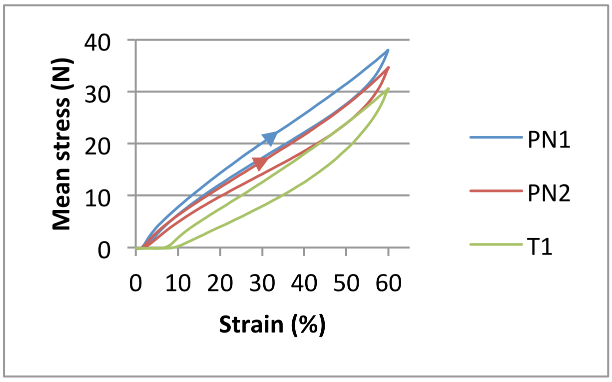
Figure 4.5 Elastic behaviour of single layer L1, L2 & L3 at 40% strain; a) warp direction b) weft direction

Figure 4.5a demonstrates that L3 requires most force to be extended to 40% strain in the warp direction, followed by L1 and L3. The difference of force required to extend L3 and L1 is 27%. At the same time, the force difference of L3 and L2 is 42%. This shows that in the warp direction, L3 is the most powerful fabric and will exert greatest pressure on the underlying limbs when a garment is lined in this fabric. The hysteresis shown in Figure 4.5a indicates that L3 and L1 will not recover as well as L2 due to a smaller hysteresis. For instance, at 30% strain the difference in hysteresis between L3 and L1 is 33%, compared with L3 and L2 that is 83%. The steep slope of the curve for L3 indicates a larger resistance to the applied force of this fabric, while L1 and L2 had a gentle slope consequently having a smaller resistance to the same amount of force applied.

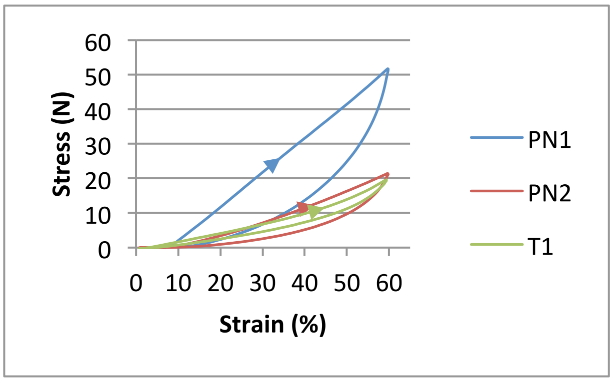
It can be seen from Figure 4.5b, that in the weft direction L3 requires the most force to be extended at 40% strain, L1 and L2 have an almost identical curve signifying they require the same amount of force to be extended. The difference of force between L3 and L1/L2 is 40%. Figure 4.5b demonstrates that the hysteresis of L1/L2 is bigger than L3 by 16%, this shows that L3 has a better ability to recover after extension. The steep slope of the curve for L3 shows that L3 had a larger resistance to the applied force, while L1 and L2 have an almost identical slight slope hence having a smaller resistance to the same amount of force.

Single layers at 60% strain

The stress-strain curves of single layer for PN1, PN2 and T1 at 60% strain are shown in Figure 4.6.



a



b

Figure 4.6 Elastic behaviour of single layer PN1, PN2 & T1 at 60% strain; a) warp direction b) weft direction

Figure 4.6a demonstrates that PN1 requires most force to be extended to 60% strain in the warp direction, followed by PN2 and T1. The difference of force required to extend PN1 compared to PN2 is 5%, whereas the difference between force for PN1 and T1 is 19%. This illustrates that at 60% strain, PN1 will exert the most pressure on limbs. On the other hand, PN2 and T1 would require a higher extension to generate the same amount of pressure on the limb of the same size. From Figure 4.6a, it can be seen that T1 had the largest hysteresis signifying poorer recovery than PN1 and PN2 in the warp direction. For example, at 35% strain the difference in hysteresis between T1 and PN1 is 33%, whereas the difference between T1 and PN2 is 50%. The steep slope of the curve for PN1, PN2 and T1 indicates a higher modulus and larger resistance to the force applied of this fabric.

Figure 4.6b determines that PN1 requires the highest amount of force to be extended to 60% strain in the weft direction, followed by PN2 and T1. The difference of force required to extend PN1 and PN2 is 60%, whereas the difference of force required for PN1 and T1 is 62%. This shows that PN1 also in the weft direction is more powerful and will exert a greater pressure on limbs when the garment made from PN1 is worn. Figure 4.6b shows that PN1 had a larger hysteresis signifying the fabric doesn't recover after extension compared with PN2 and T1. For instance, the difference of hysteresis at 35% strain between PN1 and PN2 is 63% and the difference between PN1 and T1 is 94%. The steep slope of the curve for PN1 indicates a significantly larger resistance to force in the weft direction, while PN2 and T1 had a slight slope thus having a smaller resistance to force of the same strain.

The stress-strain curves of single layer for L1, L2 and L3 at 60% strain are shown in Figure 4.7.

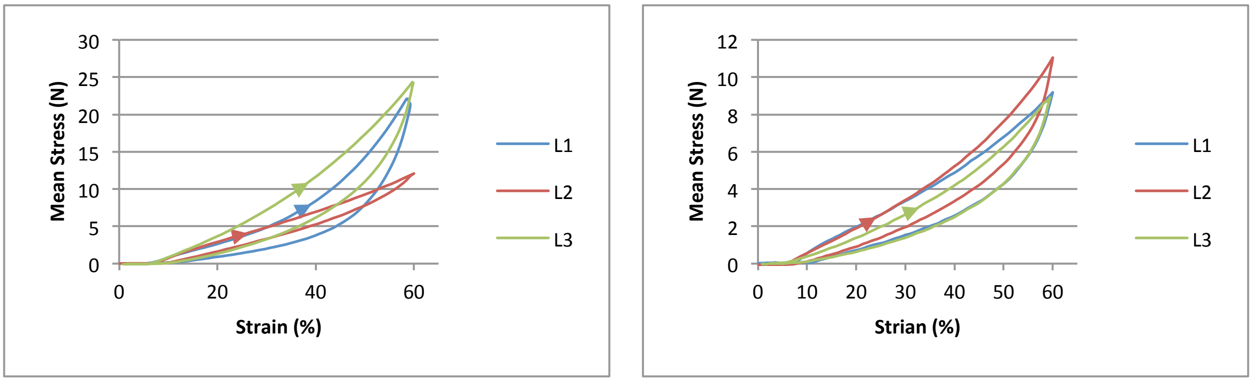


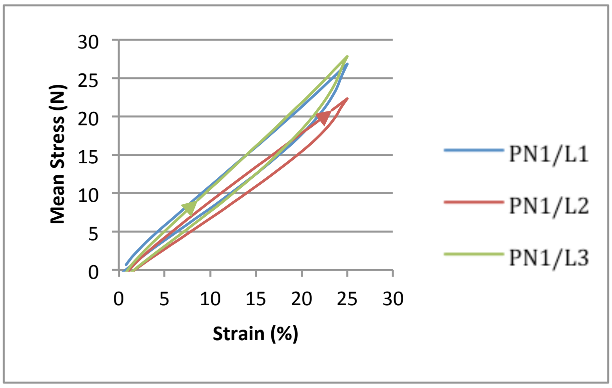
Figure 4.7 Elastic behaviour of single layer L1, L2 & L3 at 60% strain; a) warp direction b) weft direction

From Figure 4.7a it can be seen, that L3 requires most force to be extended to 60% strain in the warp direction, followed by L1 and L2. The variance of force required to extend L3 compared to L1 is 13%, whereas the variance of force between L3 and L2 is 50%. This shows that at 60% strain, L3 is the most powerful fabric in the warp direction signifying it will generate the most pressure to the underlying limb. On the other hand, L2 will require a higher extension to generate the same amount of pressure to the limb of the same size. Figure 4.7a demonstrates that L1 and L3 hysteresis is bigger than L2, indicating L2 had a better ability to recover after extension. For example, at 60% strain the difference in hysteresis between L1 and L2 is 67%, whereas the difference between L3 and L2 is 83%. The steep slope of the curve for L1 and L3 in Figure 4.7a signifies a higher modulus and a larger resistance to the force applied of this fabric. L2 had a gentle slope thus having a smaller resistance to the same amount of force.

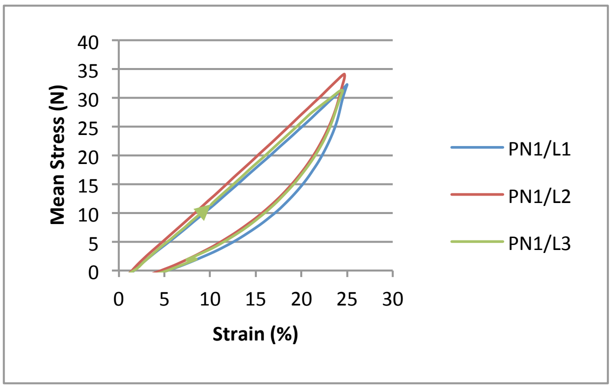
Figure 4.7b shows that L2 requires the most force to be extended to 60% strain in the weft direction, followed by L1 and L3 which require the same amount of force to be extended to 60% strain. The difference of force between L2 and L1/L3 is 18%. This shows that at 60% strain, L2 will apply the most pressure on the underlying limbs when a garment is lined with this fabric. Figure 4.7b determines that L1 has a bigger hysteresis then L2 and L3 signifying that L1 doesn't recover as well after extension compared with L2 and L3. For instance at 45% strain, the difference in hysteresis between L1 and L2 is 16% and the difference between L1 and L3 is 40%. The steep slope of the curves for L1, L2 and L3 indicates a larger resistance to force in the weft direction at 60% strain.

Fabric assemblies at 25% strain

The stress-strain curves of fabric assemblies for PN1/L1, L2 and L3 at 25% strain are determined in Figure 4.8.



a



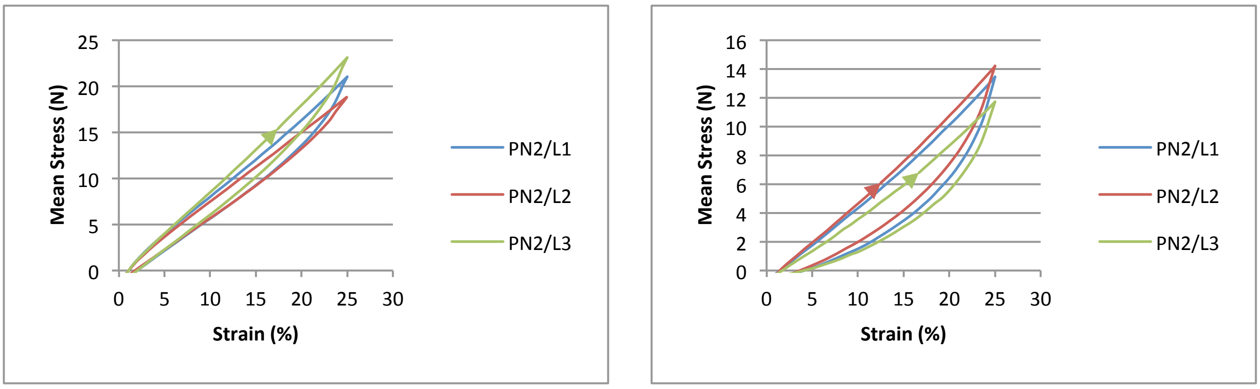
b

Figure 4.8 Elastic behaviour of fabric assemblies PN1/ L1, L2 & L3 at 25% strain; a) warp direction b) weft direction

It can be seen from Figure 4.8a, that PN1/L1 and PN1/L3 require the same amount of force to be extended to 25% strain in the warp direction followed by PN1/L2. The difference of force between PN1/L1 and PN1/L3 compared with PN1/L2 is 22%. This demonstrates that PN1/L1 and PN1/L3 are the most powerful fabric assemblies in the warp direction at 25% strain. These fabric assemblies will generate the most pressure on the underlying limb of a patient wearing a garment made from these fabric assemblies. On the other hand, PN1/L2 will require a higher extension to generate the same amount of pressure to the limb of the same size. Also, Figure 4.8a shows that PN1/L1 and PN1/L3 had a very similar hysteresis indicating they had the same ability to recover compared with PN1/L2. For example, the difference in hysteresis at 15% strain between PN1/L1 and PN1/L2 is 33%. The steep slopes of PN1/L1 and PN1/L3 indicates a higher modulus and a larger resistance to the applied force of this fabric while PN1/L2 had a slight slope consequently having a smaller resistance to the same amount of force applied.

In addition Figure 4.8b displays that in the weft direction PN1/L2 requires most force to be extended to 25% strain, like in the warp direction PN1/L1 and PN1/L3 require the same amount of force to be extended to 25% strain. The difference in force between PN1/L2 compared with PN1/L1 and PN1/L3 is 9%. This shows that in the weft direction PN1/L2 is most powerful and will exert a greater pressure on limbs when the garment made from PN1/L2 fabric assembly is worn. Figure 4.8b demonstrates that the fabric assemblies at 25% strain in the weft direction had a very similar hysteresis showing the fabrics recover similarly after extension. For instance, at 15% strain the difference in hysteresis between PN1/L1 compared with PN1/L2 is 25% whereas, the difference in hysteresis between PN1/L1 and PN1/L3 is 11%. At 25% strain in the weft direction PN1/L1, PN1/L2 and PN1/L3 had a very similar curve; the steep slope of the fabric assemblies indicates a large resistance to force.

The stress-strain curves of fabric assemblies for PN2/L1, L2 and L3 at 25% strain are shown in Figure 4.9.



a b

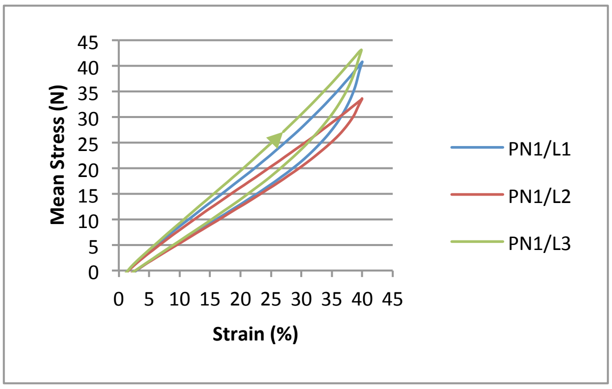
Figure 4.9 Elastic behaviour of fabric assemblies PN2/ L1, L2 & L3 at 25% strain; a) warp direction b) weft direction

From Figure 4.9a it can be determined that PN2/L3 requires the most force to be extended to 25% strain in the warp direction, followed by PN2/L1 and PN2/L2. The difference of force required to extend PN2/L3 compared with PN2/L1 is 5%, whereas the difference in force between PN2/L3 compared with PN2/L2 is 23%. This shows that fabric assembly PN2/L3 is the most powerful fabric assembly and will generate the most pressure on limbs of patients wearing a garment made from this fabric assembly. It can also be seen, that the hysteresis of the fabric assemblies at 25% strain are very similar, thus they had equivalent ability to recover after extension. For example, at 15% strain the difference between PN2/L1 and PN2/L2 is 33% whereas, the difference between PN2/L1 and PN2/L3 is 0%. The steep slope of the curves for PN2/L1, PN2/L2 and PN2/L3 indicates a higher modulus and a larger resistance to the force applied of these fabrics.

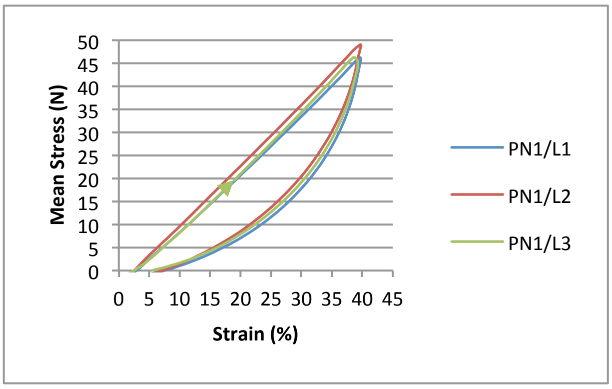
Figure 4.9b concludes that PN2/L2 requires the most force to be extended in the weft direction followed by PN2/L1 and PN2/L3. The difference of force required to extend PN2/L2 and PN2/L1 is 7% whereas, the difference in force required to extend PN2/L2 and PN2/L3 is 21%. This shows that in the weft direction PN2/L2 is the most powerful fabric and will exert a greater pressure on the limbs when a garment made from PN2/L2 is worn. Figure 4.9b shows the fabric assemblies PN2/L1, PN2/L2 and PN2/L3 had a similar hysteresis. The hysteresis difference at 15% strain between PN2/L1 and PN2/L2 is 0% indicating they had the same recovery, whereas PN2/L1 and PN2/L2 is 25%. At 25% strain in the weft direction PN2/L1, PN2/L2 and PN2/L3 had a very similar curve. Also, the steep slope of the fabric assemblies indicates a large resistance to force.

Fabric assemblies at 40% strain

The stress-strain curves of fabric assemblies for PN1/L1, L2 and L3 at 40% strain are displayed in Figure 4.10.



a



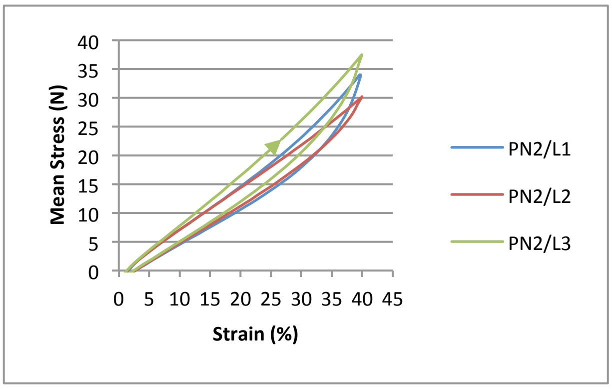
b

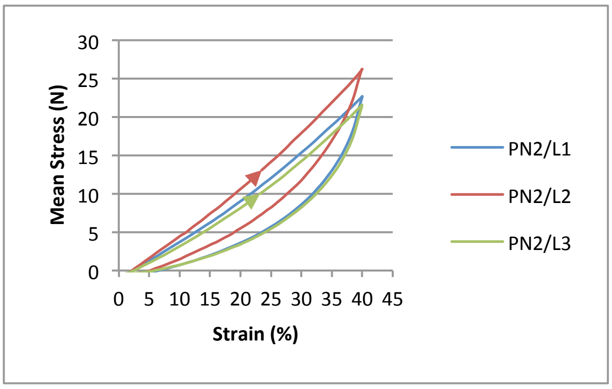
Figure 4.10 Elastic behaviour of fabric assemblies PN1/ L1, L2 & L3 at 40% strain; a) warp direction b) weft direction

From Figure 4.10a it can be seen that PN1/L3 requires the highest amount of force to be extended to 40% strain in the warp direction, followed by PN1/L1 and PN1/L2. The difference of force required to extend PN1/L3 compared with PN1/L1 is 5%, whereas the difference of force required to extend PN1/L3 with PN1/L2 is 23%. This shows that PN1/L3 is the most powerful fabric in the warp direction, thus it will generate more pressure on the underlying limb of the patient wearing a garment made from this fabric assembly. Figure 4.10a determines that PN1/L2 had a smaller hysteresis than PN1/L1 and PN1/L3, indicating a better ability to recover after extension. For instance, at 30% strain the difference in hysteresis between PN1/L1 and PN1/L2 is 50%, whereas the difference between PN1/L1 and PN1/L3 is 25%. Figure 4.10a shows that PN1/L1 and PN1/L3 had a steeper slope, while PN1/L2 had a gentler slope thus having a smaller resistance to the same amount of force.

Figure 4.10b indicates that in the weft direction PN1/L2 requires the highest amount of force to be extended to 40% strain, followed by PN1/L1 and PN1/L3 which require the same amount of force to be extended. The difference of force required to extend PN1/L2 compared with PN1/L1 and PN1/L3 is 6%. This shows that in the weft direction PN1/L2 is more powerful and will exert a greater pressure on limbs when the garment made from PN1/L2 is worn. Figure 4.10b shows that PN1/L1, PN1/L2 and PN1/L3 have a very similar hysteresis indicating the fabric recovers similarly after extension. At 30% strain, the difference in hysteresis between PN1/L1 and PN1/L2 is 0% and the difference between PN1/L1 and PN1/L3 is 6%. In the weft direction PN1/L1, PN1/L2 and PN1/L3 have a steep slope indicting a larger resistance to force and a higher modulus.

The stress-strain curves of fabric assemblies for PN2/L1, L2 and L3 at 40% strain are displayed in Figure 4.11.





a b

Figure 4.11 Elastic behaviour of fabric assemblies PN2/ L1, L2 & L3 at 40% strain; a) warp direction b) weft direction

It can be seen from Figure 4.11a, that in the warp direction, fabric assembly PN2/L3 requires the highest amount of force to extend the fabric to 40% strain, followed by PN2/L1 and PN2/L2. The difference in force required to extend PN2/L3 and PN2/L1 is 8%, whereas the difference required to extend PN2/L3 and PN2/L2 is 19%. This illustrates that PN2/L3 fabric assembly is the most powerful and will exert the most pressure on the underlying limb of a patient wearing a garment made from this fabric assembly. Figure 4.11a demonstrates that PN2/L1 and PN2/L3 had a similar hysteresis at 30% strain. For example, at 30% strain PN2/L1 and PN2/L3 hysteresis difference is 0% whereas, PN2/L2 the hysteresis difference is 42%. The steep slope of the curve for PN2/L1 and PN2/L3 in Figure 4.11a indicates a higher modulus and a larger resistance to the force applied of this fabric assembly, while PN2/L2 had a slighter slope indicating a smaller resistance to the same amount of force.

Figure 4.11b determines that PN2/L2 requires the most force to be extended to 40% strain in the weft direction followed by PN2/L1 and PN2/L3. The difference of force required to extend PN2/L2 and PN2/L1 is 15%, compared with the difference of force required to extend PN2/L2 and PN2/L3 is 19%. This shows that PN2/L2 in the weft direction is more powerful and will exert a greater pressure on the limbs when a garment made from PN2/L2 is worn. Figure 4.11b shows that PN2/L1, PN2/L2 and PN2/L3 had a similar hysteresis. For example, the difference between PN2/L2 and PN2/L1 hysteresis is 28% and the difference between PN2/L2 and PN2/L3 is 14%. The steep slope of the curve for PN2/L2 indicates a larger resistance to force in the weft direction, while PN2/L1 and PN2/L3 had a gentler slope thus having a smaller resistance to the force of the same strain.

Fabric assemblies at 60% strain

The stress-strain curves of fabric assemblies for PN1/L1, L2 and L3 at 60% strain are exhibited in Figure 4.12.

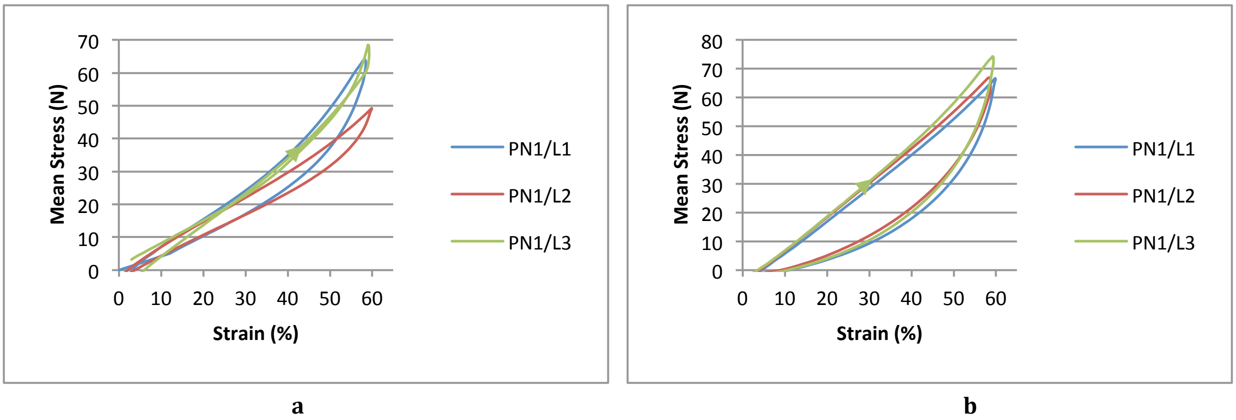


Figure 4.12 Elastic behaviour of fabric assemblies PN1/ L1, L2 & L3 at 60% strain; a) warp direction b) weft direction

It can be seen from Figure 4.12a, that PN1/L3 requires the most force to be extended to 60% strain in the warp direction followed by, PN1/L1 and PN1/L2. The difference in force between PN1/L3 and PN1/L1 is 10% whereas, the difference in force between PN1/L3 and PN1/L2 is 27%. This demonstrates that PN1/L3 is the most powerful fabric assembly in the warp direction, meaning that PN1/L3 will generate the most pressure when extended thus a greater pressure on the underlying limb of the patient wearing the garment made from this fabric, compared to the other two fabric assemblies. On the other hand, PN1/L2 will require a considerably higher extension to generate the same amount of pressure to the limb of the same size. Figure 4.12a shows that PN1/L3 had no hysteresis indicating a better ability to recover after extension, compared with PN1/L1 and PN1/L2. At 50% strain the hysteresis difference between PN1/L1 and PN1/L2 is 10%, whereas the difference in hysteresis between PN1/L1 and PN1/L3 is 100%. The steep slope of the curve for PN1/L1 and PN1/L3 indicates a higher modulus and a larger resistance to the force applied of this fabric assembly, while PN1/L2 had a slight slope consequently having a smaller resistance to the same amount of force.

Figure 4.12b determines that PN1/L3 requires the highest amount of force to be extended to 60% strain in the weft direction, followed by PN1/L2 and PN1/L1. The difference of force required to extend PN1/L3 and PN1/L1 is 8%, whereas the difference of force required to extend PN1/L3 and PN1/L2 is 7%. This shows that also in the weft direction PN1/L3 is more powerful fabric assembly and will exert a greater pressure on limbs when the garment made from PN1/L3 is worn. Figure 4.12b displays that fabric assemblies PN1/L1, PN1/L2 and PN1/L3 have a similar hysteresis. For instance, at 50% strain the hysteresis difference between PN1/L3 and PN1/L1 is 5% whereas, the difference between PN1/L3 and PN1/L2 hysteresis is 19%. It can be seen that fabric assemblies PN1/L1, PN1/L2 and PN1/L3 had a steep slope of the curve indicating a larger resistance to force in the weft direction.

The stress-strain curves of fabric assemblies for PN2/L1, L2 and L3 at 60% strain are defined in Figure 4.13.

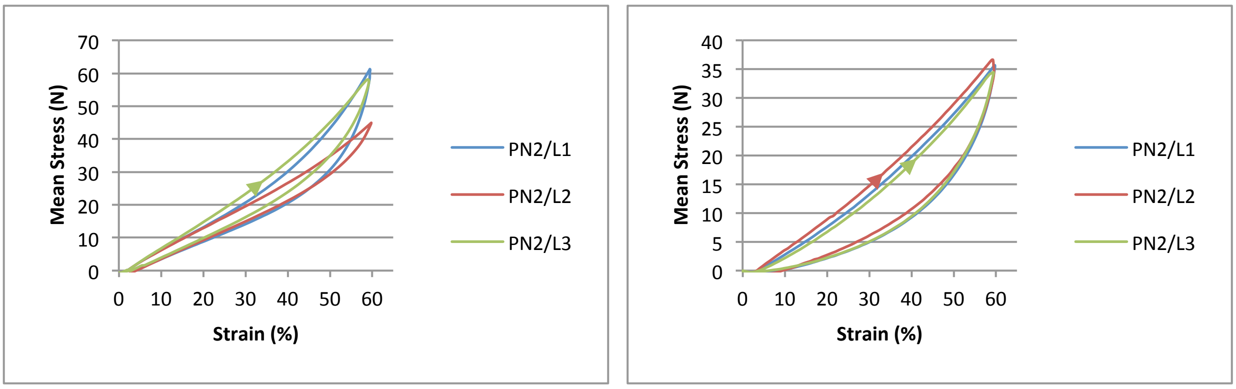


Figure 4.13 Elastic behaviour of fabric assemblies PN2/ L1, L2 & L3 at 60% strain, a) warp direction b) weft direction

Figure 4.13a indicates that in the warp direction, PN2/L1 requires the most force to be extended to 60% strain followed by PN2/L3 and PN2/L2. The difference of force required to extend PN2/L1 compared to PN2/L2 is 25%. At the same time, the force of PN2/L1 and PN2/L3 is the same. This illustrates that PN2/L1 is more powerful in the warp direction and will exert a greater pressure on the underlying limbs of the patient wearing the garment made from this fabric. Figure 4.13a shows that PN2/L2 had a smaller hysteresis than PN2/L1 and PN2/L3, indicating a better ability to recover after extension. For example, at 50% strain in warp direction the hysteresis difference between PN2/L1 and PN2/L2 is 33%, whereas the difference between PN2/L1 and PN2/L3 is 66% at the same strain. The steep slope of the curves for PN2/L1 and PN2/L3 indicates a higher modulus and a larger resistance to the force applied of this fabric assembly, while PN2/L2 had a slight slope consequently having a smaller resistance to the same amount of force.

From Figure 4.13b it can be seen, that PN2/L2 requires most force to be extended to 60% strain on the warp direction, followed by PN2/L1 and PN2/L3 which require the same amount of force to be extended. The difference of force required to extend PN2/L2 compared with PN2/L1 and PN2/L3 which is the same. This shows that in the warp direction PN2/L2 is marginally more powerful and will exert the most pressure on the underlying limb compared with PN2/L1 and PN2/L3 fabric assemblies. Figure 4.13b demonstrates that PN2/L1, PN2/L2 and PN2/L3 had a similar hysteresis. For example, at 50% strain the hysteresis difference between PN2/L2 and PN2/L1 is 23%, whereas the difference between PN2/L1 and PN2/L3 is

0%. The slopes of the curves for PN2/L1, PN2/L2 and PN2/L3 had a steep slope thus having a larger resistance to force in the weft direction.

4.2.2 Determination of tension decay for five minutes in single layers and fabric assemblies

To determine the susceptibility for fatigue of experimental fabrics, fabrics were tested for tension decay at 25% strain for five minutes in single layers and also as fabric assemblies.

The tension decay for PN1, PN2 and L1 in single layers and also PN1/L1and PN2/L1 fabric assemblies are shown in Figure 4.14.

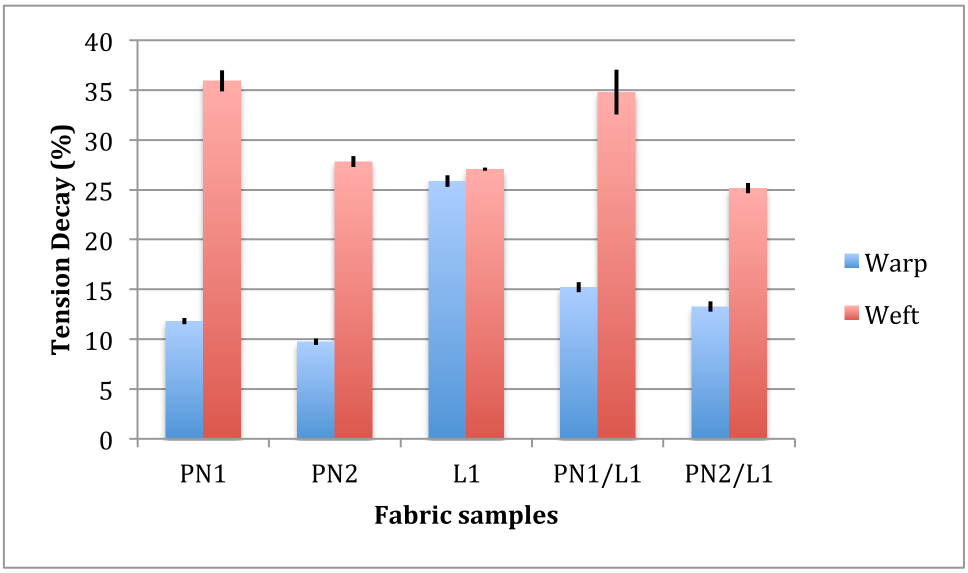


Figure 4.14 Tension decay for five minutes for selected fabrics in single layers and fabric assemblies

Figure 4.14 demonstrates that overall in the weft direction, the single layer fabrics and their assemblies have a considerably higher tension decay compared to tension decay in warp direction. In addition, it is clear that PN1 has the higher tension decay in the weft direction followed by PN2 and L1 for single layers. Tension decay of PN1 in the warp direction is 11% whereas the tension decay in weft direction is 36% making it 68% higher than in the warp direction than in the weft direction. As the garments are normally constructed in such a way, that the warp direction of the fabric aligns along the length of the body and the limbs while, while the weft is aligned across the body and the limbs. The higher tension decay of the fabric in the weft direction will result in a considerable drop in pressure generated by the garment on the underlying limb. The tension decay of PN2 is 9.7% in the warp direction and 27% in the weft direction. Similarly to PN1, tension decay for PN2 is 64% higher in the weft direction than in the warp direction. This fact will lead to the same implications as outlined above when the garment is worn. Figure 4.14 determines that tension decay for L1 in the warp direction is 26% and in the weft direction is 27%, which is only 3.7% difference. This correlates very well with the results of L1 at 25% strain, where the mean stress resulting from the strain of this fabric in warp direction is very close to the stress result when fabric is extended in the weft direction. We can conclude from this that fabric L1 is almost non-directional in its elastic attributes. Use of this fabric will result in multidimensional ease of movement for the wearer.

It can also be seen from Figure 4.14, that fabric assembly PN1/L1 has a higher tension decay than PN2/L1 in both the warp and weft direction. The tension decay difference between the warp and weft direction for PN1/L1 is 57% whereas, the difference between the tension decay in the warp and weft direction for PN2/L1 is 46%. Also, in the warp direction for PN1/L1 and PN2/L1 the difference in tension decay is 13%, compared with tension decay in the weft direction of PN1/L1 and PN2/L1 that is 28%. Figure 4.14 shows a higher tension decay in the weft direction for both PN1/L1 and PN2/L1 fabric assemblies.

From Figure 4.14, it can also be determined that PN1 in the warp direction has 22% less tension decay than PN1/L1 fabric assembly. However, L1 in the warp direction has 41% higher tension decay than PN1/L1 fabric assembly. When PN1 and L1 are assembled together the tension decay of PN1 increases in the warp direction. In the weft direction, PN1 single layer has 3% more tension decay than PN1/L1 fabric assembly. At the same time, tension decay of L1 in the weft direction is 22% lower than PN1/L1 fabric assembly. Thus, tension decay in the weft direction decreases when PN1 is assembled with L1.

Figure 4.14 shows that in the warp direction, PN2 single layer has 26% lower tension decay than PN2/L1 fabric assembly, whereas L1 single layer has 49% higher tension decay in the warp direction than PN2/L1 fabric assembly. The tension decay in the warp direction of PN2 single layer in the fabric assembly will increase once assembled with L1 single layer. In the weft direction tension decay of PN2 single layer is 10% higher than PN2/L1 fabric assembly in the same direction. Whereas, L1 single layer has 7% higher tension decay than PN2/L1 fabric assembly in the weft direction. The tension decay of PN2 single layer in the fabric assembly will decrease once assembled with L1 in the weft direction.

It can be seen from Figure 4.14, that if a power net with a lower tension decay is assembled with a lining with higher tension decay, tension decay in the weft direction decreases, whereas in the warp direction tension decay increases.

4.2.3 Determination of tension decay for twelve hours in single layer and fabric assemblies

To determine the susceptibility to fatigue of experimental fabrics, fabrics were tested for tension decay at 25% strain for twelve hours in single layer form and also as fabric assemblies. The tension decay for PN1, PN2 and L1 in a single layers and also PN1/L1and PN2/L1 fabric assemblies are determined in Figure 4.15.

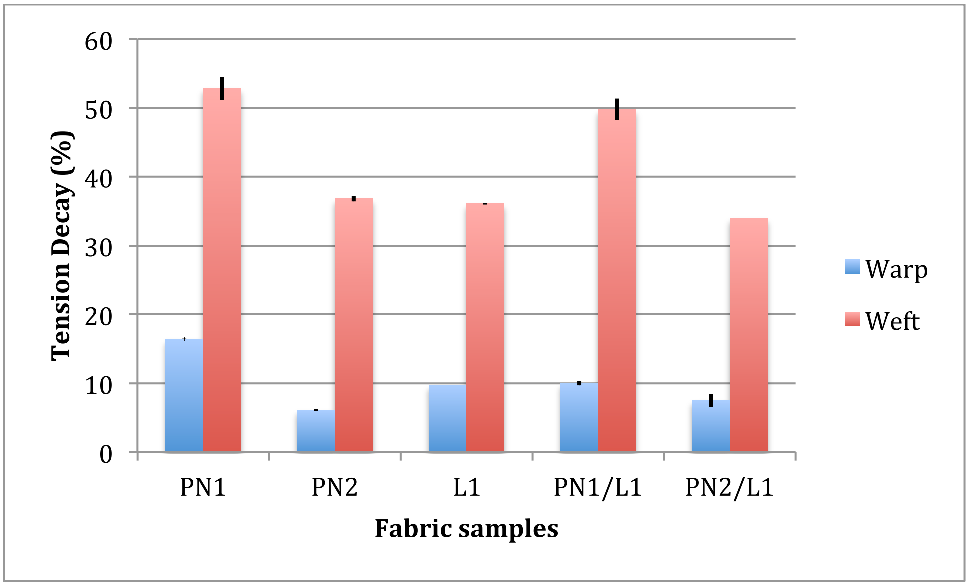


Figure 4.15 Tension decay for twelve hours for selected fabrics in single layers and fabric assemblies

Figure 4.15 demonstrates that overall in the weft direction, the single layer fabrics and their assemblies have a considerably higher tension decay compared to tension decay in the warp direction. It is evident that PN1 has the highest tension decay in the weft direction followed by PN2 and L1 for single layers. Tension decay of PN1 in the warp direction is 16% whereas, the tension decay in the weft direction is 53%, which is 70% higher than in the warp direction. From Figure 4.14, it can be seen that the difference in tension decay for PN1 in the warp was 68% compared with Figure 4.15 where, PN1 tension decay is 70%. The tension decay difference between Figure 4.14 and Figure 4.15 PN1 is 2%. The warp direction of the fabric aligns along the length of the body and limbs while the weft is aligned across the body and limbs when a garment in constructed. In the weft direction, the higher tension decay of the fabric will result in a considerable drop in pressure generated by the garment on the underlying limb. Figure 4.15 displays that, the tension decay of PN2 is 6% in the warp direction and 37% in the weft direction. Also, tension decay in the weft direction is 84% higher than the warp direction. The difference in tension decay between Figure 4.14 and Figure 4.15 PN2 is 24%. This fact will lead to the same implications as outlined above when the garment is worn. Figure 2 shows that tension decay for L1 in the warp direction is 10% and in the weft direction is 36%, which is 72% difference. This is considerably different to what was seen from Figure 4.14, where L1 is a almost directional fabric.

It can be seen from Figure 4.15, that fabric assembly PN1/L1 has a higher tension decay than PN2/L1 in both the warp and weft direction. The tension decay difference between the warp and the weft direction for PN1/L1 is 80% whereas, the difference between the tension decay in the warp and weft direction for PN2/L1 is 76%. Additionally, in the warp direction for PN1/L1 and PN2/L1 the difference in tension decay is 20%, compared with tension decay in the weft direction of PN1/L1 and PN2/L2 that is 32%. Figure 4.15 a shows higher tension decay in the weft direction for both PN1/L1 and PN2/L2 fabric assemblies.

From Figure 4.15, it can also be determined that PN1 in the warp direction has 37% more tension decay than PN1/L1 fabric assembly. However, L1 and PN1/L1 in the warp direction had the same tension decay. When PN1 and L1 are assembled together the tension decay of PN1 decreases in the warp direction. In the weft direction, PN1 single layer has 6% more tension decay than PN1/L1 fabric assembly. At the same time, tension decay of L1 in the weft direction is 28% lower than PN1/L1 fabric assembly. Thus, tension decay in the weft direction decreases when PN1 is assembled with L1.

Figure 4.15 shows that in the warp direction, PN2 single layer has 18% lower tension decay than PN2/L1 fabric assembly, whereas L1 single layer has 30% higher tension decay in the warp direction than PN2/L1 fabric assembly. The tension decay in the warp direction of PN2 single layer in the fabric assembly will increase once assembled with L1 single layer. In the weft direction tension decay of PN2 single layer is 8% higher than PN2/L1 fabric assembly in the same direction. Similarly, L1 single layer also has 8% tension decay in the weft direction. The tension decay of PN2 single layer in the fabric assembly will decrease once assembled with L1 in the weft direction.

It can be seen from Figure 4.15, that if a power net with a lower tension decay is assembled with a lining with higher tension decay, tension decay in the weft direction decreases, whereas in the warp direction tension decay increases.

4.2.4 Summary for elastic characteristics and tension decay

It is evident from the experimental elastic characteristics that the most powerful fabrics are the powernet fabrics in both the warp and weft direction as single layers. The brushed powernet didn't exert as much stress to be extended as the non-brushed powernet, which is due to the brushed powernet having 8% less elastane. Also it is noted that, as the fabric strain increases the force required to extend the fabric increased. However, in the weft direction the stress is higher for the same strain than in the warp direction. The powernet fabrics are able to generate the most pressure on the underlying limb of the patient wearing a garment made from these, compared with the lining fabrics. Garments can be engineered to specific reduction factors if the stress and strain of the fabric is known.

When another fabric was introduced as a fabric assembly, the pressure also increased in comparison to single layers in the warp and weft direction for both powernets, however, the non-brushed powernet still generated the most pressure. Also, garments wouldn't be expected to be constructed from lining fabrics; linings may be introduced in garments to enhance the overall comfort of the patent. Additionally, by layering pressure garments, pressure can be increased in severe cases of venous diseases and it would also be possible to better vary and engineer the layers to deliver more precise pressure to the underlying limb and a smooth next to skin feeling for the patient.

The experimental tension decay characteristics of the powernet fabrics can determine that in the weft direction there was a higher tension decay compared to that in the warp direction. In the weft direction, the higher tension decay of the fabric will result in a considerable drop in pressure generated by the garment on the underlying limb of the patient, so it should be closely examined at the stages of fabric selection and garment engineering.

4.3 Fabric comfort attributes with emphasis on moisture management, thermal and water-vapour resistance.

4.3.1 Moisture management capabilities of single layers and fabric assemblies

To determine the moisture management properties of experimental fabrics, fabrics were tested for wetting time, absorption rate, maximum wetted radius, spreading speed, accumulative one-way transport index (AOTI) and overall moisture management capabilities (OMMC). All the selected fabrics were tested in single layers and as fabric assemblies. Pressure garments must have the ability to transport liquid moisture as quickly as possible from the inner surface, to the outer surface of the garment to be spread over a large area for evaporation into the environment.

The 'top' surface represents the side of the fabric in contact with the skin during practical wear and the 'bottom' surface is the opposite side facing the environment. During the test 'sweat' droplets are deposited onto the 'top' of the fabric to mimic the sweating skin and transferred to the 'bottom' of the fabric to the outer environment.

Moisture management capabilities of single layers

The wetting time of top and bottom surfaces of single layers for PN1, PN2, L1, L2 and L3 can be seen in Figure 4.16.

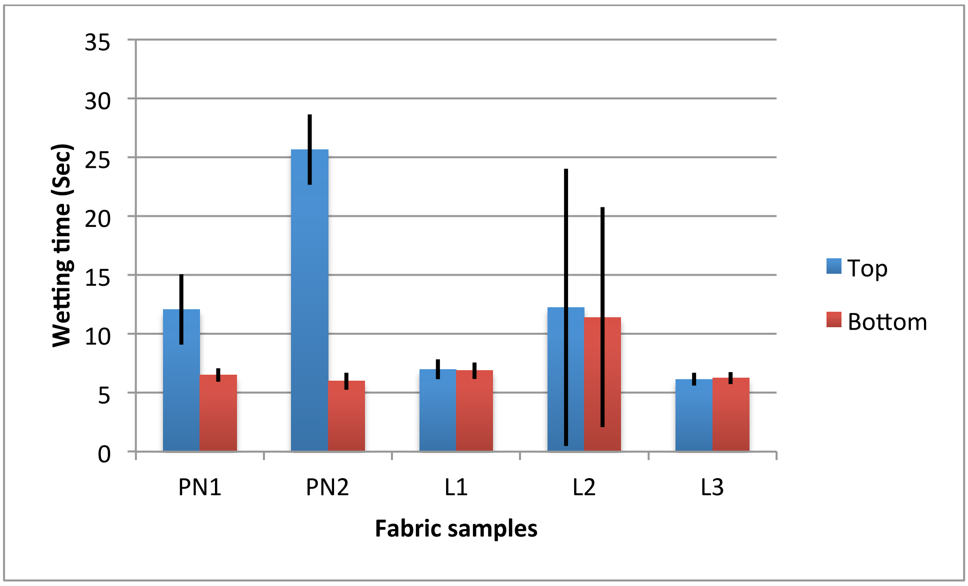


Figure 4.16 Wetting time of top and bottom surface for PN1, PN2, L1, L2 & L3

Figure 4.16 demonstrates that, the bottom side of fabrics PN1 and PN2 wets faster than the top. When comparing PN1 and PN2 bottom wetting times, PN2 has a marginally faster wetting time. This shows that the sweat drops onto the fabric next to skin side and quickly transfers to the bottom, away from the skin. This is an ideal situation for the wearer of pressure garments made from these fabrics. Also, Figure 4.16 exhibits that PN2 has considerably slower wetting time for the top surface in comparison to PN1 top surface wetting time. This demonstrates that when wearing a pressure garment made from PN2, the fabric next to skin will become wet slower, making the wearer feel drier. The slower top wetting time of PN2 could be due to the brushed back of the fabric. The brushed back adds comfort next to skin but also can contribute to the wetting time of fabrics as shown in Figure 4.16.

Furthermore, Figure 4.16 shows that L1 has a slightly higher wetting time for both top and bottom surface compared to L3 top and bottom surface wetting times. This indicates that when a pressure garment is made from L3, sweat can marginally transfer faster from top to bottom of the fabric. In addition, L2 bottom surface wets faster than the top surface. This illustrates that sweat could be transported to the bottom surface quicker. It is worth noting that L2 has a high degree of wetting time variation. This could be attributed to uneven treatment applied to the fabric such as a softener, which makes the performance of the fabric unstable and thus unreliable in practical wear. From the above it is obvious that PN2 overall performs best in terms of wetting time, with L3 performing best of the lining fabrics.

The absorption rate of top and bottom surfaces of single layers for PN1, PN2, L1, L2 and L3 are exhibited in Figure 4.17.

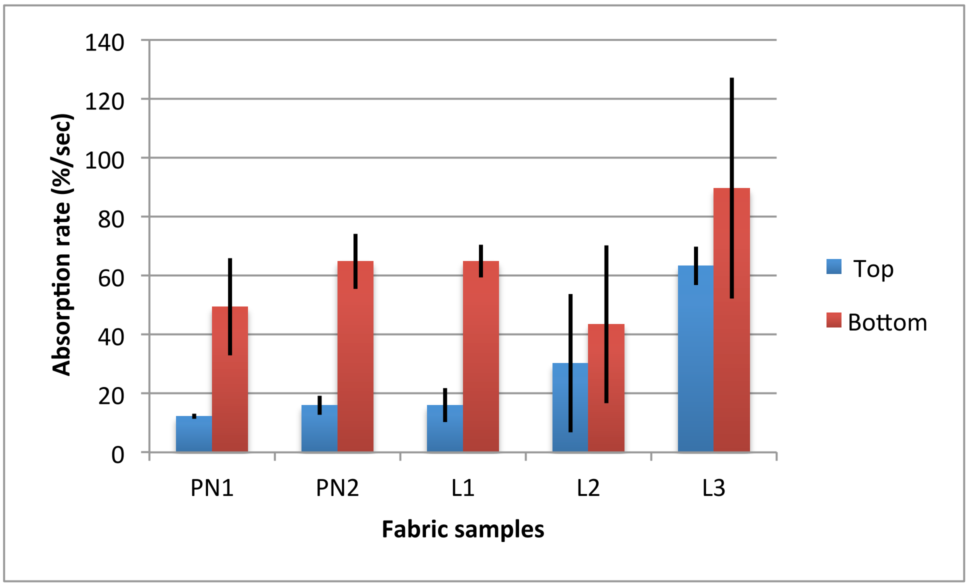


Figure 4.17 Absorption rate of top and bottom surface for PN1, PN2, L1, L2 & L3

For all the fabrics, the bottom surface absorbed significantly more liquid in comparison to the top surface. This indicates that the bottom surface in all fabrics has a higher ability to absorb moisture than the top surface of the fabric. As the bottom surface absorbs more moisture than the top surface, the top surface remains drier than the bottom surface, which is ideal for the wearer.

Moreover, it can be seen from Figure 4.17 that PN2 has a higher bottom absorption rate compared with PN1 bottom absorption rate. This shows that the amount of moisture transferred from the top surface to the bottom surface is higher for PN2. A pressure garment made from

PN2 will keep the wearer drier in comparison to PN1, as the moisture has been transported to the bottom surface and isn't next to the skin. Additionally, Figure 4.17 shows that among lining fabrics L3 has a higher bottom absorption rate compared with L1 and L2, indicating higher moisture content on the bottom surface at the end of the experiment. However, the difference in absorption rate between the top and bottom surfaces of L1 compared to the top and bottom surfaces of L3 is substantially different with L3 having a closer top and bottom absorption rate, indicating that other parameters need to be taken into consideration when considering moisture management properties.

The maximum wetted radius of top and bottom surfaces of single layers for PN1, PN2, L1, L2 and L3 are shown in Figure 4.18. It is desirable that the top wetted radius is small while the bottom wetted radius is comparatively larger to aid the evaporation of the liquid to the environment.

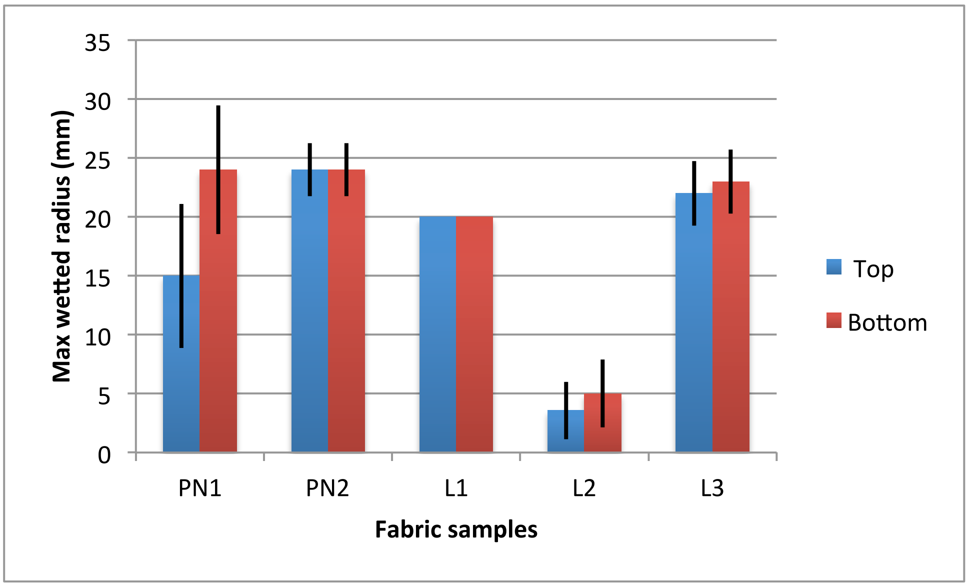


Figure 4.18 Maximum wetted radius of top and bottom surface for PN1, PN2, L1, L2 & L3

Figure 4.18 demonstrates, that PN1 bottom radius is larger than the top radius. This is an ideal situation for the wearer of the garment made from this fabric. The moisture substantially spreads on the outside surface of the garment and can easily be evaporated into the environment, which could be due to the open structure of PN1. Also, the radius for the top and bottom of PN2 are the same. This shows that PN2 will take longer to dry, as the fabric will feel wet and uncomfortable next to skin when worn. It is illustrated in Figure 4.19 that the maximum wetted radius of PN1 bottom is larger than that of the top, which leads to an ideal situation for the wear.

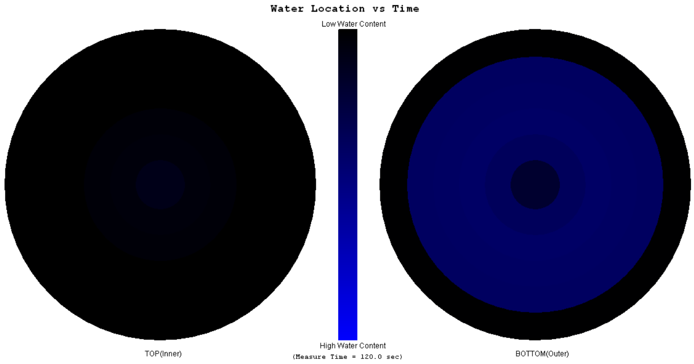


Figure 4.19 Ideal situation for wetted areas on the two surfaces for PN1 (area with colour is wetted)

Moreover, Figure 4.18 expresses that among the lining fabrics L3 has a bigger top and bottom radius compared with L1 and L2 top and bottom radius. This demonstrates that sweat spreads creating a larger radius, so fabric can evaporate sweat faster on the outside. Additionally, Figure 4.18 displays that L2 had a small top and bottom maximum wetted radius compared with L1 and L3 top and bottom radius. This illustrates the inability of sweat spreading which could be due to the hydrophobic fibres used to construct the fabric. From Figure 4.20 it is evident that the top and bottom radius of L1 are the same. Indicating fabrics will take longer to dry, as sweat hasn't been transferred to the bottom surface of the fabrics.

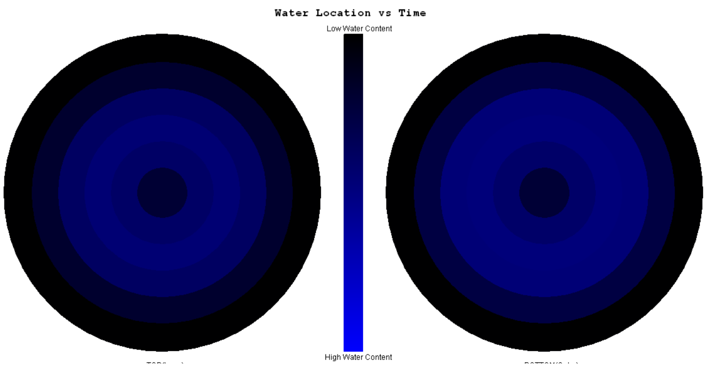


Figure 4.20 Wetted top and bottom surface for L1 (area with colour is wetted)

The spreading speed of top and bottom surfaces of single layers for PN1, PN2, L1, L2 and L3 are exhibited in Figure 4.21.

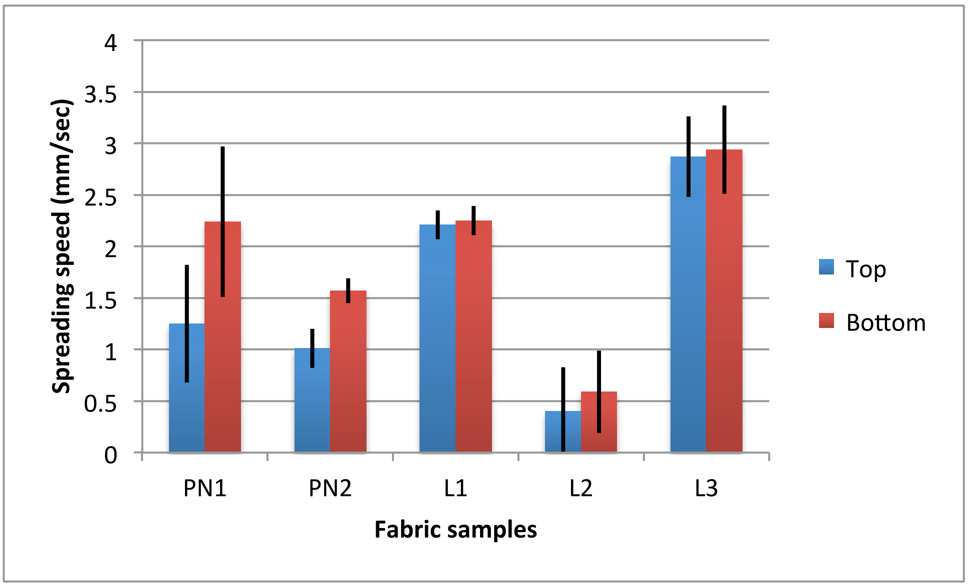


Figure 4.21 Spreading speed of top and bottom surface for PN1, PN2, L1, L2 & L3

From Figure 4.21 it can be determined, that PN1 for top and bottom surfaces had a faster spreading speed compared with PN2 top and bottom surface. This shows that once the sweat was dropped on PN1, it spreads fasters to its bottom surface compared to PN2. PN1 spreads on the bottom surface faster than the bottom surface of PN2. If we compare with the radius in Figure 4.18, it can be seen that the bottom radius for PN1 and PN2 is the same, however, PN1 spreads to the bottom radius quicker than PN2 indicating better spreading speed properties.

Moreover, it can be seen from Figure 4.21 that L3 has the fastest top and bottom spreading speed compared with L1 and L2 top and bottom spreading speed. This indicates that the sweat will evaporate faster into the environment. Additionally, Figure 4.21 displays that L2 has a very slow spreading speed, indicating sweat does not spread. This was also evident in Figure 4.18 that shows a small top and bottom radius.

The accumulative one-way transport index of single layers for PN1, PN2, L1, L2 and L3 are displayed in Figure 4.22.

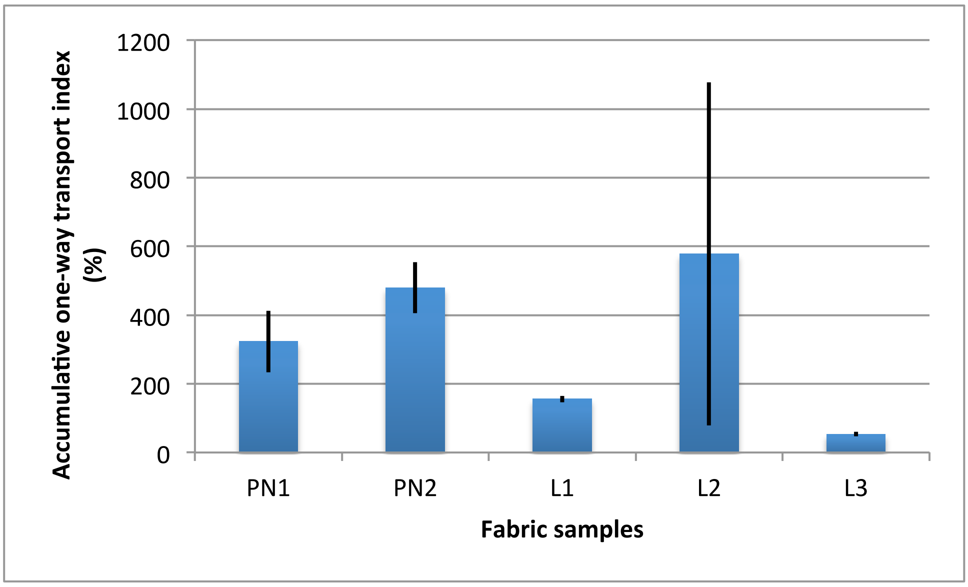


Figure 4.22 Accumulative one-way transport index for PN1, PN2, L1, L2 & L3

Figure 4.22 determines that, PN2 has a higher AOTI compared to PN1. This indicates that PN2 has a better ability to transport moisture from the top surface of the fabric to the bottom surface of the fabric. A garment made from this fabric will have quicker drying and evaporating capabilities when compared to a garment made from PN1.

Furthermore, Figure 4.22 illustrates that L2 has a higher accumulative one-way transport compared with L1 and L3, signifying L2 can transfer sweat from the top surface, next to skin to the bottom surface, environment. However, it can be seen from Figures 4.18 and 4.20 that sweat does not spread on the bottom surfaces, this is not desirable as a wearer of the garment made from this fabric will feel wet as sweat won't spread and evaporate. Also, Figure 4.22 displays a lower accumulative one-way transport for L1 and L3 demonstrating moisture doesn't transfer as easily from the top to bottom surface. But Figures 4.18 and 4.21 show higher spreading speed and wetted radius for top and bottom compared with L2, which enables the sweat to be evaporated easier when a garment is made from L1 and L3.

The overall moisture management capabilities of single layers for PN1, PN2, L1, L2 and L3 are shown in Figure 4.23.

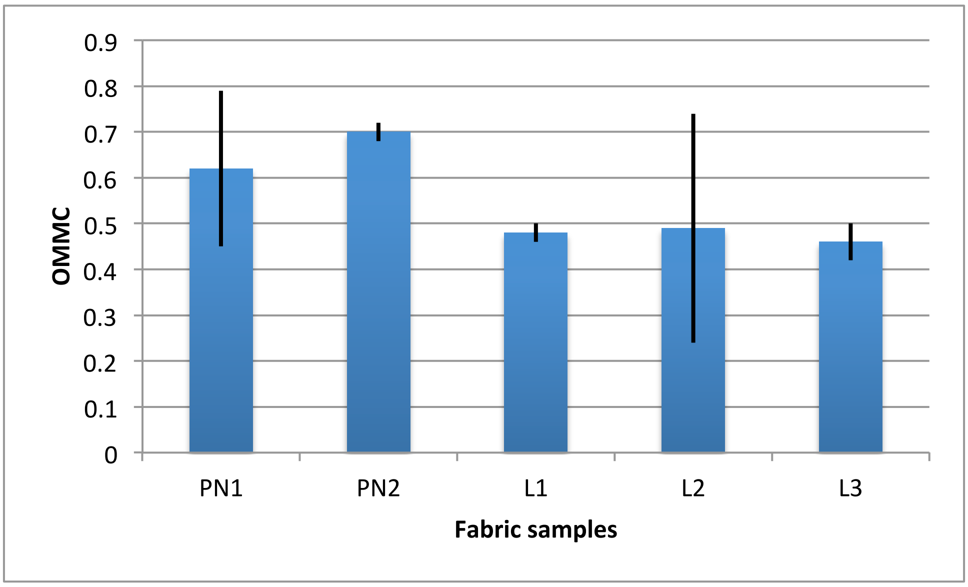


Figure 4.23 Overall moisture management capabilities for PN1, PN2, L1, L2 & L3

It can be seen from Figure 4.23 that, PN2 has the highest overall moisture management capabilities compared with PN1. When a garment is made from PN2, the fabric the garment is made from will be able to absorb, transport and spread moisture insuring the wearer feels dry and comfortable. The important factors that contributed to PN2 having more moisture management capabilities compared with PN1 is quicker wetting time on the bottom side in comparison to the top side, spreading speed and also transport of moisture. The larger the difference in wetting time between the top and bottom the more influence it has on the overall performance. For example, in Figure 4.16 the difference in top and bottom surfaces of PN2 is much higher than the difference in top and bottom surfaces in PN1. Also the spreading speed and radius, the higher the spreading speed and radius on the bottom the better ability to evaporate sweat. Additionally, PN2 could transfer moisture from the top surface to the bottom more effectively. Furthermore, PN2 has a substantially smaller degree of variation in comparison to PN1. This shows that PN2 is a more stable fabric in terms of moisture management properties.

Moreover, L1, L2 and L3 have good overall moisture management capabilities. Also, it should be noted that L2 has a high degree of variability. However, L1 and L3 have better ability to absorb and spread moisture compared with L2. Similarly to PN2, L1 and L3 have a smaller degree of variation compared with L2.

Moisture management capabilities of fabric assemblies

The top and bottom surface wetting times for fabric assemblies L1,L2,L3/PN1 and L1,L2,L3/PN2 are displayed in Figures 4.24 and 4.25. The lining here is a top surface and a powernet is a bottom surface.

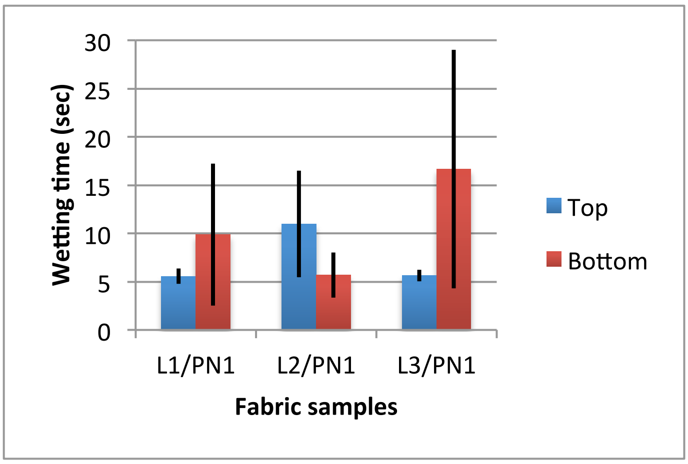


Figure 4.24 Top and bottom surface wetting times for L1,L2,L3/PN1

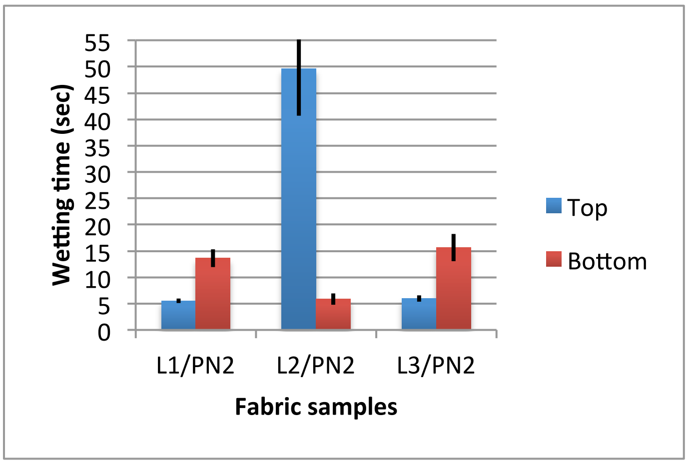


Figure 4.25 Top and bottom surface wetting times for L1,L2,L3/PN2

Figure 4.24 concludes that, the top surface of fabric assemblies L1/PN1 and L3/PN1 wets faster than the bottom surface. When comparing the top surface wetting times of L1/PN1 and L3/PN1 both wet at the same time. However, L1/PN1 bottom wetting time is faster than L3/PN1 bottom wetting time, indicating that sweat is transferred from the top surface of L1/PN1 to the bottom surface faster than L3/PN1. This is not an ideal situation for the wearer of a garment made from these fabrics, as the lining next to skin will wet first thus leaving the wearer wet next to skin. Also, Figure 4.24 expresses that L2/PN1 has a faster bottom surface wetting time compared with L1/PN1 and L3/PN1 bottom surface wetting time. This signifies that when sweat drops onto the fabric L2, next to skin side it quickly transfers to the bottom surface of PN1 into the environment. When wearing a garment from L2/PN1 fabric assembly the fabric next to skin will become wet slower, which will make the wearer feel drier.

It can be seen from Figure 4.25 that, L1/PN2 and L3/PN2 top surface wets faster than the bottom surface. Both L1/PN2 and L3/PN2 fabric assemblies have similar wetting times for both the top and the bottom surfaces, indicating dropped sweat on the fabrics will behave alike when considering wetting time properties. Additionally, Figure 4.25 displays that L2/PN2 bottom surface wets faster than the top surface. A garment made from this fabric assembly will keep the wearer drier as sweat is transferred from the top surface to the bottom surface of the fabric.

Furthermore, when comparing L1/PN1 and L1/PN2 in Figures 4.24 and 4.25 it can be determined that the top surface wetting times are equal, though the bottom surface of L1/PN1 wets faster than the bottom surface of L1/PN2, indicating sweat transfer is faster with fabric assembly L1/PN1. Also, L3/PN1 and L3/PN2 have the same top wetting time but L3/PN1 has a marginally faster bottom wetting time. However, when comparing the bottom surface wetting times of L2/PN1 and L2/PN2 they are the same but the top surface wetting times are different, L2/PN2 tops surface will take considerably longer to wet. The wearer of the pressure garment made from fabric assembly L2/PN2 will feel drier as the top surface, next to skin layer will take longer to wet.

The top and bottom surface absorption rate for fabric assemblies L1,L2,L3/PN1 and L1,L2,L3/PN2 are presented in Figures 4.26 and 4.27.

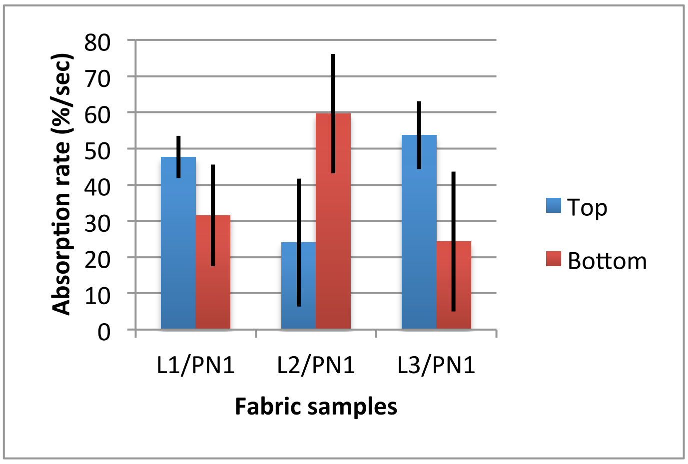


Figure 4.26 Top and bottom surface absorption rate times for L1,L2,L3/PN1

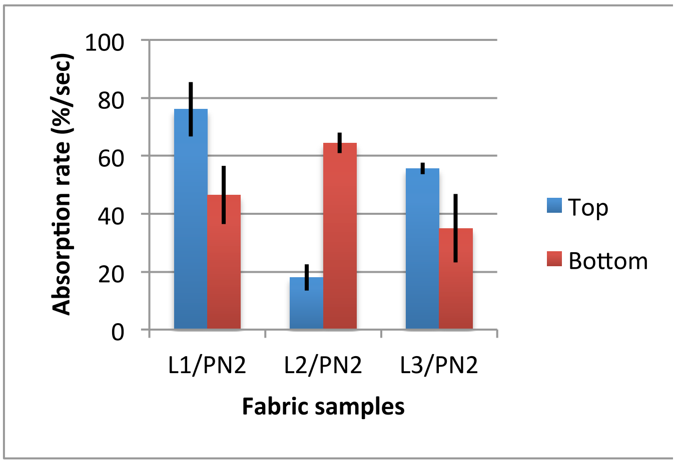


Figure 4.27 Top and bottom surface absorption rate times for L1,L2,L3/PN2

Figure 4.26 displays that L1/PN1 and L3/PN1 has a higher top absorption rate compared with the top absorption rate of L1/PN1. This indicates that moisture was not transferred to the bottom surface of fabrics L1/PN1 and L3/PN1. Whereas, L2/PN1 the bottom surface absorption rate is higher compared with L1/PN1 and L3/PN1. This shows that moisture has been absorbed by the bottom surface which is ideal situation, as the top surface remains drier.

Figure 4.27 shows that the top surface absorption rates of L1/PN2 and L3/PN2 are higher than the bottom surface absorption rates. This concludes that more moisture is absorbed on the top surface of the fabric than the bottom surface of the fabric. While, the bottom surface absorption rate of L2/PN2 is higher than the top surface absorption rate. This expresses that the bottom surface of L2/PN2 can absorb more moisture keeping the top surface drier and better for the wearer.

Overall, Figures 4.26 and 4.27 shows that PN2 fabric assemblies have a higher absorption rates than PN1 fabric assemblies. Signifying fabric assemblies made from PN2 fabric will absorb more moisture and keep wearer drier than fabric assemblies with PN1 fabric.

The top and bottom maximum wetted radius for fabric assemblies L1,L2,L3/PN1 and L1,L2,L3/PN2 are displayed in Figures 4.28 and 4.29.

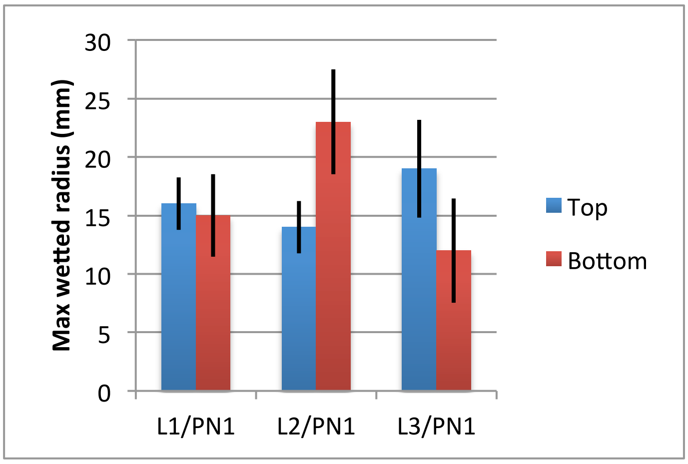


Figure 4.28 Top and bottom surface maximum wetted radius times for L1,L2,L3/PN1

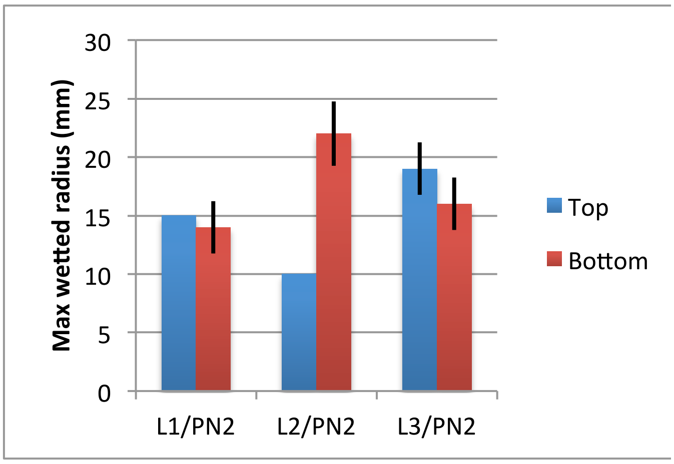


Figure 4.29 Top and bottom surface maximum wetted radius times for L1,L2,L3/PN2

Figure 4.28 demonstrates that for fabric assembly L1/PN1 the maximum wetted radius is marginally different on both the top and bottom surfaces. This shows that moisture has evenly spread on both surfaces of the fabric. A garment made from the fabric assembly L1/PN1 will take longer to dry, as the moisture has not been transferred to the bottom surface of the fabric. Also, it can be seen from Figure 4.28 that the bottom surface of L2/PN1 has a greater maximum wetted radius than the top surface. This indicates that the moisture has been transported to the bottom surface and will subsequently spread on the outside thus being evaporated into the environment. Furthermore, L3/PN1 has a larger maximum wetted radius on the top surface. This is not an ideal situation for the wearer, as the fabric next to skin will feel wetter than the outside surface of the fabric.

Figure 4.29 illustrates, that L1/PN2 has the same top and bottom surface maximum wetted radius. This denotes that moisture has spread evenly on both sides of the fabric assembly. When a garment of L1/PN2 is worn, it will feel wet next to the skin and uncomfortable. It is evident from Figure 4.29 that the bottom surface of L2/PN2 had a larger maximum wetted radius. This shows that moisture will spread more on the bottom surface of the fabric consequently sweat will evaporate into the environment. Also, L3/PN2 has a larger top surface maximum wetted radius than the bottom surface. The wearer of a garment made from L3/PN2 will feel wet next to skin as moisture has not been transported to the bottom surface of the fabric.

Additionally, from Figures 4.28 and 4.29 it can be seen that L2/PN1 has the largest bottom surface maximum wetted radius and a smaller top surface maximum wetted radius. This is an ideal situation, as the wearer will not feel wet next to skin since the radius of sweat is smaller. The sweat will be transported to the bottom and spread on the outside surface of the fabric assembly thus leaving the wear drier and more comfortable.

The top and bottom surface spreading speed for fabric assemblies L1,L2,L3/PN1 and L1,L2,L3/PN2 are indicated in Figures 4.30 and 4.31.

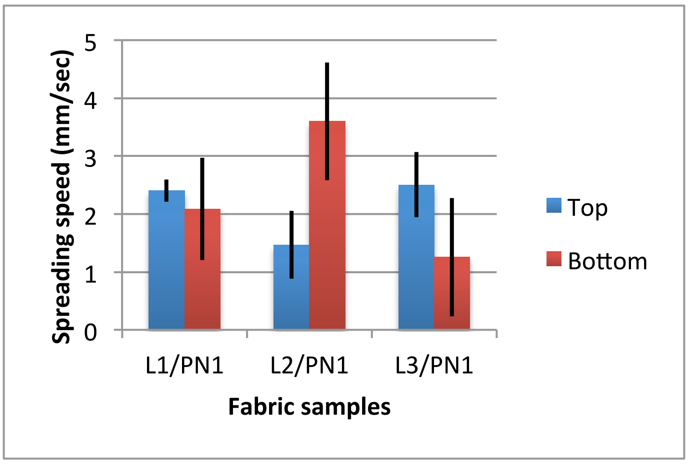


Figure 4.30 Top and bottom surface spreading speed for L1,L2,L3/PN1

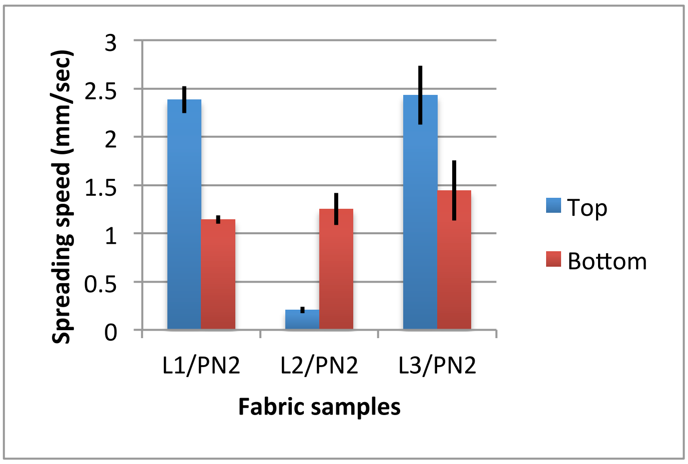


Figure 4.31 Top and bottom surface spreading speed for L1,L2,L3/PN2

Figure 4.30 determine that L2/PN1 bottom surface has the faster spreading speed than L1/PN1 and L3/PN1. This suggests that once the sweat was dropped on to L2/PN1, it spreads the fastest to the maximum wetted radius. Also, Figure 4.30 shows that L1/PN1 and L3/PN1 top surface spreading speed is faster than the bottom surface spreading speed. This indicates that the top surfaces of L1/PN1 and L3/PN1 wets before the bottom surfaces. Garments made from fabric assemblies L1/PN1 and L3/PN1 will wet faster next to skin and not spread to the outside of the fabric as shown in Figure 4.28.

It can be seen from Figure 4.31 that the top surfaces of L1/PN2 and L3/PN2 has a faster spreading speed than L2/PN2 top surface. This demonstrates that once the sweat was dropped it transferred to the bottom and spread very quickly to the outer radius. However, as the top surface of the fabric assembly is next to skin, a garment made from L1/PN2 and L3/PN2 would feel wet and uncomfortable next to the skin as the moisture isn't transferred to the bottom surface and evaporated into the environment.

The accumulative one-way transport index (AOTI) for fabric assemblies L1,L2,L3/PN1 and L1,L2,L3/PN2 are shown in Figures 4.32 and 4.33.

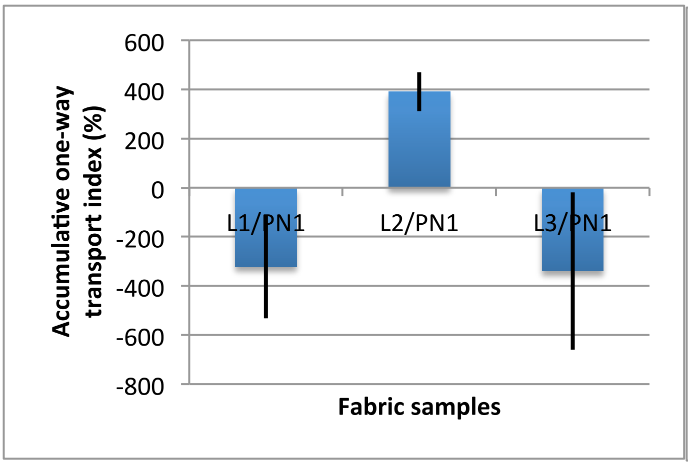


Figure 4.32 Accumulative one-way transport index for L1,L2,L3/PN1

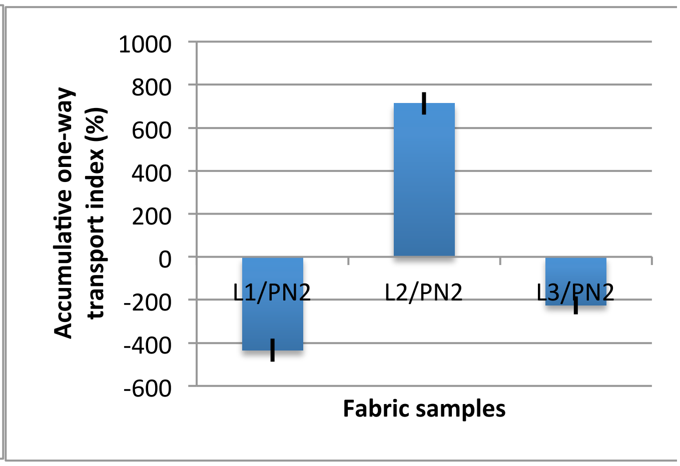


Figure 4.33 Accumulative one-way transport index for L1,L2,L3/PN2

Figure 4.32 establishes that fabric assembly L2/PN1 has the highest AOTI compared with fabric assembly L1/PN1 and L3/PN1. This implies that the positive value L2/PN1 has a better ability to transport moisture from the top surface of the fabric to the bottom surface of the fabric. Garments made from fabric assembly L2/PN1 will have quicker drying capability compared to a garments made from L1/PN1 and L3/PN1.

Also, Figure 4.33 shows that fabric assembly L2/PN2 has the maximum AOTI compared with fabric assembly L1/PN2 and L3/PN2. This denotes that L2/PN2 can transfer sweat from the top surface, next to skin to the bottom surface, environment.

Overall, from Figures 4.32 and 4.33 it can be seen that the positive value L2/PN2 has the highest AOTI. This signifies that L2/PN2 has a greater ability to transport moisture from the top surface of the fabric, which is next to skin, to the bottom surface of the fabric which is the environment. A garment made from fabric assembly L2/PN2 will feel drier and have quicker drying capabilities.

The overall moisture management capabilities for fabric assemblies L1,L2,L3/PN1 and L1,L2,L3/PN2 are exhibited in Figures 4.34 and 4.35.

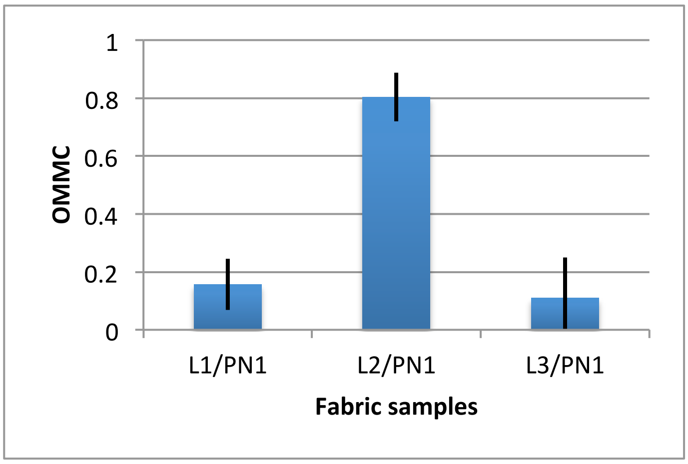


Figure 4.34 Overall moisture management capabilities for fabric assemblies L1,L2,L3/PN1

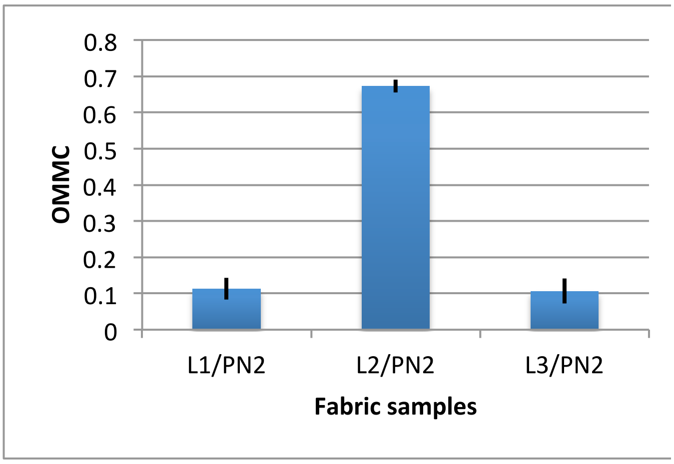


Figure 4.35 Overall moisture management capabilities for fabric assemblies L1,L2,L3/PN2

Figure 4.34 determines that fabric assembly L2/PN1 has the greatest overall moisture management capabilities. This indicates that a garment made from fabric assembly L2/PN1 will be able to absorb, transport and spread moisture better than a garment made from fabric assemblies L1/PN1 and L3/PN1.

Furthermore, Figure 4.35 shows that fabric assembly L2/PN2 had the highest overall moisture management capabilities compared with L1/PN2 and L3/PN2. A garment made from L2/PN2 will have better ability to absorb, transport and spread moisture to the outer environment.

In conclusion looking at Figures 4.34 and 4.35, it can be seen that L2/PN1 has more advance moisture management capabilities compared to L2/PN2. It is safe to assume, that a garment made from fabric assembly L2/PN1 will ensure the wearer feels dry and comfortable as it can absorb, transport and spread moisture. Other important factors that contributed to L2/PN1 having enhanced moisture management capabilities compared to L2/PN2 was L2/PN1 had a higher bottom surface wetting time, absorption rate, maximum wetted radius and spreading speed.

The top and bottom surface wetting times for fabric assemblies PN1/L1,L2,L3 and PN2/L1,L2,L3 are shown in Figures 4.36 and 4.37. Here, powernet is a top surface and lining is a bottom surface.

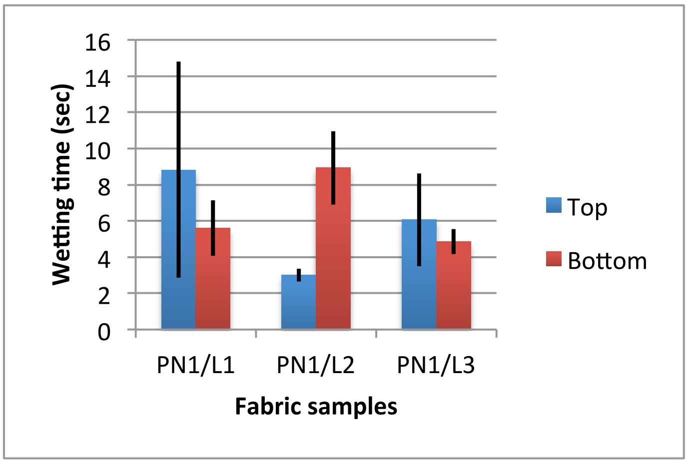


Figure 4.36 Top and bottom surface wetting times for PN1/L1,L2,L3

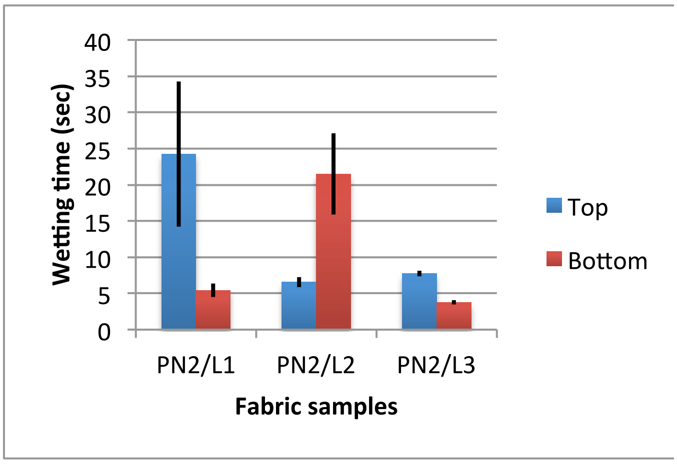


Figure 4.37 Top and bottom surface wetting times for PN2/L1,L2,L3

Figure 4.36 determines that PN1/L1 and PN1/L3 bottom surface wetting time is faster than PN1/L2 bottom surface wetting time. This indicates that once sweat was dropped onto fabric assembly next to skin, it transferred to the bottom surface quickly. Also, Figure 4.36 shows that top and bottom surfaces wetting times of PN1/L3 compared to top and bottom surfaces wetting times PN1/L1 are faster. This implies that once sweat was dropped, sweat transferred faster from the bottom surface to the top surface of the fabric assembly. Moreover, Figure 4.36 displays that PN1/L2 top surface wets faster than the bottom surface, signifying sweat doesn't transfer fast from the top surface next to skin to the bottom environment surface.
Figure 4.37 determines that PN2/L1 and PN2/L3 behave alike when considering wetting time properties. Both fabric assemblies PN2/L1 and PN2/L3 bottom surface wets faster than the top surface. This shows that sweat is transferred to the bottom surface once dropped. Figure 4.37 displays that PN2/L2 is a problematic situation for wetting time as the top surface wetting time is faster than the bottom surface wetting time. This indicates that sweat hasn't been transferred quickly to the bottom surface once dropped onto the top surface.

Furthermore, it can be seen from Figures 4.36 and 4.37 that when comparing PN1/L1 to PN2/L1 and PN1/L3 to PN2/L3, PN2/L1 and PN2/L3 performs better in terms of wetting times capabilities, this is due to the faster wetting times of the bottom surface. A garment made from PN2/L1 and PN2/L3 would be an ideal situation as sweat can be transferred away from the skin.

The top and bottom surface absorption rate for fabric assemblies PN1/L1,L2,L3 and PN2/ L1,L2,L3 can be seen in Figures 4.38 and 4.39.

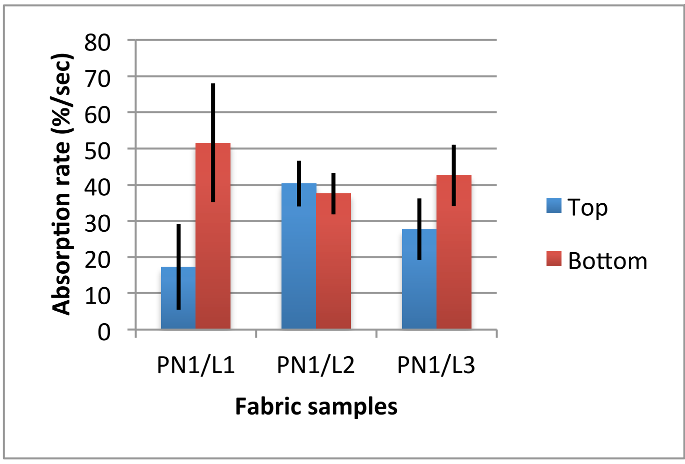


Figure 4.38 Top and bottom absorption rate for PN1/L1,L2,L3

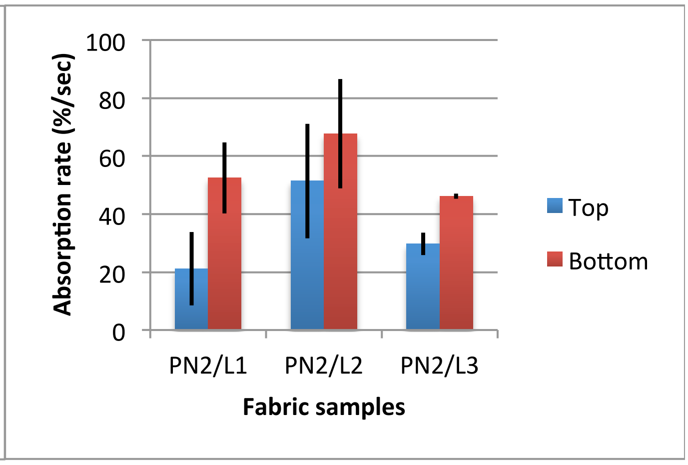


Figure 4.39 Top and bottom absorption rate for PN2/L1,L2,L3

Figure 4.38 expresses that, PN1/L1 and PN1/L3 bottom surface absorption rate is greater than the top surface absorption rate. This indicates that moisture was transported from the top surface to the bottom surface of the fabric assemblies PN1/L1 and PN2/L3. As the bottom surface has higher moisture content the top surfaces of the fabrics will remain drier, thus leaving the wearer drier. Additionally, Figure 4.38 shows that PN1/L2 that the top surface absorbed marginally more moisture than the bottom surface, signifying that moisture was not transferred from the top surface to the bottom surface.

It is evident from Figure 4.39 that fabric assemblies PN2/L1, PN2/L2 and PN2/L3 bottom surface absorption rate is higher than the top surface absorption rate. This shows that the bottom surface has a higher ability to absorb moisture than the top surface. As the bottom surface absorbs more moisture than the top surface, the bottom surface will wet thus it can evaporate into the environment. This is ideal for the wearer, as it will give a dry feeling next to the skin.

Moreover, from Figures 4.38 and 4.39 it can be determined that PN2/L2 is the best performing when considering absorption rate, as PN2/L2 has the highest bottom surface absorption rate. A garment made from PN2/L2 is an ideal situation for the wearer as moisture is transported to the bottom surface of the fabric, thus leaving the top surface drier.

The top and bottom surface maximum wetted radius for fabric assemblies PN1/L1,L2,L3 and PN2/ L1,L2,L3 are displayed Figures 4.40 and 4.41.

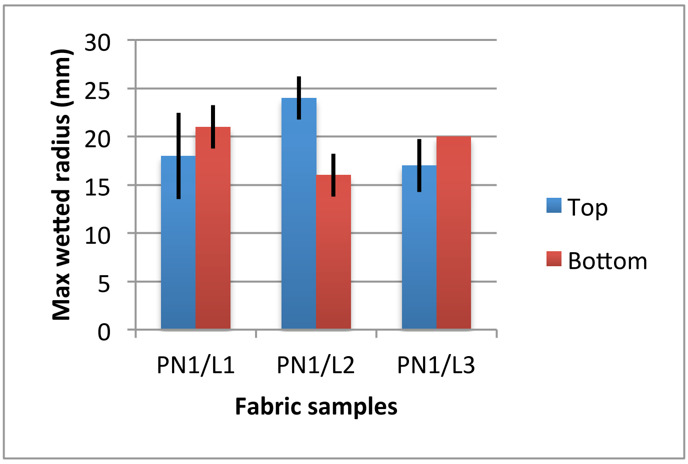


Figure 4.40 Top and bottom maximum wetted radius for PN1/L1,L2,L3

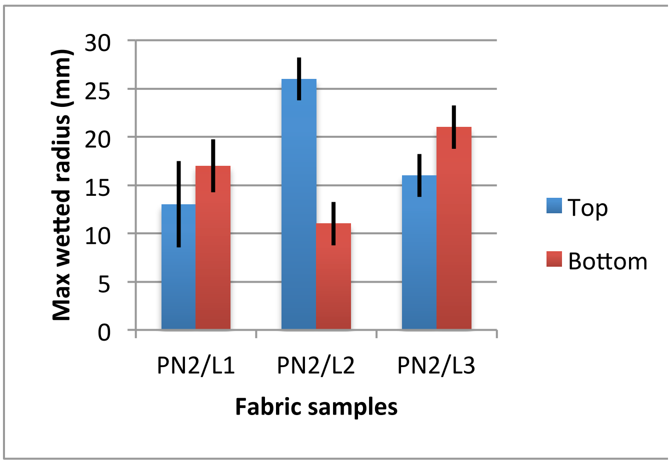


Figure 4.41 Top and bottom maximum wetted radius for PN2/L1,L2,L3

Figure 4.40 expresses that PN1/L1 and PN1/L3 have a larger bottom surface maximum wetted radius than top surface maximum wetted radius. PN1/L1 and PN1/L3 moisture spreads on the bottom surface of the fabric assembly and can be evaporated into the environment. Also, PN1/L2 in Figures 4.40 confirms that the top surface maximum wetted radius is higher than the bottom surface maximum wetted radius. A garment made from fabric assembly PN1/L2 would feel wet next to skin as the top surface radius is greater.

Moreover, Figure 4.41 illustrates that the top maximum wetted surface PN2/L2 is larger than the bottom, which leads to an uncomfortable situation for the wearer as sweat may not be evaporated from the bottom into the environment. It is evident from Figure 4.41 that PN2/L1 and PN2/L3 has a larger bottom surface maximum wetted radius than the top surface maximum wetted radius. This would leave the wearer feeling dry as sweat has been transferred from the top surface to the bottom surface and can be easily evaporated.

Overall from Figures 4.40 and 4.41, it can be seen that PN1/L1 and PN2/L3 have the highest maximum wetted radius, as the bottom surface radius is larger than the top surface radius. This would leave the wearer feeling drier as sweat is transferred and evaporated from the bottom surface.

The top and bottom surface spreading speed for fabric assemblies PN1/L1,L2,L3 and PN2/ L1,L2,L3 are expressed Figures 4.42 and 4.43.

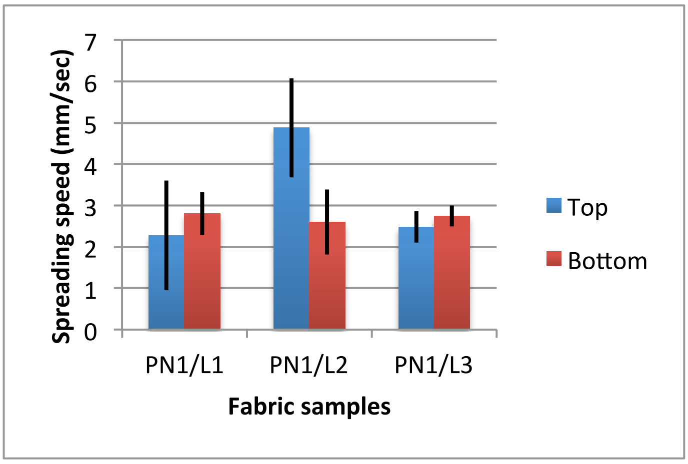


Figure 4.42 Top and bottom spreading speed for PN1/L1,L2,L3

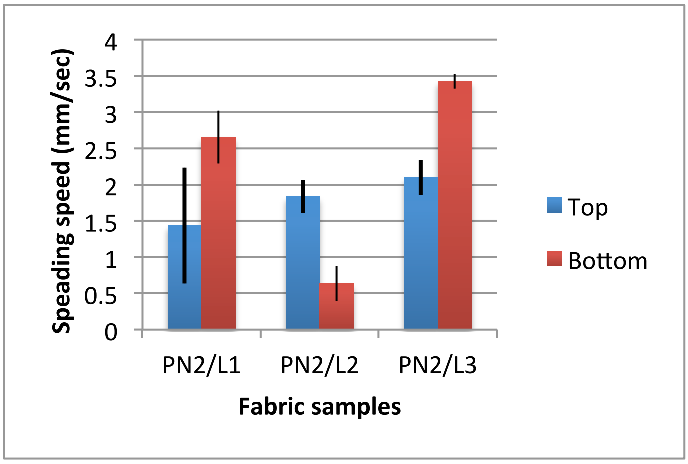


Figure 4.43 Top and bottom spreading speed for PN2/L1,L2,L3

It can be determined from Figure 4.42 that PN1/L1 and PN1/L3 has a faster bottom surface spreading speed than the top surface spreading speed. This is a model situation as once sweat was dropped, it spreads fastest to the bottom surface maximum wetted radius. This would leave the wearer of the garment feeling drier as the sweat can evaporate faster into the environment. Also, PN1/L2 has a faster top surface spreading speed than the bottom surface spreading speed. This shows that sweat was not transferred to the bottom surface of the fabric assembly, leaving the wearer feeling wet next to skin.

Moreover, Figure 4.43 displays that PN2/L1 and PN2/L3 has a faster bottom surface spreading speed than top surface spreading speed. This implies that sweat spreads faster on the bottom surface of the fabric which is the surrounding environment. This would leave the wearer feeling dry next to their skin as the sweat has been evaporated. In contrast, PN2/L2 is a not an ideal situation for a wearer as the top surface spreading speed is faster compared to the bottom surface spreading speed. This would leave the wearer feeling wet next to skin and uncomfortable.

Furthermore, from Figure 4.42 and 4.43 it can be determined that PN2/L3 is the idyllic situation for the wearer as sweat spreads fastest on the bottom surface of the fabric assembly, leaving the wearer drier.

The accumulative one-way transport index (AOTI) for fabric assemblies PN1/L1,L2,L3 and PN2/ L1,L2,L3 are shown Figures 4.44 and 4.45.

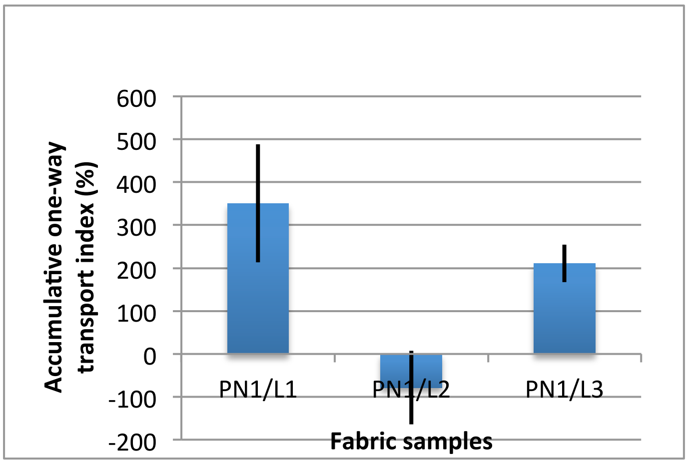


Figure 4.44 Accumulative one-way transport index for fabric assemblies PN1/L1,L2,L3

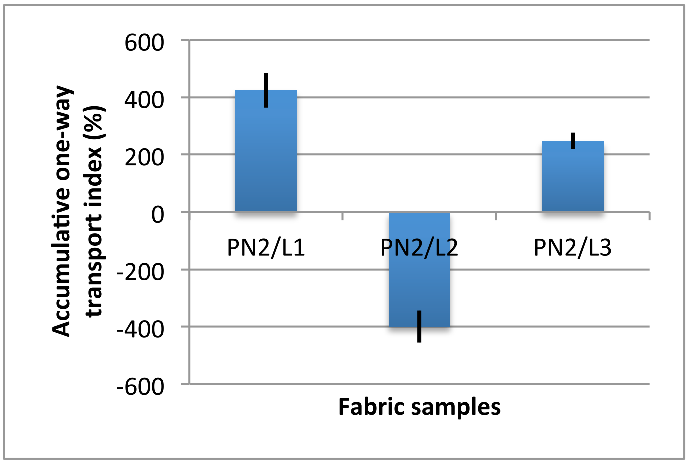


Figure 4.45 Accumulative one-way transport index for fabric assemblies PN2/L1,L2,L3

It can be seen from Figure 4.44 that, PN1/L1 has the highest AOTI followed by PN1/L3 and PN1/L2. This denotes that PN1/L1 has a better ability to transport moisture from the top surface of the fabric to the bottom surface of the fabric. A garment made from PN1/L1 will have quicker drying and evaporating capabilities than a garments made from PN1/L2 and PN1/L3. Moreover, Figure 4.45 indicates that PN2/L1 has a greater ability to transport moisture from the top surface of the fabric to the bottom, signifying a garment made from this fabric will have better evaporating and drying capabilities. Figures 4.44 and 4.45 displays that overall PN2/L1 has the superior AOTI, transferring moisture from the top surface to the bottom surface.

The overall moisture management capabilities for fabric assemblies PN1/L1,L2,L3 and PN2/ L1,L2,L3 are illustrated Figures 4.46 and 4.47.

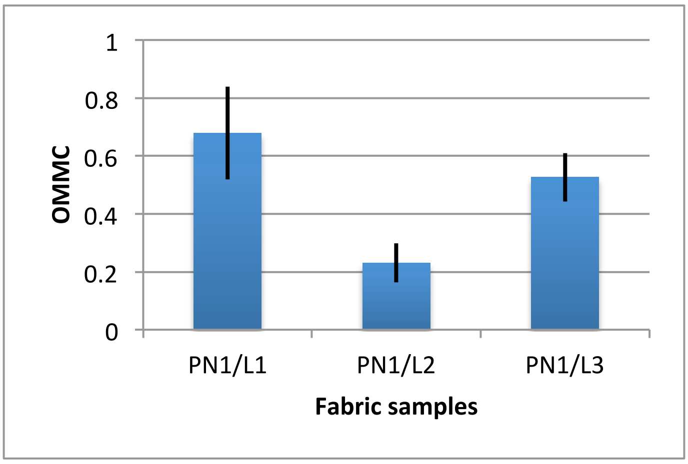


Figure 4.46 Overall moisture management capabilities for fabric assemblies PN1/L1,L2,L3

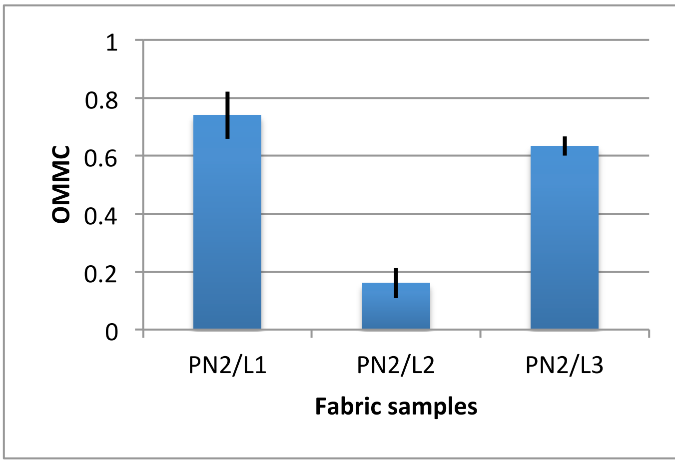


Figure 4.47 Overall moisture management capabilities for fabric assemblies PN2/L1,L2,L3

It can be determined from Figure 4.46 that, PN1/L1 has the overall best moisture management capabilities compared to PN1/L2 and PN1/L3. The principal factors that contributed to PN1/L1 having the best moisture management capabilities are highest bottom surface absorption rate, greatest bottom surface maximum wetted radius, fastest spreading speed and highest AOTI.

Figure 4.47 displays that PN2/L1 has the optimum overall moisture management capabilities. This is due to the fabrics assemblies ability to wet the bottom surface fastest once sweat has been dropped on the top surface and the capacity to transfer moisture from the top surface to the bottom surface of the fabric assembly. On the whole from Figures 4.46 and 4.47, it can be seen that PN2/L1 has the greatest moisture management capabilities due to being able to absorb, transport moisture from the top surface of the fabric to the bottom and spread to evaporate into the environment.

Overall, it has been determined that L2/PN1 is the best performing in terms of moisture management for fabric assemblies followed by PN2/L1. This is due to the ability to wet the bottom surface of the fabric assembly, absorb moisture in the bottom surface, spread moisture in the bottom surface and transfer moisture from the top surface to the bottom surface of the fabric assembly.

4.3.2 Summary for moisture management capabilities of experimental fabrics and their assemblies

As a single layer the brushed powernet fabric has the most outstanding moisture management capabilities compared with the other fabrics in a single layer. The bottom side of the non-brushed powernet wetted the fastest among all fabrics indicating that once the sweat was deposited onto the fabric (next to skin side), it quickly transferred from the top of the fabric (skin side) to the bottom of the fabric (away from the skin), which would keep the wearer drier. Also, the maximum wetted radius of the non-brushed powernet fabric was largest on both the top and bottom of the fabric. This demonstrates that the moisture spreads both on the inside and outside of the fabric. However, the ideal situation would be that the bottom surface has a larger maximum wetted radius compared with the top. Additionally, the spreading speed of the non-brushed powernet is faster on the bottom surface than the top, this indicates the sweat spreads to the maximum wetted radius the fastest on the bottom surface.

When a second layer is introduced as a fabric assembly, a well performing fabric still would enable sweat to be drawn off the skin quickly, given that the second fabric in the assembly is not going to significantly impede its performance. From the results, it can be seen that the fabric assemblies with lining next to the skin and powernet on the outside had the greatest moisture management properties. The fabric assemblies must wet the bottom surface of the fabric assembly, absorb moisture in the bottom surface, spread moisture in the bottom surface and transfer moisture from the bottom surface to the top surface to enable evaporation of sweat into the environment. This process will facilitate the fast removal of sweat from the skin of the patient thus keeping the patient drier and more comfortable. It is interesting to note that fabric assemblies with lining next to skin had the highest moisture management capabilities however, fabric assemblies with powernet next to the skin moisture management capabilities were lower than fabrics as single layers, which indicates that the introduction of a fabric assembly into a garment would only be worth while if the moisture management capabilities were superior than a single layer.

4.3.3 Thermal and water vapour comfort properties of experimental fabrics in single layers and fabric assemblies

Thermal resistance of experimental fabrics in single layers

The thermal resistance (R_{ct}) of single layer fabrics can be seen in Figure 4.48.

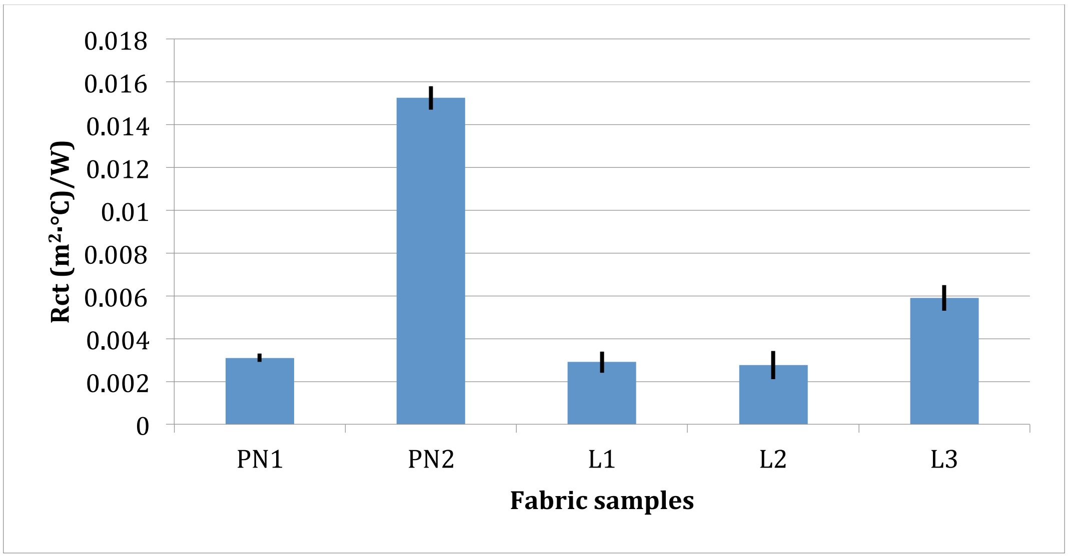


Figure 4.48 Thermal resistances of single layer experimental fabrics

Figure 4.48 determines that, PN1 has a considerably lower R_{ct} compared to PN2. This indicates that a garment made from PN1 would have a lower resistance to heat as it is easier to dissipate through the fabric next to skin and into the surrounding environment. The higher R_{ct} of PN2 could be due to the fabric construction, the back surface of PN2 is brushed. Air can be trapped in the construction that will add insulation as air has a high insulating property, this needs to be taken into consideration at the stage of garment construction when selecting a brushed fabric. It can also be noted that the thickness of PN1 and PN2 were the same, however, the R_{ct} of PN2 is higher this could be due to the brushed back. Also, PN2 has a lower optical porosity thus less heat will pass through the fabric compared to PN1. Furthermore, Figure 4.48 displays that L1 and L2 have a very similar R_{ct} and L3 has a higher R_{ct} compared with L1 and L2.

The overall thermal resistance for all single layers and their assemblies can be seen in Figure 4.49.

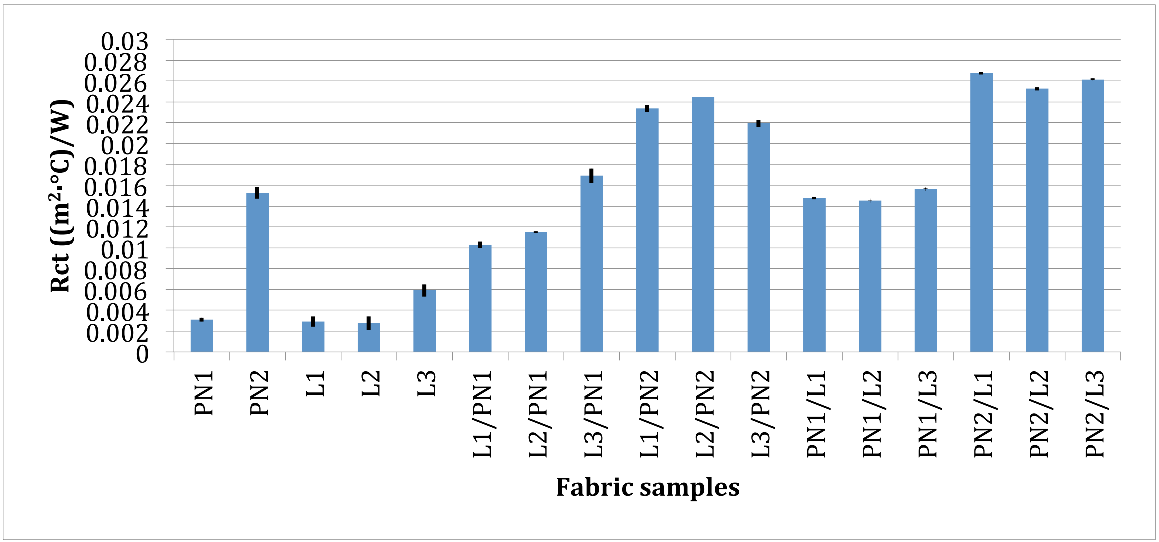


Figure 4.49 Fabric samples overall thermal resistance (Rct) in single layers and fabric assemblies

Figure 4.49 displays that for single layers PN1 has the lowest thermal resistance. This indicates that when a patient is wearing a garment made from PN1, the heat generated by the body can be easily dissipated through the fabric and into the surround atmosphere. The higher R_{ct} values of PN2 and L3 can be attributed to influencing parameters such as morphology of the components of fibres, the yarn structures and properties, the physical and structural characteristics of fabrics and the effect of finishing agents.

On the whole, Figure 4.49 illustrates that fabric assemblies PN2 have a higher thermal resistance compared to PN1 fabric assemblies. Also, Figure 4.49 shows that fabric assemblies PN1/L1 and PN1/L2 had higher R_{ct} values when compared with L1/PN1 and L2/PN1. This determines that fabric assemblies with lining next to the skin have lower thermal resistance and insulating properties, which is in turn good for the wearer as heat can be transported through the fabric into the environment. It is also expressed in Figure 4.49 that fabric assemblies PN2 lowest thermal resistance and insulation was when the lining fabric was next to the skin. This denotes that having lining next to the skin, the body will not have to use as much energy to release heat and will be able to dissipate and transfer to the atmosphere better than if the power net fabrics were next to the skin.

Water vapour resistance of experimental fabrics in single layers

The water vapour resistance (R_{et}) of single layer fabrics can be seen in Figure 4.50.

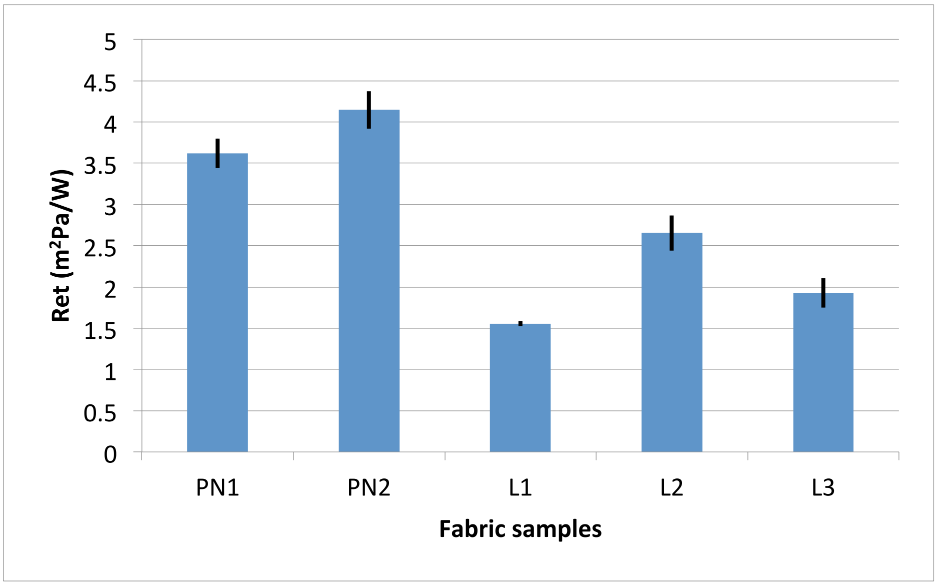


Figure 4.50 Water vapour resistances of single layer experimental fabrics

It can be determined from Figure 4.50 that, PN1 has a lower R_{et} compared to PN2. In terms of water vapour resistance a lower value is desirable as water vapour can be transported through the fabric and into the environment, thus resulting in drier skin and improved thermal comfort. Also, Figure 4.50 shows that a patient wearing a garment made from PN2 may perspire more than a person wearing garment made from a garment made from PN1, as the body will generate more heat and not allow perspiration to be evaporated from the skin and into the environment. The slightly higher R_{et} of PN2 could be due to the fabric construction which may allow less perspiration to pass through the fabric compared to PN1. Moreover, Figure 4.50 displays that L2 has the highest R_{et} followed by L3 and L1. This shows that L1 has the overall superior R_{et}, as water vapour can be conveyed through the fabric from next to the skin and be evaporated into the atmosphere. If a garment is lined with L1 it will result in the body of the patient feeling cooler and in a more comfortable state.

The overall water vapour resistance for all single layers and their assemblies can be seen in Figure 4.51.

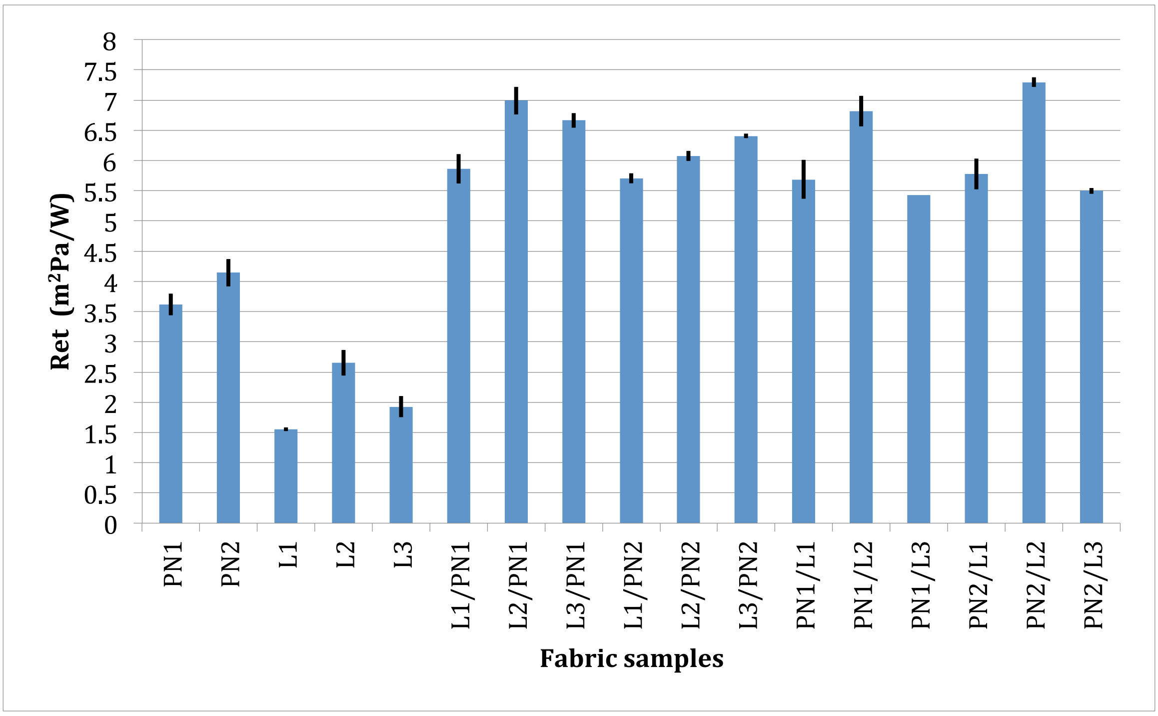


Figure 4.51 Fabric samples overall water vapour resistance (Ret) in single layers and fabric assemblies

Overall, Figure 4.51 exhibits that for single layers L1 has the lowest water vapour resistance. This indicates that perspiration generated by the body can be easily be dissipated through the fabric assembly and into the surround atmosphere. The higher R_{et} values of PN1 and PN2 can be attributed to influencing parameters such as morphology of fibres, yarn properties, the physical and structural characteristics of fabrics and the effect of finishing agents. Moreover, Figure 4.51 shows that fabric assemblies with L1, L2 and L3 next to skin and PN1 opposite the environment have higher R_{et} values when compared with L1, L2 and L3 next to skin and PN2 facing the environment. This indicates that garments made from fabric assemblies with PN2 will have a better ability to transfer perspiration through the assembly and into the surrounding atmosphere. Also, Figure 4.51 demonstrates that fabric assemblies with PN2 next to skin and L1, L2 and L3 opposite the environment have a higher R_{et} when compared with PN1 next to skin and L1, L2 and L3 facing the environment. This establishes that garments made from PN1 next to skin and L1, L2 and L3 fronting the environment, perspiration will be transported through the fabric and into the environment, resulting in drier skin and thus improved comfort. On the whole from all the fabric assemblies PN1/L3 has the lowest R_{et}. This signifies that as the temperature of a patient body rises, perspiration or sweat is produced to reduce high temperatures. As the perspiration is transported through PN1/L3 and is transmitted to the environment, the body temperature is reduced and the body feels cooler giving a better overall perception of comfort.

4.3.4 Summary for thermal and water-vapour resistance

For thermal resistance, it can be seen from the experimental results that a non-brushed powernet has the best dry heat transfer properties, this could be due to the back of the fabric not been brushed as air becomes trapped in the raised fibres which acts as an insulator. If a garment is constructed from a non-brushed powernet fabric; the heat generated by the body can be easily dissipated through the fabric and into the surround atmosphere. The different thermal resistance values of other fabrics can be attributed to influencing parameters such as morphology of the components of fibres, the yarn structures and properties, the physical and structural characteristics of fabrics. The fibres and fabric structure will have an impact on the thermal and water-vapour resistance due to how they allow heat and moisture to pass through the stature. Additionally, as fabric assemblies it is interesting to note that the addition of two single layers together equals the thermal resistance of the fabric assembly. In most cases the thermal resistance is slightly higher but marginal this could be due to the entrapped air between the two layers.

From the water-vapour characteristics it can be noted that a non-brushed powernet has the best water-vapour transfer characteristics, which could be attributed to the smooth surface of the next to skin side of the fabric compared with the brushed side of the brushed powernet as the heat and vapour will not become trapped in the fibres. Also, as in thermal resistance, the addition of two single layers together equals the water vapour resistance of the fabric assembly. Furthermore, for thermal resistance, fabric assemblies with lining fabric next to skin had a lower resistance and for water vapour resistance powernet fabrics next to skin had a lower resistance. This indicates that the end use of the garment would need to be taken into consideration to select the best fabric assembly.

4.3.5 Thermal and water vapour comfort properties of experimental garment

In order to fully understand the thermal behaviour of clothing systems, a thermal manikin with human features (ie. capable of generating heat and perspiration) was used in this experimental investigation. The two main properties of the clothing that affect the thermal balance between the wearer and the environment being investigated in this chapter are thermal resistance (R_{cf}) and water vapour resistance (R_{ef}).

Thermal resistance of experimental garment

The mean thermal resistance (R_{cf}) of the different sections of the experimental garment is shown in Figure 4.52. The segments of the garment match those of the thermal manikin (Figure 3.6).

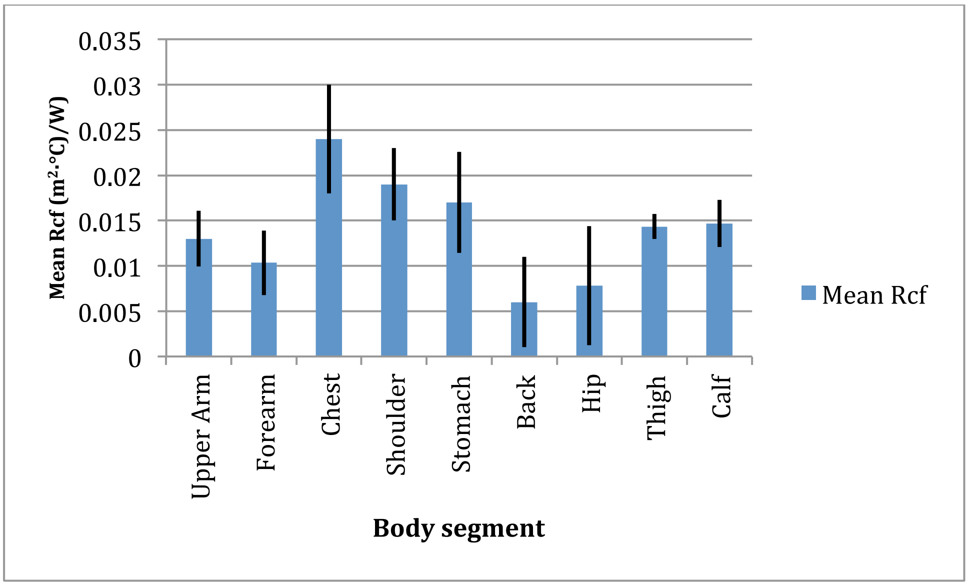


Figure 4.52 Mean thermal resistances of different segments of experiment garment

From Figure 4.52 it can be seen that different segments of the garment have significantly different thermal resistance. The R_{cf} is highest in the chest, shoulders and stomach segments: these regions are more curved out on the body and also due to the applied reduction in the garment pattern; the garment fabric is stretched more in these areas in comparison to other areas. The openings in the fabric stitch structure become bigger as the garment is stretched while worn on the manikin, consequently allowing more air to be contained in the structure, which leads to higher thermal insulation.

As the experiment was carried out at standard conditions (ASTM F1291, 2010), the required air velocity in the climatic chamber is minimal. Due to this the measured thermal resistance of the garment sections containing more still air is higher. The experimental results from testing to the standard methods in cases like the present one have to be carefully considered in a garment utility comfort aspects, where in reality the person and/or environmental air will be moving, resulting in higher heat transfer by convection as compared to 'still' air conditions. However these dynamic conditions were not a part of the current investigation and would have to be considered in future studies.

Furthermore, the zip on the chest/ stomach segments (Figure 3.1) could be contributing to higher R_{cf} of the corresponding segments. The thigh and calf segments have the overall highest surface area but a lower R_{cf} compared with the chest, shoulders and stomach which indicates that this could be due to the fabric stretch being lower in the thigh and calf segments. Also, the upper arm and forearm surface areas are comparable to the back and hips surface area. However, the R_{cf} of the upper arm and forearm is higher, which could be due to higher fabric stretch in these segments compared with the back and hips. The back and hips segments had the lowest R_{cf} this could be due to the lowest fabric stretch in these segments.

Water vapour resistance of experimental garment

The mean water vapour resistance (R_{ef}) of the different segments of the experimental garment is shown in Figure 4.53.

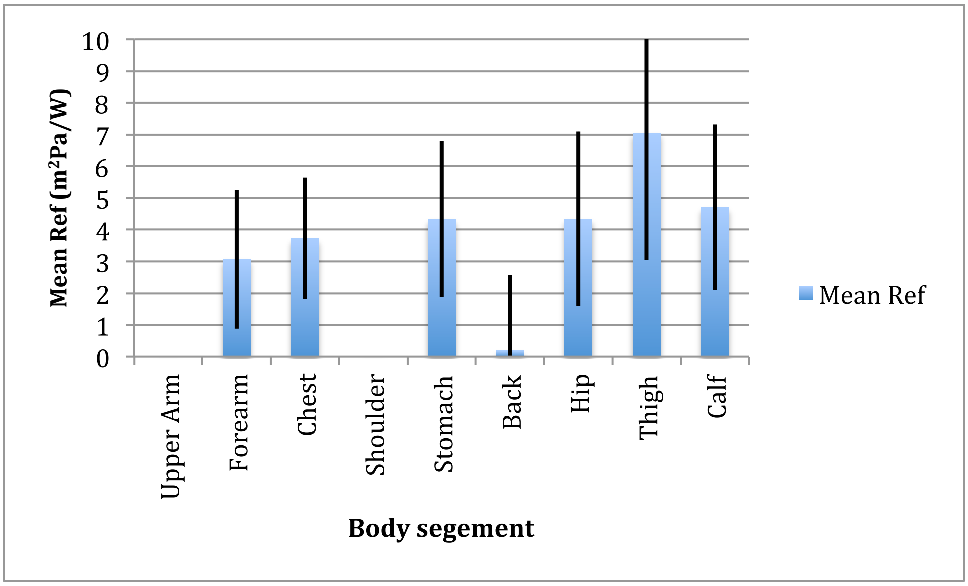


Figure 4.61 Mean water vapour resistance of different segments of experiment garment

From the experimental results it is clear that R_{ef} of different garment segments significantly differs from each other and there is substantial variability of experimental data, which can be seen from the error bars. From Figure 4.53 it can be determined that the R_{ef} for the upper arms, shoulders and back segments has minimal water vapour resistance. This could be due to the inconsistency of the sweating rate of the manikin which may lead to the drying of the upper segments and the accumulation of moisture in the lower segments of the manikin's body due to gravity. Also, the chest/ stomach segment (front of the manikin) had significant R_{ef}, whereas, R_{ef} of the shoulders/back segment (back of the manikin) is insignificant. This possibly indicates that the shape of the body and the geometry of the garment could influence the water vapour resistance of particular garments. The R_{ef} of the thigh segment is higher than other body segments because of higher moisture accumulation in this zone thus the R_{ef} would be higher. However, it is interesting to consider in case of the garment vapour resistance that the total vapour resistance R_{eT} for the medical compression suit was R_{eT}=22.33m^{2}Pa/W, while the total vapour resistance for the commercial polypropylene underwear of similar style is R_{eT} =27.51m^{2}Pa/W (Troynikov et al. 2013). So it would be fair to conclude that wearing a medical compression suit of this style would impart thermo-physiological burden on a wearer similar to wearing thermal underwear of the same style.

4.3.6 Summary of thermal and water vapour comfort properties of experimental garment

The thermal resistance of the garment is different in each segments of the body, which could be due to each of the body segments being a different surface area and curvature. This fact has to be taken into consideration during compression garment design and construction. Evidently the 'reduction factor' and the elastic properties of the materials are key to pressure generation by the garment, however their implication on parameters relevant to garments thermo-physiological comfort have to be considered. The limitations of the study include the 'still' air conditions where there is no air movement over the garment.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The research methodologies adopted and developed in this study lay a practical foundation for the evaluation and selection of the materials for effective and comfortable therapeutic pressure garments. The purpose of this study was to evaluate and compare functionality attributes of knitted fabrics used in garments for scar management and venous insufficiencies, in terms of their elastomeric performance and thermo-physiological comfort attributes in both single layers and as fabric assemblies.

In the present research six commercial knitted experimental fabrics were selected to be evaluated and compared for their elastomeric performance and comfort attributes in both single layers and as fabric assemblies. The physical parameters of mass per unit area, thickness, stitch density, optical porosity and air permeability were determined for single layers and fabric assemblies.

The elastic characteristics of experimental fabrics were tested at 25%, 40% and 60% strain to determine their relevant elastic attributes at each strain applied. Additionally, the fabrics were tested for tension decay. It is demonstrated from the elastic characteristics that the most powerful fabrics are the powernet fabrics in both the warp and weft direction as single layers. The brushed powernet didn't exert as much stress to be extended as the non-brushed powernet, which could be due to the brushed powernet having 8% less elastane and also due to fibres being not as aligned as in non-brushed fabric due to brushing. The powernet fabrics would be able to generate the most pressure on the underlying limb of the patient wearing a garment made from these, compared with the lining fabrics due to their strong elastic characteristics. Quantification of elastic attributes of the fabrics enables the design and engineering of therapeutic pressure garments to specific reduction factors, which in turn provide the required pressure application to underlying body of the wearer.

When a second layer of fabric was introduced as a fabric assembly, the power of the assembly increased in comparison to single layers in the warp and weft direction for both powernets, however, the non-brushed powernet still generated the most power in the warp and weft direction. Also, garments wouldn't be expected to be constructed from tricot fabrics alone; these fabrics may be introduced into garments as inner or outer linings to enhance the next to skin comfort of the patient or enhance the aesthetics of the garment with, for example, placement of print on the outside. Additionally, by layering pressure garments, pressure can be increased in severe cases of venous diseases and it would also be possible to better vary and engineer the layers to deliver more precise pressure to the underlying limb and a smooth next to skin feeling for the patient. The experimental tension decay characteristics of the powernet fabrics can determine that at the equal stress applied, in the weft direction there was a higher tension decay exhibited as compared to that in the warp direction. In the weft direction, the higher tension decay of the fabric will result in a considerable drop in pressure generated by the garment on the underlying limb of the patient, so fabric should be closely examined for these performance attributes at the stages of fabric selection and garment engineering.

The thermo-physiological comfort characteristics of fabrics were also determined. It was discovered that on the whole for moisture management capabilities, a single layer of brushed powernet had better moisture management capabilities compared with other fabrics. The bottom side of the non-brushed powernet wetted the fastest among all fabrics indicating that once the sweat was deposited onto the fabric (next to skin side), it quickly transferred from the top of the fabric (skin side) to the bottom of the fabric (away from the skin), which would keep the wearer drier. Also, the maximum wetted radius of the non-brushed powernet fabric was largest on both the top and bottom of the fabric. This demonstrates that the moisture is able to spread both on the inside and the outside of the fabric. However, the ideal situation would be that the bottom surface has a larger maximum wetted radius compared with the top. Additionally, the spreading speed of sweat for the non-brushed powernet is faster on the bottom surface than the top, this indicates the sweat spreads to the maximum wetted radius the fastest on the bottom surface. Most likely this is due to the effectiveness of applied moisture management treatments, however having additional fibre filaments on the brushed side of the fabric might play a role.

When a second layer is introduced as a fabric assembly, a well performing fabric when next to skin still would enable sweat to be drawn off the skin quickly. From the experimental results, it was concluded that the fabric assemblies with lining next to the skin and powernet on the outside had the greatest moisture management properties. The fabric assemblies must wet the bottom surface of the fabric assembly, absorb moisture in the bottom surface, and transfer moisture from the bottom surface to the top surface to enable evaporation of sweat into the environment. This process will facilitate the fast removal of sweat from the skin of the patient thus keeping the patient drier and more comfortable. It is interesting to note that fabric assemblies with lining next to skin had the greatest moisture management capabilities, however, fabric assemblies with powernet next to the skin moisture management capabilities were lower than fabrics as single layers, which indicates that the introduction of a fabric assembly into a garment would only be worth while if the moisture management capabilities were superior than a single layer.

In terms of thermo physiological performance attributes, the study demonstrated that a non-brushed powernet has the best dry heat transfer properties, which could be due to the back of the fabric not been brushed as air becomes trapped in the raised fibres in brushed fabric which acts as an insulator. Also, the non-brushed powernet has a more open structure and higher optical porosity compared with other experimental fabrics allowing more air to trap in the structure. If a garment is constructed from a non-brushed powernet fabric; the heat generated by the body can be easily dissipated through the fabric and into the surrounding atmosphere. When a fabric assembly is introduced the thermal resistance rises. Additionally, for fabric assemblies it is interesting to note that the addition of two single layers together seem to equal the thermal resistance of the fabric assembly. In most cases the thermal resistance is slightly higher than the addition of two single layers but it is marginal; this could be due to the entrapped air between the two layers.

From the water-vapour characteristics it can be noted that a non-brushed powernet has the best water-vapour transfer characteristics, which could be attributed to the smooth surface of the next to skin side of the fabric compared with the brushed side of the brushed powernet. The non-brushed powernet has a more open structure and higher optical porosity compared with other experimental fabrics which allows more water-vapour to pass through the structure. Also, as in case of thermal resistance, the addition of two single layers together equals the water vapour resistance of the fabric assembly. Furthermore, for thermal resistance, fabric assemblies with lining fabric next to skin had a lower resistance and for water vapour resistance powernet fabrics next to skin had a lower resistance. This indicates that the end use of the garment would need to be taken into consideration to select the best fabric assembly for the end use.

Furthermore, when the garment made of non-brushed fabric was investigated for thermal comfort attributes on thermal manikin Newton, the thermal resistance of the garment is different in different segments of the body, which is due to the fact each of the body segments being a different surface area and curvature. This fact has to be taken into consideration during compression garment design and construction. Evidently the 'reduction factor' and the elastic properties of the materials are key to pressure generation by the garment, however their implication on parameters relevant to garments thermo-physiological comfort have to be considered.

The limitations of this study were for thermo-physiological comfort attributes experiments, fabrics were only tested in a relaxed state. Also, thermo-physiological comfort attributes for the garment were only considered in static air conditions where there is no air movement over the garment.

5.2 Recommendations

As a result of the present research the following recommendations can be made:

- To assist in the recovery of patients with scar or venous insufficiencies, powernet fabrics would provide the highest pressure to the underlying limb of a patient.
- If moisture management was a concern for patients, brushed powernet fabrics would provide the most comfort garment in terms of moisture management as a single layer. For a fabric assembly linings next to skin and powernet fabrics on the outside would provide most comfort in terms of moisture management and elastic attributes.
- If thermal or water vapour resistance was a concern for patients, a garment made from a non-brushed powernet would be suitable.
- To asses thermo-physiological comfort attributes, fabrics should be tested further in an extended state.
- Testing garment in dynamic conditions to assess the thermo-physiological comfort attributes more close to the real wear conditions would be beneficial.
- More detailed investigation into possible correlations between chosen performance attributes, physical parameters and layering of the garments would also be beneficial

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