DOI: 10.26717/BJSTR.2017.01.000309
N Gokarneshan. Biomed J Sci & Tech Res

BIOMEDICAL Journal of Scientific & Technical Research
ISSN: 2574-1241

Case Report

Open Access

Design of Compression/Pressure Garments for Diversified Medical Applications

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Received: August 12, 2017; **Published:** August 29, 2017

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Abstract

Compression garments have been extensively in varied medical and sports applications. The article critically reviews the design aspects of knit compression garments for suitability in sports and medical applications. The influences of physical attributes of suitable knitted fabrics on the amount of pressure generated on the underlying body have been studied. The tensile properties of the knit fabrics having various orientations to stretch, predictive pressure generated by compression garments have been primarily considered. Subsequently a method of validating the reliability of laplace law for calculating applied pressures for calculation of applied pressures that are generated by compression garments have been highlighted. Modeling of compression garments has been done with the intended value of unit pressure for the body circumference of a variable curvature radius. The basis of modeling considered can be applied in designing compression garments supporting external treatment such as after burn therapy and lymphadema. The physical and mechanical properties of nylon/spandex knitted fabrics used as commercial medical compression garments have been analyzed. The findings help to understand whether a fabric is suitable for engineering compression garments and also for estimating the required compression force for designing an individualized compression with the medical compression fabrics. The dynamic pressure attenuation of compression garment is studied experimentally. The findings enable a better understanding of the characteristics of elastic fabric used for making compression garments, and prove useful for medical practitioners with scientific developments and for effective applications. The physical and mechanical properties of nylon/spandex knitted fabrics as commercial medical compression garments have been investigated. Specifically fabric elasticity and bursting strength have been studied to show the applicability of the fabrics for providing satisfactory compression. Such study is necessary to understand whether a fabric is suitable for engineering compression garments and also for estimating the required compression force for designing an individualized compression garments with medical compression fabrics. Study has been carried out to evolve an effective design and development of various high stretch compression products by analyzing fabric size, stretch properties and clothing pressure for different knit structures.

Keywords: Compression Garment; Design, Laplace Law; Medical Applications; Model; Polyester Single Covered Yarn; Pressure; Sports Applications

Introduction

Over a period of time the compression garments have been tried out by athletes in sports as an ergogenic, performance improvement and recovery aid. Advantages such as improved blood flow, better muscle oxygenation, reduced fatigue, faster recovery, reduced muscle oscillation and reduced muscle injury have been reported for most of the commercial branded garments presently available for sport applications. Few works have reported in identification of performance effects and the related physiological mechanisms related to such types of garments [1-3]. A unit pressure applied on the parts of the covered body is a crucial factor of compression garments that supports the process of external therapy. Based on the kind of therapy, the range of values of this factor is determined from the medical aspect. The range should be complied in practice [4-9]. Compression garments are used for operational reasons, like in the case of tight-fitting garments or girdles, or medical reasons, like medical stockings or bandages in the treatment of venous ulceration, deep vein thrombosis or burns [10]. Compression garments have been used to apply a defined pressure to the body for various reasons like in the case of medical, sports and body shaping purposes [11-18]. In the area of medical applications they have been used in the treatment of burns (scar management), low blood pressure, muscle strains and sprains. They have also been used to accelerate the healing process and prevent deep vein thrombosis during long haul flights. Garment pressure is an essential component of clothing comfort [19]. An appropriate clothing pressure maximizes the efficiency of physical exercise and heals hypertrophic skin burn scars. The degree of clothing pressure depends on material, design, wearing type, and physical features; in addition, stretch properties represents a significant mechanical property of clothing material that influences clothing pressure. Stretch properties are measured as the percentage of fabric stretch and fabric growth, recovery.

Factors determining usefulness of compression garments in sports

But there is no known report available which quantifies pressure produced by such garments and the interactions between the garment and the underlying body of an athlete. It has been found that the fastest venous flow would occur at an optimal mercury pressure gradient of 18mm at the ankle, 14 mm at the calf, 8 mm at the knee, 10 mm at the lower thigh and 8 mm at the upper thigh [20]. In the case of commercial branded sport garments the graduated mercury pressures generated lies between 19.0-30.0 mm at the ankle to 17.6-25.0 mm at the calf and to 9.1-18.0 mm at the thigh [21,22]. However, no research has justified such claims. The extent of pressure created by a compression garment is based on complex interrelation between the following key parameters:

a. The garment fit and construction

b. Structure and physical properties of its materials

c. The size and shape of the part of the body to which it is applied, and

d. The type of the sport activity involved.

Available research pertaining to the use of compression garments for treatment of the hypertrophic scars shows that prediction of the magnitude of the pressure that can be applied to a cylindrical body of known radius by applying specific amounts of tension to an external fabric covering can be done by applying the Laplace law formula [23].

Considerable work has been done on sport compression garments relating to the benefits of the graduated pressure generated from the ankle section to the thigh section, which is found to decrease. Also the garments have been found to be robust. As per laplace formula, the ratio of the tensile force to circumference for a given fabric represents a quantitative measure of the relevant structural properties of that particular fabric. A tight fitting fabric relates to a high ratio and a looser fitting relates to a low ratio [24]. Test fabrics having a greater ratio created higher predictive pressure on the underlying athlete's limbs. This single quantitative measure may provide an approximation of many fabric properties that are relevant in the design of compression and general sport garments, and may provide insight for the development of a predictive model for the behavior of garments under tension. But, owing to the nonlinear dynamics of stretching and deformation in fabrics and garments, the ratio (tensile force/circumference) may not be constant over a whole garment over time. But, the ratio measurement can prove useful in garment design for any particular region of interest. Since majority of the fabrics will lose a considerable amount of their initial tension overtime owing to fabric fatigue that leads to decrease in applied pressure, the predictive pressure value is only relevant during the time of application. In a compression garment the extent of predictive pressure created are strongly influenced by garment construction, fabrics used, garment fit and positioning on an athlete's body. The actual pressure values will be different from the calculated predicted pressure values and will have a non uniform distribution since an athlete's limb will show a marked difference in radius at different points around its circumference. In order to predict and measure the pressure created by compression garments more developed is necessary. A comprehensive methodology based on 'state-of-the-art' pressure sensors and pressure mats with associated electronics, data acquisition, and processing software has been jointly developed. A full mapping of pressure caused by compression over the entire body can be achieved.

Modelling and Designing of Compression Garments

In the case of therapies for varicose veins the range of unit pressure values the most unambiguous. The pressure values are divided into four phases based on the severity of the disease [25]. The human body comprises of many parts that have almost circular or elliptical cross section. Reported works relating to the modeling of a unit pressure are based on the model of the human body, wherein its circumferences are considered to be circles [26-29]. In the case of a cone, finite element method has been used for the results of modeling the unit pressure [27]. The finite element method has also been used, as a second option after the analytical model using the Laplace law, for compression bands covering a cylindrical model of the body part [29]. The experimental assessment of unit pressure is another research area related to the application of compression garments. The experimental techniques involving developed measurement procedures normally utilize the Laplace law [29,30]. The modeling has been aimed towards finding out the dependencies of the dimensions of knitted fabric in a free state as a function of mechanical parameters thereof, the unit pressure necessary and the value of circumference of the body covered and its geometrical factors. In order to design knit compression garments of required pressure, the derived dependencies of the dimensions of knitted compression garments in a free state form the basis, and used in the following cases:

a. For body parts of circumferences in the form of a circle

b. For body parts of circumferences of different curvature radius.

The following assumptions are made

a. Laplace law forms the basis of modeling the pressure.

b. ii. Forces in the knitted fabric along the circumference of the human body are constant, as they are equalized during use.

c. During the relaxation phase in the 5^{th} cycle of hysteresis of stretching and decompressing the mechanical characteristics of the knitted fabric should be known, that is, the relation of the force in the band and relative elongation determined for the values of these parameters.

d. In the case of circumferences of the human body having various curvature radii, the unit pressure can be found out with the intended value only for a chosen part of the circumference, which can be expressed by a part of the circle – the known value of the curvature radius for this part of the human body is required

e. The susceptibility of the body to the action of unit pressure is omitted.

In the design of knit compression garments of required unit pressure, the final effect of modeling to determine the dimensions of knitted fabric in a free state forms the basis. An analytical model has been developed for determining the dimensions of circumferences of compression garments in a free state for circle-shaped cross sections of the body.

An elaborate study of this model and its empirical verification has been described [28]. The fundamental equation that explains the relationship between the unit pressure on a cylindrical model of given circumference and circumferential force in a band of given width is given by the Laplace law. Investigations on the mechanical properties of typical knitted fabrics designed for compression garments showed a general relation between the force and relative elongation in the decompression phase after the 5th stretching cycle. There is dependence for the circumference of knitted fabric in a free state as a function of pressure and circumference required for a certain characteristic of knitted fabric. In the case of after burn therapy and lymphedema, compression garments that support the process of external treatment do not provide a constant unit pressure along the circumference of individual body parts with varying curvature radii. The curvature radius has to be taken into account at a point subjected to press therapy in the procedure of designing the product, so as to satisfy the needs pertaining to providing a certain value of unit pressure in the place of hypertrophic scars (keloids) for parts of the body with different curvature radii of the circumference [31]. The value of circumference of knitted fabric in a free state has been determined by an equation. Some geometrical factors have been considered in sample calculations of unit pressure made for the circumference of a body in the form of an ellipse as well as a circle of specific radius. The intended unit pressure differed in these cases.

Properties of Medical Compression Fabrics

When a burn injury has healed, the skin often scars due to production of collagen, and is hard and dark in color. Application of pressure using a compression garment can possibly enable to flatten the scar, though it cannot be sufficiently proved to support the widespread use of pressure garment therapy for the prevention of abnormal scarring after burn injury [32]. Compression garments can increase blood flow by compressing the body muscles, and thereby enhances performance, decreases the risk of injury, and accelerates muscle recovery during and after exercise. Thus the use of a compression garment, specifically a gradual compression garment, in sports activities is a common trend, and many professional players and athletes already wear compression clothing on a regular basis. There is a good demand for compression garments used as shapewear to improve body image, like creating attractive contours, lifting breasts, and decreasing abdominal size. They are worn under normal loose fitting clothing. The majority of medical compression garments are individually designed and produced for a specific part of the body, like stockings, gloves, sleeves, face masks and body suits. They have been worn for a specific period, based on the requirement of medical treatment. A compression garment usually has lesser circumference than that of the human body. The garment can be stretched as per the need, enabling optimum compression to be achieved. Based on the requirement, special garments are also used to provide targeted compression on particular groups of muscles. The pressure usually exceeds the capillary pressure, 24 mmHg, though good results can also be obtained with a low level of compression (5{15 mmHg) [33].

The level of compression is governed by the garment size as well as the amount of fabric stretching. Fabrics for compression garments are usually engineered with stretchable structure and containing elastomeric material to achieve highly stretchable and appropriate compression. In the case of compression garments elastic recovery is considered crucial performance index. As a fabric is stretched to a degree lower than its breaking strength and is then permitted to recover, the fabric normally does not immediately regain its original shape. Its elastic recovery depends on the compression force provided, the length of time that the force is applied for, and the length of time that the fabric is allowed for recovery. The durability of every compression garment is expected to last for at least several months. For instance, compression garments for preventing hypertrophic scarring after severe burns can be used for a period of up to 2 years. Fabric fatigue occurs when a fabric is repeatedly stressed at a force level less than that needed to cause failure in a single application. For compression fabrics, the residual extension should be as small as possible after fatiguing. It is therefore essential that compression garments maintain good durability and do not stretch out of shape after repeated wear and laundering. The objective has been to evaluate and better understand the mechanical properties of some knitted compression fabrics used for making long lasting compression garments.

The properties of medical compression fabrics made from Nylon/Spandex have been investigated. The fabrics have been knitted with an open structure having stable dimensions, and Spandex is only present in the wale direction [34]. Tensile evaluation has shown that the compression fabrics are strong and having a breaking load above 200 N, and possess excellent stretch ability with breaking extension well above 200% in wale as well as course directions. The stretching force of the fabric is proportional to extension as it is stretched to below 100% elongation. Also, the fabrics exhibit high bursting strength and extension which are well suited for use as compression garments. After fatigue stretching, the average immediate recovery of compression fabric is more than 95% and the average elastic recovery after an extended period of relaxation (1{24 hours) is at least 98%. The compression fabric shows only about 2% residual extension after 3 week service and a few hours relaxation.

Practical Studies On The Dynamic Pressure Attenuation Of Elastic Fabric For Compression Garment

In order to assess the comfort, function and security aspects of the compression garment, garment pressure is considered an important aspect. Normally, the comfortable properties of garment comprise of heat–moisture comfort, tactile comfort and pressure comfort. The moisture management behavior and water vapor permeability of various knitted fabrics have been studied and related to their heat–moisture comfort [35,36]. Investigations have been carried out relating to the comfort properties such as air permeability, water vapor transmission rate and thermal behavior, with regard to elastic fabrics at extension levels from 0% to 60% [37]. The pressure threshold of discomfort has been found to be around 70 g/cm^2 which were close to the average capillary blood pressure of 80 g/cm^2 near the skin surface [38]. The pressure comfort zone for the normal condition is less than 60 g/cm^2. An inappropriate compression garment will affect the energy, work efficiency and health of the wearer. Insufficient pressure will limit efficiency, and perhaps reduce the aesthetic appeal of the garment, while too much pressure will result in reducing heart and lung functions, and perhaps cause serious damage to health [39,40]. The garment pressure is divided into static pressure and dynamic pressure. Static pressure is defined as the pressure exerted on a special area of human body when the compression garments have no additional deformation, while dynamic pressure is defined as the pressure exerted during the multi-dimensional deformation of compression garments [41]. Compression garments are produced from elastic fabric. Their crucial properties are elasticity and recovery, since they are able to exert continuous pressure on the human body. The stretch and recovery characteristics of two types of knitted fabrics have been studied at various extension levels, and found that spandex plated cotton fabric is more excellent in dynamic elastic recovery than spandex core cotton spun fabric [42]. The fineness of spandex and yarn structure has effect on its elastic recovery percentage [43].

The stretch and recovery properties of all-cotton, nylon, and polyester/spandex core stretch fabrics have been investigated. It reveals that yarn type and inter fiber friction can significantly influence the stretch and recovery properties [44]. Apart from elasticity and recovery, elastic fabric also shows a phenomenon of hysteresis, which is the stress relaxation of an elastic fabric after it has been subjected to repeated stretching and recovery [45,46]. The stress relaxation phenomenon was first observed by Ng, he found that all samples had relaxed their stress significantly, and the degree of stress relaxation would also increase with lengthening the time that a sample was under stretching [47]. It has also been found that under constant deformation fabrics having a high percentage of elastic yarns had serious stress relaxation problems [48]. Stress relaxation cam result in pressure degradation. Studies have shown that the change in clothing pressure has been mainly based on its biaxial extension and stress relaxation properties. The tension decay and pressure decay of a tubular elastic fabric has been theoretically studied [49]. The relation between clothing pressure of knitted fabrics and stress under extension and recovery processes by simultaneous measurements has been established [50]. The pressure behavior of tubular knitted fabrics has been studied after 48 hours at various levels of extension. The findings show that stitch length and extension rate are the considered crucial in affecting its interfacial pressure and decrease of pressure [51]. As the compression garment had to be worn continuously for about 23 hours a day, the fabric was correspondingly under stress at a given extension level over a prolonged period of time before such tension was released [52]. Views of doctors, therapists and patients support their findings: they comment that the pressure of elastic fabric is time-dependent, so that slackening occurs in compression garments when patients wear them over a period of time [53]. Hence the decay of pressure can influence the effectiveness of compression therapy.

Briefly stated, major portion of the studies related to the stress relaxation and static pressure, ignoring the dynamic pressure performance. It has been established that the dynamic pressure performance is more important than it was realized to date [54]. The human body is always in a state of relative movement: even sitting, knee flexion deformation frequently changes between 60o and 120o [55]. Garments adapt to human movement by relatively sliding and partially stretching between garment and human body. It has been found that under conditions of wear the pressure functional performance of compression garment is an integrated effect arising from the multidimensional deformations of its knitted fabrics that are closely related to their multi-mechanical behavior like stretching, shearing, bending and type of fabric surface [56,57]. Since every type of compression garment has its own characteristics based on the material, fabric structure and knitting method, one should be familiar with them for their suitability for applications. Hence, the dynamic pressure attenuation has been experimentally studied. Studies have been carried out relating to the influences of spandex feeding rate and the fabric structure of elastic fabric. Such findings enable a better understanding of the characteristics of fabrics used for making compression garments, and are beneficial for medical practitioners with scientific developments and for effective end uses.

The dynamic pressure attenuation has been studied experimentally. The influences of fabric factors on dynamic pressure at 1st test cycle and on dynamic pressure attenuation have also been studied.

a. With the increase in the feeding rate of spandex, the dynamic pressure of plain knitted fabrics increases within 20% extension. The dynamic pressure of the fabrics is reduced with the increase in spandex feed rate, between 25% to 40% extension. In the case of rib knitted fabrics, the dynamic pressure increases with the increases in the spandex feeding rate at all extensions between 10% and 40%. The plain fabrics show higher dynamic pressure than rib fabrics at all the extensions.

b. There is decrease in the dynamic pressure with the repeated extension and recovery. The pressure attenuation of the fabric increases with the variation in the extension level between 10% to 40%. At the 10% extension, samples 3-6 have the similar dynamic pressure attenuation. With the increase of the feed rate of spandex the dynamic pressure attenuation of plain fabrics is reduced at extensions 20%, 25%, 30% and 40%. At an extension of 40%, the rib fabric shows less pressure attenuation due to more feed rate of spandex. At extensions of 10%, 20%, 25% and 30%, the dynamic pressure attenuation of all the rib knitted fabrics is subtle, and the difference value is less than 25 Pa. The plain fabrics exhibit greater dynamic pressure attenuation than those of the rib fabrics having same feed rate at the same levels of extension levels. The findings enable a better understanding of the characteristics of elastic fabrics used for making compression garments, and prove useful for practitioners with scientific developments and for effective end uses [58]. Further study is required to extend the study of pressure attenuation to real trials, and to study the deformation of human body under external compression.

Properties of polyester SCY knit fabric

There are two kinds of stretch fabric in use, namely, comfort stretch (25-30 %) and power stretch (30-50 %) [59]. Stretch fabrics find particular applications in the design of active sports clothing, swim suits, and athletic clothing. In some of the present applications, power stretch fabrics should have higher extensibility and faster recovery. Compression therapy utilizes medical compression garments and functional body shaping underwear design that are made with high stretch fabric. Fabric elasticity is based on fiber extendibility and structure. A knitted fabric has better elasticity than a woven fabric owing to an interloped structure. In the knit fabrics when a loop is pulled horizontally it extends by the whole length, whereas when a loop pulled vertically it extends by half its length [60]. Human skin can be extensible from 20 to 200 % due to physical movement. Hence, compression materials can be developed that can exert the exact required pressure on the body utilizing the elasticity of knitted fabric. But, in designing compression products a suitable structure has to be chosen, arranged and used for particular body parts since various knit structures exhibit various stretch properties even in the same fabric. The clothing and material stretch properties have been well researched by a number of researchers. In the garment patterns using knitted fabrics the relationship between mechanical properties of material and clothing pressure, and the influence of clothing pressure on the body, serve as an example [61-71]. But, little research has been reported on the relation between structural characteristics of high stretch knitted fabric and clothing pressure. High stretch knitted fabric is often used as a material for the compression garments because compression garments should fit very tightly to apply a firm and even pressure on skin. The pressure level of high stretch knitted fabric depends on knit structure, yarn composition, and knitting type; however, little is known about the correlation of fabric size, stretch properties, and clothing pressure of high stretch knitted fabric [72].

Earlier research has discussed the type of knit structure and characteristics of commercially available compression garments [71]. Also the knit structures have been classified into four groups with regard to terms of three primary knit loops. The discussion herein facilitates the design of high stretch compression garments and the development of various products by analyzing dimension features, stretch properties, and correlation of clothing pressure for high stretch knitted fabric to offer a proper knit structure appropriate for the demands of phased compression. The manner in which clothing material interacts with the human body relates to garment pressure, and depends on the way in which material stretches and recovers vis-a-vis fabric structure. Such investigation compares the size and stretch properties of high stretch knitted fabric having various structures and studies the correlation with clothing pressure. Shrinkage takes place in both course and wale-wise directions of knitted fabrics as yarns are drawn closer together by the floats. Yarn overlapping caused release in course wise and shrinkage in wale-wise due to tuck. There has been greater influence on the weight and thickness of knitted fabrics due to high density caused by shrinkage in the course-wise due to floating of yarn rather than overlapping [69].

Decrease in elasticity in course wise direction has been due to miss of yarn, which on the other hand increased wale-wise elasticity of high stretch knitted fabrics. But, the elasticity in either directions decrease due to overlapping of yarn. In elastic recovery, the gap of recovery value among knitted specimens was lower at 1 h than at 60 s with no significant recovery value change. Hence, the stretch properties have been influenced by size change of knit structure. Measurement of clothing pressure in knit structure showed that the clothing pressure value of 'PF' was higher than 60 % that of 'P'. But, no significant pressure value change has been observed between 'PT' and 'P'. The dimensional change in course-wise had more effect on clothing pressure than in wale-wise for the correlation among fabric size, stretch properties and clothing pressure. Thus, a smaller size course-wise leads to higher clothing pressure. 'PT' had slightly higher value than that of 'PF' for elastic recovery. The clothing pressure value of 'PF' was higher than 'PT'; because weight and thickness change of 'PF' was heavier and thicker than the 'PT' that exerted a strong influence on clothing pressure vertically press down on the body. An appropriate knit structure and arrangement approach has been proposed in consideration of fabric size and stretch properties of high stretch knitted fabric and correlation with clothing pressure. The findings of the study proves that a variety of clothing pressure effects could be implemented by a combination of knit structure using principles of knitting and a proper knit structure arrangement when designing compression garments based on economics. A useful market data has been provided for the effective development of more diverse garment compression-related products along with the localization of manufacturing for functional and medical compression garments.

Conclusion

Compression garments have gained importance in sports and medical applications. The influences of physical attributes of suitable knitted fabrics on the extent of pressure created on the underlying body have been studied. The reliability of laplace law has been validated for calculation of applied pressures which are generated by compression. Such a study is beneficial in sports applications. Compression garments have been modeled and designed having unit pressure assumed for body circumferences of a variable curvature radius and finds useful in designing compression garments supporting external treatment such as after-burn therapy and lymphadema. Compression garments apply pressure to the body to provide health bene¯ts, such as increasing the blood circulation, shaping the body and supporting healing after medical procedures. Fabrics used for compression garments are elastic, and the amount of fabric stretching and the ability of maintaining the stretching force are directly related to the compression effectiveness. However, there is currently little information about the fabric and its mechanical properties, and there is a demand from compression garment manufacturers to better understand the fabric properties and their serviceability. Study of the fabric physical and mechanical properties become crucial to understand whether a fabric is suitable for engineering compression garments, and also for estimating the required compression force for designing an individualized compression garments with the medical compression fabrics. The constant pressure of compression garments exerted on human body is very essential, and the success of the application is extremely dependent on this pressure. However, elastic fabric has a characteristic of hysteresis which contributes to the pressure decay during wearing. Studies on the dynamic pressure attenuation of elastic fabric provide a better understanding of characteristics of elastic fabric used for making compression garments, and are beneficial for medical practitioners with scientific developments and for effective applications relating to treatment of venous ulceration, deep vein thrombosis or burns. Attention has been focused towards an effective design and development of various high stretch compression products by analyzing fabric size, stretch properties, and clothing pressure for various knit structures. Dimensional change in course-wise had a greater effect on clothing pressure than in wale-wise in the correlation among fabric size, stretch properties and clothing pressure. Weight and thickness change exerted a strong influence on clothing pressure which vertically presses down the body. The clothing pressure value of knitted specimen having a lower stretch ratio was higher in course-wise direction.

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