

**STUDIES ON THE CHARACTERISTICS OF ELASTIC
KNITTED FABRIC TUBES AND THEIR INFLUENCE
ON PRESSURE GENERATION**

by

MOUMITA BERA

Department of Textile Technology

Submitted

in fulfilment of the requirements of the degree of

Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

June 2013

Dedicated to my mother

Tripti Bera

CERTIFICATE

This is to certify that the thesis titled '**Studies on the Characteristics of Elastic Knitted Fabric Tubes and their Influence on Pressure Generation**', being submitted by **Ms. Moumita Bera** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a record of bonafide research work carried out by her. She has worked under our guidance and supervision and fulfilled the requirements for submission of the thesis which has attained the standard required for a Ph.D. degree of this Institute.

The results contained in this thesis have not been submitted, in part or in full, to any other university or institute for the award of any degree or diploma.

Dr. Deepti Gupta
Professor
Department of Textile Technology
Indian Institute of Technology Delhi
New Delhi 110016, India

Dr. R. Chattopadhyay
Professor
Department of Textile Technology
Indian Institute of Technology Delhi
New Delhi 110016, India

ACKNOWLEDGEMENTS

I would like to profoundly thank my supervisors Prof. Deepti Gupta and Prof. R. Chattopadhyay for their constant interest, invaluable supervision, meticulous encouragement and cooperation throughout this research work. I am really indebted to them for their invaluable guidance and support that they bestowed on me right from the inception to the successful completion of this endeavour.

My sincere gratitude also goes to the members of my research committee Prof. V. K. Kothari, Prof. R. S. Rengasamy and Prof. P. V. Madhusudhan Rao, who have contributed significantly to the progress of my research work and encouraged me throughout the course of this study. I also express my sincere gratitude to all other faculty members of Department of Textile Technology, IIT Delhi for their invaluable moral and technical support and assistance. I would specially thank Prof. P. K. Banerjee, Dr. Dipayan Das of Department of Textile Technology and Prof. S. N. Maiti of Centre of Polymer Science and Engineering, IIT Delhi for their invaluable suggestions and supports.

I express my heartfelt thanks to the staff members of all the laboratories and offices of Department of Textile Technology, IIT Delhi for extending their helping hand whenever needed. My sincere thank goes to Mr. B. Biswal, Mr. M. Kundu, Mr. M. Singh, Mr. V. A. Passi, Mr. Amarjeet, Mrs. S. Verma, Mr. R. K. Tejanian, Mr. S. Sharma, and Mr. A. K. Sehgal for their kind and enthusiastic cooperation.

I like to acknowledge a few of the numerous people who went out of their way and helped me during all these years of my doctoral study. My whole hearted thank goes to Mr. Sanjay Jain and Mr. Raj Kumar Jain of Bonjour Socks Manufacturing Company, Greater Noida, UP, India for providing all kind of support to manufacture the fabric samples.

I also express my heartfelt thanks to all my friends, PhD seniors, colleagues and lab-mates, who supported and helped me a lot to make this project successful. I am especially

thankful to Dr. K. Bal, Dr. S. Rana, Dr. B. Das, Dr. N. Padaki, Dr. A. Bhattacharya, Dr. K. Samanta, Dr. S. Sen, Mr. S. Maiti, Mr. J. Sardar, Ms. A. Srivastava, Ms. S. Paul, Mr. A. Mondal, Ms. S. Biswas, Ms. S. Deb, Dr. S. Banerjee, Dr. S. Patra, Mr. M. Barman, Mr. S. Hazra, Dr. P. Guha, Ms. P. Hatua, Ms. R. Thakur, and Mr. & Mrs. Sabaridharan of IIT Delhi for their constant cooperation and help.

Last but, not the least, I would like to thank my mother Ms. Tripti Bera for being my friend, philosopher and guide in my life. I am also thankful to my father Mr. Vivekananda Bera and my little sister Ms. Anwesha Bera for their support. Lastly, I am left with lack of words to acknowledge my strength, motivation and stable force, my husband Mr. Arun Kumar Pradhan and my son Abir. I am deeply indebted to them for all the pains they bore to complete this thesis.

Moumita Bera

ABSTRACT

Pressure garments are used to generate positive pressure over human body parts. They are produced from elastic knitted fabrics. Their size is deliberately kept smaller than the size of the body part they enclose so that they remain in stretched state. Pressure garments are used in various medical conditions, such as, scar management, venous and lymphatic disorders, bone and muscle problems. In each of these applications, the therapeutic pressure required is different. Application of precise amount of pressure on the body requires an understanding of the factors affecting the generation of pressure. The important factors include the tension generated in the fabric per unit width, fit of the garment, and curvature and compressibility of the body part on which it is worn.

Fit of the garment is decided by reduction factor (R_f) which is the percentage difference between body and garment circumference. 10, 15 or 20% reduction factor is normally applied to the patient's circumferential measurements without considering the nature of fabric and body characteristics. The curvature of the body depends on the limb shape and size. More pressure is generated on low circumferential body parts and vice versa. Further, compressibility of the body tissues also matters. Low and high pressure can be found on soft tissue part (like thigh) and bony part (like ankle), respectively. The body compressibility is a complex factor and varies over a wide range between subjects for the same body part. To reduce the variability in the experiment, researchers use rigid body, such as wooden leg or rigid cylinder. But pressure generated on rigid body may not correctly estimate the pressure generated on soft human body.

Tension generation in the elastic fabric is dependent on the extent of extension the fabric experiences at the wearing condition known as the fit of the garment. Higher the tension higher is the exerted pressure. In this respect the tensile behaviour of the constituent yarns and fabric construction has an important role. The fabrics used in pressure garments are

warp or weft knitted structures containing in-laid elastic yarns. Power net fabrics produced on raschel warp knitting machine are also used. In case of weft knitted structures, rib and single jersey structures have been used. Nylon filament yarn (50- 400 denier) is used along with a fine spandex yarn for loop formation. Spandex yarns of 280 – 560 denier or rubber threads (1500-3000 denier) are inlaid (6 to 16 per cm) in the structure to impart elasticity. Hence, there exists a wide range of fabric types for production of pressure garments. The structure property relationship of elastic knitted fabric is of great interest.

Bare spandex filaments are generally not used in the fabric for tactile discomfort. They are first covered with nylon or polyester filament and the covered yarns are subsequently used in fabrics. The effect of covering by nylon on the properties of spandex filament has been investigated. Load extension and stress strain behaviour of bare and covered spandex filaments were graphically plotted and discussed. It was found that covering of spandex increased its linear density and diameter. Covering changes the load extension behaviour of yarns. Covered spandex yarn showed less stress at a given strain than bare spandex filament.

The elastic yarns are always inserted in the fabric at a fixed input tension. Variation in input tension needs to be avoided to uniformly maintain the stretch characteristics of the fabric. The effect of level of input tension of elastic inlay yarn on the characteristics of fabrics has been studied. Input tension of inlay yarns were kept at four levels and fabric samples were prepared. Constructional, physical and mechanical properties of fabrics were tested and analyzed. It was found that with the increase in input tension in inlay yarn, loops became narrow in width and longer in height. This caused the change in dimension of fabric tubes. The circumference of the fabric tube decreased with the increase in input tension. However the effect of input tension of inlay yarn on tensile properties of the fabrics was marginal especially up to initial 100% extension level.

In order to study the effect of linear density of inlay yarn on characteristics of elastic fabrics several fabric tube samples were prepared at fixed input tension by varying linear density of inlay yarns. The samples were characterized in terms of their constructional, physical and mechanical properties. It was found that with the increase in linear density of inlay yarn, the loops became wider and shorter in height. Fabric thickness and weight increased with the increase in linear density of inlay yarn. At any given extension, tension in coursewise direction of fabric increased as linear density of inlay yarn increased. Hence, varying the linear density of inlay yarn could be an easy way to change the level of tension development in the fabric.

It has been found that, the change in input tension of inlay yarn affect the dimension of fabric tubes. The question arises whether this change in dimension makes any difference in the pressure generated by the fabric tube on rigid cylindrical body? It was found that, at fixed reduction factor and body curvature there is no effect of input tension of inlay yarn on pressure development.

To understand the effect of linear density of inlay yarn, reduction factor of the fabric tube and curvature of body on pressure generation, a set of experiments based on mixed level factorial design was carried out. The main and interaction effects of the parameters were also studied by response surface methodology. In order of importance the factors affecting the pressure generated on a cylindrical body was found to be the linear density of inlay yarn followed by reduction factor, and curvature of the cylinder.

To understand the relationship between body compressibility and pressure generation, pressure was measured on both rigid and soft cylinder. A PVC cylinder was covered by foam to make the surface soft. The compressibility of the foam was characterized. The knitted fabric tubes with varying reduction factor were mounted on the same keeping the pressure sensor in between. The pressure was found to decrease on foam covered cylinder. A model

based on energy consideration was developed to predict the pressure on soft cylinder. The predicted pressure showed good fit with experimental data.

The pressure generated by fabric tubes on human subjects was also studied. Ten males and ten females were selected. Pressure was measured on upper arm of right hand. The variation in amount of pressure on male and female bodies was also noted. The deviation from theoretical pressure calculated from Laplace's Law and actual measured pressure was analyzed. It was found that, under identical conditions, pressure generated was less in females as compared to that in males. Laplace's law was found to be unsuitable for predicting the pressure generated on human body.

As the pressure garments are used next to skin, the comfort aspect of the fabric becomes a critical issue. Patients stop using pressure garments because of perspiration, itching, rashes, warmth. It was found in the literature that, comfort properties are dependent on the fibre type and fabric structure. Mostly nylon fibre is used for construction (50-85%). But it is hydrophobic in nature. Some amount of hydrophilic fibre can be incorporated in the fabric. It is interesting to investigate the effect of fibre content on comfort behaviour. Fabric tube samples were produced varying the nylon and cotton proportion. Thermal property, water vapour permeability, air permeability, in-plane wicking and surface friction properties were found out and analyzed. It was found that, water vapour permeability increased and wicking property decreased as cotton percentage increased in the fabric.

Fabric in a pressure garment remains in an extended state during use. As a result, the loop shape, stitch density and thickness of the fabric changes. The comfort characteristics of the fabric are expected to be totally changed during use. Available information on this aspect is not enough. Thermophysiological properties of an elastic knitted fabric were tested in various extended state. The extension of the fabric was varied from 10-60%. Results suggested that, in extended state, permeability improved and thermal resistance decreased

thereby indicating that actual comfort during wear was enhanced compared with fabric in relaxed state.

From this study it could be concluded that there are three important parameters - intrinsic properties of elastic yarn, its physical dimensions and the reduction factor of the garment, that have a strong bearing on the tension development in the fabric and consequently the pressure. It was also seen that addition of cotton to the fabric can be used to improve its comfort characteristics.

Findings of the study provide useful insight into the structure- property relationships of elastic knitted fabrics and tubes made from them. These findings can be used to “engineer” pressure garments to regulate the exact amount of pressure exerted on the human body. Comfort properties can also be controlled as per requirement.

TABLE OF CONTENTS

Certificate		i
Acknowledgements		iii
Abstract		v
List of figures		xix
List of tables		xxv
List of symbols		xxvii
Chapter 1	Introduction	1
1.1	Pressure garments	3
1.2	Motivation for the study	4
1.3	Objectives	5
1.4	Organization of the thesis	5
Chapter 2	Review of literature	7
2.1	Introduction	9
2.2	Principle of pressure generation	11
2.3	Factors affecting pressure generation	15
2.3.1	Body curvature	16
2.3.2	Tissue compressibility	17
2.3.3	Tension generated in the fabric	18
2.4	Fabric construction	20
2.4.1	Fibres	20
2.4.2	Yarns	20

2.4.3	Fabrics	22
2.5	Testing of elastic knitted fabrics	26
2.5.1	Tensile properties	26
2.5.2	Comfort properties	33
2.6	Garment production	34
2.6.1	Garment sizing	34
2.6.2	Garment construction and making up	36
2.6.3	Fasteners	38
2.6.4	Wash and care	40
2.7	Standards for pressure garments	41
2.8	Measurement of pressure	42
2.8.1	Subjective assessment	42
2.8.2	Objective assessment	44
2.8.2.1	Fluid displacement based sensors	44
2.8.2.2	Resistive ink based sensors	45
2.8.2.3	Capacitive pressure sensor	46
2.8.2.4	Elastic optical fibre based sensor	47
2.8.2.5	Strain gauge based pressure sensor	48
2.8.2.6	Mannequin based pressure sensor	49
2.9	Applications of PGs	51
2.9.1	Scar management	52
2.9.2	Venous problem	53
2.9.3	Air flight socks	56
2.9.4	Muscle and bone joint problems	57
2.9.5	The use of PGs in sports	57

2.10	Summary	59
Chapter 3	Influence of inlay yarn properties on characteristics of elastic knitted fabrics	61
3.1	Introduction	63
3.2	Experimental	63
3.2.1	Sample preparation	63
3.2.1.1	Loop yarn	63
3.2.1.2	Inlay yarn	64
3.2.1.3	Fabric sample preparation	64
3.2.2	Fabric characterization	66
3.2.2.1	Yarn structure	66
3.2.2.2	Tensile properties of yarns	66
3.2.2.3	Structural and physical properties of fabrics	66
3.2.2.4	Tensile properties of fabric	67
3.3	Results and discussion	67
3.3.1	Image of bare and covered spandex filaments	67
3.3.2	Tensile properties of spandex filaments	68
3.3.2.1	Load extension behaviour	68
3.3.2.2	Stress strain behaviour	69
3.3.3	Influence of covering on the tensile behaviour of spandex yarn	70
3.3.3.1	Load extension behaviour	70
3.3.3.2	Stress strain behaviour	72
3.3.4	Effect of inlay yarn linear density on the properties of the	74

	elastic knitted fabric	
3.3.4.1	Structural parameters	74
3.3.4.2	Fabric tube diameter	77
3.3.4.3	Load extension behaviour of yarns and fabrics	78
3.3.5	Effect of input tension of inlay yarn on fabric characteristics	79
3.3.5.1	Effect of input tension on inlay yarn	79
3.3.5.2	Knit structure parameters	80
3.3.5.3	Thickness of fabric	84
3.3.5.4	Fabric weight per unit area	85
3.3.5.5	Fabric tube circumference	86
3.3.5.6	Tensile behaviour	87
3.4	Conclusions	89
Chapter 4	Pressure generation on rigid and soft cylindrical surface	91
4.1	Introduction	93
4.2	Influence of input tension on pressure generation	94
4.2.1	Experimental	94
4.2.1.1	Materials	94
4.2.1.2	Pressure measurement	94
4.2.2	Results and discussion	96
4.2.2.1	Relationship between reduction factor and fabric extension	96
4.2.2.2	Effect of input tension of inlay yarn on pressure generation	97
4.3	Study the effect of linear density of inlay yarn, reduction factor and curvature on pressure generation	98
4.3.1	Experimental	98

4.3.1.1	Materials	98
4.3.1.2	Method	99
4.3.2	Results and discussion	100
4.3.2.1	Relationship among linear density of inlay yarn, curvature and reduction factor	100
4.3.2.2	Pressure generated by fabric tubes	101
4.3.2.3	Effect of R_F , inlay yarn linear density and interaction between them (xy) on pressure generation	103
4.3.2.4	Effect of R_F and body curvature and interaction between them (xz) on pressure generation	105
4.3.2.5	Effect of linear density of inlay yarn and curvature and interaction between them (yz) on pressure generation	106
4.4	Influence of body compressibility on pressure exerted by fabric tubes	108
4.4.1	Experimental	109
4.4.1.1	Fabric tube	109
4.4.1.2	Foam	109
4.4.1.3	Measurement of compressibility of foam	110
4.4.1.4	Preparation of foam covered PVC cylinders	110
4.4.1.5	Pressure measurement on foam covered PVC cylinders	111
4.4.2	Results and discussion	112
4.4.2.1	Compressibility characteristics of foam	112
4.4.2.2	Pressure generation on foam covered PVC cylinder	113
4.4.2.3	Determination of pressure on soft surface	114

4.5	Conclusions	121
Chapter 5	Pressure generation on human body	123
5.1	Introduction	125
5.2	Experimental	125
5.2.1	Materials	125
5.2.1.1	Fabric tubes	125
5.2.1.2	Subjects	126
5.2.1.3	PVC rigid cylinders	128
5.2.2	Method of pressure measurement on human body	128
5.3	Results and discussion	129
5.3.1	Pressure exerted by fabric tubes	129
5.3.2	Comparison between pressure exerted by fabric tubes on human limbs	132
5.3.3	Comparison of pressure generated on different bodies	134
5.4	Conclusions	136
Chapter 6	Comfort characteristics of elastic fabric tubes in relaxed and extended state	137
6.1	Introduction	139
6.2	Effect of fibre content on thermophysiological behavior	140
6.2.1	Fabric tubes	140
6.2.2	Methods	141
6.2.2.1	Fibre content	141
6.2.2.2	Physical, constructional and tensile properties of fabric	142

6.2.2.3	Thermo physiological properties	142
6.2.2.4	In-plane wicking	143
6.2.2.5	Surface friction	143
6.2.2.6	Measurement of pressure on rigid cylindrical surface	144
6.2.3	Results and discussion	144
6.2.3.1	Fibre content	144
6.2.3.2	Structural characteristics	144
6.2.3.3	Thermal behaviour	145
6.2.3.4	Water vapour transmission rate	146
6.2.3.5	Air permeability	147
6.2.3.6	In plane wicking	148
6.2.3.7	Surface friction	149
6.2.3.8	Effect of fibre content on pressure generation on rigid cylindrical tube	150
6.3.	Comfort properties at extended state of elastic knitted fabrics	152
6.3.1	Experimental	152
6.3.1.1	Fabric tube	152
6.3.1.2	Methods	152
6.3.1.3	Measurement of pressure	153
6.3.2	Results and Discussion	154
6.3.2.1	Pressure exerted by the fabric tube on PVC cylinder	154
6.3.2.2	Effect of fabric extension on air permeability	155
6.3.2.3	Effect of fabric extension on water vapour transmission rate	156
6.3.2.4	Effect of fabric extension on the thermal properties	157
6.4	Conclusions	160

Chapter 7	Conclusions	163
Chapter 8	Suggestions for future work	169
References		173
Appendices		189
Bio data		199
List of publications		201