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STRUCTURE AND ANALYSIS OF WOVEN COMPRESSION BANDAGES FOR VENOUS LEG ULCERS

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SUMMARY OF THE THESIS

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Abstract

Woven compression bandage (WCB) is one of elastic textiles that exert pressure on muscles. With a defined tensile strength, it is possible to create the required compression on the given body parts. The proposed study aims to investigate the relationship between woven fabric deformation, porosity, and tensile stress properties of three main types of woven compression bandages. All bandage samples are applied on human leg using two and three layers bandaging techniques. The study investigated the commercial yarns available in the bandage market in addition to yarns spun at a wider range of ply twist. Moreover, the study analysed the influence of yarn material and bandaging techniques on corresponding pressure at the ankle and mid-calf positions. Results revealed that the optimum twist for plied yarn should be (1800 – 2200 turns per meter) to produce highly extensible WCB.

Another part of the dissertation was a modification of the structure and construction of a WCB made of 100% cotton, where the bandage includes an integrated tension sensor, which causes a colour change of the bandage during its deformation. The solution is sensors in the bandage in the form of threads with a colour different from the other structure of the bandage, which become visible due to deformation / stress in the bandage. Implementation is possible by applying weft threads with different colours through the weft insertion during weaving. The measured pressure using PicoPress was compared with theoretical compression calculated by Laplace's law and Al-Khaburi's equations. The bandage porosity is calculated for all frames at different weave angles using NIS elements software. Woven bandage construction parameters which are given by the warp and weft yarns preparation, twist, count, and density along with woven fabric weave, type of weaving and finishing process are the main factors influence the bandage properties. Experimental results confirm that bandage porosity is directly proportional to the bandage extension and weave angle that ranges from 44º to 90º. The novelty of candidate study is to introduce practical remarks to the patient for optimizing the required bandage pressure by suitable extension or applied tension or weave angle for two and three layers bandaging systems.

Thermal resistance (R_{ct}) and water vapour resistance (R_{et}) are evaluated for four types of WCB, then compared with thermal foot model (TFM). Flexor Carpi (FC), Soleus (SO), and Medial Gastrocnemius (MG) muscles are selected to represent the wrist, ankle, and mid-calf muscles respectively, which are then evaluated by EMG electrical voltage test with and without wearing WCB. Using WCB significantly decreased the muscle's activation and was associated with higher median frequency for both SO and MG muscles during the tested activities.

Keywords:

Plied warp yarns; twist level; woven bandage elasticity; short-stretch woven bandages; durability; Picopress compression; Laplace's equation; Thermal resistance; Muscle's activation.

Anotace

Tkané kompresní obinadla jsou jednou z možností pružných textilií, které vyvíjejí při aplikaci tlak na svaly. Při aplikaci obinadla, při definované pevnosti v tahu, je možné vytvořit požadovanou kompresi na danou část těla. Jedna z navrhovaných studií si klade za cíl zkoumat vztah mezi deformací tkaného obinadla, pórovitostí a vlastnostmi namáhání v tahu u tří hlavních typů kompresních obinadel. Všechny vzorky obinadel se aplikují na lidskou nohu pomocí dvou a třívrstvých technik bandáže. V rámci realizace disertační práce studie byla zaměřená na zkoumání mechanických vlastností komerční 100% bavlněné příze dostupné na trhu pro výrobu kompresního obinadla a experimentálně navržená sada přízí spřádaných v širším rozsahu zákrutu pro možnou výrobu kompresních 100% bavlněných obinadel. Studie navíc analyzovala vliv konstrukce příze versus bandážovací technika na odpovídající tlak v poloze kotníku a lýtka. Výsledky odhalily, že optimální zákrut pro přízi by mohl být (1800 - 2200 Z/m), aby se vytvořil WCB.

Další části disertační práce byla modifikace struktury a konstrukce kompresního tkaného obinadla ze 100% bavlny, kde součástí obvazu je integrovaný senzor napětí, které způsobí barevnou změnu obvazu při jeho deformaci. Řešením jsou senzory v obinadle v podobě nití s barevností odlišnou

od ostatní struktury obinadla, které se stanou viditelnými vlivem deformace/napětí v obinadla. Realizace je možná aplikací útkových nití s odlišnou barevností barevným házením během tkaní.

Naměřený tlak pomocí PicoPress byl porovnán s teoretickou kompresí vypočítanou Laplaceovým zákonem a Al-Khaburiho rovnicemi. Porozita obinadla se následně přepočítá ze snímaného obrazu pro všechny snímky využitím softwaru NIS elements. Hlavní parametry ovlivňující vlastnosti obinadla jsou konstrukční parametry: a) dostavou osnovních a útkových nití, zákrutem osnovních a útkových nití, materiálovým složením nití obinadla a vazbou tkaného obinadla, typem tkaní a dokončovacím procesem. Experimentální výsledky potvrzují, že pórovitost obinadla je přímo úměrná prodloužení obvazu a úhlu deformace nití v provázání nití, který se pohybuje od 44 ° do 90 °. Modifikaci konstrukce kompresního obinadla, vložením barevných vzorů a nití v obinadle, lze použít také k jednoznačné identifikaci, zda tento obvaz je vhodný například pro vysoký či nízký stupeň komprese. Zabrání se omylům při aplikaci.

Poslední části práce je zhodnocení chování obinadel z pohledu tepelného odporu, kde tepelný odpor (R_ct) a odpor vodních par (R_et) se hodnotí pro všechny typy WCB s následným porovnáním s modelem tepelné nohy (TFM). Pro reprezentaci svalů zápěstí, kotníku a středního lýtka jsou vybrány svaly Flexor Carpi (FC), Soleus (SO) a Medial Gastrocnemius (MG), které jsou poté hodnoceny testem elektrického napětí EMG s nebo bez nošení WCB. Použití WCB významně snížilo aktivaci svalu a bylo spojeno s vyšší střední frekvencí pro svaly SO i MG během testovaní.

Klíčová slova:

Dvojmo skaná příze, úroveň zákrutu, tkané obinadlo, obinadlo s krátkým tahem, Picopress komprese, Laplacova rovnice; svalová aktivace, tepelný odpor.

List of Abbreviations and Nomenclature

CB	Compression bandage	MG	Medial Gastrocnemius
CBs	Compression bandages	SO	Soleus
WCB	Woven compression bandage	TFM	Thermal foot manikin
WCBs	Woven compression bandages	R_{ct}	Thermal resistance
CO-PA-PU	Cotton-Polyamide-Polyurethane	R_{et}	Water vapour resistance
VI-PA	Viscose-Polyamide	R_{ct0}	Initial thermal resistance
EMG	Electromyography	tpm	The yarn twist/meter
PVP	Poly Vinyl Pyrrolidone	Sample D_1	Immersed in Glucose for 1 min
NPs	Nano particles	Sample D_2	Immersed in Glucose for 60 min
RMS	Root mean square	BL-CO-2	100% bleached Cotton, two layers of bandages
OE	Open end yarn	BL-CO-3	100% bleached Cotton, three layers of bandages
E.C.	Escherichia Coli	CO-PA-PU-2	Cotton-Polyamide-Polyurethane, two layers of bandages
S.A.	Staphylococcus Aureus	CO-PA-PU-3	Cotton-Polyamide-Polyurethane, three layers of bandages
CFU	Colony forming units	VI-PU-2	Viscose-Polyurethane, two layers of bandages
FC	Flexor Carpi	VI-PU-3	Viscose-Polyurethane, three layers of bandages
Std.	Standard Deviation	CO-2-TFM	100% Cotton, 2 layers on thermal foot manikin
VI-PU	Viscose-Polyurethane	CO-3-TFM	100% Cotton, 3 layers on thermal foot manikin
VI-PU-2-TFM	Viscose-Polyurethane, two layers on thermal foot manikin	CO-PA-PU-2-TFM	Cotton-Polyamide-Polyurethane, two layers, thermal foot manikin
VI-PU-3-TFM	Viscose-Polyurethane, three layers on thermal foot manikin	CO-PA-PU-3-TFM	Cotton-Polyamide-Polyurethane, three layers, thermal foot manikin

Contents

1. Introduction

Compression bandage (CB) is considered one of the widespread applications of the medical textiles for leg ulcers or athletic performance. There are two main categories of these medical components, namely, knitted and woven compression bandages (WCBs). The knitted CB is usually in tubular form, but it is practically different than the compression socks (hosiery). Whereas the WCBs have vast variety of types and techniques. Compression bandaging remains a key interference in the management of venous and lymphatic diseases. This apparently simple intervention depends on the optimum selection and practical application of four complex central properties of compression bandages, namely, applied pressure, number of layers, components, and elastic properties [1].

Venous ulceration is the most common type of leg ulcers and a significant clinical problem. Chronic leg ulcers affect approximately 1% of the population and 3% of people over 65 years of age in the developed countries. The majority of leg ulcers are due to venous diseases [2]-[4]. Compression therapy by medical compression bandage can be achieved using short- or medium- or long-stretch techniques at maximum stretch ranges (<70%) or (70-140%) or (>140%) respectively [5], [6]. Short-stretch CB such as 100% Cotton and two-component compression system are mainly used for venous leg ulcers and oedema. With a short-stretch CB, the muscle contraction causes an intermittent narrowing of the veins, a reduction of venous reflux, and thus an improvement in the venous pump function when the patient is walking. Long-stretch CB is suitable for uncomplicated varicose veins or athletic performance, such cases require medium pressure (30-40 mmHg) [5]. In order to design effective compression bandages, researchers have attempted to describe the interface pressure applied by these bandages using mathematical models [7]-[10]. Few studies have been focused on the optimization and best combinations of CBs for venous leg ulcers, oedema healing, and prevention of recurrence. Most of patients depend on specialist practitioners or traditional experience. Compression therapy limits the flow of diseased surface veins, increases the flow through deeper veins, and reduces swelling. Patients who are compliant with compression therapy have significantly improved ulcer healing rate and decreased rate of recurrence. Compression is thought to either correct or improve venous hypertension, mainly owing to an improvement of the venous pump and lymphatic drainage. Compression also improves the blood flow velocity through deep and superficial veins [11].

There are three methods for producing compression bandages to achieve the optimum stretch and elasticity; first method is using highly twisted warp yarns. The optimum elastic recovery of this WCB can be achieved by adjusting the hot water treatment without tension (such as 100% cotton) [12]. The second method is using elastomeric filament (elastane or rubber) with Viscose or Polyamide to produce long-stretch CB. The third method is using two polymeric yarns which have different melting point by steaming and heat setting. Medical CBs are designed to meet both the safety and the comfort of human beings, especially patients. The thermal resistance of fabrics is a primary determinant of body heat loss in cold environments. In hot environments or at high activity levels, evaporation of sweat becomes an important avenue of body heat loss and fabrics must allow water vapour to escape on time to maintain the relative humidity between the skin and the first layer of clothing about 50% [13]-[16].

Electromyography (EMG) is 'the subject which deals with the detection, analysis, and utilization of electrical signals emanating from skeletal muscles'. The electric signal produced during muscle activation, known as the myoelectric signal, is produced from small electrical currents generated by the exchange of ions across the muscle membranes and detected with the help of electrodes [17]. EMG aims to measure the muscle's activation level and provide estimation for exercise intensity of selected muscles during activity. EMG signal can contribute to enhance the human body muscle's function [18].

2. Purpose and the aim of the thesis

The purpose of thesis is to study the structure and behaviour of short-stretch cotton woven compression bandages (WCBs). The aims of thesis is focused on main three parts: definition of structure of WCBs, modification of construction of WCBs as well as analysis of properties, and behaviour of WCBs. Based on definition of structure as well as behaviour of WCBs, it is possible to create better condition during application of bandage by patient, nurse, and athletic user. Based on modification of construction of WCBs, we are able to find a connection between structure and applied tension of bandage during static and dynamic applications. Moreover the motivation of this research is to investigate the optimum conditions for compression therapy using long- and short-stretch WCBs. The methodology is based on evaluating the elastic recovery of both types of bandages during uniaxial stress and cyclic loading-unloading to simulate the real activities of patient or athletic performance during resting and walking actions. The main topics of this thesis are:

1) Analysis of input staple twisted cotton yarn for producing 100% cotton bandages

1.1. Staple twisted (plied) cotton yarn versus mechanical properties.

1.2. Modified surface of input threads to produce multifunctional WCBs.

2) Analysis and modification of cotton woven bandage structure

To achieve the required goals of the thesis, it was necessary to:

1.3. Evaluate the structure of three basic types of WCBs showing the material, production as well as deformation viewpoint during the uniaxial stress.

1.4. Study and modify the construction as well as the structure of woven cotton bandage: The bandage includes an integrated tension sensor, which causes a change in the spacing of coloured threads during its deformation. The solution is sensors in the bandage in the form of a different colour pick from the other structure of the bandage. Different colour picks with regular distance become visible due to deformation / stress in the bandage. The production of this bandage it is possible by applying weft threads with different colours by fancy picking mechanism of weaving machine. The colour patterns and threads in the bandage can also be used to uniquely identify whether the bandage is suitable, for example, for a high or low degree of compression. Thanks to this sensor, it is possible to accurately quantify the tensile force in the bandage, during its application and during the ongoing compression of living tissue. It is therefore both a matter of facilitating the application of the bandage and of checking the condition of the bandage after its application. Appropriate adjustment of the tensile force in the bandage will be beneficial for accelerating the healing processes.

1.5. Introduce a new method to predict the corresponding bandage tension by measuring the bandage extension and porosity using digital camera attached to the tensile testing device.

1.6. Compare the practical pressure measured by PicoPress with theoretical compression forces calculated by a modified Laplace’s law equation.

1.7. Evaluate the elastic recovery of WCBs during cyclic loading-unloading on the tensile testing device then compare these results with the bandage application on mannequin and human leg at different positions and activities.

3) Evaluation of other individual properties of woven bandages

1.8. Study the effect of compression bandages on lower leg muscles' performance using eMotion wireless EMG system.

1.9. Discuss the factors affecting thermal comfort properties of WCBs, using the

ALAMBETA and PERMETEST at different extension levels. Moreover compare the obtained results with the thermal foot manikin as a virtual simulation of the real bandaging system.

1.10. Validate the experimental results of thermal resistance on ALAMBETA and thermal foot manikin with three mathematical models.

2.1. Influence of fibre and yarn characteristics on mechanical properties of bandages

There is a strong positive correlation between the cotton warp yarns ply twist and the required cotton bandage elasticity. This bandage elasticity can be defined as 'the elastic recovery after extension or compression when it is subjected to repeated stresses and activities'. Moreover the yarn strength is a function of the fibres characteristics (mainly the fibre fineness, cross-section, and tenacity) as well as the yarn parameters (i.e. twist coefficient, number of fibres in cross-section, and yarn evenness).

This study sheds light on the effect of ply twist on yarn extension that is being used as warp yarns in woven bandages and discusses the influence of yarn material and bandaging technique on corresponding pressure at the ankle and mid-calf positions. It is known that the geometrical arrangement of filaments (fibrils) in the structure of twisted fibre bundles can be described by a model of concentric helixes, the so-called ideally helical model [19], [20].

Previous research concluded that increasing the twist level decreased the yarn mass coefficient of variation, yarn diameter, coefficient of variation, and hairiness [21], [22]. Meanwhile, increasing the twist level of staple yarn improved their tenacity, however, the higher twist of multifilament yarns reduced their strength which is an important factor in terms of their end-use, especially for technical applications [5]. Altas, et al. concluded that, in carded yarns, an increase of twist coefficient increases the evenness, tenacity, and elongation values and decreases hairiness and diameter values significantly. In combed yarns, the increase in twist coefficient increases tenacity and elongation and decreases the number of thick places, neps, hairiness, and diameter values significantly [23].

There is scarce information relating to the effect of high ply twist on the warp yarns elasticity that are being used in woven bandages [24]. Therefore, this study initially investigates the commercial yarns available in the bandage market in addition to yarns spun at a broader range of ply twist. Moreover, the study reveals the influence of bandage material and the number of layers on its elasticity and durability since there are limited sources about this point [25]-[27].

3. Overview of the current state of the problem

There are two categories of bandages in the market (normal and smart bandages): The simple or normal bandages, their price is cheap, their structure is simple and based on the plain weave, as shown in Figure 3.1 [28]. The second category is smart CBs which have sensors to give the user direct reading of the exerted pressure on the part of the body during any activity, but it's so much costly compared to the first category, see Figure 3.2 [29].

		
Cotton 100%	Cotton 78%, Polyamide 16% Polyurethane 6%	Viscose 56%, Polyamide 44%

Figure 3.1. Three basic types of WCBs [28]

Figure 3.2. Smart CBs with sensor [29]

The compression of living tissue using textile bandages is only estimated based on the personal experience of the bandage applicator. The main aim of thesis is focused on modification of construction of short-stretch cotton WCBs. The bandage includes an integrated tension sensor (fancy picking of different picks), which causes a change in the spacing of coloured threads during its deformation. Based on the study and evaluation of this deformation we are able at the end to give the patient, nurse, or any other user an accurate remarks to adjust the applied compression to the body part, see Figure 3.3. It is possible to convert the simple bandage to smart bandage by modifying the bandage structure such as adding the blue marks (rectangles of 2cm x1cm to be squares of 2x2 cm^2 at 100% extension) or adjusted according to the required bandage tension, as illustrated in Figure 3.4. This modification could control the bandage tension as a function of the applied extension that ranges from 50 to 100% depending on the bandage construction and the number of layers [28].

Secondly, the total production cost could be reduced by using different coloured weft repeated every 1 cm during the weaving process as illustrated in Figure 3.5, instead of printing or adding the coloured marks after bandage production. Moreover, multifunctional antimicrobial double weft WCB can be produced using highly twisted warp yarns (ply twist 1800 to 2300 twists/m) and only the surface weft yarns in contact with the patient skin will be treated with Zinc or Titanium Nano-particles [12]. As a result, the bandage cost would significantly be reduced and the final product would achieve the smart performance which might gain higher marketing prices and benefits.

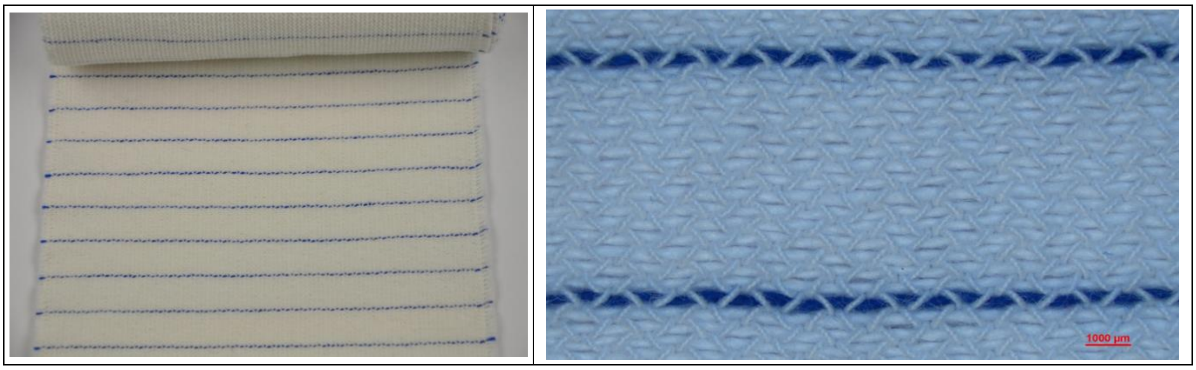
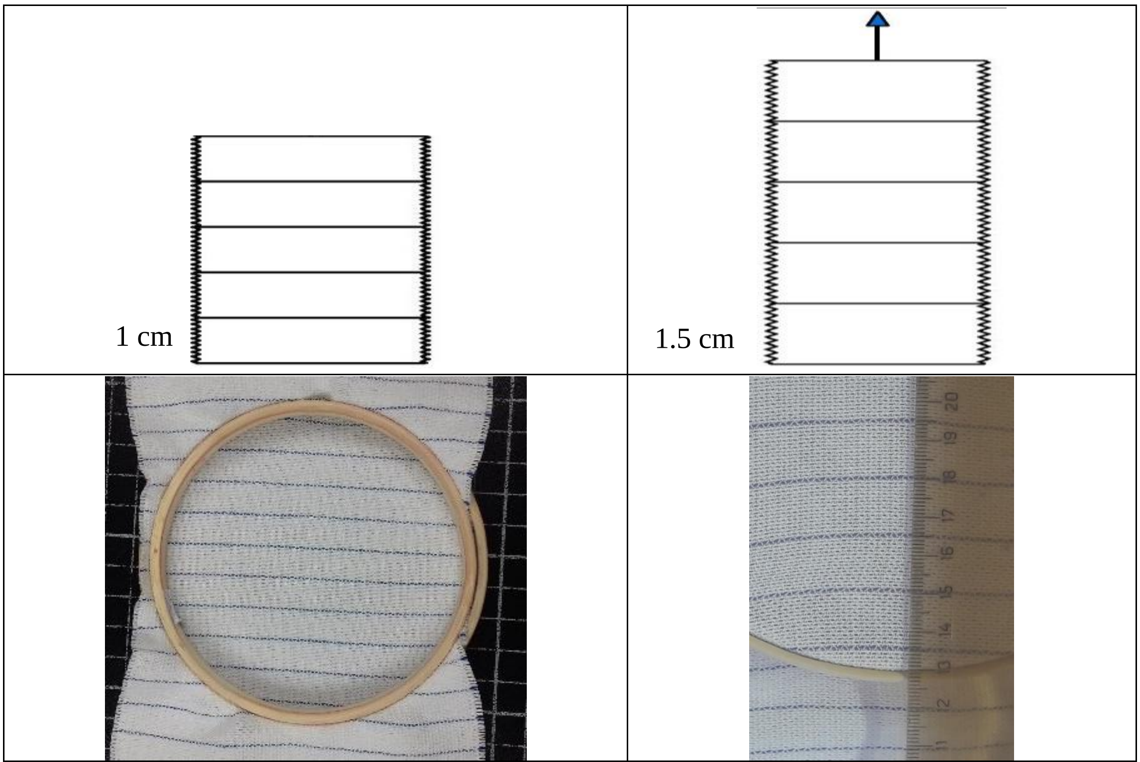


Figure 3.3. Presentation of the innovated cotton WCB and its structure

Figure 3.4. The blue marks on the three basic types of WCBs



a) The bandage at 0% extension | b) The bandage at 50% extension

Figure 3.5. A Coloured weft repeated every 1 cm during the bandage weaving

4. Methods Used, Studied Materials, Summary of Results, Part 1

4.1. Analysis and Evaluation of the Warp and Weft Yarns for Cotton WCBs

The methodology plan was divided to two steps, the 1st was to evaluate the mechanical properties of the used plied warp yarns for producing WCB in market. Moreover as a result, the 2nd step was to produce a special range of warp yarns at ply twist 600 to 2200 twists/m to achieve the required high extensibility and elasticity of the WCB. The main factors influencing the cotton WCB tensile properties are the warp yarns twist, linear density, and tenacity as well as the bandage structure and weaving parameters.

4.1.1. The mechanical behaviour of twisted short staple yarn structures

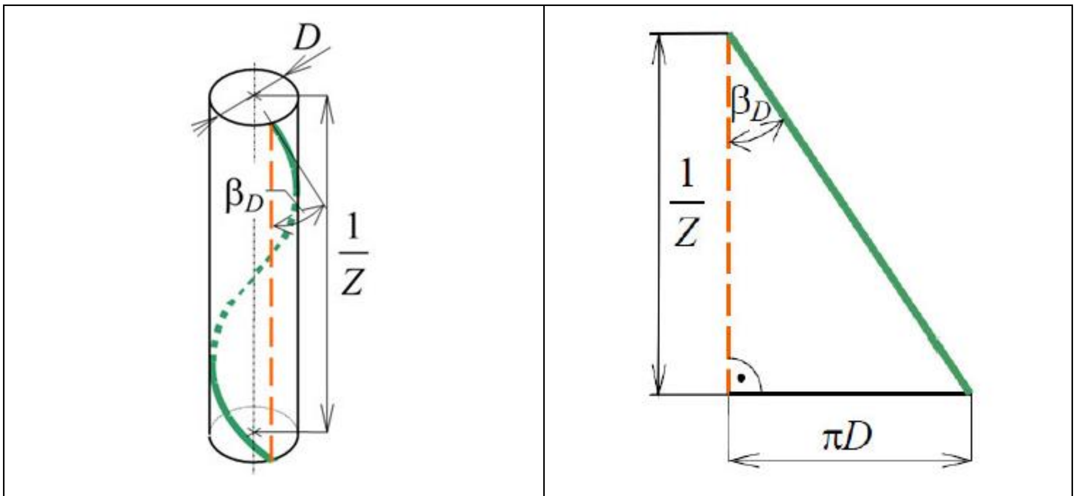
Mertová et al, [19], [20] considered that peripheral fibres have the shape of a helix with an angle of fibre slope to the multifilament yarn axis (β_D) and the height of one fibre coil is 1/Z. The surface of multifilament yarn forms a triangle. According to Figure 4.1 they obtained equation (4.1):

$$\tan \beta_D = \pi D Z = \frac{2\sqrt{\pi \propto}}{\sqrt{\mu \rho}} \tag{4.1}$$

Where β_D denotes the slope angle of peripheral fibre to the linear axis of the twisted fibre bundle (the angle of peripheral fibre), D is the diameter of cylindrical helix of peripheral fibres axis, Z is the number of twists per unit length of the twisted fibre bundle, α is Koechlin's twist coefficient, ρ is the fibre density, and μ is the packing density of fibre bundle. The relationship between twist (Z) and fineness (T) of the twisted fibre bundle was derived by Koechlin, see equation (4.2):

$$\boldsymbol{Z} = \frac{\propto}{\sqrt{\boldsymbol{T}}} \tag{4.2}$$

They confirmed that increasing the twist level has increased the angle of peripheral fibres (β_D) and the angle between the axis of fibre on the surface and the line parallel to the yarn axis (β') increased as well. There was shortening (twist take-up) of the multifilament yarn because of twisting. It was associated with an increase in yarn count value which was expressed by the substance cross-sectional area of multifilament yarn.



(a) (b)

Figure 4.1. A peripheral fibre in helical model of multifilament yarn of diameter *D* [19],
a) One coil of a helical fibre on yarn surface and **b)** Unrolled yarn surface

The load-elongation curve of the warp yarns was measured according to the standard test method ASTM D2256 [30]. Twist per meter was measured on TWIST LAB-2531C twist testing machine according to standard procedure CSN 80 0701. The yarn linear density was measured from a lea of one hundred meters according to the standard test method CSN 80 0050. To produce the new proposed WCB, single ring-spun yarns were produced from Egyptian cotton fibres - Giza 86, according to the following spinning parameters, as listed in Table 4.1.

Table 4.1: Produced single yarn properties, ring-spun raw yarns

Nominal yarn count (Tex)		15	15	20	20	25	25	30	30
Twist direction		S	Z	Z	S	S	Z	Z	S
Actual yarn count (Tex)	Average	14.7	15	19.7	19.8	24.6	24.7	29.5	29.8
	C.V. (%)	1.6	1.7	1.6	1.3	1.2	1.11	1.1	1.04
	Std. (Tex)	0.24	0.26	0.32	0.26	0.30	0.27	0.32	0.31
Twist/m		1031	1062	910	925	803	799	751	748

The linear density of the weft yarns was kept 60 Tex for all bandage samples. As far as the warp yarns are concerned, among all above single yarns, the 20 Tex yarns in S and Z-direction were chosen to be plied on DirecTwist twister on two plies at a nominal twist level ranges from 600 to 2200 twist/m and at different twist direction as demonstrated in Table 4.2.

Table 4.2: Produced plied yarn properties, ply of ring-spun yarns 20x2 Tex

Twist direction, SS-Z		SZ-Z		ZZ-S	
Ply twist, twists/m	Actual yarn count, Tex	Ply twist, twists/m	Actual yarn count, Tex	Ply twist, twists/m	Actual yarn count, Tex
606	40.03	597	40.87	602	39.63
1181	41.88	1216	42.18	1204	41.29
1761	45.78	1793	46.68	1773	48.40
2185	52.26	2168	55.45	2172	54.42

4.2. Modification of the surface of used yarns

Most of the available WCBs are designed to achieve the gradual compression for leg ulcer healing or athletic performance. Current study aims to introduce multifunctional performance by compression therapy, antimicrobial, and wound care for the normal user or patients. So it is necessary to treat the warp and weft yarns which in contact with the human body with effective antibacterial agent such as Silver Nanoparticles (NPs) or Zinc Oxide or Titanium Dioxide.

4.2.1. Preparing Cotton yarns treated with Silver NPs

Colloidal form of Silver NPs was prepared using Glucose as reducing agent. Uniform Ag-NPs were obtained by reduction of Silver nitrate at 70°C under atmospheric pressure. Poly Vinyl Pyrrolidone (PVP) was used as stabilizer. Glucose Ag-NPs were synthesized by dissolving $AgNO_3$ (157 mg) and PVP (5 g) in 100 ml of 40% (w/w) of Glucose syrup. 5 ml of sodium chloride were added to the samples for complete reaction and to convert all the ionic Silver to NPs [31]. Ten samples, 200-300 m of bleached Cotton yarns were winded on perforated Polypropylene bobbins, their thickness ranges from 5-10 mm. Five samples were immersed in Glucose Ag-NPs solution for 1 min (D_1) and the other samples for 60 min (D_2).

4.2.2. Silver NPs activity of treated yarns

For the tests, pathogenic bacterial strains were used for the qualitative test method (AATCC 147) and quantitative test method (AATCC 100). Escherichia Coli (E.C.) - CCM 2024 (ATCC 9637), gram-negative rod-shaped bacteria and Staphylococcus Aureus (S.A.) - CCM 2260 (ATCC 1260), gram-positive rod-shaped bacteria were purchased from Czech Collection of Microorganisms, Masaryk University in Brno.

A) Method AATCC 147: 1 ml of the bacterial inoculums (E.C. and S.A.) at a concentration of 108 Colony forming units (CFU/ml) was individually inoculated onto Petri blood agar plate, the test sample was inserted into the middle of the plate. The prepared samples were cultivated in thermostat 24 hours / 37 °C [32].

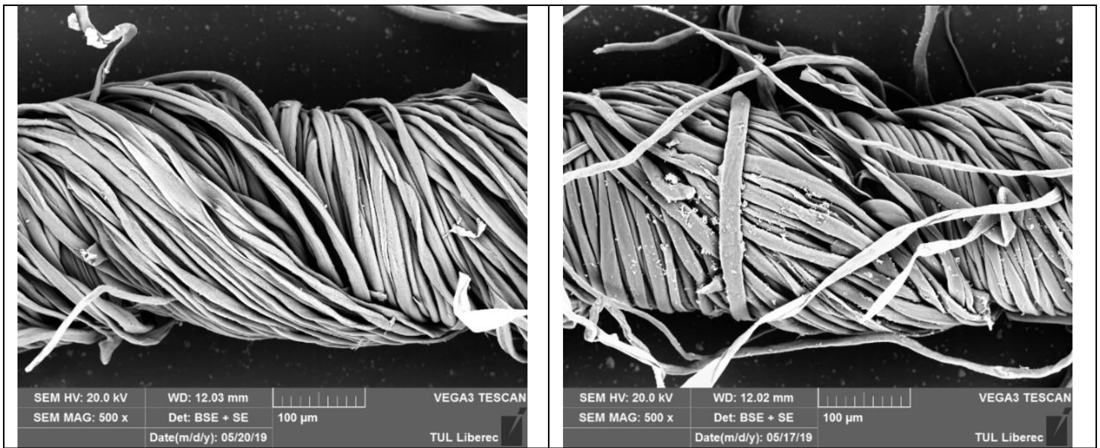
B) Method AATCC 100: 10 ml of E.C. and S.A. at a concentration of 108 CFU/ml were applied on the sample. The sample was placed in a sterile container and cultured 24 hours / 37 °C. After 24 hours, 10 ml of physiological solution was added and the sample was shaken. 1 ml of solution was removed and plated onto Petri blood agar plate. The samples were cultured for 24 hours / 37 °C. The antibacterial activity of AgNPs treated cotton fabrics was quantitatively determined before and after washing using bacterial percentage reduction test (AATCC 100-2004) according to the American Association of Textile Chemists and Colorists Technical Manual (2010) [33].

4.2.3. Testing the Nanoparticles size and its distribution

Some samples of single and plied warp yarns were treated with silver nanoparticles. Moreover two types of the new produced bandage samples were treated with three concentrations of zinc oxide nanoparticles in powder form with 15 g/L binder. The nanoparticles size and its distribution were evaluated using the scanning electron microscopy (SEM) and the energy dispersive X-ray (EDX) for the treated and un-treated single and plied yarn samples as well as the two types of WCBs.

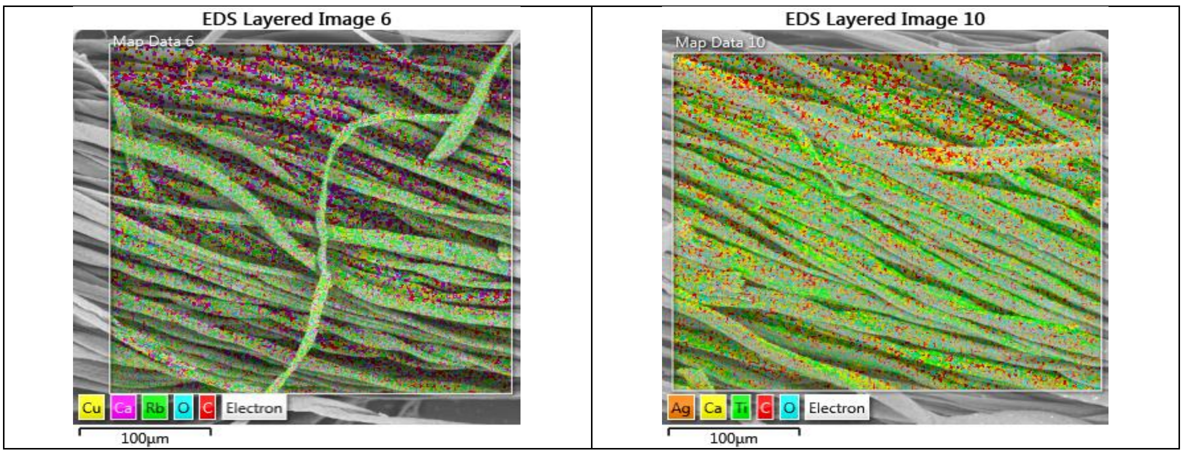
4.2.3.1. Scanning electron microscopy and energy dispersive X-ray of the yarns

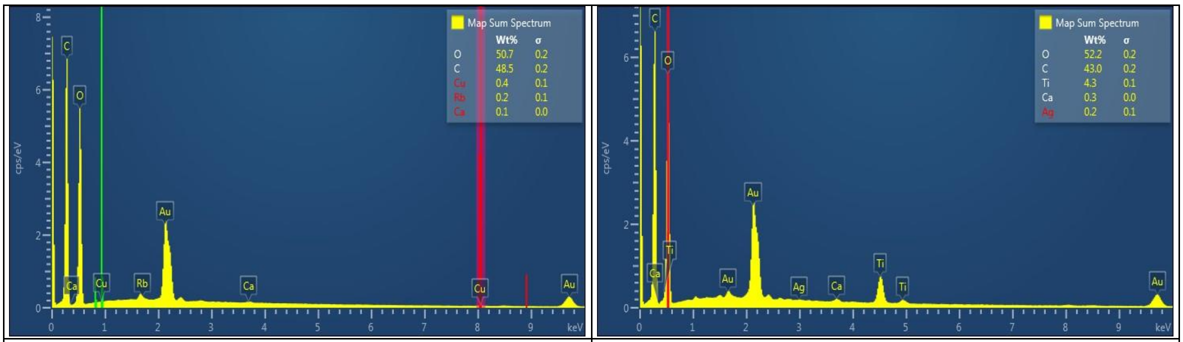
The scanning electron microscopy of the treated and un-treated plied cotton yarn samples are illustrated in Figure 4.2. The silver NPs size and distribution are totally clear for the treated yarn samples. Moreover the energy dispersive X-ray mapping for the yarn samples confirmed the NPs percent in the total composition of yarn EDX mapping, see Figures 4.3 & 4.4.



Un-treated plied yarn	Treated plied yarn

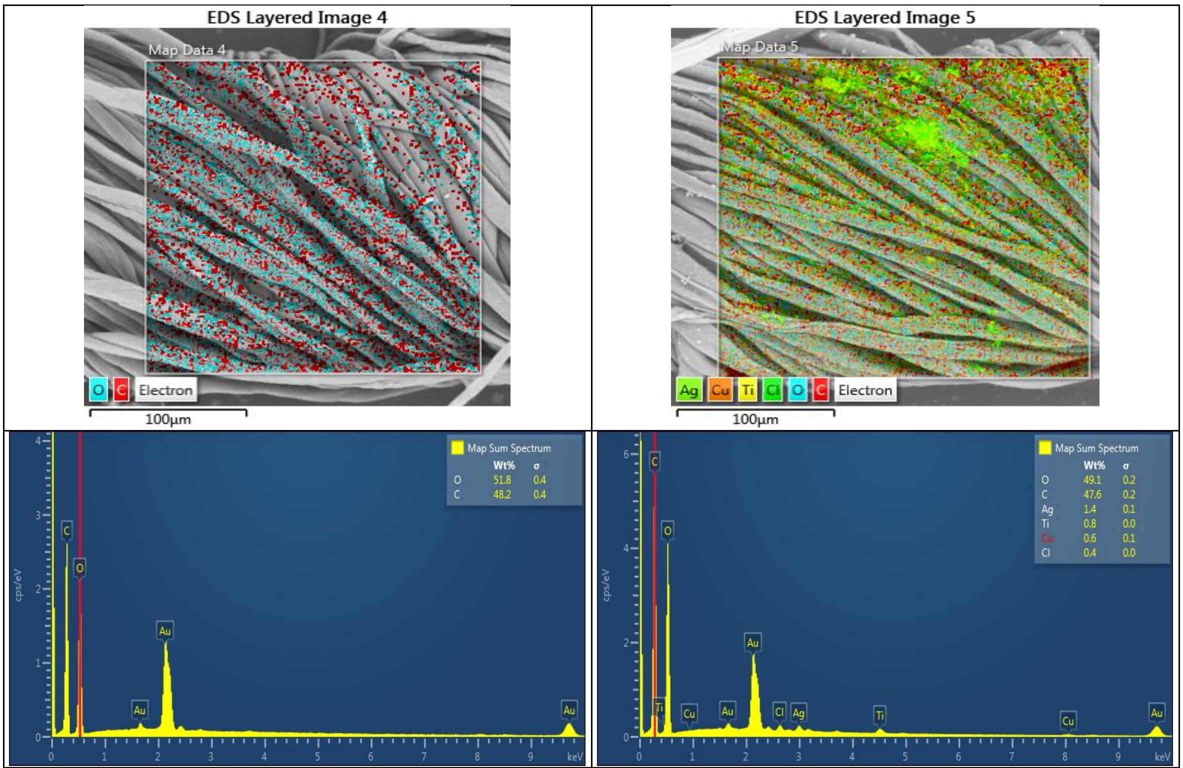
Figure 4.2. Scanning electron microscopy of the un-treated and treated plied yarns





Un-treated single yarn | Treated single yarn

Figure 4.3. Energy dispersive X-ray mapping of the un-treated and treated single yarns



Un-treated plied yarn | Treated plied yarn

Figure 4.4. Energy dispersive X-ray mapping of the un-treated and treated plied yarns

4.3. Relationship between yarn twist and tenacity

Figure 4.5 illustrates that increasing the plied yarn twist, in group 1, from 300 to 600 twist/m increases the yarn tenacity and breaking elongation by 5.16 and 8.21% respectively. After that, the yarns breaking load gradually decreases by increasing the yarn twist from 900 up to 1800 twist/m, on the contrary, the yarns extension significantly increases by 27.48%. Whereas the plied yarn, group 2, at twist 2100 twist/m is giving fewer tenacity values than 1850 twist/m by 20.86%, moreover the tenacity decreased by a percent 15.73% at 2300 twist/m. These lower values of tenacity may be due to the increase in twist angle near to the perpendicular level (wrapping angle ≈ 87°) at the highest levels of ply twist, as a result the horizontal component of the forces contributing in yarn strength is decreasing.

The obtained results in Figures 4.5 - 4.7 contribute to selecting the optimum yarn twist, but it's not conclusive because the twist range and the yarns count are different. At least (1500-1800 twist/m) are required for producing high extension Cotton compression bandages, whereas to achieve 100% elastic Cotton compression bandage (2200 – 2300 twist/m) would be used. The optimum extension level and applied load entirely depend on the final end-use of the compression bandage either for venous leg ulcers or athletic performance. These yarn parameters can be displayed as shown in Figures 4.6 & 4.7

to give accurate comparison and best selection of the optimum (critical) yarn twist. The candidate results of yarn tenacity and breaking elongation wouldn't be reached when producing the elastic WCBs because these bandages are only produced using the elastic region of the warp yarns. The 1st group of plied yarns achieves higher tenacity values than the 2nd group but lower extension. So the best selection of the yarn twist and count depends on the end use of the compression bandage, see Tables 4.3 & 4.4.

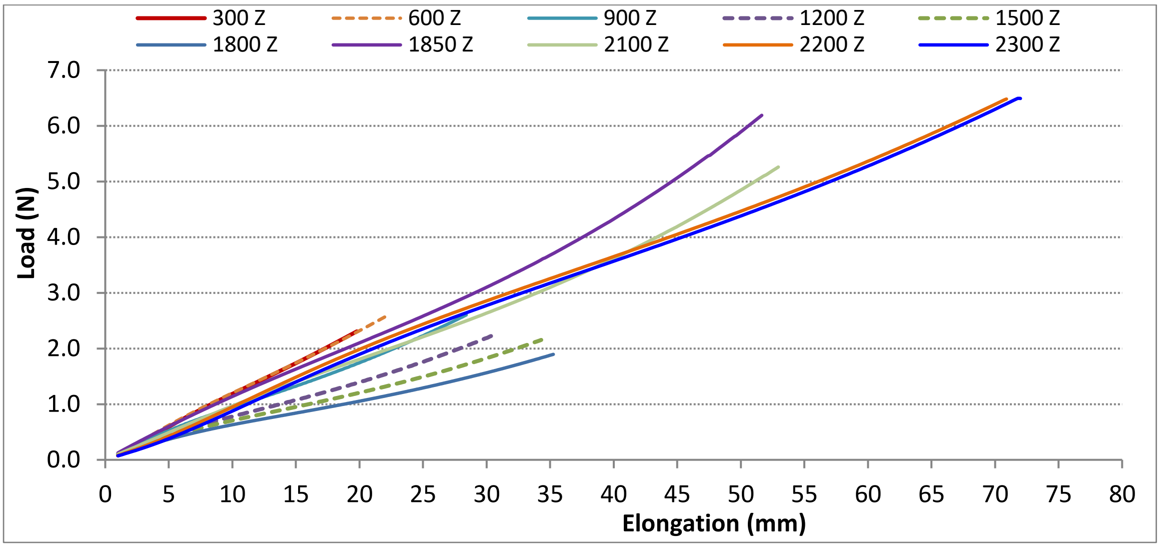


Figure 4.5. Load-elongation curves of the 1st and 2nd groups of yarns

Taking into consideration the yarn properties; the comparison would be using the tenacity (cN/Tex) and extension (%) of the yarns as illustrated in equations (4.3) to (4.5).

$$\text{Tenacity} = \text{Breaking load (N)}*100 / \text{Yarn count (Tex)} \quad (4.3)$$

$$\text{Strain} = \Delta L / L_1 \quad \text{or} \quad \text{Extension (\%)} = \Delta L *100 / L_1 \quad (4.4)$$

$$\Delta L = L_2 - L_1 \quad (4.5)$$

Where:

L_1 is the initial (gauge) length; L_2 is the extended length of yarn.

Table 4.3: Yarn properties, Group 1: plied yarns, 6x2 Tex

Yarn twist (twist/m)	Actual yarn count (Tex)	Tenacity		Extension	
		Average (cN/Tex)	Standard deviation Std. (cN/Tex)	Average (%)	Std. (%)
300	11.78	23.64	1.4275	4.75	0.6118
600	12.16	24.86	1.5201	5.14	0.6515
900	12.87	23.51	1.9156	6.44	0.8210
1200	13.24	20	1.7504	6.98	0.7502
1500	13.71	18.09	1.4808	7.67	0.6346
1800	13.96	16.49	1.5827	8.21	0.6783

Table 4.4: Yarn properties, Group 2: plied yarns, 21x2 and 30x2 Tex

Yarn twist (twist/m)	Nominal yarn Count (Tex)	Actual yarn count (Tex)	Tenacity		Extension	
			Average (cN/Tex)	Std. (cN/Tex)	Extension (%)	Std. (%)
1850	21x2	49.37	15.53	1.2982	12.01	0.6491
2100		51.15	12.85	1.2596	12.19	0.6298
2200	30x2	74.72	9.86	1.4965	15.78	0.7483
2300		80.27	8.52	1.2289	15.77	0.6144

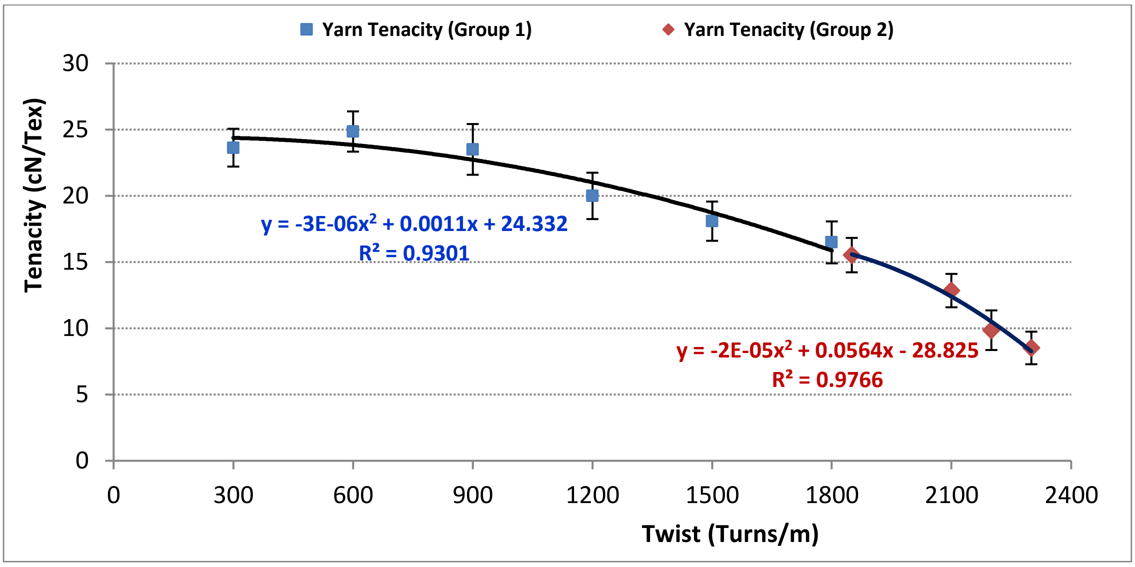


Figure 4.6. Effect of plying twist on yarn tenacity for market yarns

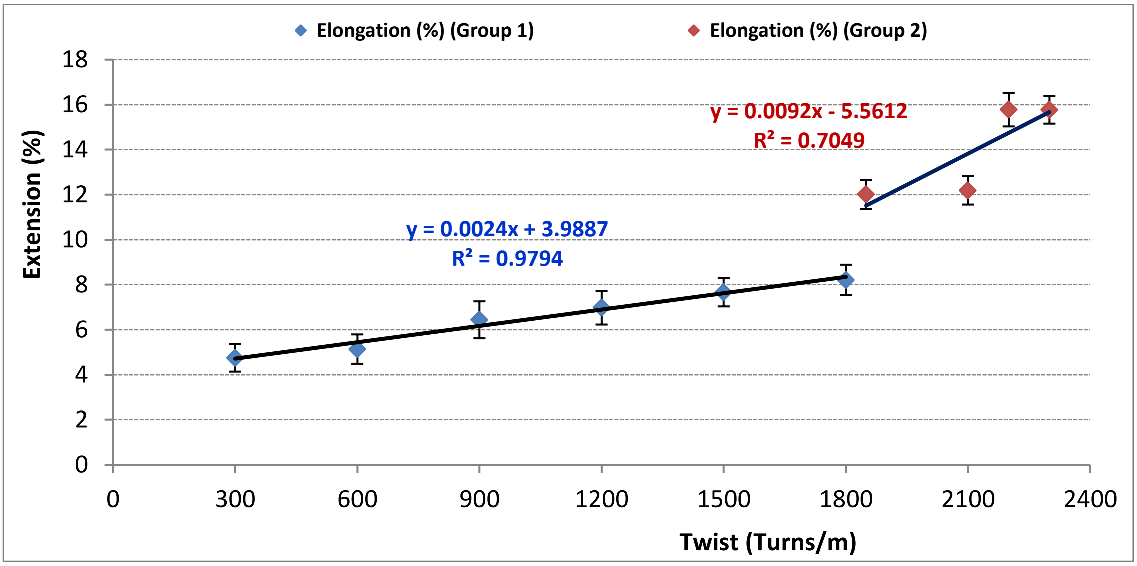


Figure 4.7. Effect of plied yarn twist on its extension, market yarns

The evaluation of the used plied warp yarns in market for producing the WCB and the new produced yarns concluded that the warp yarn tenacity should be greater than 16 cN/Tex and its extension should be at least 12% to produce the highly stretched 100% Cotton WCB, as displayed in Figures 4.6 – 4.9. The twist range (1500 - 1800 twist/m) is required – at least – for producing high extension Cotton compression bandages, whereas to achieve 100% elastic Cotton compression bandage (2200 – 2300 twist/m) would be used. The optimum extension level and applied load totally depends on the final end-use of the WCB either for venous leg ulcers or athletic performance.

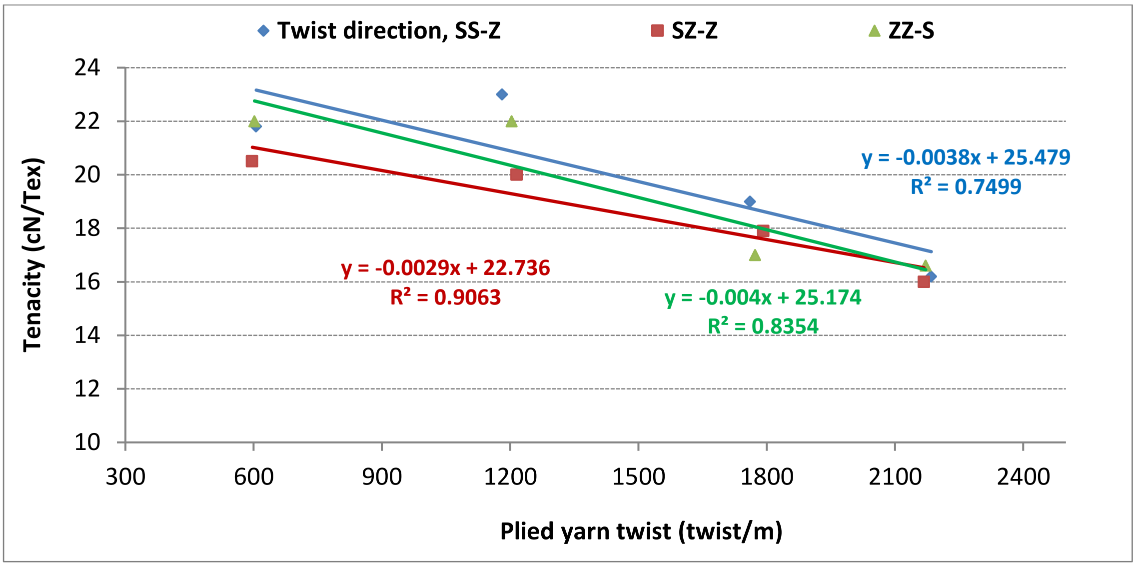


Figure 4.8. Effect of plying twist on yarn tenacity for produced yarns

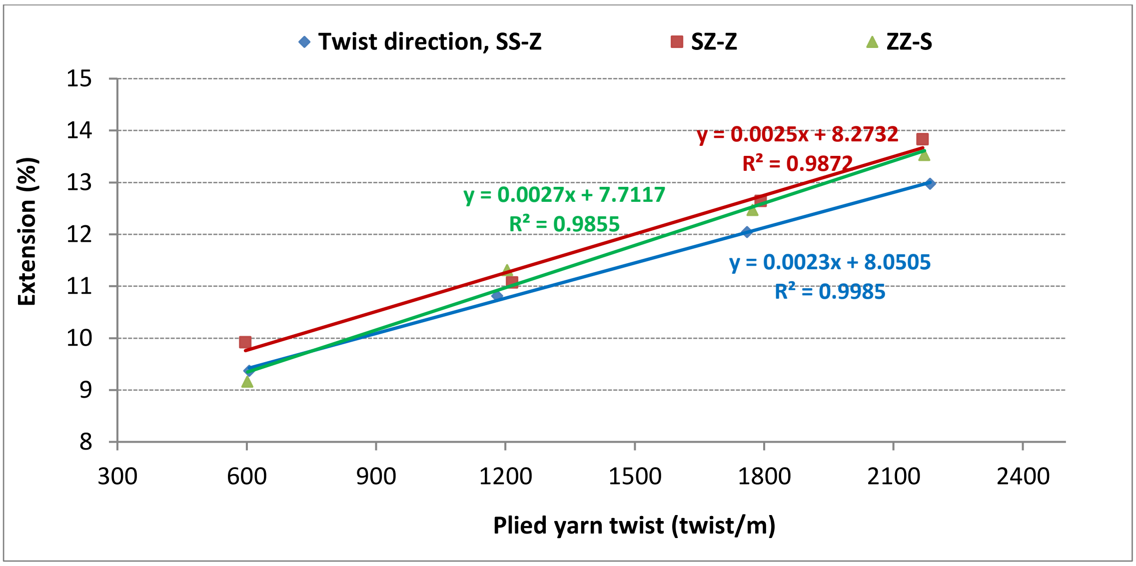


Figure 4.9. Effect of plied yarn twist on its extension, produced yarns

5. Part 2, Analysis of Woven Compression Bandages' Properties

5.1. Methods used, studied material

5.1.1. Analysis of mechanical properties of WCBs

A) Three types of WCB were used for testing as shown in Figure 5.1. These bandages' structures are plain weave. Yarn counts and densities are different depends on the construction and technology of the final product.

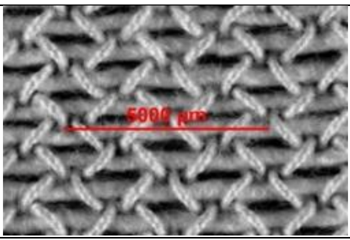
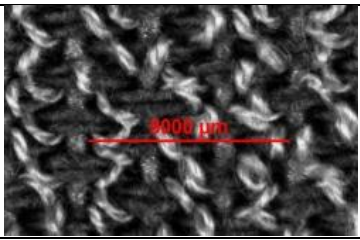
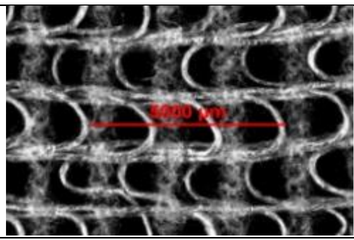
		
a) 100% Bleached Cotton Warp set: 8 ends/cm Weft set: 15 picks/cm Warp count: Cotton, 20x2 Tex, 2x1200 twist/m, SS/Z, ZZ/S Weft count: Cotton, 75 Tex, OE. Fabric weight: 210.25 g/m^2 Fabric thickness: 1.06 mm	**b) CO-PA-PU bandage** Warp set: 11 ends/cm Weft set: 18 picks/cm Warp count: Cotton, 10x2 Tex - Polyamide, 7.8 Tex - Polyurethane, 42.5 Tex Weft count: Cotton, 36.9 Tex Weight: 236.48 g/m^2 Thickness: 1.09 mm	**c) VI-PA bandage** Warp set: 12 ends/cm Weft set: 14 picks/cm Warp count: Viscose,16.5 Tex, open end (OE), Polyamide – 7.8 Tex Weft count: Viscose, 16.5 Tex. Weight: 83.34 g/m^2 Thickness: 0.91 mm

Figure 5.1. Experimental woven compression bandages description

B) Compression bandages tension is evaluated according to the standard test method ISO 13934-1:1999(E) [34]. Testometric M350-5CT was used to measure the tension developed in the bandage while extension at a constant speed of 100 mm/min. The device gauge length was set to 100 mm.

C) Bandage porosity is calculated by measuring the binary area fraction using high resolution camera. While subjecting the bandage samples to a constant extension, the resultant images were recorded using digital camera. There are 120 frames (images) for each sample; these images were analysed by NIS-Elements software to measure binary area fraction using Threshold technique as shown in Figures 5.2 & 5.3.

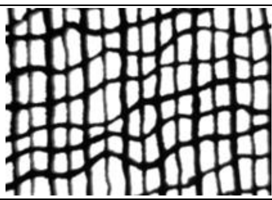
		
(a) At 1 sec 0% extension	(b) 60 sec 100% extension	(c) 120 sec 200% extension

Figure 5.2. Binary area of Cotton bandage during tension

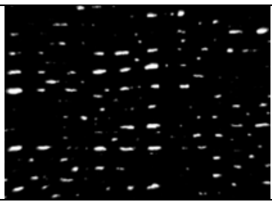
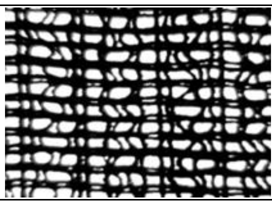
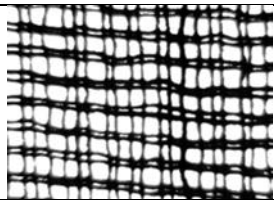
		
(a) At 1 sec 0% extension	(b) 60 sec 100% extension	(c) 120 sec 200% extension

Figure 5.3. Binary area of Viscose/Lycra bandage during tension

5.1.2. Testing of bandage pressure using PicoPress

The same three types of bandages were worn on both mannequin model and real leg to test and analyse the effect of WCB extension and porosity on bandage pressure at ankle and mid-calf position in both static and walking conditions. Practical bandage pressure is measured using Microlab Picopress instrument M-700 tester, which gives both digital readings and graphical charts as well. The ankle and calf positions were adjusted to leg circumferences of 21.4 and 32.4 cm respectively for mannequin model, 25.6 and 38.9 cm respectively for real leg, as illustrated in Figure 5.4 [35]. The obtained results are both digital numbers and graph forms. There are three levels of bandage tension (low: 50% extension and 50% overlap, medium: 100% extension and 50% overlap, and high: 100% extension and 66% overlap) applied on 1st position (ankle at radius 4.07 cm), 2nd (mid-calf at radius 6.19 cm), and 3rd (below the knee at radius 4.9 cm) [28].

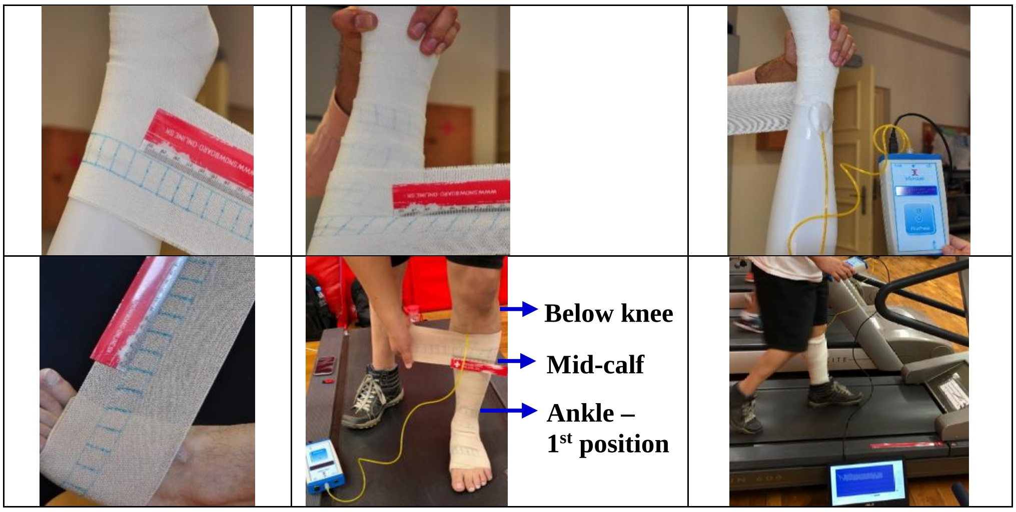
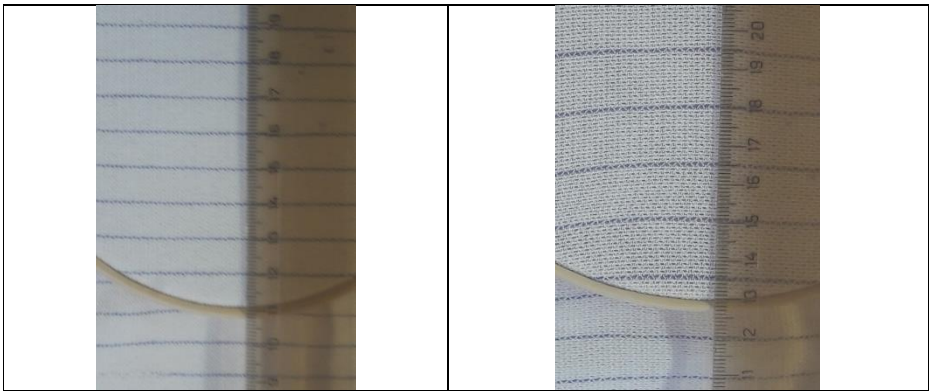


Figure 5.4. Application of compression bandage on mannequin and real leg

5.1.3. Relationship between the change in coloured weft spacing and compression during bandage application

Candidate study added the blue coloured weft during the weaving process of the 100% cotton WCB, as previously illustrated in Figure 3.4 as well as Figure 5.5. These blue marks (repeated lines every 1 cm) enables for accurate adjustment and evaluation of the applied bandage extension (100% extension at blue line spacing 2 cm). The activity of the new WCB could be evaluated using the same previous procedure to achieve the associated optimum pressure by the compression bandage on any part of the body, see Figures 5.4 and 5.5.



a) The cotton bandage at 0% extension | b) The cotton bandage at 50% extension

Figure 5.5. Adjusting the bandage extension using the blue lines (coloured weft threads)

5.1.4. Treatment of the surface of cotton WCB with zinc oxide

Two types of WCB (fabric) samples has been treated with three concentrations of ZnO nanoparticles as follows, 1%, 2%, and 3% in powder form with 15 g/L binder. The samples' coding for un-treated and treated cotton WCB with zinc oxide nanoparticles is described in Table 5.1 and the antibacterial tests were performed according to the following standards:

1. AATCC 147 Test Method: 147-2012 - Assessment of Antibacterial Activity of Textile materials: Parallel Streak Method. **2.** AATCC 100 Test Method: 100-2019 - Assessment of Antibacterial Finishes on Textile Materials.

Table 5.1: Samples' codes for treated cotton WCB with zinc oxide nanoparticles

State	Sample code	Sample code
Untreated, standard	1- with blue colour every 1 cm	2- without colours
Treated, 1% ZnO NPs	[1-1]	[2-1]
Treated, 2% ZnO NPs	[1-2]	[2-2]
Treated, 3% ZnO NPs	[1-3]	[2-3]

5.1.5. Testing the muscles activation when applying WCBs

Viscose-Polyamide and two types of Cotton compression bandages were used for hand and lower leg muscles testing respectively [36], [37]. VI-PA bandage was used to test the Flexor Carpi (FC) muscle voltage during different wrist actions (flexion-extension, squeezing a soft roll) with and without wearing CB, as shown in Figure 5.6. The applied compression by VI-PA bandage is adjusted and standardized to medium compression ranges 22±2 mmHg (through 70% bandage extension and 50% overlap). Bleached Cotton and CO-PA-PU bandages were used to test Medial Gastrocnemius (MG) and Soleus (SO) muscles behaviour during the standardized protocol actions (flexion-extension and while walking). The lower leg bandage pressure was adjusted to compression ranges 30±2 mmHg (by 100% bandage extension and 50% overlap) [38]. In order to investigate the change of muscles activity, root mean square (RMS) is processed by exporting the filtered signals to MATLAB software using band-pass filtering between 20–500 Hz.

Figure 5.6. EMG system for Flexor Carpi, Medial Gastrocnemius and Soleus muscles [39]

5.1.6. Analysis of thermal comfort properties of WCBs

The main three types and Viscose-Polyurethane (VI-PU) WCBs were wrapped on thermal foot manikin (TFM) at range of extension (10 to 80%) using both 50 and 66% overlap (i.e. two and three layers bandaging respectively). Thermal resistance (R_{ct}) was measured using TFM for all types of CBs as shown in Figure 5.7 [40]. Relative water vapour permeability (%) and water vapour resistance (R_{et}) were measured using the PERMETEST instrument [41] (Sensora, Czech Republic) according to ISO 11092 standard, at laboratory conditions (T: 22±2 °C, RH: 50±2%), as shown in Figure 5.8 [42]. The obtained results of R_{ct} were compared to ALAMBETA [43] testing device results, according to ISO 8301, see Figure 5.9 [44].

a) Cotton bandage	b) CO-PA-PU	c) VI-PA	d) VI-PU bandage

Figure 5.7. Woven CB samples on thermal foot manikin

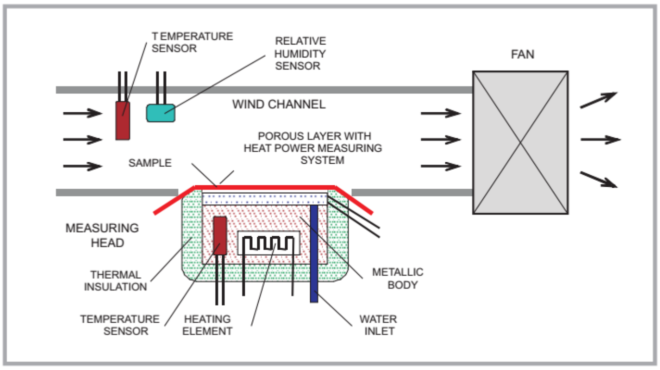


Figure 5.8. PERMETEST device for testing R_{et} and R_{ct} [42]

Figure 5.9. ALAMBETA testing device [44]

5.1.7. Adjusting the thermal resistance measurement on Thermal Foot Model

The following steps are practical example to show how to adjust and stabilize the optimum conditions of TFM to test R_{ct} of CB, see Figure 5.10. Segments 1, 3 are kept OFF because WCB effect usually starts after these segments, device door is opened. There are two types of testing (i.e. nude and clothed manikin) [45]. For accurate comparison, mercerized Cotton socks are used to cover TFM as underwear for all measured samples to ensure more stabilization and steady conditions.

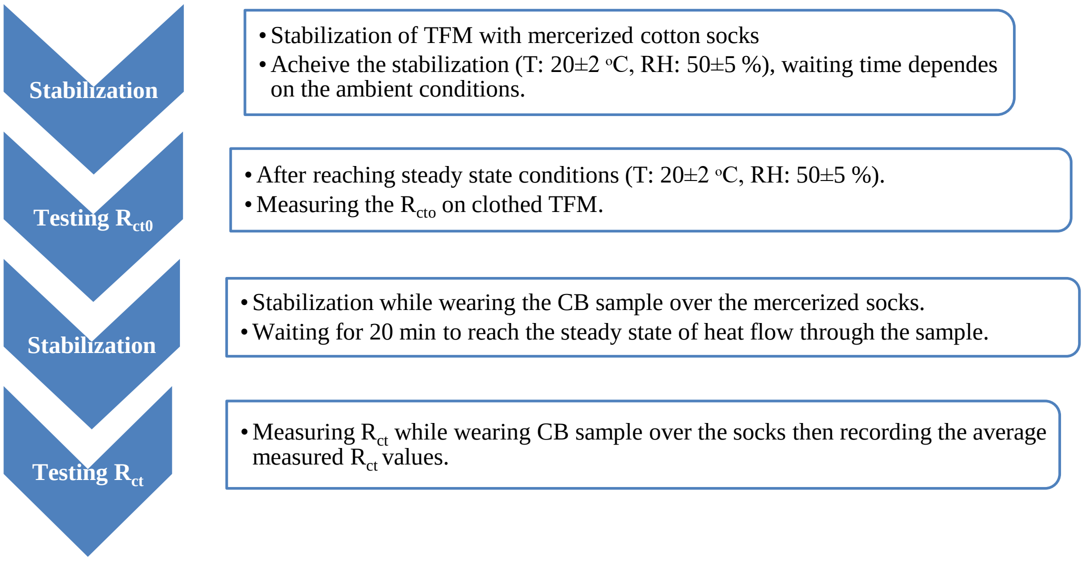


Figure 5.10. Optimum testing procedure of measuring R_{ct} on TFM

5.2. Summary of the achieved results

5.2.1. Evaluation of the mechanical properties of woven compression bandages

5.2.1.1. Optimum fabric tension for woven compression bandages

As the optimum required bandage tension is approximately 10N, that value is achieving the average bandage pressure (4000 Pa or 30 mmHg) according to Laplace's equation (5.7) for two layers bandaging at leg radius 5 cm and bandage width 10 cm. Figure 5.11 confirms that CO-PA-PU and VI-PA bandages require 110% and 92% extension respectively while Cotton bandage requires only 60% extension to achieve the required bandage tension 10N. The Cotton bandage extension depends on the highly twisted plied yarns (1200 twist/m) that enable to achieve the required bandage stretch, but these bandages have lower extension (short-stretch) compared to CO-PA-PU that contains 6% of elastomeric filament (Polyurethane) which gives higher extensibility (long-stretch bandage). Whereas the VI-PA bandage consists of two types of yarns having different thermal and melting points, in which case the stretch is given by steaming then heat setting at the required percent of shrinkage.

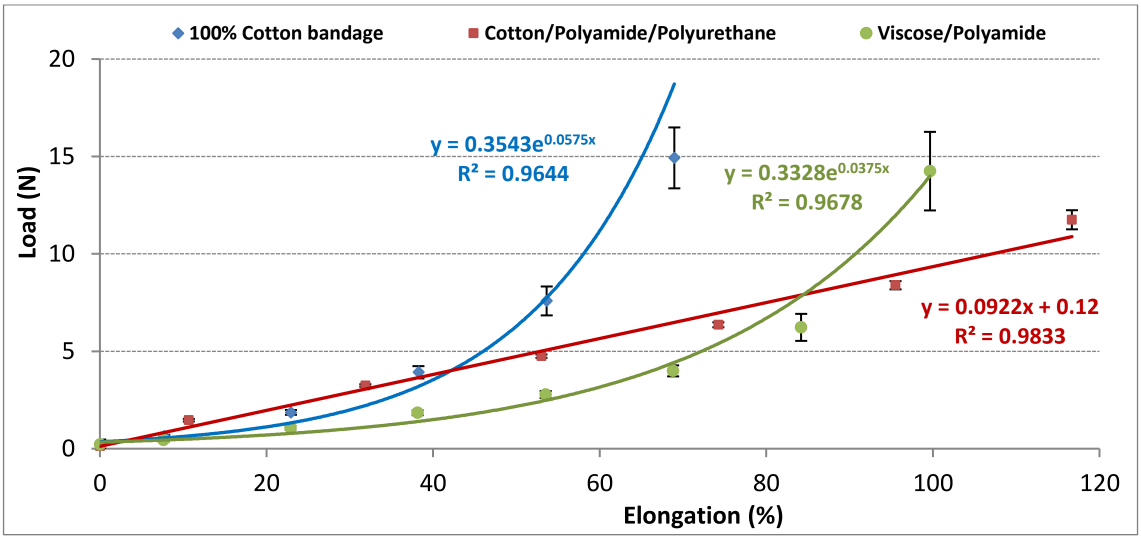


Figure 5.11. Optimum fabric tension for Cotton, CO-PA-PU, and VI-PA bandages

5.2.1.2. Effect of extension level and yarns angle on bandage porosity

The factors affecting bandage porosity such as (warp and weft yarns count, density, twist, cover factor, and fabric structure) are changing during the bandage extension. One of the main variables during bandage application is the applied tension to achieve the required compression. A lot of models were presented for the description of porosity in woven fabrics, some of them described the porosity between yarns in the fabric (the inter-yarn porosity), and the others described the porosity between fibres inside the yarn (the intra-yarn porosity). According to theory of a 2-D model, the horizontal porosity (ε_h) is defined as 'a complement to the woven fabric cover factor (CF)', see Figure 5.12.

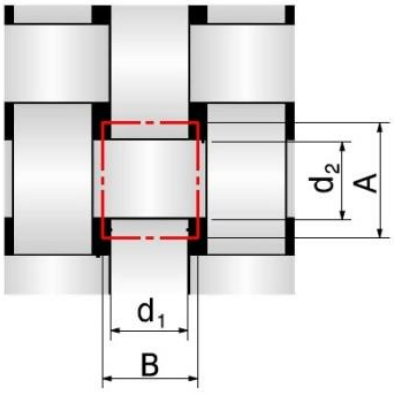


Figure 5.12. Structure of interlacing cell in woven fabric crossing point of plain weave, warp and weft diameter (d_1, d_2), warp and weft distance (B, A).

Woven fabric cover factor is given on the basic of illustrated structure of woven fabric in Figure 5.12 by equation (5.1) as followed:

$$\{ CF = \frac{visible\ area\ covered\ by\ yarns}{total\ area\ of\ cell} = \frac{d_1 A + d_2 B - d_1 d_2}{AB} = CF_{warp} + CF_{weft} - CF_{warp} CF_{weft} \} \quad (5.1)$$

Based on known parameters of warp and weft density (D_1 and D_2), we can write equation (5.2):

$$A = \frac{1}{D_2} \quad \textbf{and} \quad B = \frac{1}{D_1} \qquad (5.2)$$

The horizontal porosity (ε_h) can be calculated by image analysis as 'the area of pores in a perpendicular projection of woven fabric' [46]. Real values can be measured as illustrated in equation (5.3):

$$\varepsilon_h = 1 - CF = 1 - (d_1 D_1 + d_2 D_2 - d_1 d_1 D_2 D_2) \qquad (5.3)$$

While dealing with two dimensional fabrics, porosity is defined as 'the ratio of the projected geometrical area of the opening across the material to the total area of the material' [47], [48]. A classical 2-D model of porosity seems insufficient for a tightly woven fabric. Neighbouring yarns are very close and the projected area of inter-yarn pores approaches to zero. As air flows through the woven fabric, it flows around the yarns and it does not flow only in the perpendicular direction [49], [50]. Gee introduced the well-known 'ends plus intersection theory', which he modified, and called the 'curvature theory' [51]. Until then a 'maximum theory' had been the subject of several research. Some researchers [52]-[56] have used a more theoretical approach, whereas others [57] used more experimental means. Kienbaum has successfully joined theoretical and experimental investigations, and presented his own theory which can be applied to all weaves and different yarn structures [46].

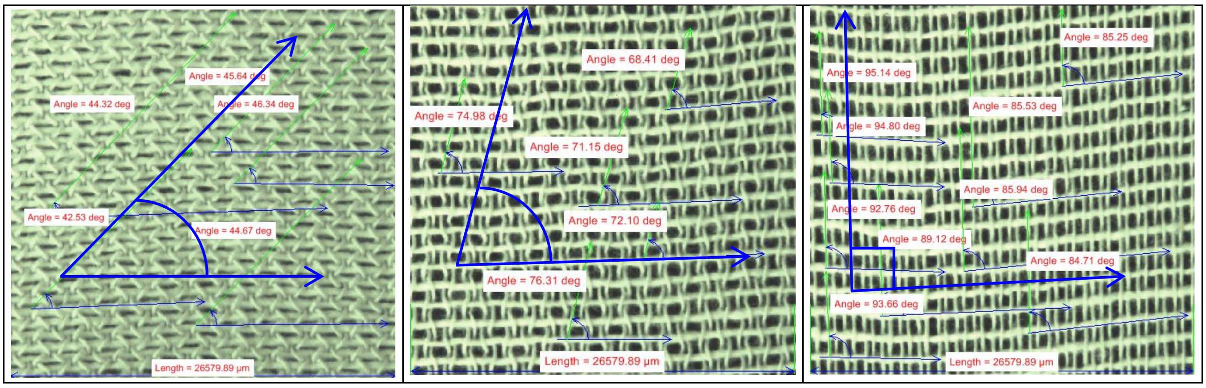
The overall volume porosity (ε) can be defined theoretically as 'the fraction of void space in a porous medium', see equations (5.4) and (5.5).

$$\textbf{Overall porosity } (\boldsymbol{\varepsilon}) = \mathbf{1} - \boldsymbol{Fabric\ packing\ density} \qquad (5.4)$$

$$\boldsymbol{\varepsilon} = \mathbf{1} - \frac{\rho_F}{\rho_f} = \mathbf{1} - \frac{w}{t\ .\ \rho_f} \qquad (5.5)$$

Where ρ_F is the fabric density and ρ_f is the fibre density (g/cm^3), w is the fabric weight (g/m^2), and t is the fabric thickness (mm) [58].

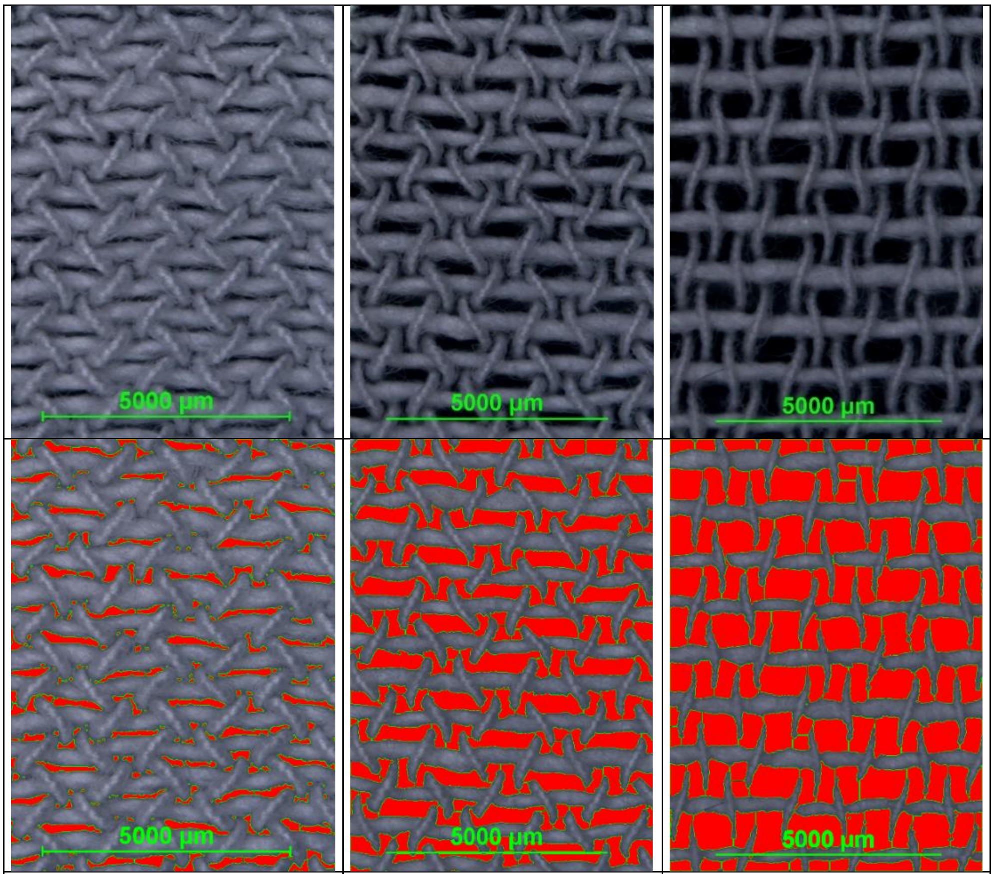
Figure 5.13 confirms that the horizontal porosity of cotton bandage is significantly improving by increasing the bandage extension and the angle between warp and weft. The statistical analysis of the obtained results is summarized in Table 5.2. The bandage extension and type have significant effects on weave angle and porosity (significance level, P= 0 < 0.05) using both one and multiple variable linear regression. The same trend has been analysed for CO-PA-PU and VI-PA bandages during the uniaxial stress on the Testometric M350-5CT testing device.



0% extension	**50% extension**	**100% extension**
Average yarns angle θ = 44.1°, Std. = 1.97° Sum of pores area = 0.98 cm^2 Total fabric area = 6.85 cm^2 Bandage porosity can be calculated by binary area fraction = 0.243	θ = 72.59° , Std. = 2.81° Sum of pores area = 2.41 cm^2 Total fabric area = 6.85 cm^2 Bandage porosity = 0.392	θ = 90.05° , Std. = 3.76° Sum of pores area = 2.81 cm^2 Total fabric area = 6.85 cm^2 Bandage porosity = 0.514

Figure 5.13. Effect of extension and warp to weft yarns angle on porosity of Cotton bandage

As for the application of 100% cotton bandage on real leg, the bandage horizontal porosity has been analysed as a function of the bandage extension level and the angle between warp and weft threads as displayed in Figure 5.14.



0% extension	**40% extension**	**80% extension**
Average weave angle θ = 43.68°, Std. = 1.58° Bandage porosity = 0.191	Average weave angle θ = 60.84° , Std. = 2.15° Bandage porosity = 0.395	Average weave angle θ = 78.96°, Std. = 1.27° Bandage porosity = 0.554

Figure 5.14. Effect of extension level on the horizontal porosity of cotton bandage during application

Table 5.2. Statistical analysis of relation between bandage extension and yarns angle

ANOVA [c]						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	16175.052	1	16175.052	343.050	.000[a]
	Residual	2027.478	43	47.151		
	Total	18202.530	44			
2	Regression	16574.873	2	8287.437	213.849	.000[b]
	Residual	1627.657	42	38.754		
	Total	18202.530	44			
a. Predictors: (Constant), Extension						
b. Predictors: (Constant), Extension, Bandage Type						
c. Dependent Variable: Angle between warp and weft						

5.2.2. Analysis of bandage pressure using PicoPress

Experimental pressure of WCBs (100% Cotton and VI-PU) is measured using PicoPress on mannequin leg, as shown in Figure 5.15. The same compression test is carried out for all types of bandages on real leg at the 1st, 2nd, and 3rd positions, as previously illustrated in Figure 5.4. The first type of bandages is 100% Cotton using highly twisted plied Cotton yarns. Average compression values at 1st position for the three tension levels (low, medium, high) were about (24, 37, 59 mmHg) respectively. The obtained results at 1st position are decreasing by average percent 12% after three hours, whereas compression values for 2nd position were (16, 29, 50 mmHg) decreasing by average percent 11%, as shown in Figures 5.22 - 5.25. These loses may be due to the bandage slippage or less fixation on leg model.

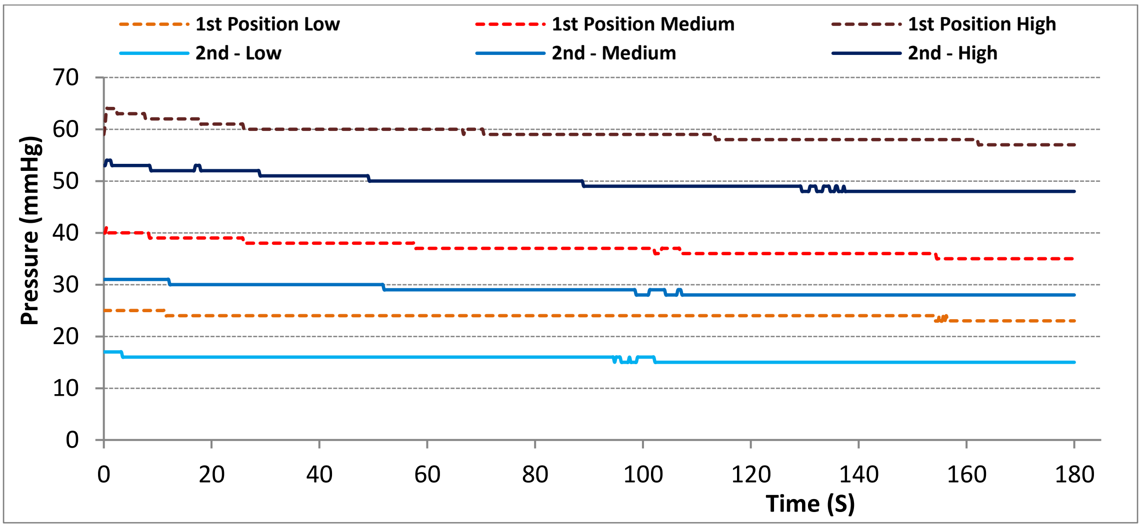


Figure 5.15. Pressure of Cotton bandage on leg model

As for applying compression bandages on a real leg; all compression tests were applied on the same group of 4 men, their age ranges 28 to 37 years old. Figure 5.16 emphasizes the significant change of compression during walking, which is oscillating between (18-33, 27-43, and 36-61 mmHg) for 1st position, (8-16, 18-27, and 35-51) for 2nd position. These oscillations during walking and running should be considered while wearing the compression bandages for long time to achieve effective healing rates. Meanwhile the pressure of CO-PA-PU WCB was evaluated while walking; that is ranging (10-19, 20-35, and 34-50 mmHg) for 1st position, (17-23, 22-26, and 27-37 mmHg) for 2nd position, and (12-15, 13-18, and 13-19 mmHg) for 3rd position. Oscillating ranges of CO-PA-PU bandage are lower than the 100% Cotton bandage because of more extensibility. The bandaging techniques were significantly influencing on the measured pressure by PicoPress, as illustrated in Table 5.3 and Figure 5.17.

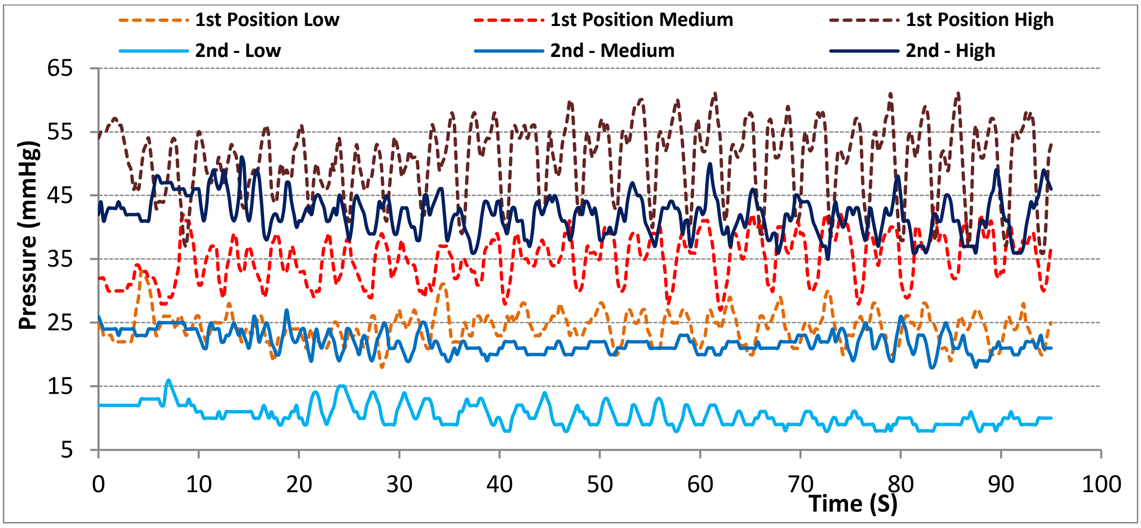


Figure 5.16. Pressure of Cotton bandage on real leg while walking.

Table 5.3. Statistical analysis of the effect of testing position and extension level on the measured pressure by PicoPress

	Regression Summary for Dependent Variable: Pressure (PicoPress pressure-Full results) R= .96026393 R^2= .92210681 Adjusted R^2= .92203839 F(2,2277)=13478. p<0.0000 Std. Error of estimate: 3.8462					
N=2280	b*	Std. Error of b*	b	Std. Error of b	t(2277)	p-value
Intercept			19.4759	0.322196	60.4472	0.00
Testing position	-0.429365	0.005849	-11.8263	0.161098	-73.4106	0.00
Extension Level	0.858925	0.005849	14.4875	0.098652	146.8544	0.00

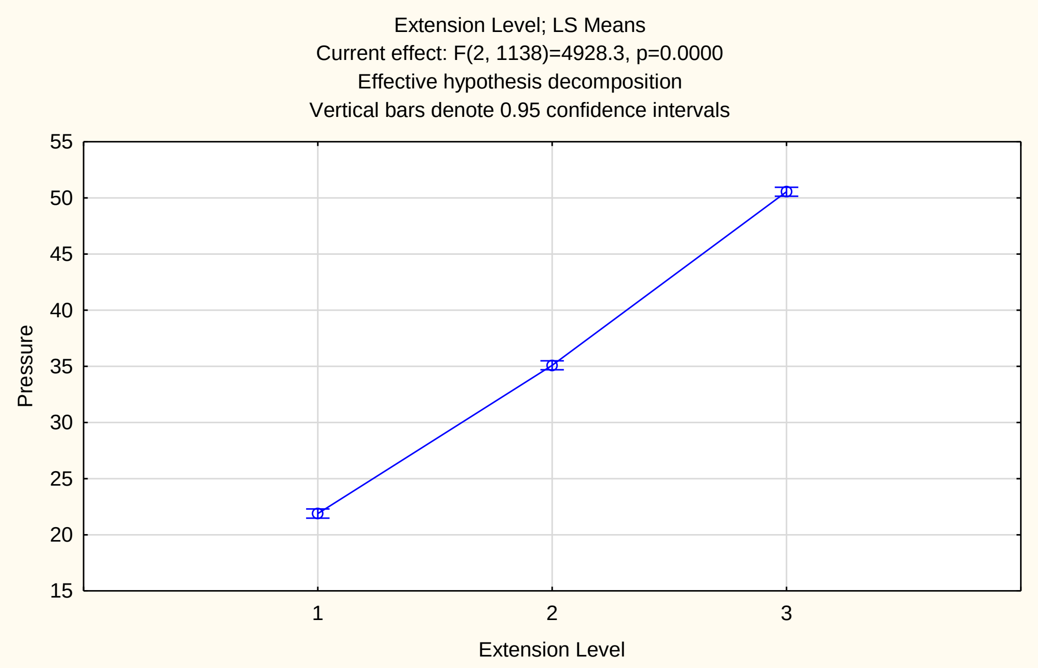


Figure 5.17. Effect of bandage extension level on the measured pressure at the ankle position for cotton bandage, statistically analysed by main effects ANOVA

5.2.3. Comparison between calculated and measured compression using PicoPress

100% Cotton, CO-PA-PU, and VI-PU bandages were worn one by one on real leg to test the real compression pressure at ankle and mid-calf position in both static and walking conditions at different extension levels. Ankle and calf positions were adjusted at leg circumference of 25.6 and 38.9 cm respectively. Deviation percent, equation (5.8), was calculated as the difference between measured compression using PicoPress and calculated pressure by Laplace's equation (5.7) [8, 9, 59, and 60], as illustrated in Table 5.4.

$$Pressure\ (Pascal) = \frac{Tension\ (N) * No.\ of\ Layers}{Radius\ (m) * Bandage\ width\ (m)} \quad (5.6)$$

$$Pressure\ (mmHg) = \frac{T\ (N) * n}{R\ (m) * W\ (m)} * 0.0075 \quad (5.7)$$

The level of pressure exerted on a medical device matches with the Laplace's equation stating that the pressure (P expressed in Pa) of a compression applied to the skin surface is directly proportional to the tension (T in N) of the compression material and number of layers, and inversely proportional to the radius of curvature (R in m) of limb surface to which it is applied and the bandage width (W in m) [61].

$$\textbf{Deviation percent}\ (\%) = \frac{P_{Calculated} - P_{Picopress}}{P_{Calculated}}\ x\ 100 \quad (5.8)$$

The obtained results in Figures 5.18 – 5.21 and Tables 5.4 & 5.5 confirm that there are significant deviations when applying Laplace's equation for two and three layers bandaging ranging ±0.68 to ±15.64%, especially at high extension levels on ankle position. The highest deviation values were clearly significant at high extension 60-80%, this might be due to the compactness and high compression at ankle position. Moreover Jawad Al Khaburi developed this equation (5.9) to include the increase in limb circumference due to multilayer bandaging; this equation has decreased the deviation range to be ±0.07: ±12.55% as illustrated in the following equations [62]:

$$P = \sum_{i=1}^{n} \frac{T_i\ (D_i + t_i)}{0.5 * W_i * D_i^2 + W_i * t_i\ (D_i + t_i)} * 0.0075 \quad (5.9)$$

$$\text{Where} \quad D_i = D + \sum_{i=1}^{n} 2\ t_{i-1} \quad (5.10)$$

Results of Figures 5.20 & 5.21 conclude that the deviation when applying Laplace's equation for mid-calf position is ranging ±0.27 to ±13.14%, while the deviation range of Al Khaburi's equation is ±0.14 to ±11.04%.

Table 5.4. Calculated pressure by Laplace's equation vs. measured values at ankle position (R= 4.07 cm)

Bandage type	No of layers	Extension (%)	Applied Tension (N)	Std. of tension	Measured compression PicoPress (mmHg)	Calculated pressure values (mmHg)			
						Laplace's equation	Deviation percent (%)	Al Khaburi's equation	Deviation percent (%)
100% Cotton bandage	2	20	1.75	0.19	7.02	6.45	-8.84	6.29	-11.52
		30	2.81	0.07	10.84	10.36	-4.67	10.11	-7.24
		40	3.94	0.12	14.62	14.52	-0.68	14.17	-3.16
		50	6.06	0.31	21.71	22.33	2.79	21.80	0.41
		60	9.79	0.82	35.19	36.08	2.47	35.22	0.07
		70	13.37	1.41	45.71	49.28	7.24	48.09	4.96
		80	17.26	1.92	56.83	63.61	10.66	62.09	8.47
	3	20	1.8	0.22	10.58	9.95	-6.32	9.60	-10.22
		30	2.92	0.11	16.39	16.14	-1.53	15.57	-5.25
		40	4.05	0.17	21.83	22.39	2.50	21.60	-1.07
		50	6.24	0.39	32.67	34.50	5.29	33.28	1.83
		60	10.12	0.94	51.61	55.95	7.75	53.97	4.37
		70	13.85	1.55	68.38	76.57	10.69	73.86	7.42
		80	17.93	2.13	83.62	99.12	15.64	95.62	12.55
CO-PA-PU bandage	2	20	1.41	0.19	5.57	5.20	-7.19	5.07	-9.82
		40	3.58	0.13	13.81	13.19	-4.67	12.88	-7.24
		60	5.25	0.21	20.13	19.35	-4.04	18.88	-6.59

		80	8.64	0.49	32.15	31.84	-0.96	31.08	-3.45
		100	10.73	0.73	41.62	39.55	-5.25	38.60	-7.83
		120	13.97	1.65	47.93	51.49	6.91	50.25	4.62
	3	20	1.43	0.18	8.35	7.91	-5.62	7.63	-9.49
		40	3.64	0.15	21.06	20.12	-4.66	19.41	-8.49
		60	5.37	0.19	30.49	29.69	-2.71	28.64	-6.47
		80	8.91	0.53	46.43	49.26	5.74	47.52	2.29
		100	10.94	0.97	56.39	60.48	6.76	58.34	3.35
		120	14.23	2.19	71.69	78.67	8.87	75.89	5.53

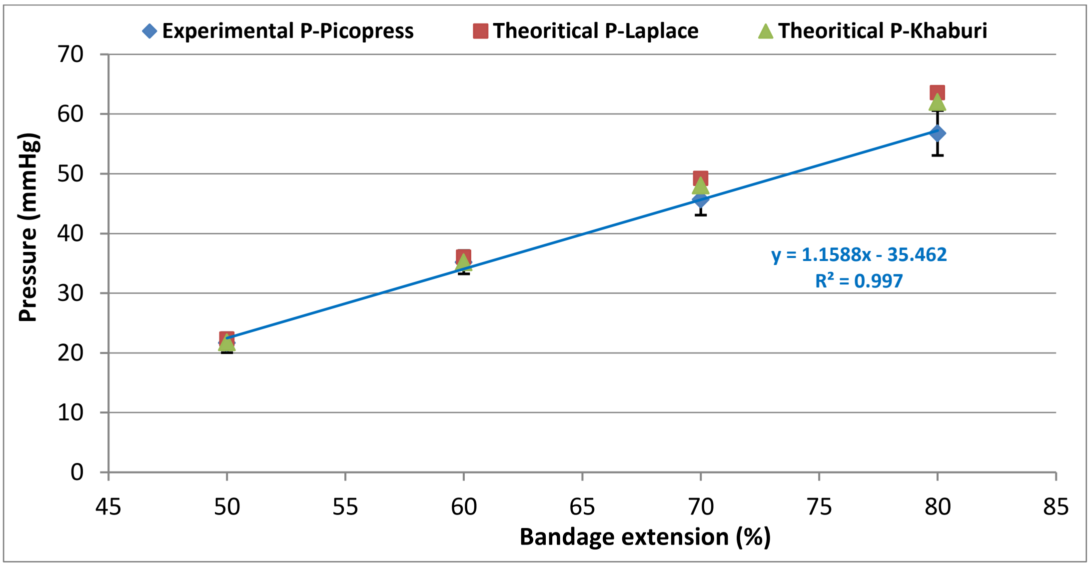


Figure 5.18. Measured bandage pressure by PicoPress vs calculated by Laplace's and Al-khaburi's equations at ankle position using two layers of cotton bandage

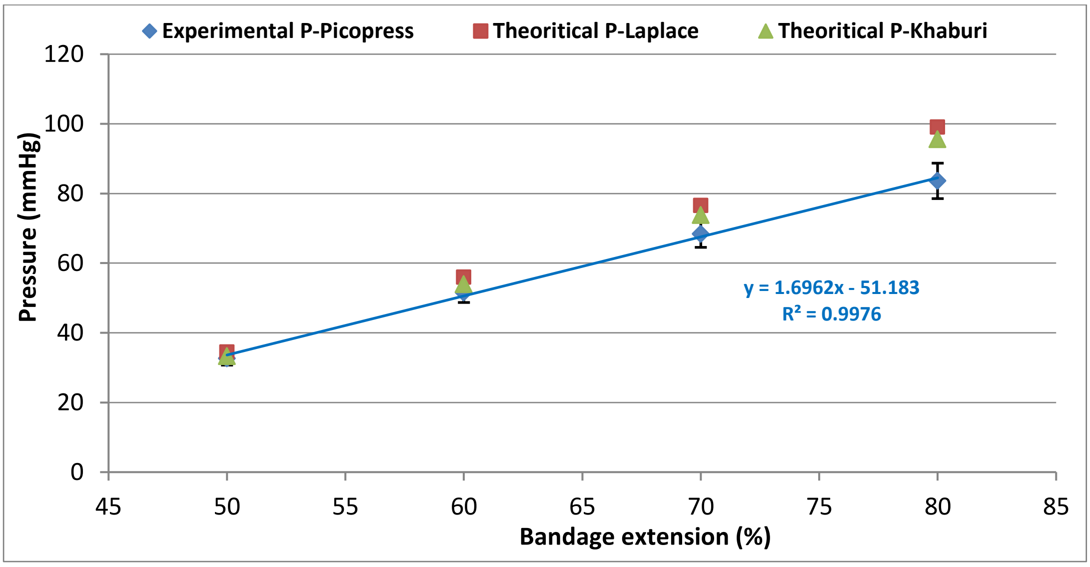


Figure 5.19. Measured bandage pressure by PicoPress vs calculated values at ankle position using three layers bandaging

Table 5.5. Multiple regression for the effect of bandage extension, number of layers, and bandage type on the measured pressure at ankle position

N=26	Regression Summary for Dependent Variable: **Measured pressure, PicoPress** (Ankle position) R= .92307130 R^2 = .85206063 Adjusted R^2 = .83188708 F(3,22)=42.237 p-value = 0.000000002671713					
	b*	Std. Error of b*	b	Std. Error of b	t(22)	p-value
Intercept			-17.3050	10.53323	-1.64290	0.114621
Bandage Type	-0.342728	0.087243	-14.7613	3.75753	-3.92845	0.000718
No of layers	0.298003	0.082003	12.7969	3.52141	3.63404	0.001466
Extension	0.929065	0.087243	0.6829	0.06413	10.64922	0.000000

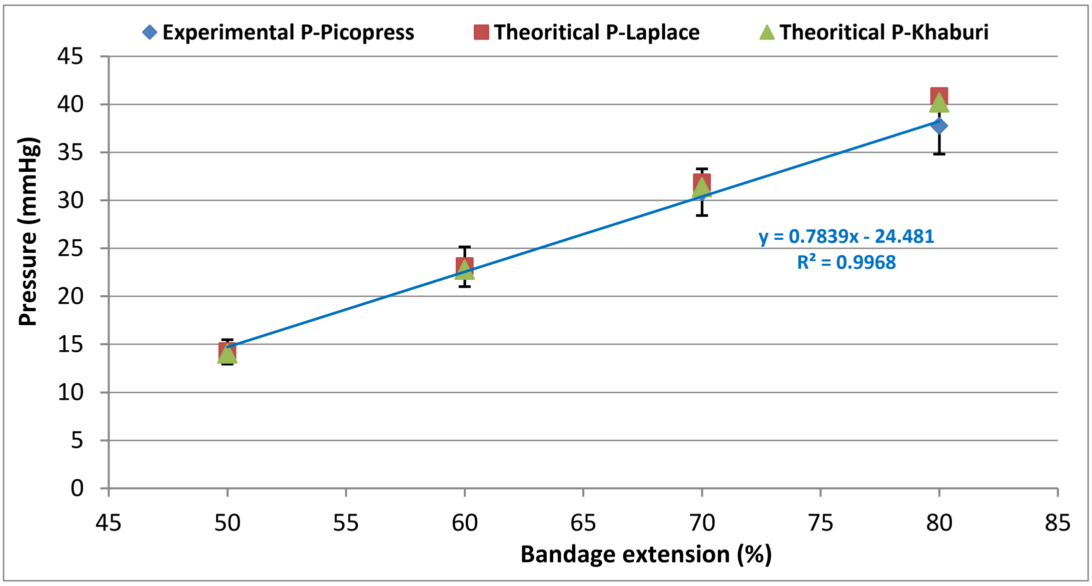


Figure 5.20. Measured bandage pressure by PicoPress vs calculated values at mid-calf position using two layers bandaging

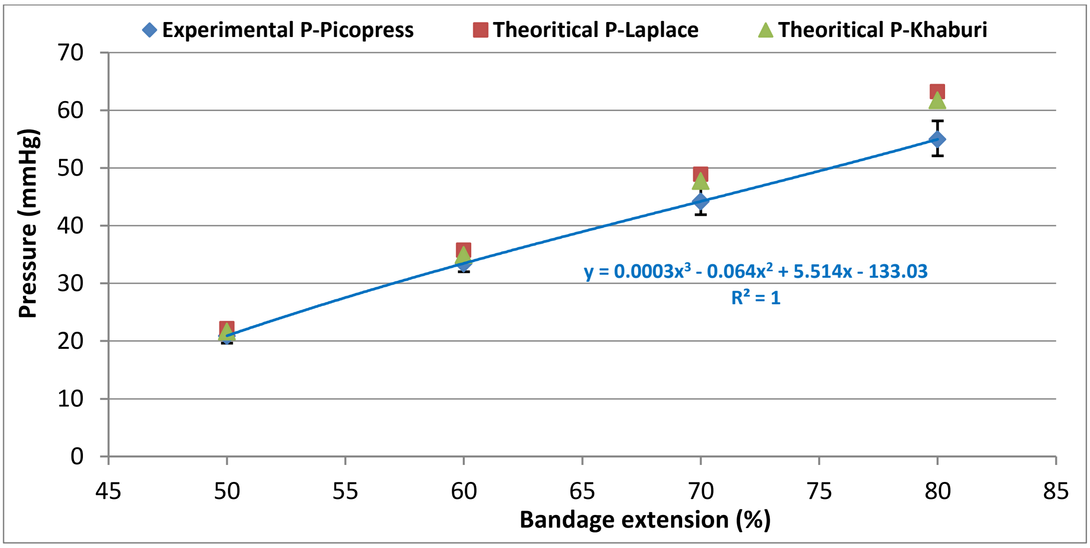


Figure 5.21. Measured bandage pressure by PicoPress vs calculated values at mid-calf position using three layers bandaging

5.2.4. Effect of cyclic loading-unloading on bandage tension and durability

Two types of WCBs (100% Cotton short-stretch and CO-PA-PU long-stretch) were selected to investigate the relation between cyclic loading and the applied bandage tension at 60% and 120% extension. Elongation by 3 cm results in extension by 60% and dwell time for 2 seconds, then unloading

1 cm reduces extension to be 40% and dwell time for 2 seconds, then repeating whole cycle for 5 or 6 repeats then relaxation. Cyclic loading-unloading could simulate the walking action when wearing WCB, but the main obstacle is that the testing time is limited compared to the bandage application time. The uniaxial load of Cotton short-stretch WCB decreased by 11.82% after 6 cycles of loading-unloading, whereas CO-PA-PU long-stretch WCB lost only 4.81% of its applied load at 60% extension. Moreover CO-PA-PU lost 18.11% at 120% extension, see Figure 5.22. So that it is essential to include and compensate these reductions of bandage tension during its selection and application.

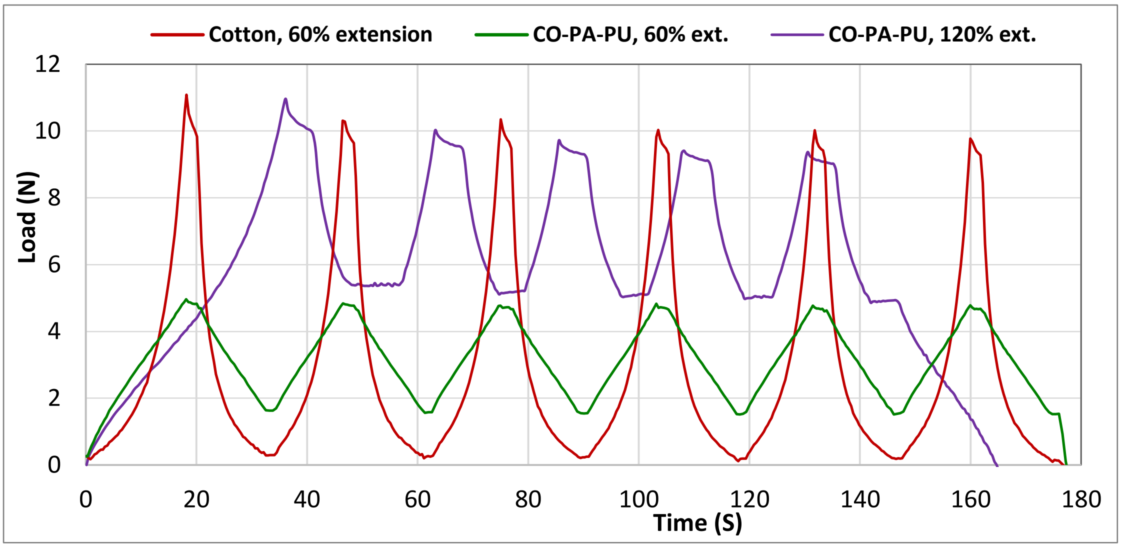


Figure 5.22. Effect of cyclic loading on bandage applied tension

5.2.5. Verification of antibacterial activity of cotton WCB treated with Zinc Oxide NPs

The treated samples with three concentrations: 1%, 2%, and 3% ZnO Nanoparticles in powder form with 15 g/L binder showed a positive results of antibacterial activity for both gram-positive and gram-negative bacteria strains as listed in Table 5.6. In samples 1-2, 1-3 and 2-3, 100% inhibition was found under the sample in both tested bacterial strains, i.e. the treatment did not allow the growth of bacteria under the WCB sample. This enhancement is very positive for the bandages' applications.

Table 5.6: The antibacterial activity of cotton WCB according to AATCC 147-2012

Sample number	***Escherichia coli*** inhibition zone size - mm / % inhibition below sample	***Staphylococcus aureus*** inhibition zone size - mm / % inhibition below sample
Standard 1	0 mm, 0%	0 mm, 0%
[1-1]	0 mm, 0%	0 mm, 0%
[1-2]	0 mm, 100%	0 mm, 100%
[1-3]	0 mm, 100%	0 mm, 100%
Standard 2	0 mm, 0%	0 mm, 0%
[2-1]	0 mm, 0%	0 mm, 0%
[2-2]	0 mm, 0%	0 mm, 0%
[2-3]	0 mm, 100%	0 mm, 100%

The quantitative method showed 95% inhibition in all tested WCB samples on both tested bacterial strains, which is 95% compared to the standard. Moreover the higher concentrations of ZnO Nanoparticles did not increase the antibacterial activity, according to AATCC 100-2019.

5.2.5.1. Scanning electron microscopy and energy dispersive X-ray of the bandage samples

The SEM of the un-treated and treated cotton WCB samples are displayed in Figures 5.23 and 5.24 to 5.26 respectively. The zinc oxide nanoparticles' size and its distribution are investigated for the treated bandage samples and the EDX mapping confirmed the percent of ZnO nanoparticles' in the total composition of bandage samples as illustrated in Figures 5.27 to 5.30.

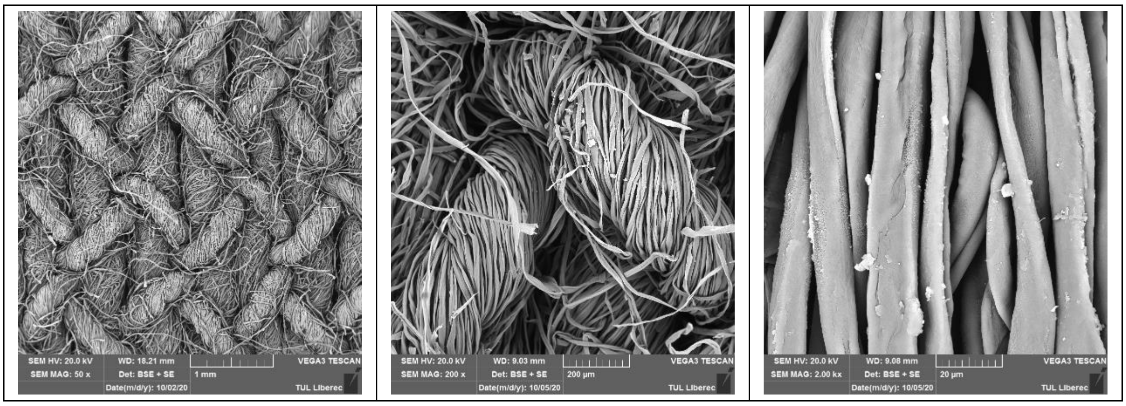


Figure 5.23. SEM of the un-treated cotton woven bandage

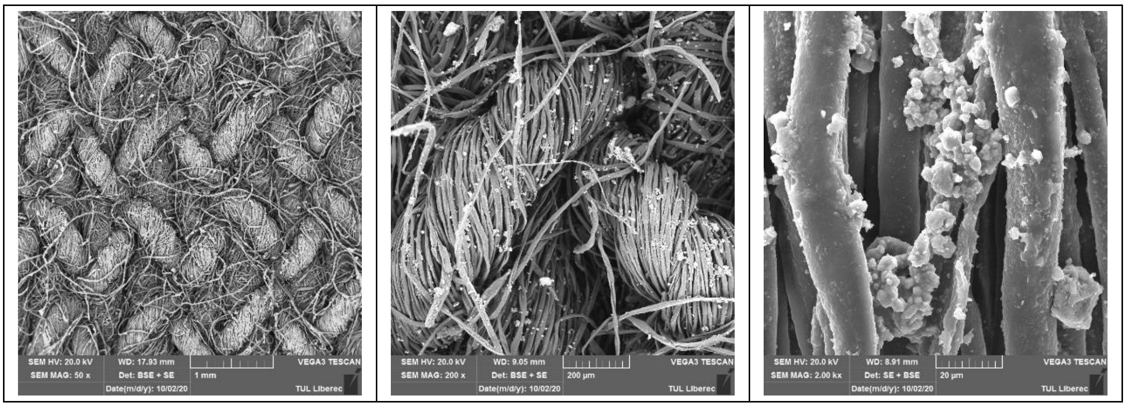


Figure 5.24. SEM of the treated cotton WCB with 1% zinc oxide nanoparticles

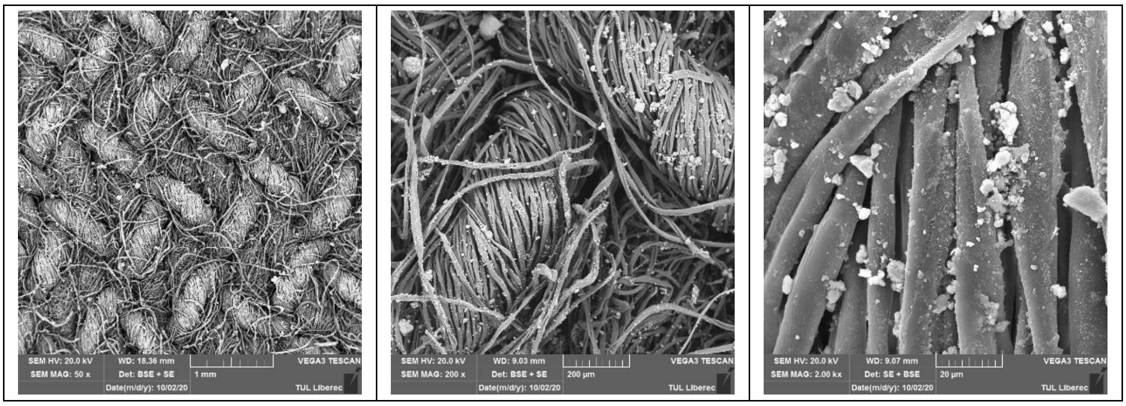


Figure 5.25. SEM of the treated cotton WCB with 2% zinc oxide nanoparticles

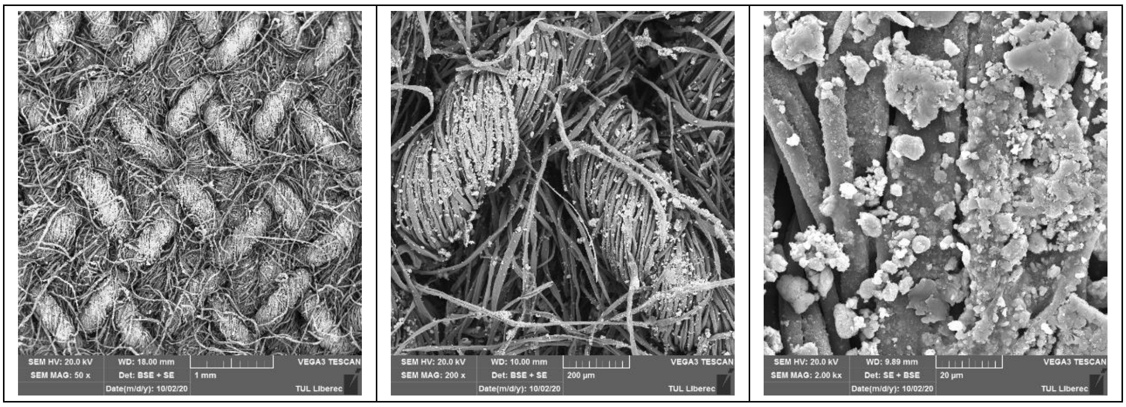


Figure 5.26. SEM of the treated cotton WCB with 3% zinc oxide nanoparticles

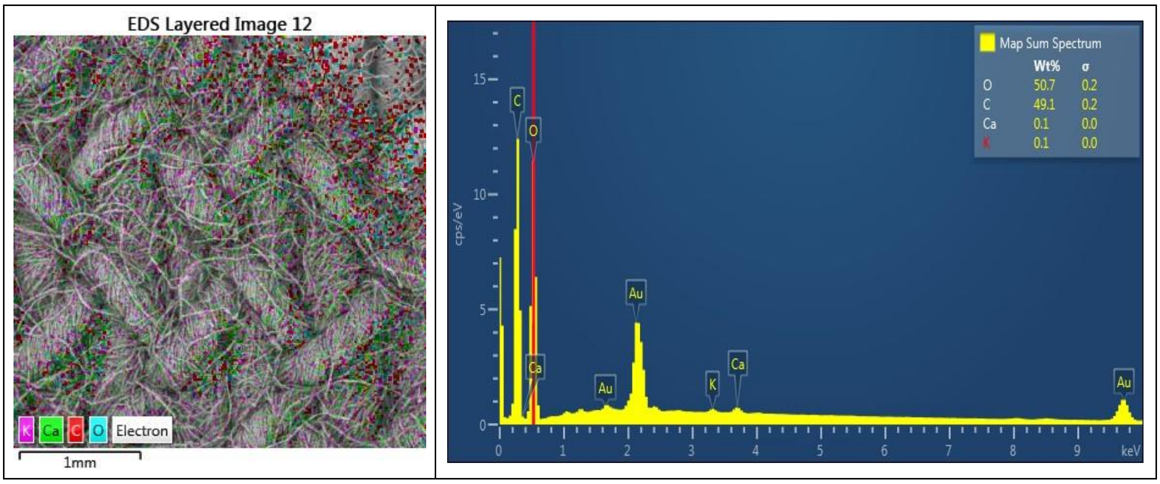


Figure 5.27. Energy dispersive X-ray map of the un-treated cotton WCB

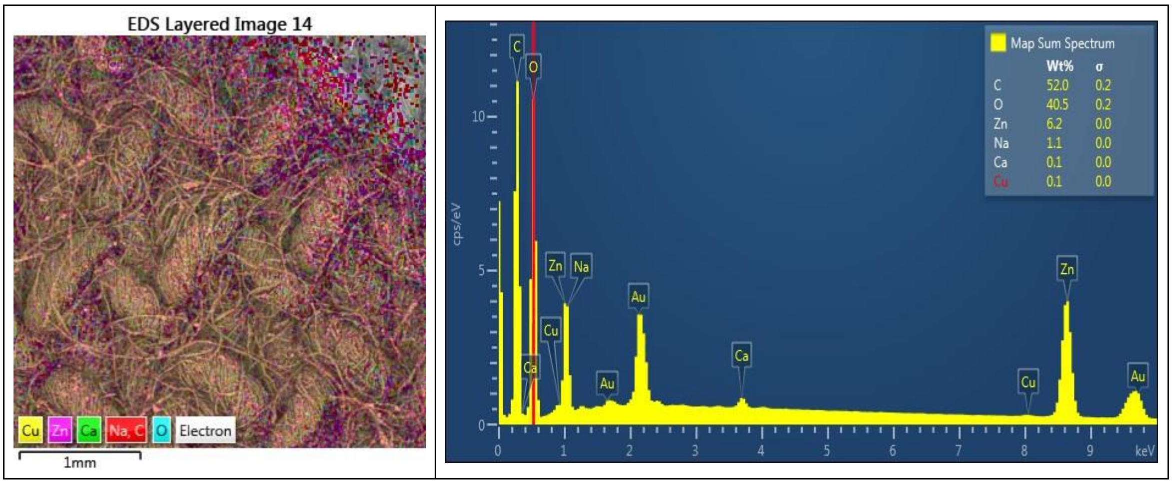


Figure 5.28. EDX map of the treated cotton WCB with 1% zinc oxide nanoparticles

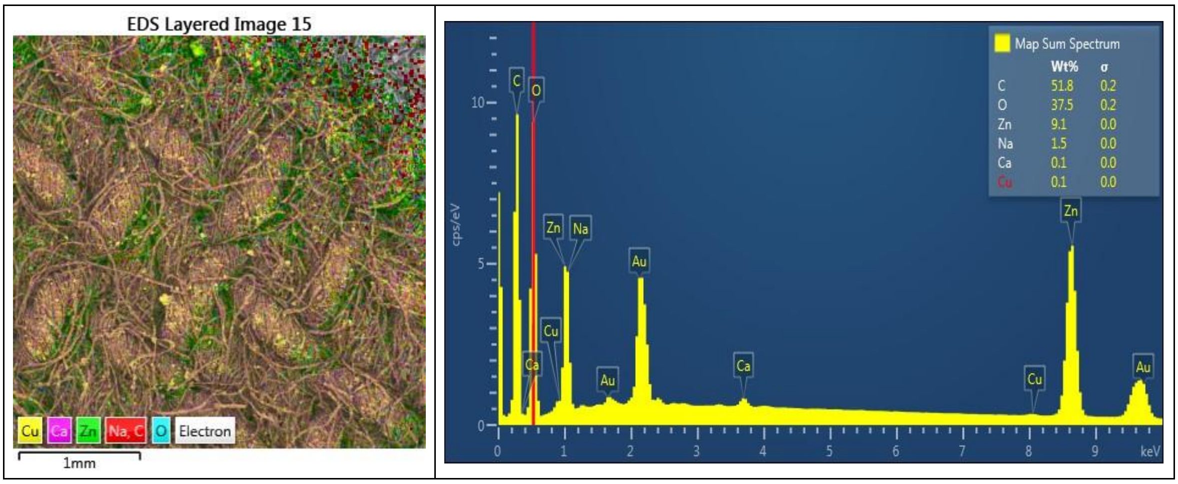


Figure 5.29. EDX map of the treated cotton WCB with 2% zinc oxide nanoparticles

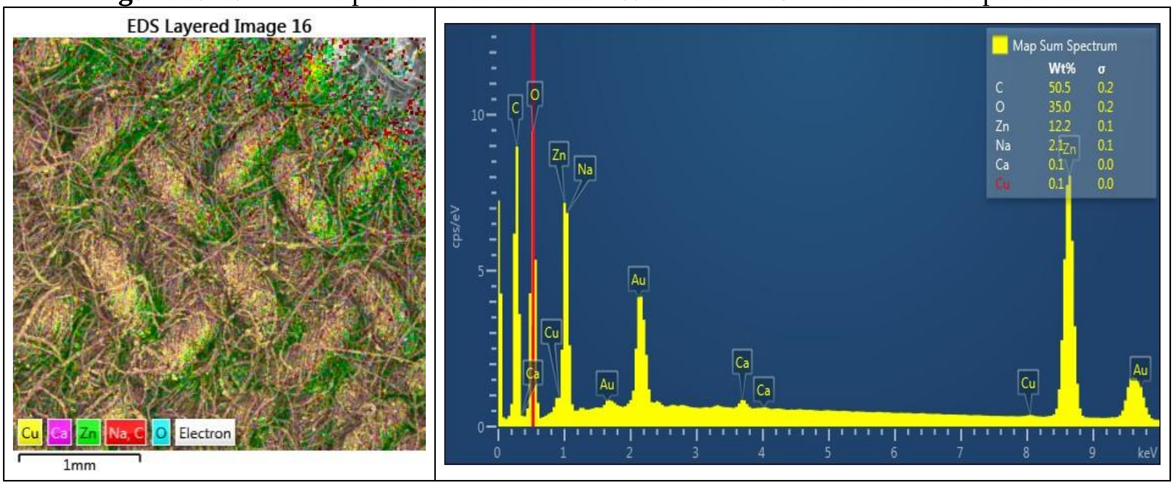


Figure 5.30. EDX map of the treated cotton WCB with 3% zinc oxide nanoparticles

5.2.6. Factors affecting the thermal properties testing

The measurement of clothing insulation with thermal manikin is a dynamically balance adjustment process. It means that continuous adjustment of heat flux makes the manikin skin temperature approach a constant temperature gradually under the heat diffusion. The final state is that the manikin skin temperature is steady in a narrow range and very close to the constant temperature [45].

5.2.6.1. Effect of bandage extension and number of layers on thermal resistance

For comparison, all bandage types were wrapped on TFM one by one at the same extension levels (10 to 80%) using both two and three layers bandaging. Figures 5.31 illustrates that R_{ct} values are significantly decreasing when bandage extension increasing from 10 to 40 % due to the decrease of total thickness of layers. Then R_{ct} slightly increases by increasing extension from 40 to 60% that may be due to the higher porosity of bandages (0.364, 0.306, 0.471, and 0,325 for Cotton, CO-PA-PU, VI-PA, and VI-PU bandages respectively). After that R_{ct} values are decreasing for all samples, especially at 80% extension. The most significant factors for this decrease are the lower bandage thickness and higher compression values. Moreover it is illustrated that Cotton bandage has the lowest R_{ct} values due to yarns material and structure. This may be due to higher moister regain of Cotton (8.5%) and Viscose (11 - 12%) compared to Polyamide (4 - 4.5%) and Polyurethane (0.3 - 1.2%), which decreases the thermal resistance of Cotton and Viscose bandages [63]-[65].

As there are many factors can affect the thermal resistance measurements, it was necessary to measure R_{ct0} before each measurement using clothed TFM. There is R_{ct0} for each R_{ct} measurement to get the precise R_{ct} values of CB and simultaneously to monitor deviations of R_{ct0} values. The actual values of R_{ct} can be calculated directly by the device software inserting the measured R_{ct0} as a reference value. Moreover the obtained R_{ct} values could enable for accurate comparison between different bandage samples as illustrated by equation (5.11).

$$\boldsymbol{R_{ct(F)} = R_{ct(all)} - R_{ct0}} \tag{5.11}$$

Where: $R_{ct(F)}$ is the net thermal resistance of the bandage sample (two or three layers), $R_{ct(all)}$ is the total thermal resistance of the (bandage sample + one layer of mercerized socks as clothed TFM), R_{ct0} is the initial thermal resistance of the clothed TFM covered with mercerized socks only.

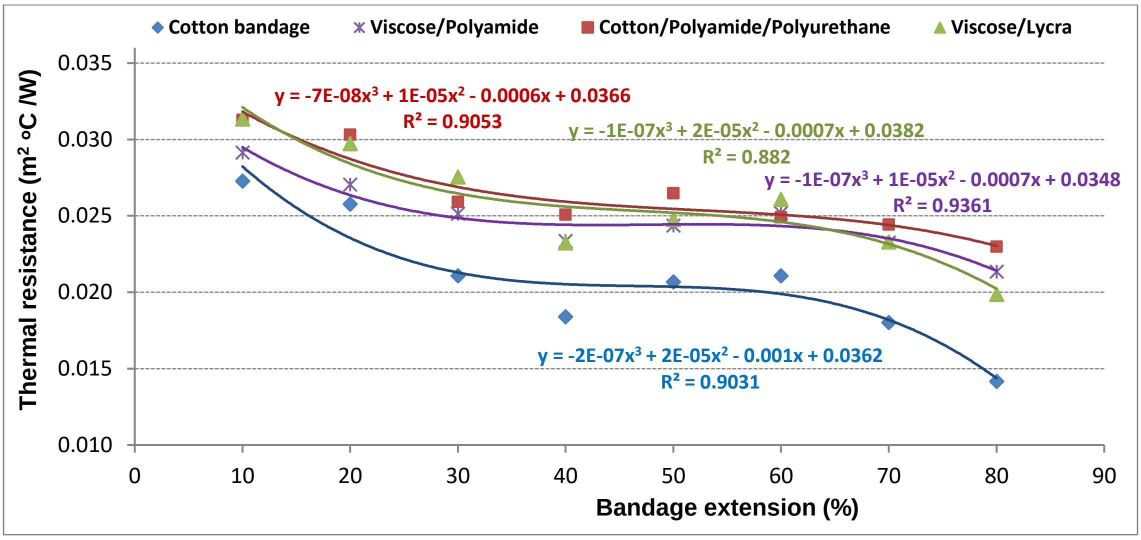


Figure 5.31. Effect of bandage extension on thermal resistance of two layers CB

5.2.6.2. Effect of total thickness of bandage layers on thermal resistance

While the bandages are wrapped on TFM at extension level ranges 10 to 80% using both 50% and 66% overlap. The total thickness of bandage layers at 10% extension is 2.04, 2.15, 1.53, and 2.07 mm. These values are decreasing at 80% to be 1.04, 1.11, 0.76, and 1.08 mm for Cotton, CO-PA-PU, VI-PA, and VI-PU bandages respectively. So that thermal resistance is decreasing by the decrease of total bandage thickness for both two and three layers bandaging, as shown in Figure 5.32. The reduction percent of R_{ct} results due to extension 10 to 80 % are 48.09, 26.63, 26.73, and 36.66% for Cotton, CO-PA-PU, VI-PA, and VI-PU bandages respectively using two layers while the reduction effect was lower for three layers as 29.37, 25.77, 18.52, and 24.08% respectively.

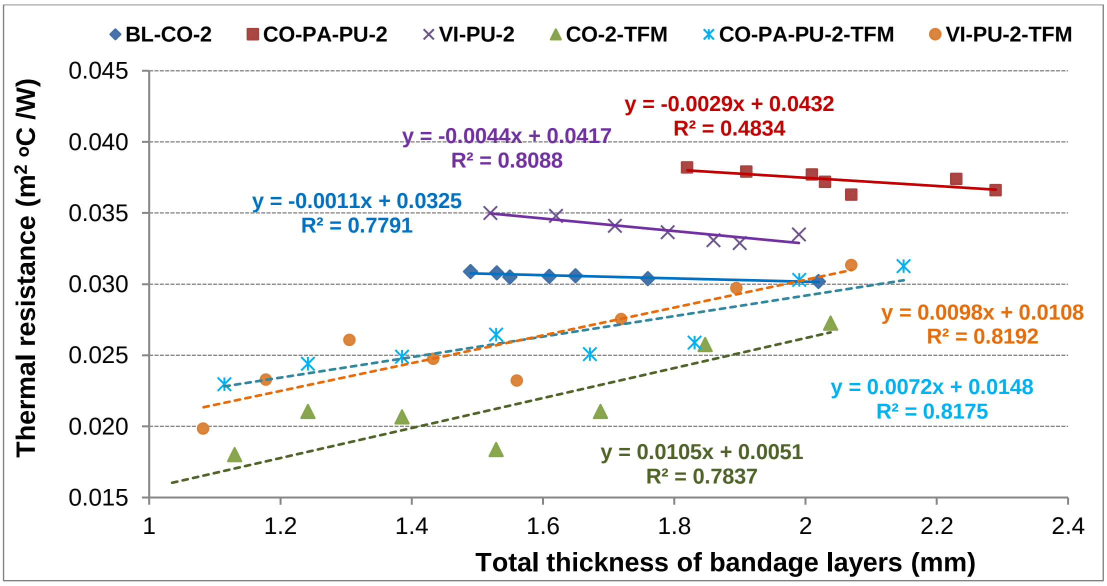


Figure 5.32. Effect of total thickness of layers on thermal resistance of two layers WCBs, on ALAMBETA and thermal foot manikin testing devices

5.2.6.3. Thermal resistance models and their applications

Thermal resistance of the fabrics can be calculated by means of experimental, analytical and numerical methods [66], [67]. There are many models to be found within the textile engineering and heat transfer fields for the thermal resistance prediction. The preference of selection depends on the requisite precision and nature of the solution. Conductive heat transfer is the simplest way to illustrate mathematically and is often the key way of heat transfer [68]. Schuhmeister suggested a relationship for the thermal conductivity prediction of fabrics by assuming one-third of fibres are parallel and two-third are in series with a homogeneous distribution in all directions [69]. Afterwards, many researchers used Schuhmeister's model by assuming different ratios of series and parallel components [70]-[72]. Presently, Mansoor et al. have modified Schuhmeister and Militky models by combining the water and fibre filling coefficient for the prediction of thermal resistance of wet socks [73], [74].

5.2.6.4. *Validation of the experimental R_{ct} results on TFM and ALAMBETA with three* theoretical models

The experimental results of R_{ct} matches with the three mathematical models that the increase in total fabric (WCB layers) thickness is associated with an enhancement in the R_{ct} values, as displayed in Figure 5.33. The ALABETA enables fast measurement of both steady-state and transient-state thermal properties, as shown in Figure 5.34. This diagram clearly demonstrated the maximum q_{max}, dynamic (transient) q_{dyn} and steady state q_{steady} heat flow [75]. Moreover there are significant similarities between the ALAMBETA results and both Schuhmeister and Militky models, approximately 92 and 93% respectively. Whereas the correspondence values for the TFM are approximately 82 and 83% respectively. This might be because the ALABETA testing is corresponded well to the use of socks inside a shoe (boundary conditions of first order).

The transient heat flow has been shown by equation (5.12), whereas the steady state heat flow has been shown by equation (5.13).

$$q_{dyn} = \frac{b.\ (T_1 - T_2)}{\sqrt{\pi\tau}} \tag{5.12}$$

$$q_{steady} = \frac{T_1 - T_2}{R_{ct}} \tag{5.13}$$

Where b is the thermal absorptivity [W $s^{0.5}$ m^{-2} K^{-1}], the temperature difference between the two convection surfaces ($\Delta T = T_1 - T_2$), and τ is the tortuosity [–] [76].

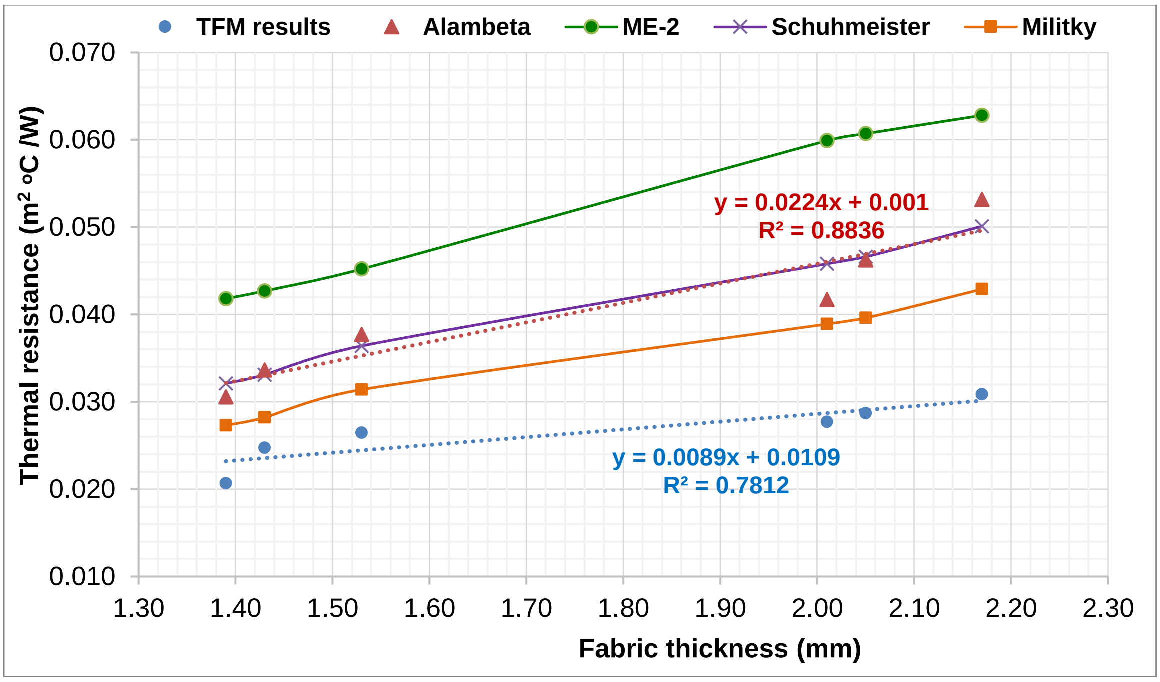


Figure 5.33. Experimental thermal resistance results for bandages by thermal foot manikin and ALAMBETA

versus theoretical calculations by Maxwell-Eucken2, Schuhmeister and Militky models

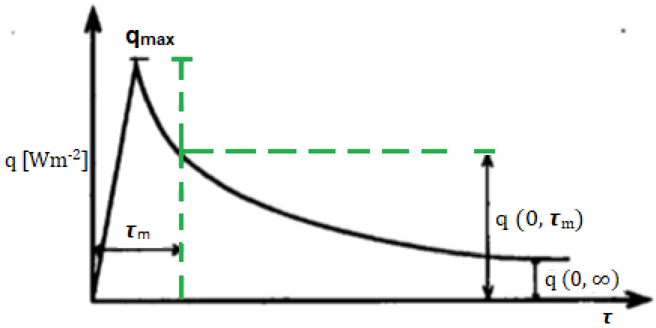


Figure 5.34. Time dependence heat flow after contact [75]

5.2.6.5. Effect of bandage extension on water vapour resistance

Water vapour permeability is the ability to transmit vapour out of the body, it can be calculated theoretically by equation (7). If the moisture resistance is too high to transmit heat, by the transport of mass and at the same time the thermal resistance of the textile layers considered by us is high, the stored heat in the body cannot be dissipated and causes an uncomfortable sensation [77]. Water vapour resistance was measured for all bandages using PERMETEST device at 0% extension, and 10 to 80% extension for two layers bandaging. Obtained results confirm that the R_{et} is decreasing when the bandage extension is increasing to 20% then it is improving till 60%, then it is significantly decreasing at 80% extension, as illustrated in Figure 5.35. However the testing on PERMETEST is fast, easy, and non-destructive test, but it is not exactly simulating the required testing method of R_{et} for CBs as compared to TFM in which case the compression influence and air layer between each two adjacent bandage layers are more significant factors.

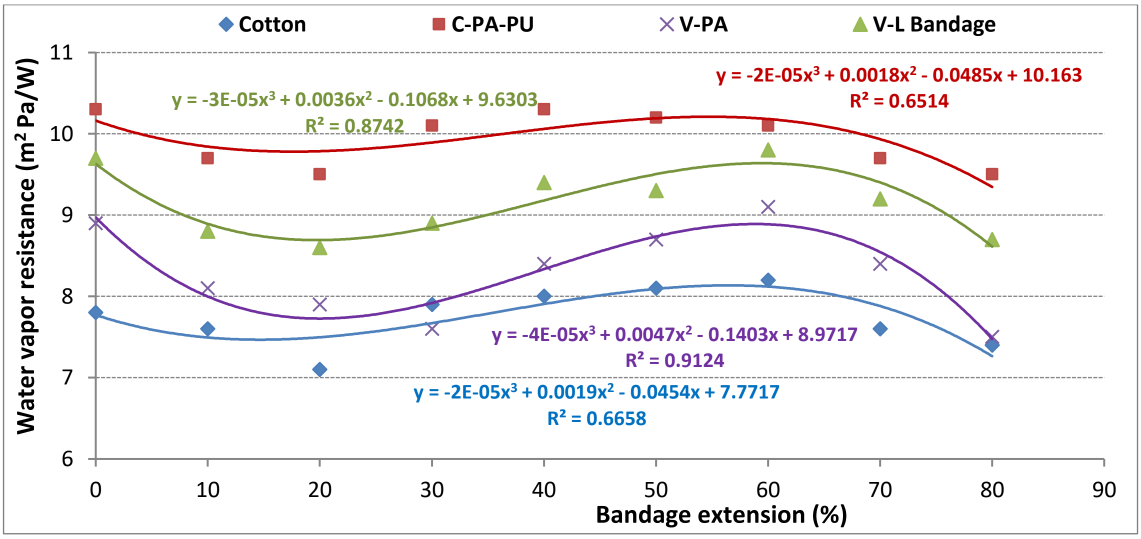


Figure 5.35. Effect of bandage extension on water vapour resistance

5.2.7. Effect of compression bandages on the muscles' activation

5.2.7.1. Electromyography test of Medial Gastrocnemius (MG) muscle

Surface EMG signals were obtained from the MG and SO muscles by pre-amplified bipolar surface electrodes [78]. Figures 5.36 & 5.37 show MG muscle's performance with and without wearing the CO-PA-PU bandage during the standardized action (flexion-extension) and using the bleached Cotton bandage for walking action. Wearing WCB enables a significant decrease in MG muscle activity during flexion-extension action by 25.56% and 4.65% while walking, see Table 5.7. This decrease may be due to the increase in the mean muscle fascicle length and the reduction in the mean muscle thickness and mean pennation angle [79]. Researchers have also claimed that the muscle force being exerted for a limb's motion and stability may be wasted on muscle flexion-extension, while compression garment may prevent muscle vibrations during sports activities which can enhance the athletic performance [38].

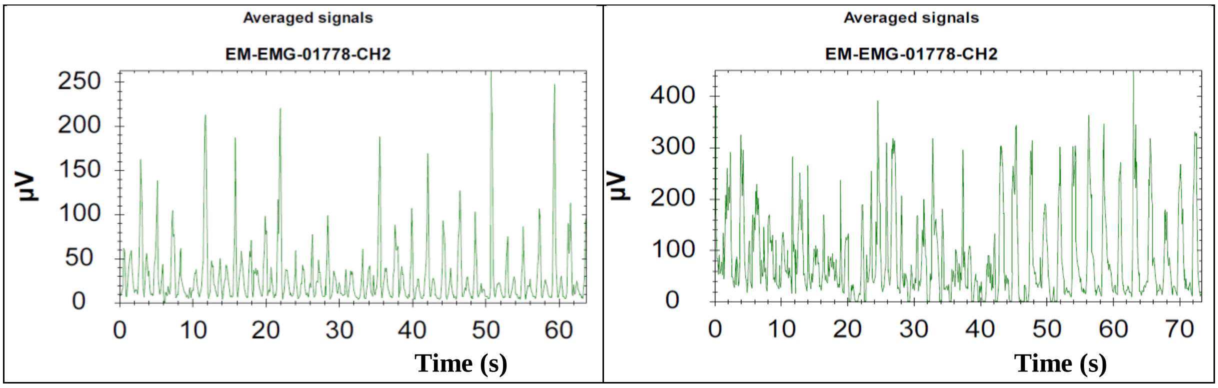


Figure 5.36. Medial Gastrocnemius muscle voltage with and without wearing CO-PA-PU bandage during (flexion-extension) action, 30 BPM.

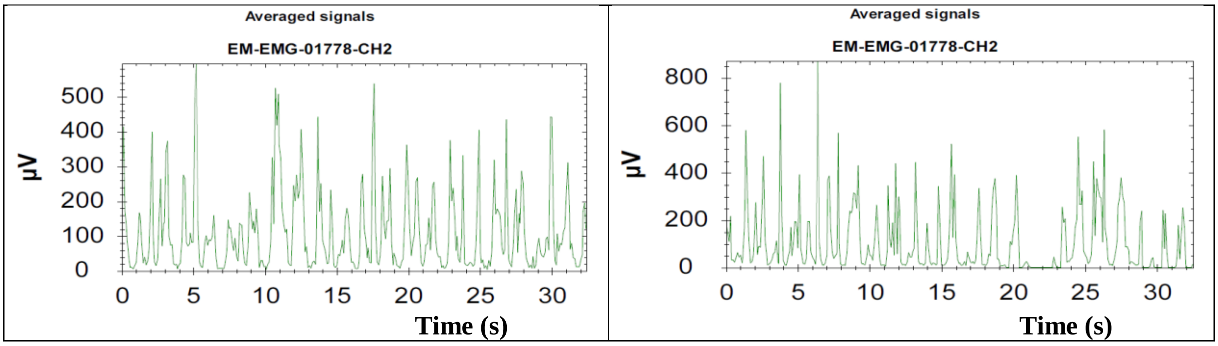


Figure 5.37. Medial Gastrocnemius muscle voltage with and without wearing bleached Cotton bandage while walking action, 40 BPM.

5.2.7.2. EMG test of Soleus (SO) muscle

Figures 5.38 & 5.39 show the SO muscle's behaviour with and without wearing the CO-PA-PU and bleached Cotton WCBs during the activities, flexion-extension and walking respectively, at same speed (using metronome beats 20, 30, and 40 beats/min), see Table 5.8. Wearing Cotton WCB decreases SO muscle activity during flexion-extension action by a percent 22.68% and 33.86% while walking as summarized in Table 5.7. These significant reductions in SO muscle activation clarify the enhancement of ankle muscle behaviour wearing WCB, because SO muscle is the main factor of controlling the walking performance while MG muscle is more effective for flexion-extension action.

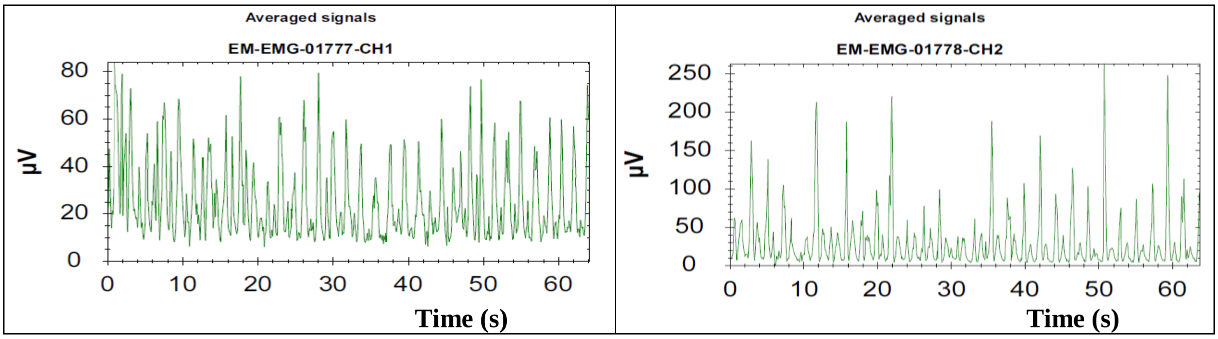


Figure 5.38. Soleus muscle voltage with and without wearing CO-PA-PU bandage during (flexion-extension) action, 30 BPM.

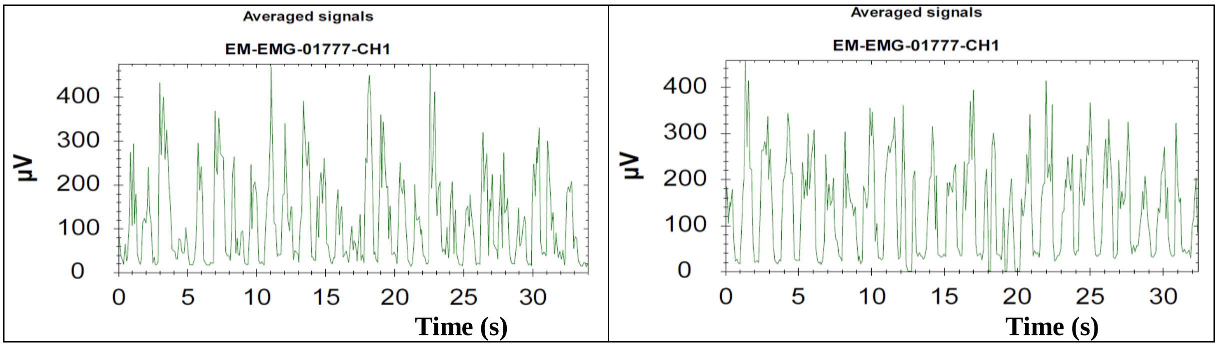


Figure 5.39. Soleus muscle voltage with and without Cotton bandage while walking action, 40 BPM.

5.2.7.3. EMG mean voltage for MG and SO muscles

EMG mean voltage for MG and SO muscles using the CO-PA-PU and bleached Cotton WCBs during the standardized activities (flexion-extension and walking) at the same speed (using metronome beats 20, 30, and 40 beats/min) can be summarized and compared as listed below in Table 5.7. Wearing bleached Cotton WCB while walking was associated with a decrease in average MG and SO muscles activation by a percent 10.66 and 18.24% respectively. Whereas using CO-PA-PU WCB decreases MG and SO muscles activation by a percent 4.65 and 33.86% respectively. While wearing CO-PA-PU bandage during flexion-extension action decreases MG and SO muscles activation by a percent 25.56 and 22.68% respectively, see Table 5.8.

Table 5.7. EMG mean voltage for leg muscles while walking (bleached Cotton bandage)

Case	Metronome beats (BPM)	Medial Gastrocnemius		Soleus Muscle	
		Mean voltage (μV)	Standard deviation	Mean voltage (μV)	Standard deviation
With bandage	20	75.33	2.87	74.00	2.94
	30	76.00	4.32	88.00	3.74
	40	103.00	6.98	117.33	4.99
	Average	**84.78**	**4.59**	**93.11**	**3.97**
Without bandage	20	80.33	3.30	96.00	5.35
	30	94.00	4.55	111.33	5.44
	40	110.33	7.04	134.33	7.04
	Average	**94.89**	**4.96**	**113.89**	**5.94**

Table 5.8. EMG mean voltage for leg muscles using CO-PA-PU WCB

Activity	Case	Medial Gastrocnemius		Soleus Muscle	
		Mean voltage (μV)	Standard deviation	Mean voltage (μV)	Standard deviation
Flexion – extension	with bandage	22.33	2.49	25.00	2.94
	without	30.00	3.74	32.33	4.92
	Reduction %	**25.56**	**33.33**	**22.68**	**40.18**
While walking	with bandage	82.00	4.55	83.33	4.11
	without	86.00	5.35	126.00	6.98
	Reduction %	**4.65**	**15.09**	**33.86**	**41.09**

6. Evaluation of results and new findings

The evaluation of the used plied warp yarns in the market for producing the WCB concluded that the warp yarn tenacity should be greater than 15.5 cN/Tex and its extension should be at least 12% to produce the highly stretched 100% Cotton WCB. The optimum twist of warp yarns was ranged 1800 - 2200 tpm for producing high extension Cotton WCBs.

Silver NPs coated yarn samples D_1 and D_2 showed a comparable antibacterial activity on both tested bacteria strains (E.C. and S.A.) using both quantitative and qualitative test methods. The NPs size and its distribution using SEM and EDX confirmed the antibacterial activity of the treated single and plied yarn samples. Moreover the new produced WCB structure were treated with Zinc Oxide NPs in powder form in addition to 15 g/L binder and had positive results of antibacterial activity for both gram-positive and gram-negative bacteria strains according to AATCC 147-2012 and AATCC 100-2019.

Candidate work introduced some modifications on the WCB structure. The bandage includes an integrated tension sensor, which causes a change in the spacing of coloured threads during its deformation. The solution is sensors in the bandage in the form of a different colour pick from the other structure of the bandage. Different colour picks with regular distance become visible due to deformation / stress in the bandage. These coloured weft threads are giving blue marks (rectangles of 2x1 cm^2 could be changed to squares of 2x2 cm^2 at 100% extension). Then presented a new method to predict the bandage tension as a function of bandage porosity; that enables the patient to use the bandage himself more easily and accurate. Long-stretch CO-PA-PU required 110% extension while short-stretch cotton WCB required only 60% extension to achieve the required mean bandage tension 10N; these values are achieving the required bandage pressure (4000 Pa or 30 mmHg) according to Laplace's law equation.

Picopress results confirmed that 100% Cotton bandages achieved the highest compression ranges (18-33, 27-43, and 36-61 mmHg) for ankle position and (8-16, 18-27, and 35-51 mmHg) for mid-calf position. Cotton SSB can be applied for severe leg ulcers and oedema cases that need high pressure ranges 50 to 70 mmHg depending on bandage extension and number of layers.

The experimental compression results were compared with theoretical pressure calculated by Laplace's equation. There is a significant deviation when applying Laplace's equation for two and three layers bandaging ranging ±0.68 to ±15.64% whereas Jawad Al Khaburi developed that equation to include the thickness and limb circumference due to multilayer bandaging; this modified equation decreased the deviation ranges to be ±0.07 to ±12.55% at ankle position.

CO-PA-PU and 100% Cotton WCBs were selected to compare between long and short-stretch WCBs in resting and working actions. The SSB enabled higher working pressure on the ankle and calf muscles due to the interaction between lower leg and WCB during walking action or any activity. On the contrary LSB had a higher resting pressure because of the elastane filaments, as a result the patient should wear-off the LSB every day before sleep. Cyclic loading-unloading test confirmed that short-stretch WCB lost approximately 28.6% of its activity whereas LSB lost only 10.05% after 5 days of application.

Four types of WCBs were used for evaluating the Rct and Ret on the TFM, ALAMBETA, and PERMETEST devices respectively using two and three layers bandaging techniques. According to TFM, Rct values significantly decreased when the bandage extension increased from 10 to 40 % due to the decrease of fabric thickness, then Rct slightly increased from 40 to 60% extension that might be caused by the higher porosity of WCBs (0.364, 0.306, 0.471, and 0,325 for 100% Cotton, CO-PA-PU, VI-PA, and VI-PU WCBs respectively). After that Rct values decreased, especially at 80% extension due to the lower bandage thickness and higher applied tension. The PERMETEST results concluded that the Ret values decreased the extension increased to 20% then it was slightly increasing at 20 to 60%, after that decreased, especially at 80% extension due to the lower total bandage thickness and the little amount of trapped air between fabric layers.

The experimental results of Rct by TFM and ALAMBETA were validated using Maxwell-Eucken2, Schuhmeister and Militky models. There were strong correlation between the Schuhmeister and Militky models with the ALAMBETA results. Obtained results of Rct confirmed that clothed TFM was more accurate for measuring Rct0 and corresponding values of Rct that might be due to the steady state condition and less effect of air convection. There were significant deviations between experimental results by the ALAMBETA and TFM because the high levels of applied tension during the bandage application were more effective on the TFM results.

The application of VI-PA WCB on hand muscles reduced the average FC muscle activation by a percent 7.17 and 8.92% during the standardized actions (squeezing a soft roll and flexion-extension) respectively. Wearing bleached Cotton WCB enabled lower muscle activation and higher median frequency for MG and SO muscles by a percent of 4.65 and 34.13% during walking action. Using CO-PA-PU CB was associated with significantly reduction of MG and SO muscles activation by 26.67 and 21.88% during flexion-extension action. The obtained RMS values using Matlab software confirmed that wearing WCB improved the performance of FC, MG, and SO muscles and could enhance muscles' fatigue.

7. References

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8. List of papers published by the author

8.1. Publications in journals

1) **Aboalasaad, A. R. R.,** Sirkova, B. K., El-Hossini, A. L. M., & HEBEISH, A. (2017). Effect of mercerization followed by cross-linking on cotton fabric properties. *TEKSTİL VE KONFEKSİYON*, *27*(3), 251-258.
2) **Aboalasaad, A.R.,** Kolčavová, B.S., & Berk, G.G. (2018, December). Effect of Compression Bandages on Muscle's Behaviour. In *IOP Conference Series: Materials Science and Engineering*, (Vol. 460, No. 1, p. 012034). IOP Publishing.
3) **Aboalasaad, A. R. R.,** & Sirková, B. K. (2019). Analysis and prediction of woven compression bandages properties. *The Journal of The Textile Institute*, 110(7), 1085-1091.
4) **Aboalasaad, A. R.,** Skenderi, Z., Kolčavová, S. B., & Khalil, A. A. (2020). Analysis of Factors Affecting Thermal Comfort Properties of Woven Compression Bandages. *Autex Research Journal*, 20(2), 178-185.
5) **Aboalasaad, A. R.**, Sirková, B. K., & Ahmad, Z. (2020). Influence of tensile stress on woven compression bandage structure and porosity. *Autex Research Journal*, 20(3), 263-273.
6) **Aboalasaad, A. R.,** Sirková, B. K., Tešinová, P., & Khalil, A. (2020). Guidelines for measuring thermal resistance on thermal Foot Manikin. *Materials Today: Proceedings*, 31, S232-S235.
7) Amany Khalil, Pavla Těšinová, **Abdelhamid Aboalasaad**. Thermal Comfort Properties of Cotton/Spandex Single Jersey Knitted Fabric, *Industria Textila*. (Manuscript ID: 1760). Accepted for publishing on 23.01.2020 in issue 3/2021
8) **Abdelhamid R. R. Aboalasaad,** Brigita Kolčavová Sirková, Pavlína Bílá, Amany A. S. Khalil. Comparative study of long and short-stretch woven compression bandages. *Autex Research Journal*. DOI: https://doi.org/10.2478/aut-2020-0035, Published online: 24 Oct 2020.
9) **Aboalasaad, A.R.R.,** Hassan, M. (2020). The relation between viscose fibers' characteristics and their yarn properties. *Vlakna a Textil*, 27(5), pp. 4-9
10) **A.R. Aboalasaad,** B. K. Sirková, T. Mansoor, Z. Skenderi, A. S. Khalil. Theoretical and Experimental Evaluation of Thermal Resistance for Compression Bandages. *Autex Research Journal*. Published online: 20 Nov 2020. DOI: https://doi.org/10.2478/aut-2020-0052
11) **Abdelhamid R.R. Aboalasaad,** Brigita K. Sirková, and Gözde G. Berk. Enhancement of Muscle’s Activity by Woven Compression Bandages. Submitted on January 21, 2020. Industria Textila Magazine, ID: 1789. Accepted on October 09, 2020 for publishing in issue 4/2021

8.2. Contribution in conference proceeding

1) **A.R.R. Aboalasaad**, B. Kolčavová S. "Analysis and Prediction of Compression Bandages Tension", International conference (CEC), PhD student day, September 14th, 2017.
2) **A.R.R**. **Aboalasaad**, Brigita S. Kolčavová, and Gözde G. Berk. "Effect of compression bandages on muscle's behaviour". AUTEX 2018 - 18th World Textile Conference, June 20-22, 2018 (**Award for best student poster presentation**).
3) Ahmad Z., Sirková B., and **Aboalasaad A.R.R.** "Yarn deformation in multifilament single layer woven structures using Fourier series", AUTEX, Istanbul, Turkey 2018, ISBN 978-961-6900-17-1.
4) **A.R.R. Aboalasaad**, Z. Skenderi, B. K. Sirková, Tariq Mansoor. "Measurement of Thermal Resistance on Thermal foot manikin Compared to ALAMBETA", PhD students day, 03.12.2018, Liberec.
5) **A.R.R**. **Aboalasaad**, B.K. Sirková, P. Tešinová, A. Khalil. "Optimum Conditions for Measuring Thermal Resistance on Thermal foot manikin". 4th International conference on natural fibres, Porto, Portugal, 1-3 July 2019. Accepted as oral presentation.
6) Khalil, A., Tešinová, P., & **Aboalasaad, A. R.** "Thermal comfort properties of single jersey knitted fabric produced at different Lycra states". Poster presentation in ICNF 2019, Porto, Portugal. pp. 422-423
7) **Abdelhamid R. R. Aboalasaad**, Brigita Kolčavová Sirková. "Effect of twist level of warp yarns on woven bandage properties". Workshop for PhD students, 12.11.2019, Liberec, Czech Republic.
8) Khalil, Amany; Tešinová, Pavla; **Aboalasaad, Abdelhamid**. "Geometrical and Thermal Properties of Stretched Single Jersey Knitted Fabric". Workshop for PhD students, 12.11.2019, Liberec, Czech Republic.
9) **Abdelhamid R.R. Aboalasaad,** Mohamed Eldessoki, and Ebraheem Shady. "Correlation between Viscose Fibers' Characteristics and Their Yarn Properties". NART Conference, 18-20 September 2019, Liberec, Czech Republic. Poster presentation.

8.3. Quotation

- Aboalasaad, A. R., Skenderi, Z., Kolčavová, S. B., & Khalil, A. A. (2020). Analysis of factors affecting thermal comfort properties of woven compression bandages. *Autex Research Journal*, 20(2), 178-185. Cited by four articles.
- Aboalasaad, A. R., Sirková, B. K., & Ahmad, Z. (2020). Influence of tensile stress on woven compression bandage structure and porosity. *Autex Research Journal*, *20*(3), 263-273. Cited by three articles.
- Aboalasaad, A. R. R., & Sirková, B. K. (2019). Analysis and prediction of woven compression bandages properties. *The Journal of The Textile Institute*, 110(7), 1085-1091. Cited by three articles.
- Aboalasaad, A. R. R., & Sirková, B. K. (2017). Analysis and prediction of compression bandages tension. In *Conf. CEC* (pp. 6-9). Cited by two articles.
- Aboalasaad, A. R., Sirková, B. K., Tešinová, P., & Khalil, A. (2020). Guidelines for measuring thermal resistance on thermal Foot Manikin. *Materials Today: Proceedings*, 31, S232-S235. Cited by two articles.
- A.R. Aboalasaad, B. K. Sirková, T. Mansoor, Z. Skenderi, A. S. Khalil. Theoretical and Experimental Evaluation of Thermal Resistance for Compression Bandages. *Autex Research Journal*. Cited by one article.
- Aboalasaad, A. R., Kolčavová, B. S., & Berk, G. G. (2018, December). Effect of Compression Bandages on Muscle's Behavior. In *IOP Conference Series: Materials Science and Engineering* (Vol. 460, No. 1, p. 012034). IOP Publishing.Cited by one article.

9. Curriculum Vitae

Personal Data

Name: Abdelhamid Rajab Ramadan Aboalasaad.
Nationality: Egyptian, Sex: Male.
Date of birth: 10.01.1981, Dakahliya, Egypt.
Permanent Address: 6 Amr Ibn Elaas Street, Mansoura, Egypt.
Army service: Exempted, Marital status: Married, has three kids.
Email: eabdo6@gmail.com & abd.elhameidrajabramadan.abo.el.asaad@tul.cz
Mobile number: +420776690508.

Education

- M.Sc. degree in textile engineering "Effect of High Concentrations of Alkaline Mediums in Wet Processing on Cotton Fabrics", 2010.
- Bachelor science in textile engineering, Mansoura University, June 2003, **"Very good with honour degree", Ranked 1st of class**.
- Undergraduate project: "Computer Application for Simulation and Prediction of Sewing Stitches Properties", with grade "Excellent".

Employment Experience

1) **PhD scholar** in Technical University of Liberec, Department of Technologies and Structures, (26.3.2015) till now.
2) **Lecturer assistant,** from (11-2010) to (3-2015), Faculty of Engineering, Textile Department, Mansoura University, Egypt.
3) **Demonstrator,** from (5-2007) until (11-2010), Faculty of Engineering, Textile Department, Mansoura University, Egypt.
4) **AutoCAD & 3D Studio Max Designer and Trainer,** from (4-2004) till (5-2007), El-Aseil office, Mansoura, Egypt.

Internship

1) Internship No. I in Egypt (23.05.2016 to 21.07.2016)
2) Internship No. II in Egypt (12.11.2016 to 11.12.2016)
3) Internship No. III in Istanbul, Turkey (02.09.2017 to 30.12.2017)
4) Internship No. IV in Zagreb, Croatia (11.07.2018 to 30.09.2018).

Training

1- Training in "Mansoura-Espania Company for Spinning and Weaving", Egypt. From (8:10-2003).

2- Training in "Misr Company for Spinning and Weaving", Mahala El Kobra, Egypt. (6:9-2002).

3- Training in "Dakahlia (DTEX) Company for Spinning and Dying" in Mansoura, Egypt. (6:9-2001).

Personal Skills

- Computer:
  - Software:
  - 3D Studio Max, AutoCAD.
  - Mat lap, C++, Auto Lisp, Adobe Photoshop.
  - Windows operation systems (Win XP, win 7, win 8, win 10).
  - Internet (Browsing, Searching…).
  - Hardware:
  - Aware of common hardware problems.
- Languages:
  - First language : Arabic (Native)
  - Second language: English (Very good)
  - Third language : French (Little listening and speaking).

Brief description of the current expertise, research and scientific activities

Brief description of the current professional research and scientific activities including mainly information on doctoral studies, teaching activities, research and other projects the student took part in.

Doctoral studies	
Studies	Textile Engineering Textile Technics and Materials Engineering full time
Exams	Textile Chemistry, KMI / D24, 26.06.2015 Mathematical Statistics and Data Analysis, KHT / D02, 23.10.2015 Structural Theory of Fibrous Assemblies, KTT / D11, 17.12.2015 Macromolecular Chemistry, KNT / 018, 19.09.2016
SDE	State Doctoral Exam completed on 19.06.2019 with the overall result passed.
Teaching Activities	
Teaching	Course title 1, time of instruction
Leading Bachelors/ Master students	Name of student, title of thesis, year defence
Research projects	1) Student Grant Scheme (SGS 21249) by Technical University of Liberec, Czech Republic, (project participant), 2018. 2) Student Grant Scheme (SGS 21316) by Technical University of Liberec, Czech Republic, (project leader), 2019. 3) Student Grant Scheme (SGS 21303) by Technical University of Liberec, Czech Republic, (project participant), 2019. 4) Student Grant Scheme (SGS 21314) by Technical University of Liberec, Czech Republic, (project participant), 2019. 5) Student Grant Scheme (SGS 21410), TUL, Liberec, Czech Republic, (project participant), 2020.
Other projects	Micro-structural imaging as a Tool for modelling fibrous materials (μ-CT GOALS), (registration number LTAUSA18135), (project participant), 2019.

Recommendation of the supervisor

TECHNICAL UNIVERSITY OF LIBEREC
Faculty of Textile Engineering

Supervisor's opinion - recommendation

Supervisor: Ing. Brigita KOLČAVOVÁ SIRKOVÁ, Ph.D.

Dissertation title: Structure and Analysis of Woven Compression Bandages for Venous Leg Ulcers

Student: Abdelhameid Rajab Ramadan ABOALASAAD

Woven and knitted fabric structures in the category of compression bandages are used in healthcare as a basic way of compression treatment for patients suffering from varicose vein problems. The bandage prevents and slows down the progression of chronic venous disease. The presented thesis entitled: Structure and Analysis of Woven Compression Bandages for Venous Leg Ulcers was focused on the study of the structure as well as the behaviour of woven compression bandages. The priority group of work is short-stretch bandage. These bandages are the most effective and healthiest for the treatment of diseases of the venous system, especially leg ulcers of venous origin.

The basis of the thesis was: the study of compression woven bandages, their construction, structure and properties. The aims of the study are divided into three basic parts:

1) Analysis and modification of input yarns for short-stretch woven compression bandages

Final elasticity of short-stretch cotton compression bandages depend on the construction parameters of the input cotton yarn. The specific number of twist in the input twisted yarn, after finishing of raw woven bandage with a hot bath without tensile stress, creates the elasticity of the bandage.

2) Analysis and modification of a short-stretch compression bandage

The study of woven compression bandages is a current and wide topic. From the point of view of publication contributions, the issue of structure is described in a minimal way. During the application of the textile bandage, the degree of compression achievement is only estimated on the basis of the personal experience of the bandage applicator (medical staff or the patient himself). The study of the structure subsequently enables the modification of the bandage from the user's point of view. It is an effort to produce a bandage with information, so-called integrated tension sensor, which will facilitate and allow the correct application of the bandage with right compression. The study is focused on description of the relationships between the construction and structure of the woven bandage and the behaviour of the bandage under stress. Development of methodology for evaluation of the structure of woven bandage in relation to stress and evaluation of the structure versus the resulting compression of the bandage in its use.

3) Study of basic relationships between bandage structure and bandage behavior during the stress (structure versus compression)

The basis of this part is the monitoring of compression (pressure) during winding of the bandage. When the bandage is wound, the structure opens. For identification of the changes in woven fabric structure it is possible to use a thread mark in the form of a rectangular mesh (rectangles) which is inserted into the structure of the bandage during weaving. The study of the compression provides guidance how it is necessary to extend the side of the rectangle in the longitudinal axis to ensure the required compression when applying the bandage. A change in the distance of two coloured wefts in the woven bandage at a given tension will inform about the pressure (compression).

The topic of the thesis is current. Thematically, it focuses on the issue of the textile structures for compression therapy. Compression therapy helps in the prevention and treatment of venous leg ulcers, lymphedema and musculoskeletal disorders. I appreciate the student's approach to the issue, where the approach was positive with great work commitment. The proposed solutions of individual thesis parts were based on the possibilities and knowledge of the student. The elaboration and description in some places lacks the deeper theoretical reflection that is expected from a doctoral student.

In my opinion, the idea of this work can be considered to be beneficial and very useful in the future. The student showed diligence in the preparation of the work and also achieved good formal levels of the submitted work.

I can recommend the work for the defence and based on a successful defence to give degree Ph.D. to a student Abdelhameid Rajab Ramadan ABOALASAAD.

Liberec 16.2.2021

Ing. Brigita KOLČAVOVÁ SIRKOVÁ, Ph.D.

Reviews of the opponents

OPPONENT'S ASSESSMENT OF A DOCTORAL DISSERTATION

Author: Abdelhamid Rajab Ramadan Aboalasaad, M.Sc.

Title: Structure and Analysis of Woven Compression Bandages for Venous Leg Ulcers

Opponent: doc. Mgr. Irena Slamborova, Ph.D.

The submitted dissertation deals with the issue of the structure of compression bandages designed primarily for patients suffering from venous leg ulcers. These compression bandages are intended for patients as part of their treatment with the aim to reduce the swelling of their legs. As previously stated, the bandages are meant to be used particularly by patients suffering from venous leg ulcers. However, their application includes patients with lymphatic system disorders.

The proper manner of bandaging legs is challenging for many patients and, as a result, they are often unable to do it correctly. The bandage is either too tight or vice versa. Therefore, this is a truly current topic and has the potential to apply the research results in practical health care.

The dissertation, compiled through researching 168 bibliographical sources, analyses the topic extensively. The theoretical analysis is suitably complemented with the results of the author's own research.

In the practical section the author looks into the modification of the structure of a compression bandage made of 100% cotton by inserting an integrated tension sensor therein. I view the idea of the integrated tension sensor, which consists of threads distinguished in colour from the remaining structure of the bandage, as a breakthrough. The patient will very easily recognize the deformation of these coloured threads as tension (deformation) occurs in the bandage, thus eliminating the issue of the wrong mechanism of applying the bandage to legs and resulting in the degree of compression that is either too high or too low.

The newly designed bandage was subjected to a wide range of mechanical tests by the author in order to examine the relations between the deformation of a woven bandage, its porosity and its properties under tensile stress. The newly obtained results were compared to a commercially available 100% cotton yarn used to produce bandages. Except for cotton, other materials such as viscose – polyamide were used in the dissertation.

I really appreciate the author's viewpoint in terms of the antibacterial surface treatment of compression bandages. Bacterial contamination is found in most leg ulcers as is secretion, which is shown by fluid leakage through bandages and subsequent fouling of the bandage. This results in further microbial contamination. Therefore, zinc oxide nanoparticles and silver nanoparticles at various rates of concentration were applied to samples and the microbial activity of G+ and G- pathogenic bacteria was examined. The results of antibacterial efficiency are very good.

When evaluating the dissertation it is necessary to point out the research results which have become a basis for a number of publication outputs; that is, articles (11), conference presentations and seminars (9).

On the whole, the dissertation is carefully laid out, with chapters being logically linked and results subsequently summarised and discussed. The results achieved by the dissertation have a great deal of potential for practical application in health care.

A minor remark on my part – the names of bacteria strains are always italicized.

I have the following questions to ask the author:

1. How were the ZnO nanoparticles immobilised (anchored) on the surface of the material?

2. Was the size of the nanoparticles measured?

3. As the bandage containing immobilised nanoparticles will come into direct contact with human skin its harmlessness for health must be taken into consideration. What tests would the author propose to prove that the nanoparticles are not released from the material and the material is therefore non-toxic (harmless for health)?

4. What will be the life span of the newly designed compression bandages?

The Ph.D. candidate has demonstrated corresponding knowledge in the field. I **recommend** the dissertation submitted by Abdelhamid Rajab Ramadan Aboalasaad, M.Sc. **for a dissertation defence** and at the same time **recommend that the Ph.D. degree should be awarded**.

In Liberec, 23 July 2021 doc. Mgr. Irena Slamborova, Ph.D.

Lodz, 13th June 2021

DSc. Marcin Barburski, Associate Professor
Lodz University of Technology
Faculty of Material Technologies and Textile Design,
Lodz, Poland

Review Report on Doctoral Dissertation

of **Abdelhamid Rajab Ramadan Aboalasaad, M.Eng.**
entitled: "**Structure and Analysis of Woven Compression Bandages for Venous Leg Ulcers** "
prepared based on invitation letter delivered on 14th May 2021
from Dean of Faculty of Textile Engineering doc. Ing. Vladimir Bajzik, Ph.D.

Supervisor:
Ing. Brigita Kolčavová Sirková, Ph.D.
Department of Technologies and Structures
Faculty of Textile Engineering
Technical University of Liberec

1. General description

The review has been performed on the basis of the Doctoral Dissertation in English.
The doctoral dissertation consists of 9 chapters, including an overview of the current state of the problem, description of experimental parts, evaluation of results and new findings and list of references. Additionally, a list of papers published by the author and a short Curriculum Vitae are included.
The material of the doctoral dissertation contains 102 pages, including 83 figures and 33 tables. The content of the dissertation presented is divided into nine individual chapters. In the beginning, the list of abbreviations and nomenclature used in the dissertation is presented.
The first chapter was an overview of the current state of the problem and a review of the scientific literature. The second chapter describes the purpose and aim of the thesis. The third chapter is focused on the comparison of different types of bandage existing on the market.
In chapter four, the characterization of yarns used in the bandage, the materials description, experimental techniques, research methodology and the experimental results are included.
Chapter five is the longest and most important chapter focused on the analysis of individual properties of woven compression bandages.
The summary of research work, evaluation of results and new findings are presented in chapter six. Finally, in the last chapter of the dissertation, 168 lists of references are included.

2. The topicality of the thesis

The main goal of the presented scientific work was to study the structure and behaviour of short-stretch cotton woven compression bandages (WCB). The thesis aims were focused on the definition of structure, then modification of construction and analysis of properties, and behaviour of WCBs. The author tries to create better condition during the application of

bandage by a patient, nurse, and athletic user and find a connection between structure and applied tension of bandage during static and dynamic applications. The motivation of this research was to investigate the optimum conditions for compression therapy using long- and short-stretch WCBs.
The research work combines textile aspects with very complex medical elements of the human circulatory system.
The research goal is an analysis of bandage; in accordance with the topic of research, the aim has been achieved. However, the scientific goal of the research has not been clearly shown. PhD candidate did not make any scientific hypotheses.
The aim of the dissertation is actual, very interesting and important from the practical point of view in medical applications, especially for the design and production of compression bandages.
Taking the above into consideration, I can state that the dissertation topic is current and relevant in the context of up-to-date research in textile material engineering.

3. Methodology

Investigations presented in the dissertation are based on three main topics:

1. Analysis of input staple twisted cotton yarn for producing 100% cotton bandages.
2. Analysis and modification of cotton woven bandage structure.
3. Evaluation of individual properties of woven bandages.

PhD candidate has measured the mechanical properties of cotton yarns and the modified surface of these yarns, then evaluated the structure of three basic types of WCBs and modified the construction of woven cotton bandage structure using an integrated tension sensor. The author also measured the bandage extension and porosity using a digital camera attached to the tensile testing device. Next, he made a comparison of pressure measured by Picopress with theoretical compression forces calculated by Laplace's law equation and evaluated the elastic recovery bandage on a mannequin and human leg at different positions and activities. In the end, the author studied the effect of compression bandages on lower leg muscles' performance using an eMotion wireless EMG system and thermal comfort properties using Alambeta and Permetest and finally validated the experimental results of thermal resistance and thermal foot manikin with three mathematical models. The characteristics of the tested yarns and fabrics were determined in accordance with the standards.
Chapter 5 presents many experiments and results with comments and analysis but lacks a summary and deeper analysis of why it is so and how these results solve the main scientific problem.
Experimental results confirmed the hypothesis, which is always true, that the type of yarns and structure of woven fabrics have significant effects on thermal resistance as well as the bandage tension and thickness of layers.
The dissertation includes results of experiments, but it is missing why some dependency exists and scientific analysis. This is because of the lack of a clear scientific hypothesis. The reader needs to conjecture it.
All applied experimental methods have been described clearly and in detail. In my opinion, the methodology is adequate to the problem which the author undertook to solve.

1. Results and discussion

All experimental results have been presented clearly and in detail. The figures, schemes, and tables are correct and supported to analyze the findings. Results have been commented on deeply, but they do not present why some results were observed and how measured parameters influenced the quality of bandage and users.

2. Conclusions

In this chapter, evaluation of results and new findings were presented with conclusions of the work. Conclusions are based on results. The conclusions take into consideration all findings of performed experiments.

The dissertation does not show the best solution for the design of a bandage. The dissertation presents test results, for example, "Wearing VI-PA bandage was associated with lower muscle activation by a percent of 8.42 % for FC muscle during the standardized activity and 14.82% during flexion-extension action". We do not know whether it is OK or not. What is the optimum? How should it be?

The most important conclusions of this work are the warp yarn tenacity should be greater than 15.5 cN/Tex, and its extension should be at least 12% to produce the highly stretched 100% Cotton WCB, and the optimum twist of warp yarns was ranged between 1800 - 2200 TPM for producing high extension Cotton WCBs.

PhD candidate design integrated tension sensor, which causes a change in the spacing of coloured threads during its deformation. The solution is sensors in the bandage in the form of a different colour pick from the other structure of the bandage. As a result, different colour picks with regular distance become visible due to deformation/stress in the bandage.

LSB has a higher resting pressure because of the elastane filaments; due to this, the patient should take off the LSB every day before sleep. Cyclic loading-unloading test confirmed that short-stretch WCB lost approximately 28.6% of its activity, whereas LSB lost only 10.05% after 5 days of application.

Experiment and simulation confirmed that wearing WCB improved the performance of muscles.

3. Bibliography

The bibliography in the dissertation is wide and actual. The references include 168 items. They are mostly the scientific articles published in world-renowned scientific journals and conference papers. The selection of references is adequate to the topic of the thesis.

4. Referee remarks, questions, and conclusions

Remarks

Figure 1.4 does not present a plain weave. This figure should be explained more deeply.

Table with List of Abbreviations and Nomenclature does not present all used Abbreviations.

In the reference, there are some mistakes. For example, the reference of figure 2.1 should be 52, not 53 and Mertová, et al. is not at position 33 etc.

The author should summarise each chapter because the reviewer needs to conjecture for what was analyzed.

In Figure 3.1, it is difficult to see the differences between the bandages.

Each chapter is well prepared, but it is difficult to understand the connection between them. It should be better explained because the reader needs to presume what is in the subsequent chapters. Please keep this in mind when you publish an article and during the defence.

Table 4.7 - 4.10 the produced yarn properties are presented, but without more profound comments on their purposes.

Questions

What do you mean by the "optimum elasticity of LSB"?

Please explain how adding the blue marks to the bandage structure could control the bandage tension as a function of the applied extension.

Please explain the methodology of optimization parameters to choose the best compression bandage.

Your present result confirmed the literature that increasing the plied yarn twist from 300 to 600 twist/m increases the yarn tenacity, then higher twist decreases tenacity, so why did you use linear trend line in figure 4.2?

From where on the images X-ray tomography (figure 5.37) has been detected gold on the surface of yarn?

What conclusions can be drawn from Figures 5.2 and 5.3?

What is new in using antibacterial finishing for a bandage? What scientific problem was solved?

Conclusions

The author of the dissertation has high scientific achievements. The results of the research have been presented in 12 scientific publications, at 9 conferences and workshops.

At the conclusion of my review, I would state that the presented dissertation fulfils all formal requirements and thesis conforms to principles and requests to the structure of scientific. Therefore, I recommend the dissertation submitted by Abdelhamid Rajab Ramadan Aboalasaad, M.Eng, for the next procedure at the Faculty of Textile Engineering of the TUL.

In case of positive results of the defence of the dissertation, I recommend awarding the title of Ph.D.