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Review Article

Shape memory textiles for smart compression management for chronic venous disorders – A review

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In conventional compression treatment using bandage or stocking, always there has been a problem of achieving and maintaining the recommended compression gradient and level. In addition, these devices are incapable of offering dynamic (massaging) compression, often preferred especially for senior and non-active patients to improve blood flow. To overcome these challenges, the application of shape memory materials is proven to provide a dynamic or selective pressure change directly on the limb. Memory material-based stockings or bandage have the potential to tackle the drawbacks of existing stockings by allowing users to modify pressure levels externally as needed during compression therapy, i.e. as a smart wound care device. This paper reports the consolidated information on traditional compression systems, their challenges, and modern methods involving active compression bandages based on smart materials technology (via shape memory polymer or shape memory alloy), which develop intermittent active pressure to alleviate the symptoms of lower limb problems.

Keywords: Compression therapy, Compression bandage, Chronic venous disorder, Shape memory polymer, Shape memory alloy, Stocking, Smart materials technology

1 Introduction

It has been estimated that 2% of the general population in the world (18-64 age group) is suffering from chronic venous ulcers[1]. This rate is further increased to 4% in people over the age of 65 in some countries like US[2]. This has significant socioeconomic impact, costing 1% of total health care budgets in developed countries, for example in the USA, this costs $2.5 billion to treat 6 million patients every year[3]. Both the incidence and cost are bound to increase in future due to changing lifestyle and growing aged population. Thus, there is a huge market in compression products for improving life quality of world population.

As a longer-term medical intervention for chronic venous disorders, e.g. venous ulcers, oedema, deep vein thrombosis (DVT) and varicose vein, textile fabrics (as compression bandage or stocking) has been used for compression therapy to apply certain level of pressure around the affected tissue on the limb to reduce the venous hypertension and improve blood flow. Nevertheless, current compression products has the following shortcomings: (i) selection of stockings with proper sizing and fitting has always been a challenge for both health practitioners and manufacturers seeking better patient compliance and effective treatment[4]; (ii) for maximum treatment efficacy, a required pressure gradient from “toe to knee” is critical yet arduous to achieve in bandage mounting due to reasons including different leg attributes (shape or size) among patients and difference in bandage materials/designs, hence requiring trained personnel and raising the treatment cost to hospitals and patients[5]; (iii) maintenance of the initially set desired pressure over time is another major challenge, due to the time and temperature dependence of the materials, leading to a diminished treatment efficacy; and (iv) for some patients, a dynamic (massaging) compression is recommended but the required equipment like the intermittent pneumatic compression (IPC) is costly, noisy, bulky, and once attached, severely constraining the patients[6]. Clearly, these inadequacies of conventional compression therapy approaches demonstrate a compelling demand for multi-functional bandage in terms of controlled static pressure and dynamic (massage effect) pressure.

These challenges in conventional compression products could be resolved if there is a possibility of self-stress (or, tension) control in the bandage or stocking materials. The stimulus-responsive polymers

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or alloys, also known as memory materials, have been used in many applications in the areas of aerospace, biomedical, transport, construction, electronic, textile and consumer products[7–9]. A shape memory material demonstrates the ability to temporarily fix a deformed shape from its original (permanent) shape; the original shape can be recovered back from the deformed after application of an external stimulus like heat (Fig. 1). Such materials can also show the potential of stress memory, whereby the stress in a polymer can be programmed, stored at temperature below its thermal transition (glass transition) temperature (T_g), and then retrieved reversibly when needed with an external thermal stimulus at > T_g. In this review paper, we are summarizing the principle, designing and characterization of shape memory in compression management.

2 Background of Compression Therapy

Compression therapy has been used to treat various ailments, including varicose veins, chronic venous illness, and deep venous thrombosis (DVT). Due to an increase in the occurrence of an economy-class syndrome, it is researched extensively; long-distance air travel causes blood clots to become dislodged and move to the heart and lungs, resulting in abrupt death. Furthermore, chronic venous illness is becoming increasingly common as the population ages. Compression treatment is also being used in sports medicine to aid in the recovery of athletes. The control of the underlying disease is the first stage in the therapeutic procedure for wound and ulcer care. Healing rates of 40 - 70% (after three months) and 50 - 80% (after six months) have been documented with compression therapy.

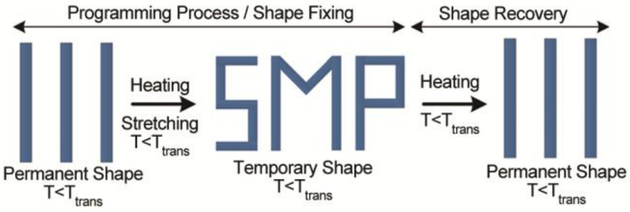

Fig. 1 — Schematic diagram representing shape memory effect in shape memory polymers

Compression therapy is the first line of defence against chronic venous insufficiency and venous ulcers. Patients with venous and lymphatic problems (Fig. 2), such as venous ulcers, lymph oedema, varicose veins and DVT, require compression therapy as part of their health care and medical treatment[10,11]. Leg ulcers are lesions or open vexatious that are generally chronic (abiding and non-healing) and cause skin damage. Appropriate management of chronic venous leg ulcers is critical for preventing further anguish and wound worsening, improving the quality of patients life, and lowering health protection expenditures connected with treating ulcer complexity, such as infection[12].

`Compression therapy's goals is to promote quick ulcer healing and prevent recurrence[13]. Older age, obesity, venous reflux or backflow in the veins and

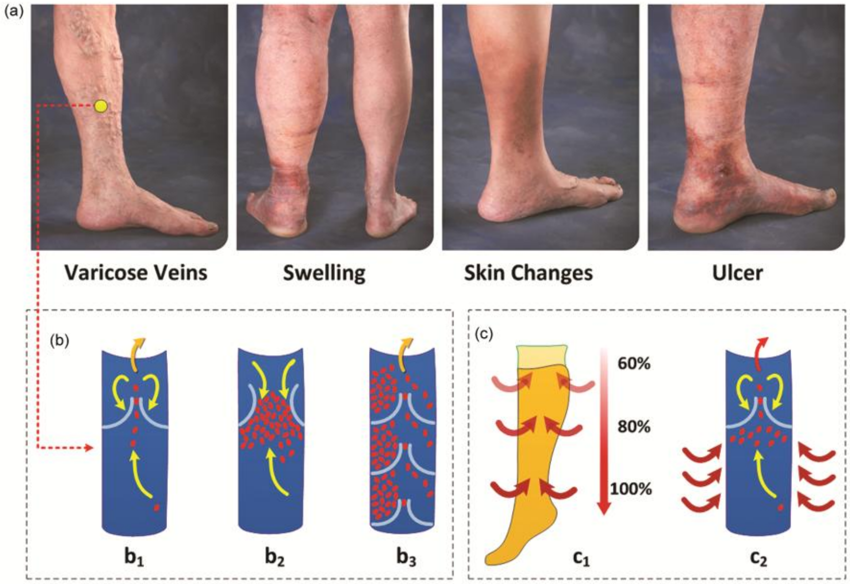

Fig. 2 — Background of compression therapy (a) types of chronic venous disorders, (b) schematic diagram showing the venous function [(b_1) functioning of normal vein, (b_2 & b_3) damaged vein] and (c) principle of compression therapy [(c_1) gradient pressure, and (c_2) normalized vein function upon therapy]

underlying artery disease are all potential barriers to recovery (poor blood flow into the leg). Long-term or large-scale wounds, as well as patients with a history of prior ulceration, require longer to heal. The optimum compression permits the patient to carry on with their typical activities, such as walking and remaining active. The standard medical support is a gradient elastic compression stocking which generates a greater compression in the foot and the pressure reduces as one moves up the leg so that the venous blood is directed toward the heart and not pushed into the foot and lower leg. Several firms offer them in a range of fabrics and materials, as well as strengths, lengths, and designs. When compared to other types of compression, compression stockings are typically less bulky and presumably more comfortable for most individuals[10].

Compression therapy's fundamental objective is to provide a set amount of pressure around the afflicted tissue on the limb to alleviate venous hypertension. The veins and one-way valves in a healthy body allow blood to flow exclusively in one direction [Fig. 2(c)]. However, due to limited movement, foot and calf muscle movement frequently does not operate well, especially in older persons, resulting in a rise in venous pressure. Venous hypertension causes excessive fluid pooling, high stress, and oxygen and nourishment deprivation in the surrounding muscles if not treated adequately. This causes skin degeneration, which leads to venous leg ulcers. The application of compression therapy around the affected tissue on the limb reduces the venous hypertension. The pressure gradient from “toe to knee” improves the flow of venous fluid returning to heart. There are various pressure levels recommended by the standard organization for venous leg ulcer management. The Wound Healing Society (WHS) suggested a classification of compression levels, such as 5mmHg, 15mmHg, 18-24mmHg, 20-40mmHg, 40-60mmHg, and greater than 60 mmHg for extra light, light, mild, moderate, strong and very strong respectively[14].

2.1 Modes of Compression

Compression therapy can be delivered via short stretch and long stretch bandages, socks, and intermittent pneumatic compression (IPC) devices (Fig. 3) according to various stages of venous ulcer. Bandages and stockings are the most utilized for these[15]. Many researchers have confirmed that the healing outcomes are better for the patients receiving compression treatment as compared to those with no compression[16]. The research focus has been on comparing and evaluating the efficiency of different compression modalities including stockings, bandages and IPCs. Each of these devices holds its own significance for the treatment. Stocking is favoured for low pressure (< 50 mmHg) and allows easy application, whereas a bandage is size independent and permits high pressure. IPC is primarily recommended for the patients with poor calf muscle function or limited ankle mobility. More than two modes (stocking and IPC) are also used to provide benefits of both static and dynamic compression, leading to healing of venous ulcers and alleviates symptoms in patients with chronic venous insufficiency[6].

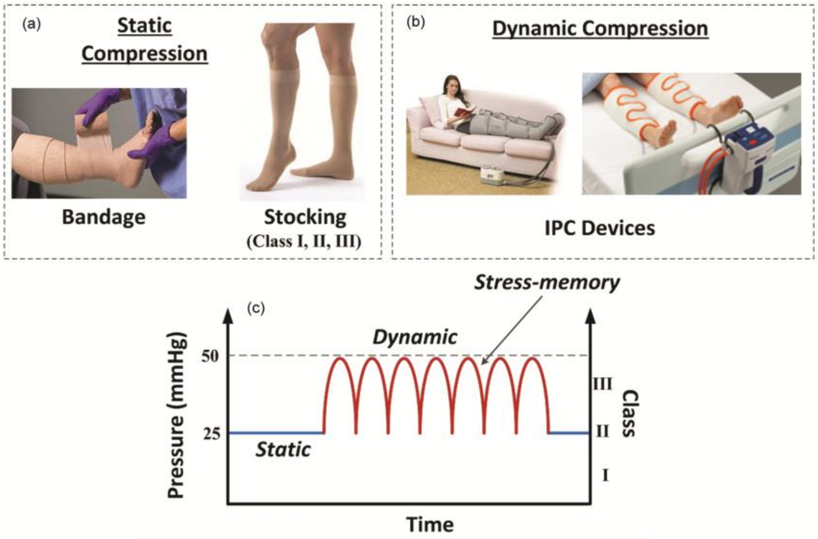

Fig. 3 — Modes of existing compression therapy (a) static compression, (b) dynamic compression, and (c) required method of compression in smart stocking

2.2 Theory of Compression

According to Laplace’s law **(**Fig. 4**)**, an internal radial pressure (*P)* exerted on the surface of skin is dependent on the internals stress developed in the tensioned stocking. The equation depicted that, as the radius of the limb reduces the interfacial pressure reduces, thereby producing a pressure gradient from ankle to knee with maximum pressure at the ankle (Fig. 4). The efficiency of compression treatment is generally dependent on the interaction of the physical structure and elastic properties of the bandage material, limb circumference, method of application of bandage and the nature of the user's physical activities. The pressure of bandage is mainly dependent on the radius of limb curvature and the tension in the fabric, which is governed by the Laplace's law [Eq. (1)] used to measure pressure around a thin cylindrical film Further, Thomas proposed a modified equation using Laplace's law which indicates the tension and number of layers of a sub bandage are directly related to the pressure, but the width and radius of the limb are inversely proportional[17], as shown below:

$$P_\alpha - P_\beta = \frac{2\gamma}{r} \qquad \ldots(1)$$

$$Interfacial\ Pressure\ (P) = \frac{T \times n}{R \times W} \qquad \ldots(2)$$

where P_α and P_β are the internal and external pressures at the surface respectively, *r* is the radius of curvature; and Υ, the tension in the film; *T*, the longitudinal tension applied over the bandage; n, the number of bandage layer used; *R*, the limb radius, and *W*, the bandage width in meter. The equation depicted that, as the radius of the limb reduces the interfacial pressure reduces, thereby producing a pressure gradient from ankle to knee with maximum pressure at the ankle.

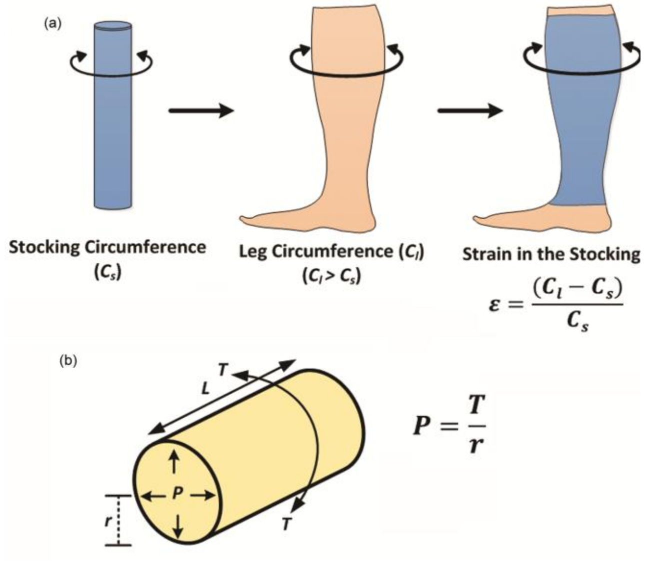

Fig. 4 — Concept of interfacial pressure development (a) schematic diagram showing the tension development in the stocking, and (b) Laplace’s law for thin-walled cylinder [*P*- internal radial pressure, *T*- Tension/unit length, *r*- radius, and *L*- length]

It should be noted that the calculation applies only for the initial application of bandage or stocking. Nevertheless, the efficiency of compression treatment is generally dependent on the interaction of the physical structure and elastic properties of the bandage material, limb circumference, method of application of bandage and the nature of the user's physical activities.

It has been reported in the literature that the tension in the bandage gradually reduces over the time and the fabric width reduces significantly over the usage, a phenomenon known as ‘necking’. Different textile fibers (nylon, PET, cotton, elastane, etc.) and fabric structural characteristics have significant effects on the pressure distributions on the skin by a compression stocking[18–20]. Incorporating more elastomeric content and creating tighter construction helps to provide a more homogeneous pressure distribution and sustenance during the course of treatment[21]. One can control the linear density of mock inlay or inlay yarns and input yarn tension to optimize stocking structure for the pressure generation[20,22]. The above factors should be considered while evaluating the interfacial pressure of the stocking or bandage[23].

2.3 Traditional Compression Systems

Various types of compression bandage are used to treat venous leg ulcers and other associated disorders. The traditional compression system, on the other hand, has the drawback of rapidly losing pressure after it has been applied during the application. With stiff, nonelastic material, pressure loss is greater than with more elastic compressional hosiery. However, various studies on multilayer conventional compressional bandages for the compressional therapy, usually done with 4 layer and 2-layer compressional bandages have been reported[24–27] (Fig. 5). Elastic or non-elastic bandages, monolayer, or multilayer bandaging, short, medium, long-stretch bandages, and hosiery are the examples of compression therapy systems[28].

Single, long-stretch bandages, paste bandages, and multilayer compression systems are the most popular

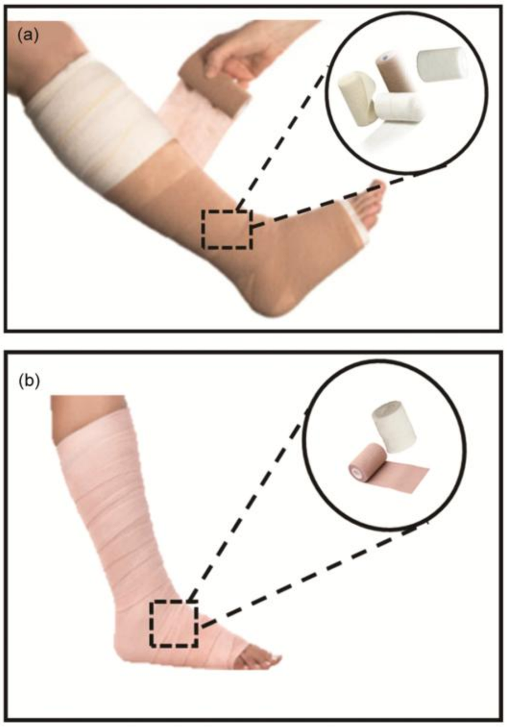

Fig. 5 — (a) Four-layer, and (b) two-layer compression bandage components

bandage systems. Single, long-stretch bandages must be reapplied every day, thus they are best for wounds that require daily dressing changes as well as edema treatment. Typically, paste bandages are impregnated using zinc oxide or calamine. Paste boots are typically inconvenient since they only give continuous compression when the patient is walking. It has been found that after 24 h of usage, these bandages lose their continuous compression[29].

Multilayer systems are the old standard in most wound centres. Traditional paste boots or single, long-stretch bandages have been shown to be less effective than these compression devices, which come in pre-packaged sets. Multilayer wraps are made up of three or four layers. To keep the system intact, three (3)-layer systems have a padding layer, compression layer and outer layer four-layer systems have an extra layer for exudate management. These graded compression devices are said to give pressures ranging from 30 mmHg to 40 mm Hg, sustain consistent compression for about a week, and are not ambulatory.

A multilayer bandage system consists of multicomponent. A popular multilayer bandage is the four-layer bandage system as shown in Fig. 5(a). This compression system is made up of four-layers that work together to generate an inelastic sleeve that conforms to the contours of the limb and maintains a consistent pressure profile. A four (4)-layer is made up of four parts, viz orthopaedic wool, a crepe bandage, an elastic bandage, and an elastic cohesive bandage on the outside[30]. According to existing moderate-quality evidence, multi-layer bandages are preferred over single-layer bandages for the treatment of venous leg ulcers[20]. A study compared the four (4)-layer compression system to the short stretch compression method and found that the four-layer bandage technique improves ulcer healing by 30%[31]. However, some researchers also performed a meta-analysis of seven randomised controlled clinical trials comparing the use of four (4) - layer bandages system and short stretch bandage for venous leg ulcer healing and concluded that after 12 - 16 weeks, there were no significant changes in the proportions of ulcers that had healed. They stated that compression therapy is selected based on the health care provider's assessment and professional skills, as well as the patient's tolerance and preference[32].

The compression systems are made up of two (2)-layers that work together to generate an inelastic sleeve that conforms to the contours of the limb and maintains a consistent pressure profile[33]. Many researchers used a two (2)-layer compression banding technique to treat venous leg ulcers[34–36]. For venous leg ulcer patients, researchers compared the two (2) -layer and four (4)-layer compressional bandage systems[24]. They found that the two (2) -layer approach had far less bandage slippage than the four-layer system. While reduced bandage slippage did not appear to affect wound healing, there was an indication that it may have changed patient preference towards the two-layer approach. The two (2) -layer and four (4) -layer compression bandages are compared and found that the two (2)-layer bandage (UrgoK2) system is therapeutically superior, easier to apply, and more comfortable to wear than a typical four-layer bandage as reported by Pilati *et al*[37]. Therefore, according to the findings of different studies and experiments, two-layer compression bandages are superior to four (4) -layer compression bandages. However, the utility of a particular bandage system depends on the severity of leg ulcers in the patient.

2.4 Challenges in Traditional Compression Treatment

The typical standards follow a compression requirement based on the severity of the condition. Severe venous disease, such as edema, eczema and ulceration, necessitates a higher level of compression, whereas mild varicose veins require a medium level of compression[38]. Table 1 shows the pressure in mmHg exerted during compression at the ankle.

The above guidelines have faced many challenges in achieving the desired pressure level in actual application. The main cause of pressure variation is the shape and size of human limbs, as well as the elastic characteristics of the fabric. Furthermore, a decline in pressure over the time is also a cause for concern. Experiments have shown that the pressure diminishes with time as the swelling of the leg falls, as does the internal stress in the bandage's fabric material[40,41]. The pressure at the interface reduces due to relaxation of stresses in bandage and also because of reduction in swelling of limb. Also, the viscoelastic properties of the fibres or yarns used in the bandage, as well as whether the wrapped bandage is in a static or dynamic state, affect the relaxation of internal stress in the fabric structure[41]. The pressure drops are unavoidable with almost all stockings or bandages, and hence replacing of stocking is required once the pressure drops below the desired level. The patient comfort also needs to be given a considerable importance as the pressure imparted by the bandage hinders the natural movement of the user and may needs to remove during the sleep[42]. The foregoing shortcoming of the conventional compression system necessitates the development of an enhanced responsive compression system that allows for pressure intensity modification via external stimuli or pressure adjustment according to requirements.

3 Introduction of Shape Memory Materials

Shape memory materials (SMMs) are stimuli responsive smart materials which are given an intensified scientific and technological significance from both academia and industries in the past few decades. The term "shape-memory" was first proposed by Vernon in the year 1941[43]. SMMs can undergo significant macroscopic deformation; can be programmed to one or many shapes and spontaneously recovered back to its permanent conformation upon exposure to an external stimulus, such as heat[44], light, electricity, moisture, and magnetic field[45,46]. These smart materials are intrinsically sensitive to ambient temperature, to have the shape memory property; they should have the responsive range within a narrow range of temperature change (Fig. 6). SMMs have been developed intensively in the past few decades[47,48] and they include shape-memory alloys (SMAs), shape-memory ceramics, and shape-memory polymers.

Table 1 — Classification of pressure requirements[38,39]

Class	Pressure, mmHg	Condition
I	14-17	Varicose veins Mild edima
II	18-24	Mild Varicose veins Prevention of ulcer recurrence
III	25-35	Severe varicose veins Post-phlebitic limb Prevention of ulcer Chronic venous insufficiency

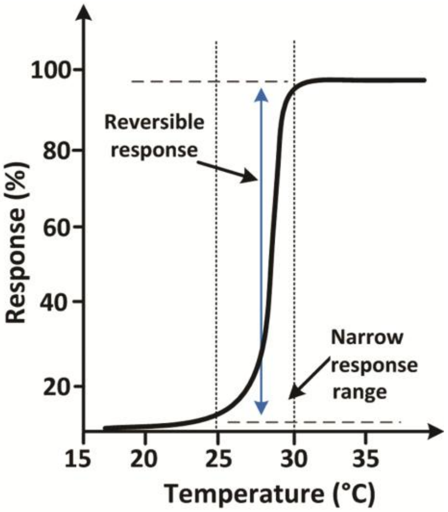

Fig. 6 — Sensitive change of smart materials at an ambient temperature

3.1 Memory Textiles

Researchers and industrial technocrats have been continuously working in the arena of memory materials to scientifically apply them into textiles. They can be applied into textile materials to enhance their smart functions in 2 ways via finishing or built-in methods. Finishing method primarily involves coating or laminating techniques and built-in method includes the blending and spinning operations[49,50]. Memory polymers (MPs) can be applied on to textiles in different forms such as emulsion, solution, film, fibre, foam, and bulk forms under specific conditions. As shown in Fig. 7, MP fibres can be prepared via spinning techniques and embedded into yarn by spinning to make flexible fabrics by knitting or weaving technique.

Generally, MPs based on glass or melting transitions, known as switches, typically have a physical cross-linking structure, crystalline or amorphous hard phase, or chemical cross-linking structure and a low temperature transition to a crystalline or amorphous phase. Generally, in the

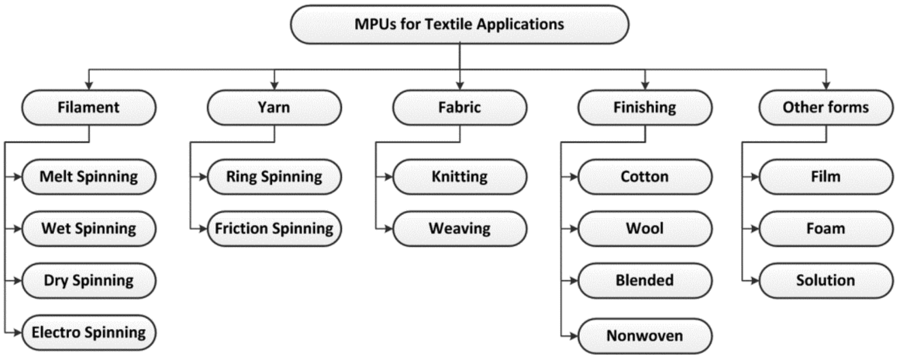

Fig. 7 — Different forms of MPUs for textile applications

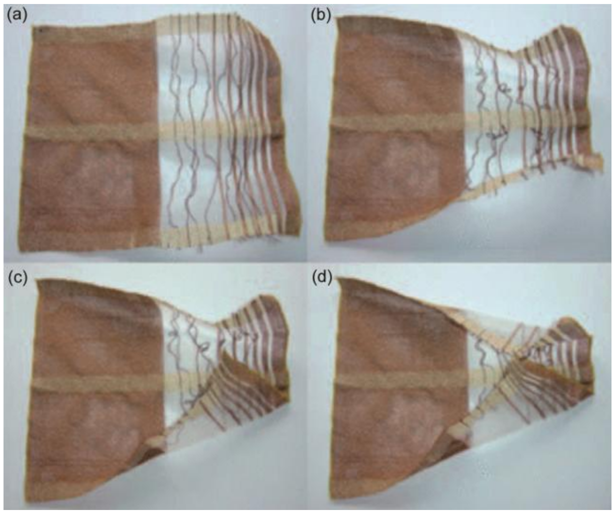

Fig. 8 — Shape recovery of a fabric having SMA spring with temperature 50°C from (a) temporary shape (b) recovered shape 1, (c) recovered shape 2, and (d) permanent shape[45]

original or permanent shape, the internal stress is either zero or significantly low. After the deformation, the applied stress will be stored in the cross-linking structure by cooling the transition. The deformed or temporary shape is fixed because of the sharp increase in elastic modulus around the glass or melting transition temperature. The MP recovers its permanent shape upon heating the polymer above the transition temperature, with the release of the internal stress stored by the cross-linked structure. Major advantages of MPs in textile applications are: (i) the switching temperature can be tailored even to set around body temperature, (ii) superior processibility, (iii) soft/tailorable mechanical properties, and (iv) high strain deformability and recoverability.

Stylios *et al.* [51] have developed shape memory alloy (SMA) (0.2 mm diameter) integrated textile smart fabrics to achieve the SME effect (Fig. 8). The aim was to develop the fabric to change aesthetic performance by changing the shape. The achievable recovery strain is limited to about 6 - 8%[51]. Due to limitation of SMAs, Stylios *et al.* [51] also showed a SME of fabric woven with T_g type of MP yarn having diameter of 0.4 mm. The MP woven fabric showed a recovery at 50°C (Fig. 9).

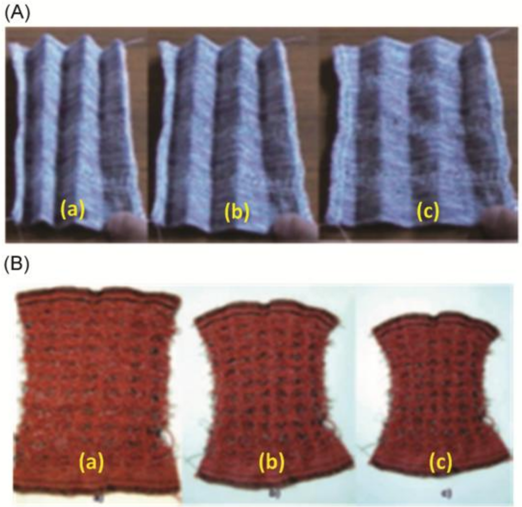

Fig. 9 — (A) Shape recovery of memory polymer composite woven uniformly and densely with memory polymer yarn at 50°C with recovery time (a) 0 s, (b) 15 s, and (c) 30 s; and (B) shape memory recovery of memory polymer composite loosely woven fabric with SMP yarn at 50 ºC with recovery time (a) 0 s, (b) 30 s and (c) 60 s

Fabrics have been developed using MPFs using knitting and weaving methods by Hu et al[52]. These MPF based knitted garments are suitable to fit the wearer's body contour and it shows relatively low vertical tension stress as compared to elastic fibres (Fig. 10). Biological properties, such as cytotoxicity, haemolytic effects, and skin erythema have been investigated for SMPU fabrics with switching temperature around body temperature and showed negative effects[53].

4 Potential of Memory Materials in Smart Compression

In conventional compression treatment using bandage or stocking, always there has been a problem of achieving and maintaining the recommended compression gradient and level. In addition, these devices are incapable of offering dynamic (massaging) compression, often preferred especially for senior and non-active patients to improve blood flow. There are other collateral problems of loss in mechanical strength of fibres, stiffness and, active ulcer, where over bandaging is not possible[54]. Therefore, modern methods are under the limelight with the advent of these functional polymers for proper compression management and overcoming the drawbacks of conventional ones.

In a memory polymer, the stress can be programmed, stored at temperature below its thermal transition temperature (T_g), and then retrieved reversibly when needed with an external thermal stimulus at > T_g (Fig. 11), thus to realize the *in-situ* material stress control[55–59]. In other words, the integration of MP fibers in the fabric structures could allow *in-situ* material stress control. If such material whose internal stress can be easily adjusted in such a way that it can compensate the deviations of the pressure from the initially designated level, then it would be possible to sustain the desired pressure on the leg and also to achieve dynamic compression benefits.

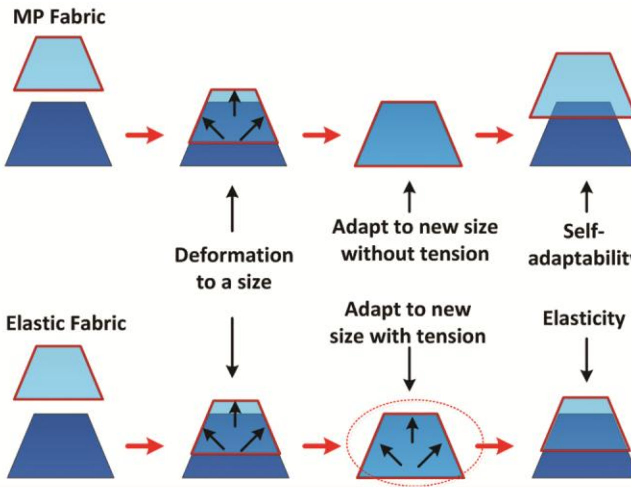

Fig. 10 — Self-adaptability of MP based garments

4.1 Shape Memory Alloy in Compression Management

Static compression management is often prescribed by the medical personnel; however, intermittent pneumatic pressure has shown a strong potential as an alternative aid with significant improvement in the arterial flow, elevating the venous outflow and pressure. The current methods to achieve pneumatic pressure has posed a limitation of restricted patient mobility[60]. Thus, there is a need for effective compression device to overcome the major pitfalls of the conventional treatments. Shape memory alloy is a temperature sensitive shape memory material, whereby material recover to its original shape from fixed deformed shape upon heat or current as the stimuli (Fig. 12). The memory effect is as result of transformation from weak asymmetric parallelogram crystal structure in martensitic phase and the highly elastic bcc crystal lattice in austenitic phase[61]. SMA are preferred in a range of applications due to its high corrosion resistance, greater fatigue performance under cyclic loading, and higher strength to weigh ratio. However, it is expensive material which has limited its usage.

Active compression devices mimic the natures mechanism to develop smart actuation. Various compression prototypes have been designed using the actuation capability of smart/shape memory alloys which are commonly nitinol (NiTi) wire that can produce large recoverable strain/force upon temperature/load as the stimuli. Coiled actuators produce large displacements; however, very low recoverable force. One of the major advantages of alloys is the generation of large force per unit area (200 MPa) and actuation using joule's heating and current. The pressure is controlled with the amount of

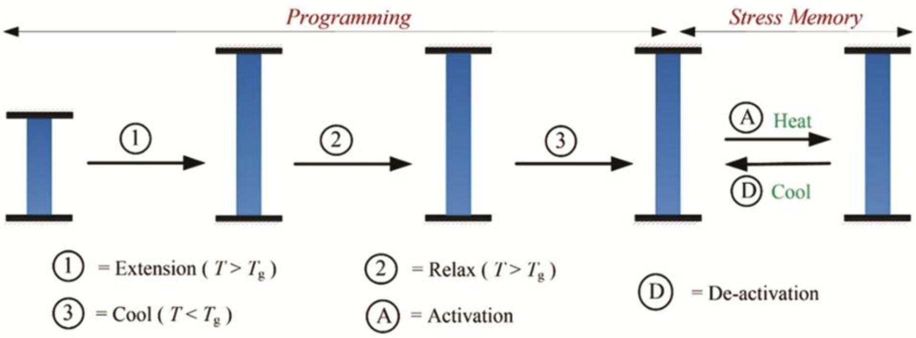

Fig. 11 — Demonstrating stress memory response in a MP through a suitable programming

electric current applied to the SMA wires. The controlled application of stress in shape memory materials for achieving dynamic compression is of utmost importance. Moein *et al.* [62] fabricated a device based on NiTi SMA wire to apply a constant pressure in the beginning and increasing variable pressure in the calf thereafter. Similar to commercial stockings, the device performed satisfactory in providing an initial consistent pressure, and active alterations is achieved with electrical stimulation. The device acquired a pressure of 9.06 mmHg with electrical stimulation of 219.88 mA current.

4.2 Shape Memory Polymer in Compression Management

A crucial parameter in pressure bandages is the right amount of gradient pressure between the ankle and knee for treating venous ulcers. The advent of stimuli-responsive smart materials, particularly shape memory polymers, has been a prime choice by generations. This class of polymers can change from a deformed shape to a permanent shape when applying a stimulus. Due to their flexi-deformation capability, high recovery ratios, and easier processability, they are preferred over memory alloys[63–65].

The pre-stretch SMPU strip is under colossal demand and is replacing the conventional compression therapy and hosiery bandages. Manzoor Ahmad *et al.* [66] prepared strip actuators using SMPU to balance gradual and cyclic stresses. The recovery force based on temperature and stress relaxation behaviour was examined based on leg circumference. The recovery force based on temperature and stress relaxation behaviour was examined based on leg circumference. Temperature and the induced pressure showed prime inter-relationship with time-dependent behaviour where re-adjustments were necessary based on the amount of decay. The cyclic curves depict repeatability based on adjustments in the temperature and pressure[67] .

Kumar *et al.* [58] has studied a prototype bandage, containing a MP fabric actuator and a heating layer as both a heat source for thermal therapy and thermal trigger to control the MP actuator. Controlled by an external programmed heating device, the result of dynamic compression of the system is shown in Fig. 13.

Similarly, Small *et al.* [68] reported the use of SMP for removing blood clots due to arterial clogs, which may cause ischemic stroke. The SMP micro actuator device can remove the vascular occlusions by laser therapy. The micro actuator corkscrew is pushed into occlusions straight and powered by the laser. The SMP device retracts back on, switching off the laser pulling the occlusions out. These tools open a promising therapy for restoring the normal blood flow in the body[69].

Smart stockings are in trend for compression management in venous ulcers. Kumar *et al.* [70] designed smart stockings using a blend of SMP and nylon yarns (Fig. 14). The external or the control pressure were designed by temperature changes that can regulate the stress level, and more than 50 % extra pressure can be created in the wrapped position due to the memory polymer.

A similar study by integration of shape memory filament in knitted fabrics is done by Narayana *et al.*[71] Shape memory polymers were synthesized using poly (1,6 hexanediol adipate) (PHA), 4,4′-diphenylmethane diisocyanate and 1,4 BDO. Shape memory filaments were prepared using melt spinning to achieve maximum memory stress in the filament. Higher memory strain imposed higher memory stress which is important to maintain the minimum baseline

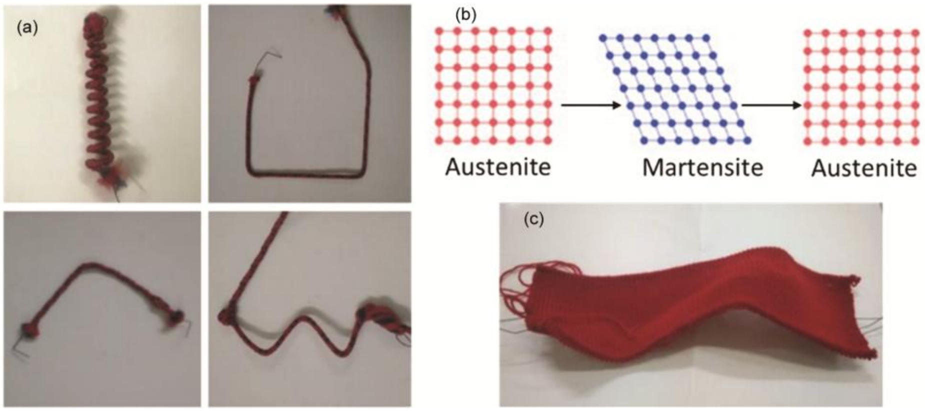

Fig. 12 — (a) SMA integrated yarn and its deformation to different fixed shapes, (b) crystal structure changes in SMA during shape memory effect, and (c) SMA integrated fabric

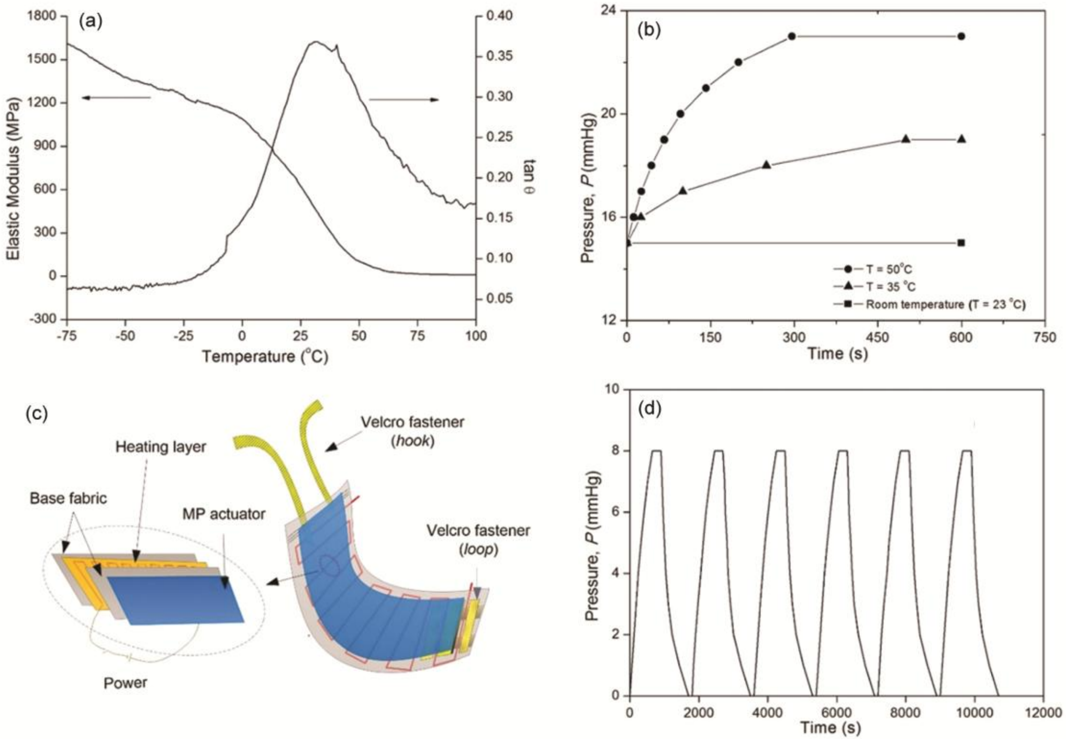

Fig. 13 — (a) DMA results of polyurethane-based MP, (b)bandage pressure control by the MP fabric at different levels of temperature, (c) schematic of the prototype showing system assembly, and (d) results of dynamic compression from the prototype

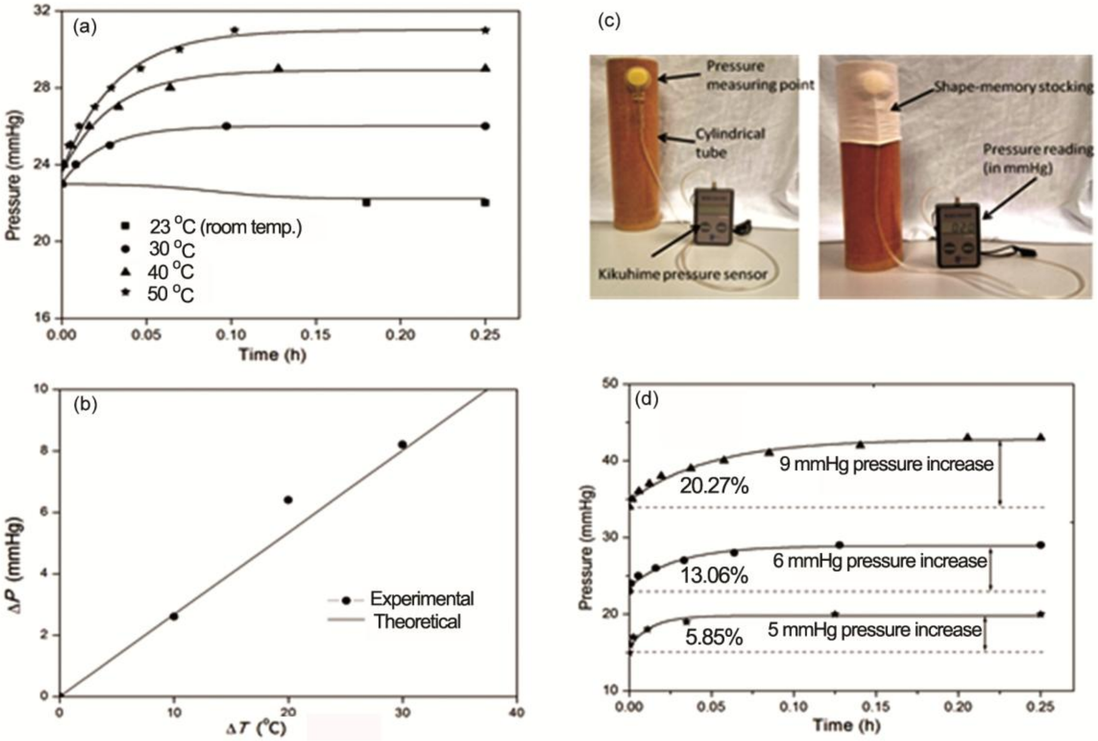

Fig. 14 — Experimental and theoretical prediction results (a) pressure variation at different temperature level, (b) comparison with theoretical prediction, (c) pressure measurement set up, and (d) pressure variation at different level of strains (T=40°C)

pressure. The approach for fabric design provides an extra massage effect that helps to maintain the memory stress on changing the temperature[72] (Fig. 15).

Hans[69] filed a US patent where he developed a medical device using shape memory material for effective compression therapy. This therapy was found useful in orthopaedic and cases of prophylaxis where a textile fabric, particularly knitted, was used to integrate shape memory material for creating a local pressure band. Similarly, Tonndorf *et al.* [73] developed knitted compression garments for smart stockings and compression garments with a blend with TPU/PCL (Thermoplastic polyurethane/polycaprolactone), of a shape fixity of 62 % and shape recovery of 99 %. The shape fixity varied with the content of the soft segment or the PCL. The melt-spun blend yarn produced can be used for compression garment therapy. Polyurethane based smart foams are also being used for dynamic pressure distribution for ulcer

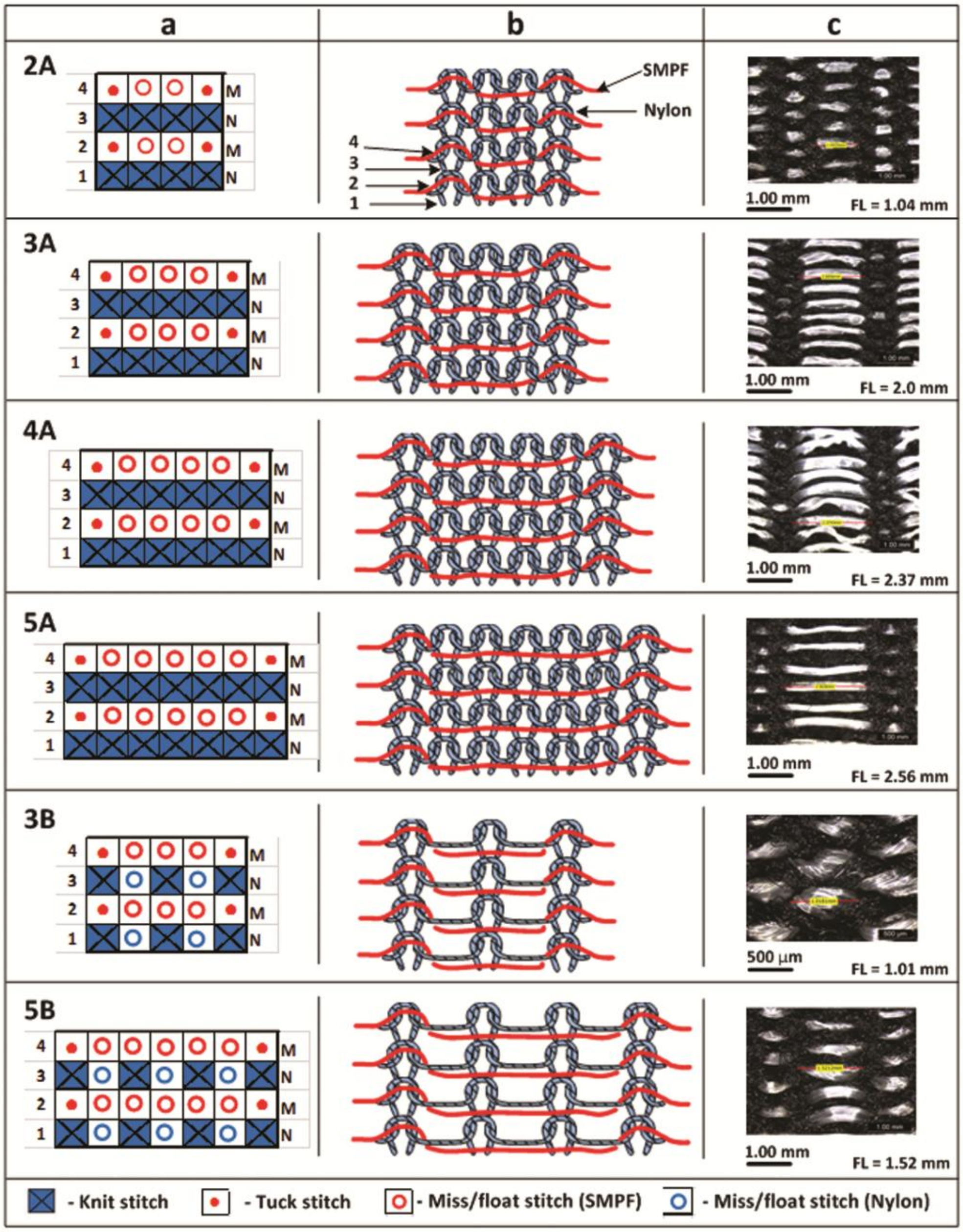

Fig. 15 — Scheme of memory fabric knit structures (a) notation diagram, (b) schematic illustration of knit structures, and (c) microscopic image of memory fabrics on technical back. [M-memory filament, N-nylon filament, and SMPF-stress memory polymeric filament]

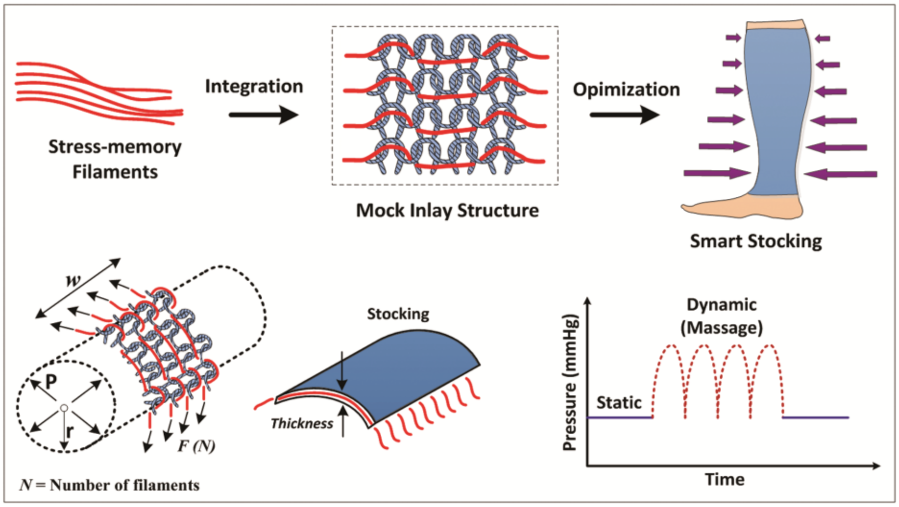

Figure 16 — Dynamic compression via a shape memory stocking

effects. The interfacial pressure showed an 80 % reduction, stored stress during the programming is observed to be 30 % and complete recovery is obtained on stimulation. The mechanism act as an effective pressure distribution system due to their repeated cyclability, particularly in the case of active ulcers[74]. Memory material-based stockings have the potential to tackle the drawbacks of existing stockings by allowing users to modify pressure levels externally as needed during compression therapy, i.e. as a smart wound care device (Fig. 16).

5 Conclusion and Future Outlook

In this review, various compression bandages, including traditional and modified using smart material technology has been discussed. The traditional pressure bandages are compared with modern bandages, which involve smart actuation using shape memory alloys and shape memory polymers. The shape memory materials are proven to provide an intermittent pneumatic pressure where after an initial constant pressure, a gradual consistent pressure is achieved at the lower limbs.

Although the idea of using stimuli-responsive smart polymers is suitable for laboratory experiments, there are a lot of challenges to meet the expectations based on their optimization and design for commercial success[75]. Following are the future suggestions or recommendations for further research directions:

- The activation of shape memory textiles needs external stimulus, herein primarily heat. Designing of the heating device is a must to achieve dynamic pressure change from a memory device. In addition to heating device, the response of the memory material and temperature level should be optimized to achieve desired pressure change on the limb.
- Melt spinning operation is performed relatively at high temperatures (~ 190 - 220 ºC), this could damage or modify the structural morphology of filaments. Hence, other alternative methods of memory polymer synthesis, processing, and filament spinning could be followed for the optimization. Preparation of mono-filament with desirable linear density might be helpful in further knitting process to avoid problems, such as unwinding and fibre fraying out.
- Most of study on memory compression deals with the analysis interfacial pressure on hard surface using cylindrical tubes. Further it can be extended to soft surface to mimic the human limb and study the pressure related parameters to deeply understand the influence of skin deformations on the applying pressure. Thus, based on scientific approach, the internal pressure can be adjusted to required level by optimizing the memory stress in the memory polymer, filament, and fabrics. To measure the minute changes in the pressure level on soft surface, highly sensitive piezo-resistive based pressure sensors can be used as an option.
- Modelling work need to be done to predict the interfacial pressure of stocking fabrics with different structures as a function of strain. The studies on the effect of fabric structures including thread density, filament linear density, and memory stress can be carried out. This would help in designing the stocking with optimized structure with desirable pressure profile required for an efficient compression therapy.

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