

Design and Development of a Textile-Based Compression Sleeve with Adjustable Pressure Levels for High-Performance Athletes

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I. INTRODUCTION

Compression garments are specialized clothes comprised of elastomeric yarns and fibers utilized to apply substantial mechanical pressure onto the surface of a specific anatomical region to stabilize, compress, and support underlying tissues [1]. They have been extensively studied and applied in the domains of sports, medicine, and body-shaping application [2]. Moderate compression sportswear is widely used in fitness and athletics, as it is believed to enhance performance, reduce injury risk, and accelerate recovery [3],[4],[5]. Numerous studies have examined recovery methods promoted by manufacturers, coaches, and athletes, which include massage, active recovery, cryotherapy, hyperbaric oxygen therapy, stretching, electromyostimulation, compression garments, and combinations of these techniques [6].

A. Static Pressure Application

When textiles apply pressure, they compress soft tissues perpendicularly, generating force vectors with specific direction and magnitude. These forces increase the hydrostatic pressure within the targeted tissue region. In simple terms, the blood flow is increased with hydrostatic pressure inserted on tissues. The applied pressure from compression stockings increases interstitial fluid pressure around capillaries, aiding in the return of excess fluid to circulation. This enhances local muscle blood flow, leading to improved tissue oxygenation and muscle function [8]. Intramuscular pressure (IMP), measured within muscles using catheters, influences blood flow and oxygen availability, with higher IMP levels potentially causing muscle fatigue [9]. Compression stockings raise resting IMP and can facilitate venous blood return during muscle contraction in daily activities [8]. However, over time, the tension in compression stockings diminishes due to the "necking" effect, reducing their effectiveness [10].

B. Graded Compression Technology

Graded compression textiles are designed to provide varying pressure levels along a given distance, but their effectiveness relies heavily on accurate limb measurements and appropriate garment selection. Since human limbs have complex anatomical structures that do not conform to uniform geometric shapes, the pressure distribution from localized compression zones is not uniform [8]. Conventional graded compression stockings apply consistent pressure within specific zones, creating a pressure gradient along the limb. However, this approach is only effective when the stockings are manufactured using the original limb measurements, as deviations can result in inaccurate pressure application.

C. Laplace's Principle

According to the law of Laplace, the pressure (P) experienced by a cylinder (or body limb volume) is dependent on the radius (r) of the cylinder as well as the force per unit width (F/w), or unit tension ($t = F/w$) of the compression stocking [11]. In an active material-based device, unit tension control is achieved by stretching the active material around a semi-static body volume with radius (r), and applying a material-specific stimulus. Upon actuation, the constrained body volume prevents significant dimensional changes, resulting in a blocked force. This generates a transition from inactive force $F(i)$ to active force $F(a)$, producing a corresponding unit tension change ($\Delta t = t(a) - t(i)$). The shift from inactive unit tension $t(i)$ to active unit tension $t(a)$ occurs with minimal or negligible width (w) variation, constrained by physical boundary conditions. This allows for precise control of the generated tension.

D. Literature on Alternative Active Compression Methods

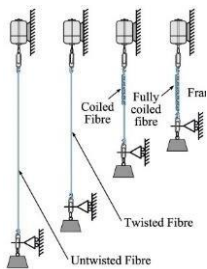
Active compression has become a focus of research in compression therapy (CT) for developing advanced compression garments. Unlike conventional compression textiles that apply static pressure, recent efforts have explored integrating smart materials (e.g., shape memory polymers, phase-changing polymers), pneumatic actuators [7], and piezoelectric substances to achieve active, controllable

compression. These can be produced in tourniquet (band) and knit (large areas) forms. This study aims to design and develop a soft, textile-based wearable compression sleeve of increased mobility with an actuation mechanism to have controllable pressure levels for athletes involved in intense workouts to support the recovery. Published research indicates wire-based mechanism to achieve variable pressure levels where compression is controlled by bidirectional driving tendons. This is a lightweight mechanism where the design is also more compact. However, a few limitations are a slow response to required force generation and difficulty of wearing in different places of the body because of the comparatively large-scale actuation mechanism [12].

II. MATERIALS AND METHODS

A. Material Selection and Development of the Actuator

Nylon Fishing Lines (STERN, USA, Fabrique aux E-U) were selected as the actuation material. The negative thermal expansion of the twisted and coiled actuator produced from these fishing lines, were utilized to exert repeatable force onto the surface.



The TCPAs were fabricated through a simple four step procedure where the nylon fishing line was twisted, exerting a pre-tension until it is coiled, followed by two oven annealing cycles at 180 °C for 1 hour, stretched 8%-10% and 30%-40% of its initial coil length respectively, and a relaxation phase at room temperature.

Fig. 1. Twisted and coiled actuator fabrication

Two heating methods were employed to actuate the TCPAs. In *Method 1*, hot air from a conventional hair dryer (Travel Dryer 1400, Remington, China) was used to heat the actuator to approximately 60°C-75°C, with surface temperature monitored using a thermal imaging camera (Fluke Ti400 IR Fusion Technology, USA). *Method 2* utilized a conductive element, specifically a thin enamel-coated copper wire, wrapped around the actuator. Furthermore, carbon yarns (22dtex 4-ply) were integrated into the coils and tested for generating joule heat. The average surface temperature during this process was measured using a thermocouple (FLUKE 52II Thermometer, USA).

B. Knit Structure Development

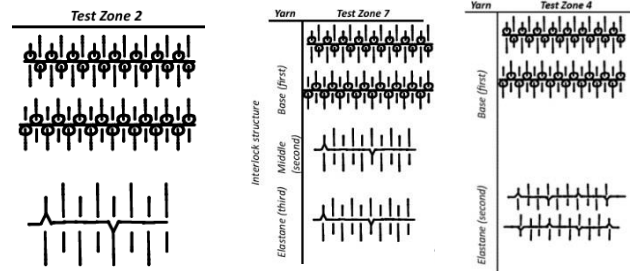
Test zone 2: The structure was fabricated using nylon 66 filament yarn (150 dtex, 31.1% elongation, 40.6 cN/tex tenacity) and Creora spandex elastane yarn (140 denier). Elastane yarn and nylon yarns were individually fed into the knitting process to control fabric stretch. The elastane yarn is integrated into the structure by making tuck loops to the base structure. First, the integration of elastane yarn was done by making three welt/ miss distances. (Shima Seiki NSVR 123 14-gauge/122 10-guage)

Test Zone 7: Nylon was added as an inlay yarn to the base structure. The plan involved using an additional yarn, with either similar or different properties, as an intermediate yarn in the existing interlock structure to create tuck loops within

a specified repeat length. Integrating such yarn was able to control overall structure stretchability as additional yarn can lock or tighten the structure by making interlacing.

Test zone 4: Then elastane yarn binds to same wale front and back beds by making tucks to front and back loops in the simultaneous course using two elastane yarns. The machine settings were kept constant, with a stitch length of 25, take-down tension of 30-35 kg, and low machine speed. Standard tension was applied using both top and side tensioning devices.

Fig. 2. Structural Notations of the Knit Zones



To integrate the actuator, which requires a temperature of 70-80°C for actuation, a tubular structure was knitted between zones to ensure user safety and minimize heat transfer to the skin. This structure creates a dedicated space for the actuator, reducing its thermal impact. The confined tunnel environment (2-3 loop size) restricts the coil's movement, allowing displacement only in the horizontal plane.

Four pressure sensors were positioned on a single horizontal plane around the circumference of a Perspex tube. The fabric sleeve was inserted into the Perspex tube, bringing the sensors into direct contact with the fabric surface. The surface pressure measurement was used to measure the pressure values of each test zones. (AMI Techno Co. LTD. surface pressure measurement)

III. RESULTS AND DISCUSSION

TABLE I. HEAT ACTUATION RESULTS WITH CARBON YARN

| Coil No. | Initial coil length (cm) | Load (N) | Length with load L (cm) | Contraction (cm) | Length Change ΔL (mm) | $\Delta L/L$ (%) | Surface Temperature (°C) |
|----------|--------------------------|----------|-------------------------|------------------|-------------------------------|------------------|--------------------------|
| A(e)-1 | 8.7 | 3 | 13.5 | 13.2 | 3 | 2.22 | 70 |

Integrating an element within the TCPA was found to impact the actuator's performance, as the incorporated carbon yarn appeared to influence the annealing process and restrict the TCPA's movement when heat was applied.

Five sample coils were developed, trained, and tested for actuation and was able to obtain a maximum contraction of 1 cm. and each of them were heated and the average surface temperature was measured as 70-78 °C. A pre-tension was given to the actuator when actuating.

TABLE II. TEST SAMPLES RESULTS

| Coil | Size(Jb) | Pre-load (g) | Initial length (cm) | Length with load (cm) | Max. Contraction (cm) | Avg. Surface Temperature (°C) |
|------|----------|--------------|---------------------|-----------------------|-----------------------|-------------------------------|
| A-1 | 20 | 300 | 15.6 | 17.5 | 0.7 | 77 |
| A-2 | 20 | 300 | 11.6 | 14 | 0.7 | 78 |
| A-3 | 10 | 100 | 14 | 15.5 | 0.7 | 76 |
| A-4 | 20 | 100 | 13.2 | 15 | 1 | 74 |
| A-5 | 20 | 100 | 19.2 | 22.5 | 0.9 | 74 |

A. Zonal Pressure Distribution

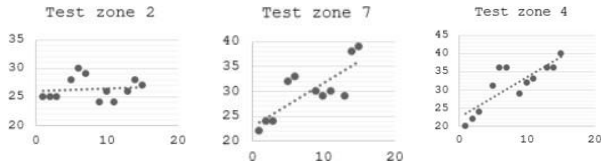


Fig. 3. Pressure distribution in the zones

Test results demonstrated that relying solely on passive compression is insufficient for optimal compression performance. Pressure distribution was inconsistent even within the same horizontal plane. The variability in yarn loop structure complicates the uniform prediction of pressure behavior across the fabric. While sensors 2, 3, and 4 showed consistent pressure readings in test zones, sensor 1, positioned at the sleeve seam, recorded lower pressures, highlighting challenges in maintaining sleeve tension at seams. Calculations using Laplace's equation aimed for a pressure range of 38-56 mmHg for a 19 cm circumference Perspex tube, but experimental values ranged from 25 to 40 mmHg. Despite this discrepancy, the fabric's stretchability indicates that reducing the circumference could achieve the target pressure without affecting wearability. Significant pressure variations between test zones 2 and 7 suggest that adjusting parameters like loop length, yarn count, and elastane content could enhance passive pressure generation. However, active compression remains crucial for maintaining a graduated pressure profile.

B. Prototype Testing

A prototype was developed by inserting a copper wire-wrapped actuator (A-1) into a tunnel within the knit structure, with the ends sewn to form a tube. The pressure was measured using surface pressure testing equipment (AMI Techno Co. LTD). A 3V voltage was applied to the copper wire using a power supply, and the wire's temperature was recorded with a thermocouple (FLUKE 52II Thermometer, USA). The testing, conducted at room temperature, aimed to evaluate the TCPA's capability to generate a controllable pressure component.

TABLE III. PROTOTYPE TEST RESULTS

| Sensor 1 | | Sensor 2 | | Sensor 3 | |
|----------|------|----------|------|----------|------|
| OFF | ON | OFF | ON | OFF | ON |
| 27.6 | 27.6 | 39.6 | 39.7 | 46.5 | 46.5 |
| 27.2 | 27.2 | 39.2 | 39.2 | 45.8 | 45.9 |
| 26.9 | 26.9 | 38.7 | 38.9 | 45.4 | 45.4 |
| 26.7 | 26.7 | 38.5 | 38.7 | 44.9 | 45.1 |
| 26.6 | 26.7 | 38.4 | 38.7 | 43.1 | 43.5 |

Under general conditions, the AMI reading dropped but when actuated constant readings were observed and after a few seconds some readings increased by +0.2 / +0.3. And when the voltage supply was disconnected, the readings began to drop again. And this was repeated five times and similar behavior was observed. The maximum contraction observed was 0.7 cm. If the contraction can be improved, there is a possibility that the pressure value can be increased by a significant value. The results showed that the pressure can be controlled. The average temperature of the copper wire was measured as 72 0C-750

-0C. 3.03 A current and 3V voltage was supplied. After the wire reached its maximum temperature, the surface temperature of the sleeve was 39.5°C. Textiles itself are good thermal insulators as they create a good heating chamber inside the tunnel.

IV. CONCLUSION

This study aims to develop a textile-based compression sleeve with adjustable pressure levels, incorporating both active and passive compression. Knitted structures were designed to adjust applied pressure, considering factors such as yarn types, properties (e.g., count and stretchability), and structural tightness. Additional variables influencing fabric tightness include the knitted structure and machine parameters like gauge, speed, side tension, take-down, and stitch length. Surface pressure measurements indicated that fabric structure significantly impacts applied pressure, with precise control being challenging due to the interplay of factors like yarn type, count, structure, loop length, and elastane content. Determining critical pressure levels and selecting suitable measurement equipment also posed challenges, with sensor variations observed during testing. Increasing fabric rigidity with high-count yarn in test zone 7 reduced stretch, enabling more uniform pressure distribution across zones. Kevlar, tested for pressure reinforcement, faced integration challenges, warranting further research. Factors such as loop length, yarn count, and additional yarns affected fabric stretchability, but overly reducing these parameters limited extensibility and wearability. Balancing these design considerations is crucial, and future research should explore the effects of yarn type, loop length, yarn feeding tension, and modulus on tension distribution to optimize pressure profiles for specific applications.

Nylon fishing lines were selected as the actuation component for their flexibility, affordability, availability, and shape memory properties, with the aim of creating an active compression component using a Nylon twisted coiled actuator (TCPA), also known as artificial muscles. The thermal-responsive TCPA, wrapped in a copper wire and heated via Joule heating, demonstrated limitations in contraction magnitude. Nevertheless, prototype testing yielded promising results, with a controllable pressure increase of +0.2/+0.3 Hgmm. The TCPA showed capability to generate an active pressure component to the passive compression zone, which could be controlled through voltage supply. With further improvements to the contraction ability and the temperature controllability (control systems) it can be able to achieve significant amount of controllable pressure. Furthermore, the pre-tension and stretchability during the TCPA annealing process also impact its contraction capacity. Despite heating the copper wire to 70-75°C, textile insulation properties kept the surface temperature around 40°C, which is safe for skin contact. Further research is needed to enhance the thermal responsiveness and contraction capacity of TCPAs, which could become crucial in soft robotics and wearable technologies, offering significant future potential.

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