

Soft Wearable Robotics: Innovative Knitting-Integrated Approaches for Pneumatic Actuators Design

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ABSTRACT

Soft wearable robotics presents an opportunity to bridge robotics and textiles, offering lightweight, flexible, and ergonomic solutions for human-robot interaction, but previous studies on wearable soft robotics primarily focus on actuator performance without also considering wearability and interactivity. A rudimentary attachment method is usually adopted using external fixation devices such as straps to attach actuators to the user's body, resulting in a poor wearing experience. This study focus on compatible and compact textile architectures to support actuators to be seamlessly integrated into daily wearing. It presents a research-through-design method to propose innovative knitting-integrated approaches for pneumatic actuator design to provide soft wearable robots with both aesthetic and functional values. Through a series of tests in which various knitting techniques and parameters are used to create sleeves that house silicone actuators, it explores design possibilities and understands the complex relationships between textiles and actuators. The findings contribute to advancing soft wearable robotics by offering practical solutions for integrating pneumatic actuators seamlessly into wearable textiles, thereby unlocking new possibilities for human-centered robotic systems.

CCS CONCEPTS

• **Hardware → Analysis and design of emerging devices and systems**; • **Human-centered computing → Haptic devices**.

KEYWORDS

Soft wearable robotics, Knitting, Pneumatic actuator, Human-robot interaction, Research-through-design

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1 INTRODUCTION

Soft robotics is a subfield of robotics that focuses on creating robots with flexible and compliant structures inspired by biological systems [7]. It involves assembling pliable materials into a flexible body, integrating actuators, sensors, a control system, a power source, and often an external structure for support and protection of the components. Rehabilitative, therapeutic, assistive, and haptics interactions provided by soft robotics can intensively work on the human's body, thus bridging the wearability and interactivity. By leveraging coordinated sensing, actuation, and computation, soft wearable robotics is regarded as an effective system for human-robot interaction, improved durability, and increased user comfort.

Previous research has established design considerations related to human wearability of soft robotics include safety, stability, comfort, and portability [7]. Most previous work has adopted a rudimentary strategy to attach the robotic device onto the wearer's body by using bulky straps/tubes/straps, making interactivity and wearability poor. Miniaturization and seamless integration of soft robotics components into wearable forms represent a critical gap, necessitating investigations into how these elements can cohesively function within garments or accessories. The development methods of lightweight and powerful actuators needs to become a research priority [6]. Therefore, the integration of textile structures should be considered as an essential part of soft wearable robotics [4]. This work explores and discusses innovative integration approaches of knit structure and pneumatic actuators to bridge identified gaps.

2 THE STUDY PHASES

The exploration of soft wearable robotics from the intersection angle between human-computer interaciont (HCI) and Fashion Textile Design is a broad topic. Starting from a specific viewpoint of the potentials of knit structures within soft robotics, this paper presents insights and progress based on the exploration of innovative practices for designing knit-integrated pneumatic actuators. This study is divided into three phases, each of which applies different research methodologies: (1) carrying out a large-scale literature review to establish a systematic theoretical basis, sort previous design cases and identify the research gaps (2) conduct an experiment to test how different knitting techniques can be effectively integrated into pneumatic actuators design; and (3) developing the full functions of pneumatic actuators with a control system to achieve more accurate interaction between humans and soft wearable robots. Phases one and two have been completed and is progressing to phase three according to the previous outcomes.

This paper primarily discuss the second phase where we adopt Research through Design (RtD) as the principal methodology. Within

this framework, the iterative prototyping method is employed to develop textile-integrated pneumatic actuators for soft wearable robotic systems. The full research study will encompass both quantitative and qualitative methodologies. However, this paper only uses a qualitative research method to facilitate observational, evaluative, and iterative improvements to the study outcomes.

3 PREVIOUS WORK

Pneumatic actuators, a class of devices that use compressed air to create motion, have shown significant potential in soft wearable robotics applications due to their low response time and relatively high output power density [3]. Compared to traditional electromechanical actuators which are heavy, bulky, and rigid, pneumatic actuators made with soft materials are lightweight, low-cost, and easily mass-produced [1]. Some textile techniques such as embroidery have already been explored to assist in the fabrication of pneumatic actuators [2].

Even though, textiles represent a favourable material platform for wearable robots due to their flexibility, low weight, breathability, and soft hand feel [5], relevant studies seldom discuss the underlying design principles between wearable textile architecture and actuators. Soft wearable robotics is a type of mechatronic system integrating multiple subsystems where a large number of actuators and complex structural layouts are required to achieve multi-joint assistance. So if the subcomponents are not optimized accordingly, the overall performance, interaction and communication efficiency will be compromised. The integration of knitting and actuators provides an opportunity to solve the problems of soft robot functionality and wearability via compatible and compact textile architectures.

4 METHODOLOGY

To investigate the efficacy of the knitting-integrated pneumatic actuators, a series of actuators were fabricated. First, we used silicone molding to fabricate pneumatic actuators as experimental subjects. Second, we fabricated a range of knit sleeves to house the silicone actuators integrated with different knitting techniques and varying parameters such as stitch density and knitting tension. Each actuator connected with a manual air pump was then inflated to qualitatively evaluate its mechanical properties and compare bending stiffness, shape-changing and relationships between actuators and knitting structure. The experiment was conducted using the air intake volume of a single squeeze of the air pump so that the changes brought about by different knitted structures and actuators can be compared under a relatively fixed inflation effect.

The primary purpose of this study is to evaluate the feasibility of textile-integrated pneumatic actuators and to identify initial design principles and main challenges of knitted pneumatic actuators. The vast tunability and ubiquity of textiles has enabled soft wearable robotic with capabilities, and the knitting technique is selected for this study because of its flexibility, stretchability, seamless construction and higher customization attribute compared to weaving techniques. Based on the two tubular knitting techniques and the two different shapes of silicone actuators, a total of eight prototypes in four comparison experimental groups were designed. The overall experimental process and the comparison group were photographed and recorded in Table 1.

4.1 Materials

Two different mold designs for forming the soft actuators were 3D printed with PLA and cast with Ecoflex™ 00-10 silicone gel. As the study is currently in the early stages, a manual air pump was chosen because of its accessibility and ease of operation.

For the knit sleeves, Super Stretch yarns made up of 81% nylon and 19% elastane were used. A gauge 7 Dubied double bed knitting machine (7 needles per inch) was used and all the test samples were knitted to a standard size with a width of 110 112 rows and a fixed height of 75 needles. Tubular stitch was selected due to its "tube" shape at the edge, creating enough volume and tension to wrap the actuators inside the double layers of knits. Two types of tubular stitch techniques were employed: the full needle and drop stitch. The main difference between these two knitting techniques is the arrangement of stitches, which enables us to customize the density and layout of the needles according to the actuator's shape and volumes.

5 RESULTS AND DISCUSSION

5.1 General Impact of Knit Structure

Silicone soft actuators often encounter uneven silicone thickness between actuator airbags with the same specifications. This sometimes results in uneven inflation of the airbags, causing some airbags to be overly inflated while others to have ineffective inflation. Generally, the knitting structure plays a role as a protective layer with a restraining force for the pneumatic actuator, which weakens the deformation effect of the actuator to a certain extent and evens the inflation effect among airbags. As shown in Figure 1, the spherical ridges on the surface of the actuator will become less obvious when wrapped in a full-needle-knitted structure. With the uniform pressure intensively wrapped from outside of the actuators, the risk of individual airbags bursting due to over-inflation is reduced.

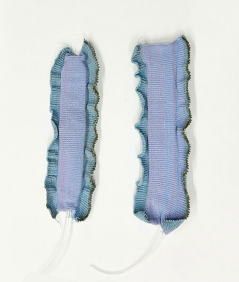
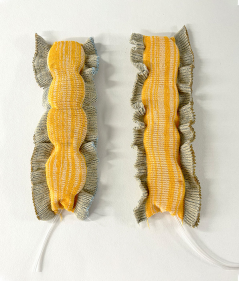
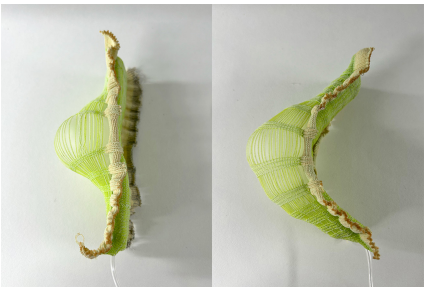
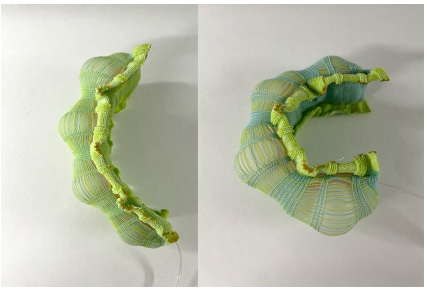


Figure 1: Actuators with and without knit layer.

5.2 Knit Tension

The experiment tested each knit-integrated actuator with varying yarn tension to investigate its impact on inflation effect. The results suggest that the restricting pressure provided to the actuators is directly proportional to the tension of the yarn. Due to the double-layered structure of tubular knitting techniques, it is important to consider the tension of both knit layers and the tension gap between them for optimal actuator performance. It is worth noting that on

Table 1: Experimental Parameters

Tubular Stitch Type	Silicone Actuator *(not inflated)*	Knit-Integrated Actuators *(not inflated)*	Knit-Integrated Actuators *(inflated)*
Full needle			
Full needle			
Drop needle			
Drop needle			

the bulging side of the pneumatic actuator, a looser tension helps reduce the pressure on the knitting layer and is conducive to the larger deformation of the airbag. On the other side of the actuator, the tighter tension can provide additional contraction force to the actuator, allowing it to increase the deformation effect. In Figure 2, the actuator on the left of each group uses the same tension of 10 on both sides, while the actuator on the right in each group uses a tension of 15-20 on the front and 7-8 on the back. This creates a difference in elasticity between the two layers of knitting and it proves that when the tension difference of the double-layer knitting is larger, it will produce significant deformation of the actuator, and vice versa.

5.3 Knit Structures and Needle Layout

The results show that by adjusting the arrangement of different needle numbers and layouts with the tubular knitting technique, the knitted structures can be employed to better fit and highlight the actuator's inflation effect. As shown in Figure 3, the samples



Figure 2: Actuator performance under different fabric tensions. The left pair of actuators uses the same tension of 10 on both sides, while the actuators on the right uses a tension of 15-20 on the front and 7-8 on the back.

with the drop-needle technique better utilize the pressure provided by the knit structure to help the actuator achieve the expected deformation and functionality. The full-needle knitting technique cannot provide an adjustable knitted structure for the fabric and is more suitable to help the actuator even out its inflation effect rather than highlight its unique inflation characteristics. The results also suggests it is important to note that the drop-needle needle arrangement corresponded with the airbag density of the soft actuator, as shown in Figure 4. This helped the knitted structure and the actuator to collaborate more intensively and effectively.



Figure 3: The same actuator with full-needle (left) and drop-needle (right) knit wrapping layer.

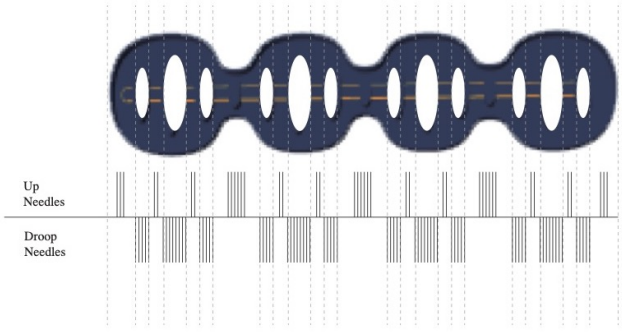


Figure 4: One of the silicone mold designs (above) and the drop-needle layout diagram (below).

6 CONCLUSION AND FUTURE WORK

Soft wearable robotics is not only an extension of traditional robotic research applied to the surface of the human body, but also a new technological paradigm of multidisciplinary integration and innovation. This study used a research-through-design approach to explore innovative knit-integrated pneumatic actuators to bridge robotics and textiles, offering lightweight, flexible, and ergonomic solutions for human-robot interaction. By conducting a series of explorations based on design prototype experiments, it contributes interdisciplinary creative methods to solve this research problem and accumulates certain experimental data to enhance the wearability of pneumatic actuators for soft robots.

In the current study phase, limitations mainly come from the experimental design and data collection approaches. From the perspective of the experiment design, more knitting techniques with different yarn properties should be considered and tested to provide insights into the integration strategies between textiles and actuators. Creative design thinking is supposed to apply to the knitting design variations, such as manual crochet seen in Figure 5, to offer more playful, diverse, and valuable integration attempts. Quantitative research methods will be used further to evaluate the accurate mechanical relationship and performance of knitted-structured pneumatic actuators. The manual air pump is also required to be replaced by the mechanical air pump to precisely control the experiment variables.

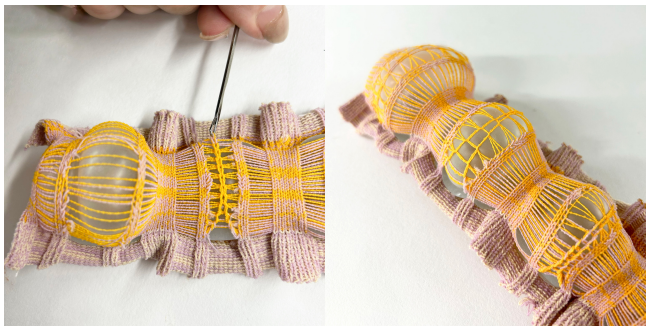


Figure 5: Additional textile manipulations of crochet design applied to the knit sleeve.

Following the completion of phase two of this study, we will next turn to the development of pneumatic actuators with a digitally-controlled system to achieve accurate interaction. The design outcomes can be integrated into a variety of assistive wearable devices, such as rehabilitation equipment, haptic suits for the visually impaired, or gaming suits to create an immersive experience. Further research will focus not only on the development of actuators' mechanical properties but also on improving the user experience. The research is expected to enhance haptic interaction between humans and robots, bursting into a huge potential in medical, entertainment, education and other application scenarios. Ultimately, the development of soft wearable robotics aligns to create inclusive technology that addresses diverse user needs and promotes social equality with a focus on usability, accessibility, and expanding the way that humans communicate in futuristic scenarios.

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