

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**TEXTILE-BASED SOFT ROBOTICS
FOR ACTIVE ASSISTANCE AND REHABILITATION**



Ph.D. THESIS

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Department of Textile Engineering

Textile Engineering Programme

JULY 2024

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**AKTİF DESTEK VE REHABİLİTASYON İÇİN
TEKSTİL TABANLI YUMUŞAK ROBOTİKLER**

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To Everyone Who Likes Science,



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ABBREVIATIONS

AFO	: Ankle Foot Orthosis
CNTs	: Carbon Nanotubes
DEAs	: Dielectric Elastomer Actuators
DIW	: Direct Ink Writing
DLP	: Digital Light Processing
DLW	: Digital Light Writing
DOF	: Degree of Freedom
FDM	: Fused Deposition Modeling
FEA	: Finite Element Analysis
IJP	: Inkjet Printing
IR	: Infrared
LCEs	: Liquid Crystal Elastomers
LCNs	: Liquid Crystal Polymer Networks
ML	: Machine Learning
NIR	: Near Infrared
PAMs	: Pneumatic Artificial Muscles
PNIPA	: Poly(n-isopropylacrylamide)
PU	: Polyurethane
PVDF	: Polyvinylidene fluoride
SH	: Self-healing
SLM	: Selective Laser Melting
SLS	: Selective Laser Sintering
SMPs	: Shape Memory Polymers
SWR	: Soft Wearable Robot
TPU	: Thermoplastic Polyurethanes



SYMBOLS

A₀	: Cross-sectional area
C	: Capacitance
ε₀	: Free space permittivity
ε_r	: Realitive permittivity
F	: Force
L	: Length
min	: Minutes
R	: Resistance
S	: Area of the conductive plates
t	: Time
ρ	: Electric resistivity
wt	: Weight
δ	: Distance between the conductive plates
τ	: Torque



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TEXTILE-BASED SOFT ROBOTICS FOR ACTIVE ASSISTANCE AND REHABILITATION

SUMMARY

Recent advancements in the field of robotics have proven that soft robots can be used as wearable supports for neuromuscular disorders due to their compliance and ability to imitate complex motions. Soft pouch motors, which are designed to mimic the natural movements of skeletal muscles, are critical to the advancement of robotics and exoskeleton technology. However, fabrication techniques frequently involve multiple stages; they lack soft sensing capabilities and are susceptible to cutting and damage. Previous research showed that elastomeric, i.e. silicone, soft pneumatic actuators have a great potential to create soft-wearable robotic devices for these applications. Nevertheless, it takes time to manufacture these types of actuators due to long preparation times. Although silicone-based materials have favorable properties, such as heat, chemical resistance, and the capacity to conform to different range motions, they do present challenges in terms of material density, stiffness, and strength.

This thesis describes a new type of textile-based pouch motor that can perform biaxial actuation and capacitive sensory functions. It is made possible by using computerized knitting technology with ultra-high molecular weight polyethylene yarn (Spectra®) and conductive silver yarn. This method allows for the rapid and scalable mass production of robust pouch motors. At 50 kPa pressure, the resulting pouch motors have a maximum lifting capacity of ten kilograms, a maximum contraction of 53.3% along the y-axis, and a transverse extension of 41.18% along the x-axis. The design and functionality of these pouch motors have been validated by Finite Element Analysis (FEA), which closely matches the experimental data. Applications requiring robotic control could benefit from the capacitance signals in relation to contraction motion, which are well-suited for detecting air pressure levels.

A practical demonstration of the potential of these pouch motors is showcased through the development of a soft ankle exosuit designed to provide lifting support for individuals with foot drop, a condition that impairs the ability to lift the front part of the foot. The exosuit effectively elevates an ankle joint simulator to a 20-degree angle. Moreover, the application of approximately 35 degrees of dorsiflexion torque to a human foot has been successfully achieved under a pressure of 50 kPa, highlighting its potential in assisting with mobility challenges. This study underscores the importance of incorporating both actuation and sensing capabilities in soft robotic systems, which can significantly enhance functionality and user experience. This work not only advances the field of soft robotics but also offers a solution for improving the quality of life for individuals with impaired muscle function. Through the integration of robust, scalable fabrication techniques and advanced materials, this research paves the way for the next generation of assistive devices, promising greater independence and mobility for users.

The most challenging aspect of this work was to provide dorsiflexion movement to the foot through a textile-based actuator. Therefore, numerous preliminary studies and methods were attempted to achieve this goal. These preliminary studies evaluated actuators that generated insufficient force for lifting the foot and were applied in exoskeleton-assisted glove applications for the hand. These studies were included in the “Previous Works” section of the thesis.

Moreover, healthy individuals naturally perform the gait phases of “heel strike,” “stance,” “heel off,” and “swing” during walking. When the swing phase begins, the ankle dorsiflexes, lifting the toes off the ground to ensure the continuity of the walking cycle, which starts with the heel strike. During the preliminary studies, a novel interdigital capacitive textile sensor was developed using knitting technology to analyze gait through human knee movements. The details of this study are included in the “Previous Works” section. However, controlling the robotic system using this sensor proved to be complex. Therefore, a simpler method was implemented: a textile-based presence/absence sensor placed on the heel. This approach simplified the control system, making it more manageable.



AKTİF DESTEK VE REHABİLİTASYON İÇİN TEKSTİL TABANLI YUMUŞAK ROBOTİKLER

ÖZET

İnsan vücudundaki iskelet kasları, günlük hayatımızda gerçekleştirdiğimiz çok çeşitli hareketlerin dinamik güç kaynaklarıdır. Bu kaslar, bir bardak tutmak gibi basit işlerden, yürüme ve spor yapma gibi daha karmaşık ve fiziksel olarak zorlayıcı aktivitelere kadar her türlü hareketi mümkün kılmaktadır. İskelet kasları, vücudun hareket mekanizmasında merkezi bir rol oynar ve bu nedenle günlük yaşamımızdaki hemen her faaliyetin temelidir. Ancak, yaralanmalar, travmalar veya belirli nöromüsküler bozukluklar nedeniyle bu kaslar işlevlerini kaybedebilmektedir. Bu tür bir kas kaybı, etkilenen bireylerin günlük yaşamında birçok zorluğa yol açar ve bağımsız hareket yeteneklerini ciddi şekilde kısıtlayabilmektedir. Kas fonksiyonundaki bozulmalar, bireylerin fiziksel aktivitelerini yerine getirme yeteneklerini kaybetmelerine, sosyal etkileşimlerinde kısıtlamalar yaşamasına ve genel yaşam kalitelerinin düşmesine neden olabilmektedir.

Bu zorluklarla başa çıkmak için, bireylerin bağımsızlıklarını yeniden kazanmalarına ve yaşam kalitelerini artırmalarına yardımcı olmayı amaçlayan yumuşak robotik sistemler geliştirilmiştir. Yumuşak robotik sistemler, geleneksel sert robotik sistemlerden farklı olarak, daha yumuşak, esnek ve kullanıcı dostu yapıları sayesinde insan vücuduna daha uyumlu bir şekilde entegre olabilmektedir. Bu sistemler, kas benzeri kasılma hareketlerini taklit eden yumuşak torba motor yapıları kullanarak, kas fonksiyonu bozulmuş bireylere önemli ölçüde yardım sağlama potansiyeline sahiptir. Yumuşak torba motorlar, doğal kaslarda gözlemlenen hareketi ve işlevi taklit etme konusundaki yetenekleri sayesinde özel bir aktüatör sınıfı olarak ortaya çıkmıştır. Bu tür sistemler, kasların doğal hareketini taklit ederek, kullanıcılara daha doğal ve rahat bir hareket deneyimi sunmaktadır. Ancak, bu sistemlerin mevcut üretim teknikleri genellikle çok aşamalı süreçler içerir, yumuşak algılama yeteneklerinden yoksundur, kesilme ve hasara karşı hassasiyet gösterir. Bu sorunlar, yumuşak robotik sistemlerin geniş çapta kullanılabilirliğini ve dayanıklılığını sınırlamaktadır.

Yumuşak torba motorlarının üretimi genellikle film ve tekstil malzemelere dayanmaktadır. Film malzemeler, esnek olmalarına rağmen, mekanik dayanıklılıkları düşüktür. Bu, uzun süreli veya yoğun kullanımda deformasyon veya yırtılma eğilimlerini artırmaktadır. Ayrıca, polimer film malzemeler esneklik sunsa da, giyilebilir cihazlar için gereken konfor seviyesini karşılamamaktadır. Uzun süreli kullanım için konfor ve esneklik hayati öneme sahiptir ve polimer film aktüatörler bu kriterleri karşılamakta yetersiz kalabilmektedir. Ayrıca, polimer film aktüatörlerinin estetik uyumu ve giyilebilir cihazlarla uyumluluğu sınırlı olabilmektedir. Bu faktörler göz önüne alındığında, polimer film aktüatörler genellikle giyilebilir teknoloji uygulamaları için çok fazla tercih edilmemektedir. Bunun yerine, tekstil gibi alternatif malzemeler; üstün konfor, esneklik ve entegrasyon yetenekleri sunarak giyilebilir cihaz tasarımı için daha uygun hale gelmektedir. Tekstiller; liflerden ipliklere, ipliklerden kumaşlara kadar uzanan hiyerarşik yapılarıyla, aktüatör geliştirme için çok yönlü bir platform sunmaktadır. Kumaş bazlı aktüatör literatürü, ağırlıklı olarak lazer

kesim ve termal yapıştırma üretim yöntemleriyle ticari olarak temin edilebilen Termoplastik Poliüretan (TPU) kaplamalı dokuma kumaşlardan üretilen aktüatörlere odaklanmaktadır ve bu aktüatörler genellikle gömülü sensörlerden yoksundur. Dokuma kumaşlar, örme kumaşlara kıyasla daha az esnektir. Bu nedenle, torba motor aktüatörlerinin hareket aralığını kısıtlar ve karmaşık hareketleri gerçekleştirme yeteneklerini engelleyebilmektedir. Ayrıca, dokuma torba motorlarının üretim süreci, kitlesel üretim için daha yavaştır. Dokuma malzemelerin birleştirilmesi, özellikle büyük ölçekte, ek yöntemler veya ekipman gerektirdiğinden, bu durum üretim süresini ve maliyetlerini artırır, ayrıca üretim sürecini karmaşıklştırabilir.

Bu çalışmada, ultra yüksek moleküler ağırlıklı polietilen iplik (Spectra®) ve iletken gümüş ipliklerin bilgisayarlı örme teknolojisiyle torba motorlarının tasarımı ve üretimi gerçekleştirilmiştir. Spectra ipliği, yumuşak torba motorlarının üretiminde temel malzeme olarak kullanılmış ve böylece kesilmeye karşı dayanıklılık gibi yüksek performans özellikleri torba motoruna aktarılmıştır. Bilgisayarlı örme teknolojisiyle üretilen torba motor aktüatörü, iki eksenli hareket ve kapasitif algılama işlevlerine sahiptir. Bu teknoloji, torba motorlarının hızlı ve ölçeklenebilir kitlesel üretimini sağlamaktadır. Ayak düşüklüğü uygulamasında kullanılması hedeflendiğinden torba motorunun boyutları, ayak genişliği, ayak ve ayak bileği bağlantı noktalarına göre optimize edilmiştir. Algılama özelliği kazandırmak için torba motorunun üretim sürecinde, iletken iplikler torba motorunun yapısına örülmüştür. Bu entegrasyon, elektrotların torba motorunun örülü yapısına sorunsuz bir şekilde gömülmesini sağlayarak, etkili elektrik iletkenliği ve işlevsellik kazandırılmıştır. Gömülü sensör, harici olarak bağlanan sensörlere kıyasla daha kararlıdır, bu da torba motorunun çalışması sırasında tutarlı ve güvenilir veri toplanmasını sağlamıştır. Örme teknolojisi kullanılarak sensörün torba motoruna gömülü halde üretim yaklaşımı, ek yapıştırıcılar veya ısı pres işlemlerine gerek duymadığı için dayanıklılığı ve uzun ömürlülüğü arttırmıştır. 12.85 gram olan torba motoru hafif tasarımıyla, kullanım kolaylığı sağlayarak yumuşak robotik uygulamaların genel ağırlığını etkili bir şekilde azaltmıştır. İzotonik (sabit yük) ve izometrik (sabit uzunluk) olarak adlandırılan aktüasyon testlerine tabi tutulmuştur. Üretilen torba motorları, 10 kilogramlık maksimum kaldırma kapasitesine, y eksenini boyunca %53,3'lük maksimum kasılma oranına ve 50 kPa basınçta x eksenini boyunca %41,18'lik enine uzamaya sahiptir. Sensör basınç duyarlılığı $722 \times 10^{-4} \text{ kPa}^{-1}$ 'dır.

Sonlu Elemanlar Analizi (FEA), torba motorlarının tasarım ve performansını doğrularak deneysel verileri %4 hata payıyla açıklamaktadır. Bu da, tasarımın ve teorik modellerin gerçeğe ne kadar uygun olduğunu göstermiştir. FEA, mühendislik tasarımlarının performansını ve güvenilirliğini değerlendirmek için kullanılan güçlü bir araçtır ve bu çalışmada, torba motorlarının gerçek dünya koşullarında nasıl çalışacağını anlamamıza yardımcı olmuştur. Ayrıca, kasılma hareketi ile ilişkili kapasitans sensörü sinyalleri, hava basıncı seviyelerini algılamak için uygun olup, robotik kontrol gerektiren uygulamalar için umut vaat etmektedir.

Bu kese motorlarının potansiyelinin pratik bir gösterimi, ayağın ön kısmını kaldırma yeteneğini bozan bir durum olan ayak düşüklüğü olan bireylere destek sağlamak üzere tasarlanmış yumuşak bir ayak bileği dış kıyafeti (exosuit) geliştirilmesiyle sergilenmiştir. Exosuit, bir ayak bileği eklem simülatörünü 20 derece bir açıya etkili bir şekilde yükseltmiştir. Ayrıca, insan ayağına yaklaşık 35 derece dorsifleksiyon torku uygulanması 50 kPa basınç altında başarılı bir şekilde gerçekleştirilmiştir, bu da mobilite zorluklarına yardımcı olma potansiyelini vurgulamaktadır. Bu çalışma, yumuşak robotik sistemlere hem hareket hem de algılama yeteneklerinin dahil

edilmesinin önemini vurgulamaktadır, bu da işlevselliği ve kullanıcı deneyimini önemli ölçüde artırabilmektedir. Bu çalışma, yumuşak robotik alanını ilerletmekle kalmayıp, aynı zamanda kas fonksiyonu bozulmuş bireylerin yaşam kalitesini iyileştirmek için bir çözüm sunmaktadır. Sağlam, ölçeklenebilir üretim teknikleri ve ileri malzemelerin entegrasyonu ile bu araştırma, daha fazla bağımsızlık ve hareketlilik vaat eden bir sonraki nesil yardımcı cihazların yolunu açmaktadır.

Bu tezin en zorlu yanı, tekstil bazlı bir aktüatör aracılığıyla ayağa dorsifleksiyon hareketinin sağlanmasıydı. Bu nedenle bunu başarmak için çok sayıda ön çalışma ve yöntem denenmiştir. Bu ön çalışmalarda ayağı kaldırmak için yetersiz kuvvet üreten aktüatörler değerlendirilmiş ve el için dış iskelet destekli eldiven uygulamalarında kullanılmıştır. Bu çalışmalar tezin “Önceki Çalışmalar” bölümünde yer almaktadır.

Ayrıca, sağlıklı bireyler doğal olarak yürüme sırasında “topuk vuruşu”, “duruş”, “topuk kalkışı” ve “salınım” yürüme evrelerini gerçekleştirmektedirler. Salınım yürüme evresi başladığında, ayak bileği dorsifleksiyon yaparak parmakları yerden kaldırır ve topuk vuruşuyla başlayan yürüme döngüsünün devamlılığını sağlamaktadır. Ön çalışmalar sırasında, insan diz hareketlerinden yürüme analizinin yapılabilmesi için örme teknolojisi kullanılarak yeni bir interdiijital kapasitif tekstil sensör geliştirilmiştir. Bu çalışmanın detayları tezin “Önceki Çalışmalar” bölümünde yer almaktadır. Ancak, bu sensörü kullanarak robotik sistemi kontrol etmek karmaşık hale gelmiştir. Bu nedenle, daha basit bir yöntem uygulanmıştır: topuğa yerleştirilen tekstil tabanlı varlık/yokluk sensörü. Bu yaklaşım, kontrol sistemini basitleştirerek daha yönetilebilir hale getirmiştir.

1. INTRODUCTION

Foot drop is an insufficiency in the voluntary control of the foot/ankle due to central, traumatic, or neuropathic causes. The inability to perform ankle dorsiflexion during the swing phase of walking prevents the foot from lifting off the ground, disrupting the walking pattern and increasing the risk of stumbling and falling. Foot drop occurs as a result of upper motor neuron diseases, which impair the central nervous system's control over the foot/ankle, or due to damage to the lower motor neurons and peripheral nerves. It has been reported that the incidence of foot drop in patients with upper motor neuron pathology ranges from 52-67% (Westhout et al., 2006). According to the World Health Organization, 15 million people suffer a stroke each year. Stroke results in death for 5 million people and causes permanent disability in nearly 5 million others. It has been reported that foot drop becomes a permanent complication in 14% of stroke patients (Carolus et al., 2019). After stroke, upper motor neuron diseases such as Multiple Sclerosis (MS) and Cerebral Palsy are the most common etiological causes of foot drop development. According to the Turkish Neurology Society, there are approximately 40,000 MS patients in Turkey (Turkish Neurology Society, 2018). Among MS patients, 31% experience walking problems, with foot drop being the most prevalent issue (Taylor PN et al., 2016).

In examining the medical market for foot drop pathology, various systems are used, each with its advantages and disadvantages. When analyzing Ankle Foot Orthosis (AFO) systems, it is noted that:

- Off-the-shelf AFOs may not fully conform to the individual's deformity and foot structure,
- Prefabricated products often require revisions and modifications,
- Custom-made AFOs depend on the expertise and experience of the orthotic technician,
- Patient-related comorbid issues,
- Material limitations,

- The need for periodic replacement of the AFO, The possibility of the AFO breaking or deforming during use,
- Limited footwear options,
- AFOs being visible under clothing, raising aesthetic concerns,
- Mechanical limitations affecting patient comfort during daily activities (Klundig, 2013).

When evaluating wearable soft AFO systems, it is observed that:

- They are biomechanically inadequate,
- They pose aesthetic concerns and comfort issues.

For external FES systems:

- They are only used for upper motor neuron lesions,
- The high cost and lack of local production of neuroprostheses,
- Contraindications such as pacemaker use, epilepsy, pregnancy, etc.,
- Complicated usage leading to issues in application,
- Skin irritation and changes in skin resistance during the day,
- Problems with electrode contact at the appropriate motor point,
- The necessity for technical support are reported disadvantages (Ozdemir, 2007; Bucklitsch, 2019).

Implantable FES systems:

- Limited to experimental applications,
- Require surgery and pose complication risks as disadvantages.

Soft robotic structures have been effectively used in assisting the treatment of neuromuscular diseases for the past 30 years. Given their flexibility, softness, and compatibility with the body, these structures offer a unique platform for developing wearable assistive devices. Unlike rigid counterparts, they are made using flexible and deformable components. Due to their high deformability and flexibility, they can perform highly complex movements. Their ability to conform to curved and irregular surfaces eliminates the disadvantages of rigid robots and provides a more compatible

system for human interactions (Majidi, 2014). Soft actuators are the main components of soft robotic systems responsible for generating such movements (Whitesides, 2018). Soft pouch motors (contractile actuators) have emerged as a notable class of actuators due to their ability to mimic the contraction function observed in natural muscles. These actuators are made using flexible materials that exhibit contraction and expansion properties when exposed to various external stimuli such as fluid pressure (Wirekoh et al., 2019), electrical stimulation, thermal changes (Sanchez et al., 2020), and chemical reactions. Another prominent feature of soft pouch motors is their high power-to-weight ratio, making them highly suitable for applications requiring lifting and high force generation. The combination of high power output and low weight enables these actuators to efficiently and effectively perform lifting movements (Zhang et al., 2019). These characteristics allow soft pouch motors to provide precise and adaptable movement responses by conforming to various conditions and requirements. However, developing scalable and mass-producible soft pouch motors with integrated sensing capabilities remains a challenge in the field of soft robotics. Automating robot production from design to assembly is crucial for reducing prototype costs and increasing scalability for mass production. Additionally, developing cost-effective, efficient, and high-quality mass production methods is necessary to meet increasing demand. Innovative approaches such as integrating sensors directly into the motor structure or designing external sensing systems have been explored to a limited extent. Particularly, using more robust materials is needed to enhance the durability and reliability of these motors in applications.

1.1 Purpose of Thesis

In this work, the design and validation of a novel biaxial soft pouch motors for foot drop assistance is presented, inspired by the contraction behavior of the human muscle. This study investigates the potential of utilizing textile knitting technology and high-performance Spectra yarn for the development of soft pouch motors with sensing capabilities. Knitting technology provides a seamless, fast, scalable, and mass-production fabrication approach, instead of relying on the assembly of individual parts. The ability of the pouch motor to perform contraction motion, driven by radial expansion and transversal extension, has been thoroughly examined. Addressing the need for improved sensing capabilities and scalable mass production methods is

crucial to unlocking the potential of soft pouch motors. It will not only expand their utility but also drive innovation in areas where their unique characteristics can make a difference. This soft pouch motor's practical use in helping people with mobility challenges is further highlighted by the fact that it is employed as an exoskeleton robot for people with foot drop syndrome.

1.2 Hypothesis

This thesis proposal is built upon three hypotheses:

- I. Pouch motors actuator with embedded sensors based on textile materials can be produced utilizing the knitting technology fabrication method.
- II. A textile knit-based pouch motors can provide the required force to lift the lower foot.
- III. Sensor data obtained from pouch motors can be utilized in establishing a feedback control mechanism for the soft robotic structure.

2. LITERATURE REVIEW

2. 1 Soft Robotic Materials

Robotics involves the development of machines equipped with specific capabilities in movement, perception, and cognition. Robots, in turn, are designed to carry out tasks for the benefit of human beings (Laschi, 2016). Conventional rigid robots are made of high-stiffness materials like steel, which require traditional mechanical machining tools to manufacture (Wang & Chortos, 2022). Traditional robots, with their rigid bodies and pre-programmed routines, often struggle in dynamic environments. This is where soft robots, a burgeoning field in robotics, step onto the scene with their unique capabilities. Soft robotics are continuum robots composed of soft materials that generate motion by creating a smooth backbone curve through continuous elastic deformation. Figure 2.1 illustrates the spectrum of soft robots, ranging from stiff structures with selective compliance on the left to entirely soft structures on the right.

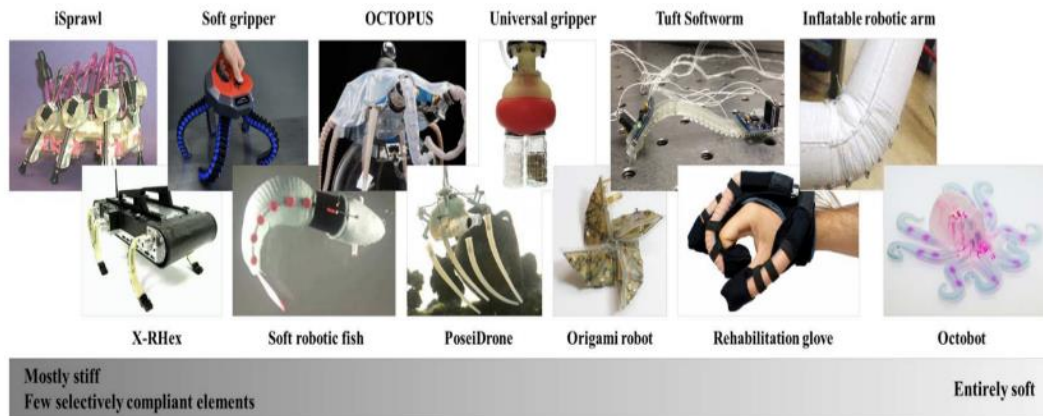


Figure 2.1: Spectrum of Soft Robots: from stiff structures with selective compliance on the left to entirely soft structures on the right (Laschi, 2016).

There are several ways to design softness: soft movement, elastic materials, soft texture, soft and deformable materials, and softness in natural and friendly interactions with people (Laschi, 2016). Unlike their rigid counterparts, soft robots are built for adaptability and resilience. Composed of easily deformable yet mechanically robust

materials (Rus & Tolley, 2015; Seok et al., 2013), they seamlessly conform to their surroundings, making them inherently safe for interaction with humans (Majidi, 2014). This attribute, coupled with the potential for cost-effective manufacturing, further strengthens their appeal (Rus & Tolley, 2015). Inspired by the marvels of nature, the design philosophy behind soft robots prioritizes versatility and multi-functionality (Kim et al., 2013). Figure 2.2 compares the properties of rigid and soft robots, emphasizing their distinct mechanical characteristics and potential applications (Fu et al. 2022). Unlike traditional robots, confined to pre-defined tasks within controlled environments, soft robots boast a higher degree of freedom (DOF) thanks to materials that mimic the elasticity of biological systems (Rus, 2015; Majidi, 2019). This not only allows for safe and adaptable interaction with their surroundings but also empowers them to react swiftly to unforeseen changes. As a result, soft robotics stands at the forefront of a new era in machine intelligence, ushering in the development of physically intelligent robots.

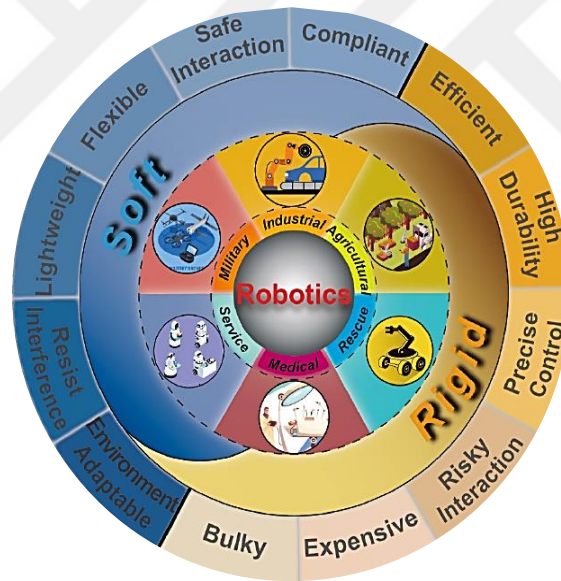


Figure 2.2: Comparison of rigid and soft robotic properties (Fu et al. 2022).

The core structure of a soft robot primarily consists of intrinsically soft or extensible materials, such as silicone, and polymers. These materials possess the ability to deform and absorb energy during collisions, mirroring the elastic and rheological properties found in soft biological matter. This characteristic enables the soft robot to remain operational even when subjected to stretching and squeezing. Additionally, soft robots exhibit a continuously deforming structure with numerous degrees of freedom (DOFs), offering unprecedented adaptability, sensitivity, and agility. Given their scarcity of

rigid materials and resemblance to natural organisms, soft robots can be classified within the broader fields of soft matter engineering or biologically inspired engineering (Lin et al., 2023).

The modulus of elasticity, also known as Young's modulus, is a quantity that scales with the force to percent elongation of a prismatic bar, or uniform cross section bar, when it is stretched along its principal axis (Fig. 2.3a). This is one way to quantify the stiffness of a material. Since Young's modulus is only defined for homogenous, prismatic bars that experience small deformations ($<0.2\%$ elongation for metals) and axial loading, it is not very applicable to soft robots or other soft-matter technologies that experience large elastic or inelastic deformations and have irregular (nonprismatic) shapes. However, Young's modulus remains a valuable metric for assessing the stiffness of materials utilized in soft robotics. As depicted in Figure 2.3b, the majority of traditional robots are constructed from materials like metals and rigid plastics, boasting a modulus exceeding $10^9 \text{ Pa} = 10^9 \text{ N/m}^2$. Conversely, materials found in natural organisms, such as skin and muscle tissue, typically exhibit a modulus ranging from 10^2 to 10^6 Pa . In essence, materials in natural organisms are 3–10 orders of magnitude less rigid than those employed in conventional robots. This significant difference in mechanical compliance is a key factor contributing to the biological incompatibility of rigid robots, making them potentially unsafe for close human interaction and limiting their ability to showcase the diverse multifunctionality and elastic adaptability observed in natural organisms (Majidi, 2014).

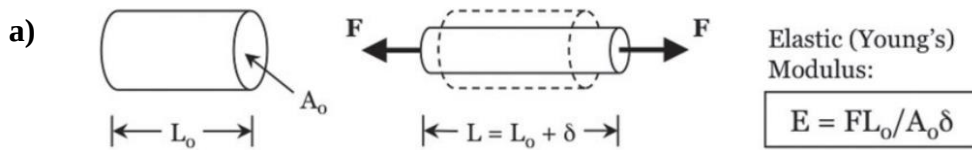


Figure 2.3: (a) The ratio of the force F to the extension d of a prismatic bar with length L_0 and cross-sectional area A_0 determines the elastic (Young's) modulus. (b) Young's modulus of different kinds of materials (Majidi, 2014).

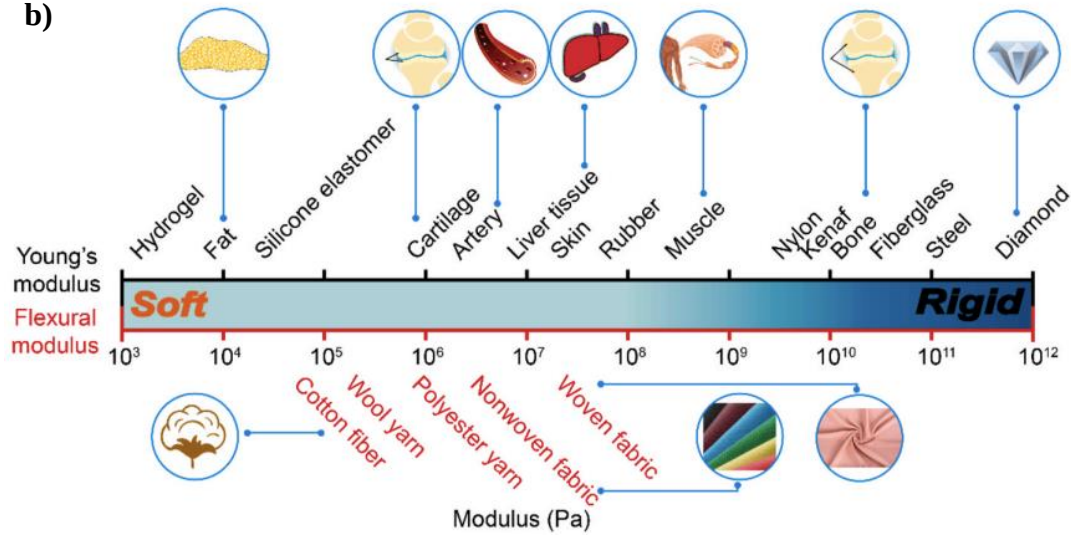


Figure 2.3 (continued): (a) The ratio of the force F to the extension d of a prismatic bar with length L_0 and cross-sectional area A_0 determines the elastic (Young's) modulus. (b) Young's modulus of different kinds of materials (Majidi, 2014).

The effectiveness and capabilities of soft actuators crucially depend on the materials used in their production. A diverse range of materials can be employed for creating soft actuators, with the selection based on specific application requirements such as desired movement or deformation, the energy source, and the operating environment. These materials enable the production of soft actuators characterized by remarkable flexibility, strength, and the ability to generate motion and deformation with minimal energy consumption, all without the need for an external actuator or motor. Elastomers (Marechal et al., 2021), shape memory polymers (SMPs) (Khalid et al., 2022), self-healing polymers, hydrogels, and textiles are among the materials commonly used for soft actuators.

2.1.1 Elastomers

Elastomers, defined as rubbery polymers with high elastic strain limits and mechanical compliance, play a crucial role in soft robotics. Figure 2.4 depicts an elastomer-based soft robotic hand developed by Zhao et al. in 2016. The design leverages the flexibility and deformability of elastomer materials to mimic the movements and functionalities of a human hand. These soft materials, including other polymers and elastomeric composites, often undergo large deformations without permanent damage. A key characteristic of elastomers is their elastic response, meaning they recover their original shape after applied tensile stress is removed. This behavior extends over a wide strain range, making them hyperelastic materials. However, due to their nonlinear

stress response, additional elastic coefficients are needed to fully describe their behavior. Typically, the Young's modulus of elastomers falls between 0.1 and 10 Mpa, with softer polysiloxanes and polyacrylate elastomers reaching as low as 0.1 Mpa related failure.

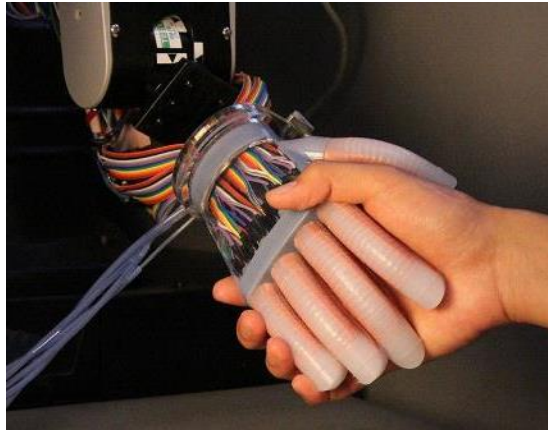


Figure 2.4: Elastomer-based soft robotic hand (Zhao et al., 2016).

The versatility of soft robotic technology benefits from a diverse range of elastomers chosen for their specific properties. Polydimethylsiloxane (PDMS), commonly used for microfluidic channels and robot bodies due to its high strain limit, low modulus, and minimal hysteresis during loading and unloading cycles. Materials like Sylgard 184 (Dow Corning) and Ecoflex 30 (Smooth-On) are lauded for their mechanical robustness and inert nature. Beyond these, polyacrylates like 3M VHB, soft polyurethanes, and block copolymer elastomers offer further options for specific design needs.

Elastomer selection for soft robots demands careful consideration of factors beyond their primary mechanical properties. Stress relaxation, creep, and other forms of inelastic deformation can contribute to energy and hysteresis losses during operation. Understanding these phenomena is crucial for optimizing robot performance and minimizing fatigue.

2.1.2 Shape memory polymers

Soft robots, encompassing various types such as grippers, crawling robots, and other complex configurations, have been successfully developed utilizing adaptable shape memory polymers.

Stimuli-responsive materials are recognized for their intelligence, as they can perceive their environment and generate direct and immediate responses (Zhang et al., 2019). Among polymeric stimuli-responsive materials, shape memory polymers (SMPs) have captivated scientific interest since the 1960s. Notably, γ -ray irradiated polyethylene (PE) has exhibited a memory effect under cycles of low-high temperature conditions (Charlesby et al., 1960). SMPs maintain a permanent shape at room temperature, deform at a high transition temperature (T_{trans}), and preserve the deformed shape upon cooling. Reverting to the permanent shape is achieved through reheating. The versatile shape memory effect has been observed in various polymers, including amorphous polymers (Peponi et al, 2013; Miaudet et al., 2007), semicrystalline polymers (Chung et al., 2008), and liquid crystalline elastomers (LCE). Actuation methods for shape memory involve electricity (Liu et al., 2018), magnetic fields (Razzaq et al., 2014), light, and water (Liu et al., 2014).

Extensive research has been conducted on one-way, two-way, and multiple SMPs. One-way shape memory effects have been identified in conventional crosslinked polymers (Berg et al., 2014), leading to their widespread adoption in commercial applications, such as heat-shrinkable tubes, labels, and toys (Zhao et al., 2015). In advanced applications, one-way self-deployable hinges (Liu et al., 2014) and smart surgery devices (Lendlein et al., 2010) have been successfully developed. Two-way SMPs, or reversible SMPs, autonomously deform at high temperatures and revert at low temperatures, enabling them to transition between two desired shapes. The mechanism involves the directional rearrangement of the molecular chain as temperature changes, utilized in the development of various LCEs (Yu et al., 2018) and semicrystalline polymers (Chung et al., 2008; Li et al., 2011). Future advancements may see two-way SMPs replace shape memory alloys, offering improved mechanical properties and shape memory performance. Additionally, polymers capable of memorizing multiple temporary shapes, referred to as multiple SMPs, could serve as copolymers with diverse T_{trans} values (Kolesov et al., 2008). This multiple-shape memory effect allows the polymer to switch between a set of shapes through a relevant programming process.

The necessity to ascertain whether the shape programming process is essential for identifying a polymer as an SMP arises. Shape memory programming, the initial step in a shape memory cycle, determines the polymer's transforming pathway. The

programming process involves shape deformation, fixing, and evacuation of external stress. Prior to programming, polymers must undergo deformation under external stress accompanied by heating. Elevated temperatures increase polymer entropy, reduce energy barriers, and facilitate molecular chain movement, enhancing the polymer's manipulability. Following deformation into a temporary shape, the polymer is fixed by decreasing temperature and external stress, involving physical and chemical changes that restrict polymer molecular chain movement. Subsequently, the temporary shape is obtained after cooling, remaining unchanged as external stress is withdrawn. The temporary shape can endure for an extended period without external stimulus. Stress and energy stored in the polymer during programming, along with increasing entropy, render the temporary shape less stable than the original shape. Upon exposure to a suitable external stimulus, internal stress and energy are released, restoring molecular chain mobility, and the polymer returns to its original shape after stimulation (Lendlein et al., 2019). The repeatable nature of the programming process allows SMPs to possess various temporary shapes while maintaining a single permanent shape. Importantly, the programming process is not contingent on material synthesis but is recognized as posttreatment to define the material's shape recovery path. A polymer capable of altering its shape under specific stimuli without the shape-programming process is considered a shape-changing polymer rather than an SMP. For instance, hydrogels comprising poly(*n*-isopropyl acrylamide) (PNIPA) can swell and deswell in water under temperature changes, primarily influenced by the physical nature of PNIPA hydrogel rather than shape programming; thus, these hydrogels cannot be classified as SMPs (Xia et al., 2021).

2.1.3 Self-healing polymers

In the realm of robotics, the application of soft materials, while offering numerous advantages, also introduces challenges, particularly concerning damage resistance. The intrinsic flexibility of synthetic materials renders soft robots susceptible to various damaging modes. The soft components, being highly vulnerable, can experience cuts, tears, and perforations from sharp objects encountered in uncontrolled and unpredictable environments, significantly limiting their overall lifespan. Employing tendon mechanisms for actuation introduces another challenge, as rigid tendons, often composed of polyamine or Kevlar wires, can gradually cut through the soft components due to abrasive damage resulting from repetitive friction. This cutting

phenomenon may also occur during overloading, causing the tendon to slice through the soft material (Figure 2.5)(Terry et al., 2021; Jeong et al., 2021).

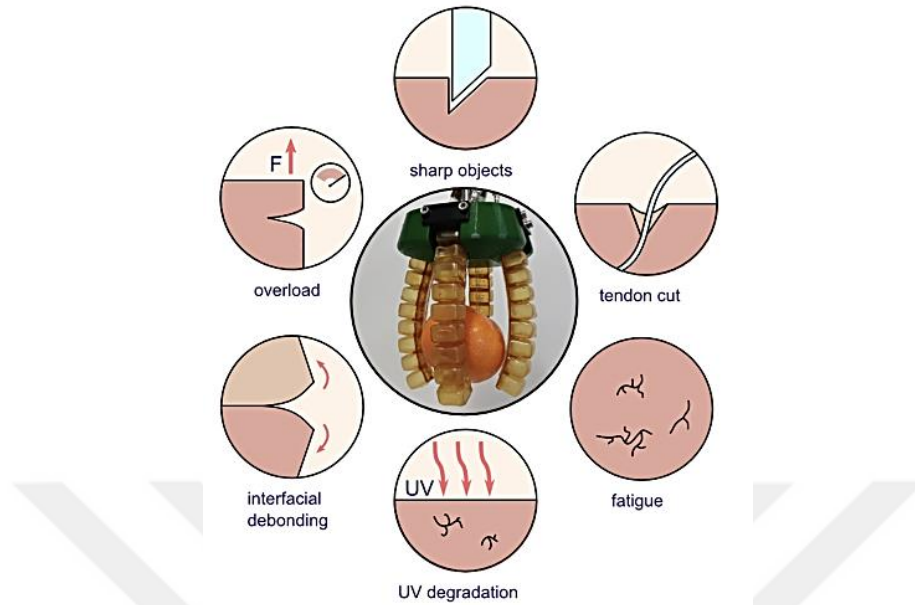


Figure 2.5: Damaging modes of soft robotics in unstructured and dynamic environments (Terry et al., 2021).

A significant portion of a soft robot's body undergoes cyclic deformation during operation, making these components prone to fatigue. Fatigue involves the development of micro damages due to repeated loading, gradually propagating into larger macroscopic damages and, ultimately, component failure. In soft pneumatic actuators, fatigue can lead to leaks, resulting in reduced efficiency, alterations in actuator dynamics, and eventual failure, as observed in the context of soft muscles. Fatigue tends to occur more rapidly and prominently in areas experiencing the highest local stress. Design principles that mitigate stress-strain concentrations can enhance fatigue life, although they may impose limitations on the design flexibility for future soft robotics (Terry et al., 2021; Miron et al., 2016).

When overloading a soft robotic component, induced stresses can exceed the mechanical strength of the elastomer, leading to the rupture of the flexible body of the robot. Ruptures can occur under high force or power output requests, external impact or collision, or when parts unintentionally snag on an object or surface. In pneumatic actuators, air chambers or channels can burst upon excessive pressurizing (Terry et al., 2021).

The production of many soft robots involves molding or casting techniques, often requiring multi-step processes, particularly for manufacturing fluidic actuators where hollow structures need to be produced, and in the case of multi-material designs. However, this multi-step manufacturing introduces weak (multi-) material interfaces in soft robots that rely almost entirely on secondary (physical) interactions rather than covalent bonds. Under extensive loading or multiple actuation cycles, these weak interfaces can fail, leading to interfacial debonding, referred to as delamination. Delamination is problematic in fluidic actuators, causing leaks and reduced performance. In some additive manufacturing techniques for soft robots, like fused filament fabrication, weak interfaces between print layers can cause delamination and failure (Terry et al., 2021).

Moreover, being constructed from organic materials, soft robots are susceptible to photodegradation when exposed to UV radiation. While not extensively reported in robotics papers, UV degradation of silicones or polyurethanes can affect the properties of soft robots over time (Terry et al., 2021).

The human body, composed largely of soft tissue prone to injury, possesses a healing ability that addresses small wounds, scratches, cuts in the skin, and even larger injuries like torn muscles or broken bones. To compensate for the fragility of soft robots, there is potential in developing soft robotic components from synthetic materials with biomimetic healing abilities. Inspired by the powerful biological healing function, chemists over the last 20 years have incorporated similar functions into synthetic materials, leading to the development of self-healing (SH) polymers (Terry et al., 2021; Islam et al. 2023).

Figure 2.6 showcases a self-healing soft gripper (Terry et al. 2021). The self-healing capability is particularly advantageous in applications involving unpredictable or harsh environments, enhancing the durability and resilience of soft grippers.

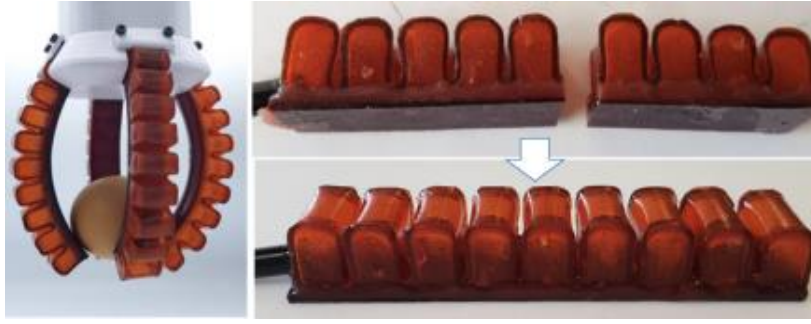


Figure 2.6: Self-healing soft gripper (Terryn et al., 2021).

2.1.4 Hydrogels

Hydrogels, consisting of water and hydrophilic polymer chains arranged in a network structure, exhibit unique properties that make them highly promising for applications in soft robotics. Cross-linked polymer chains impart a three-dimensional elastic solidity to hydrogels, allowing them to endure mechanical strain of up to $\sim 1,000\%$. The elastic modulus of hydrogels, ranging from $1-10^2$ kPa, positions them as softer than many other compliant materials, primarily due to the substantial volume fraction of water. A crucial aspect of their application in soft robotics is their biocompatibility, contingent on the use of non-toxic polymers in the polymer network. This feature enables hydrogels to expand the scope of biological applications in the field of soft robotics. The transparency of hydrogels, reaching up to $\sim 99\%$, even in the bulk state, stems from the negligible absorption of visible light by the polymer network. This high degree of transparency facilitates the transmission of optical information through hydrogels. Moreover, hydrogels exhibit responsiveness to diverse external stimuli through interactions between the polymer network and water, thereby enhancing the functionality of soft robots. Additionally, the presence of mobile ions dissolved in the water endows hydrogels with ionic conductivity of up to ~ 10 S/m. While hydrogels may have higher resistivity than other soft electrical materials, the increase in electrical resistance with strain is significantly lower due to minimal impact on the migration of mobile ions during configuration changes in the polymer network. Consequently, hydrogels can serve as electrodes when a high degree of stretchability is required, as seen in applications for soft robots. Beyond their mechanical and electrical properties, hydrogels offer versatility by accommodating a variety of additives larger than the mesh of the polymer network (Lee et al., 2020). This characteristic allows hydrogels to be equipped with multiple functions, further establishing them as a promising material for soft robots based on their fascinating features.

2.1.5 Textiles

Textiles have emerged as a highly promising material class for the development of wearable robots that seamlessly blend with everyday clothing, providing both movement and comfort. The unique properties of textiles, including flexibility, low weight, breathability, and a soft hand-feel, make them an ideal platform for wearable robots. Their hierarchical nature (Figure 2.7) allows for a unique level of programmability, enabling researchers to modify and tune properties across different material scales.

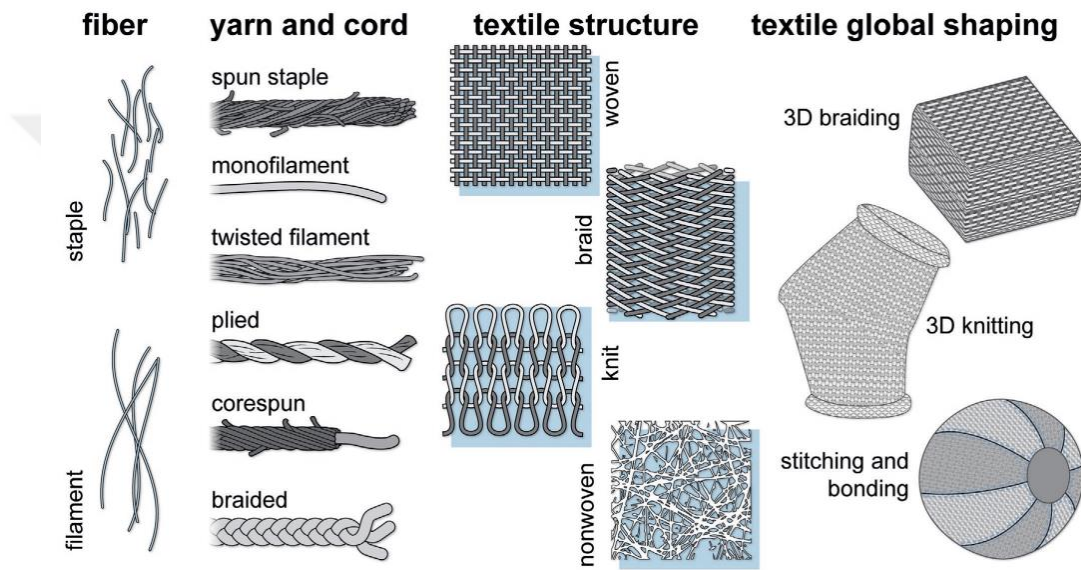


Figure 2.7: Textile structures (Sanchez et al., 2021).

In recent times, roboticists have moved beyond using textiles merely as substrates, incorporating them as functional components that govern actuation and sensing in wearable robots. Simultaneously, materials scientists are exploring new materials that respond to thermal, electrical, and hygroscopic stimuli by leveraging the structures inherent in textiles. Despite being one of the oldest human technologies, the full potential of textiles is only beginning to be realized by materials scientists and roboticists.

The adoption of textiles in wearable robots has gained traction in the field of robotics due to various advantages. When compared to rigid metals, composites, and plastics in wearable robotic exoskeletons, textiles and the garments constructed from them offer lightweight, soft, and flexible solutions, enhancing safety for both the wearer and those in close proximity. Additionally, textiles contribute to garment comfort by

allowing vapor transmission through their porous structures, facilitating evaporative heat flow away from the body. Their robust nature, abrasion resistance, and the ability of individual yarns to move make textiles durable, and they can resist tear propagation. The textile structure, with features like knit loops, enables the transformation of traditionally stiff and inextensible fibers and yarns into stretchable metamaterials. This unique textile architecture allows for the integration of traditionally hard components, such as electronic circuits, into wearable robotic systems, creating flexible and soft systems through geometric design (Sanchez et al., 2021).

2.2 Bioinspiration Designs

The capability of actuators to emulate natural motions and deformations is of significant value, especially in applications requiring precise and accurate movements. Figure 2.8 illustrates that more advanced robots take inspiration from the biological world, mimicking soft animals like worms and octopuses, as well as features from fish tails and fingertips. These biological inspirations offer a rich source of environmental adaptations and physical mechanisms for designers to leverage. The mobility of soft robots is modeled after the shapes and movement patterns of animals adapted to particular environments. Nature, at various scales, provides features that often outperform synthetic alternatives, offering valuable insights for improving designs (Pinskier et al., 2022).

Bioinspired design entails replicating various natural mechanisms into similar artificial counterparts, replacing natural shapes, behaviors, or materials with equivalent artificial versions. This heuristic approach minimizes the necessity for detailed modeling and optimization. Bioinspired designs commonly incorporate both hard and soft materials, reflecting the natural analogy of bones and tissues. Soft-bodied animals, without a rigid skeleton, can maneuver through narrow spaces, adapt to their surroundings, and create motion patterns tailored to specific tasks. Despite this, completely soft-bodied animals may lack the ability to generate high forces for continuous, high speed locomotion, often relying on external support (Pinskier et al., 2022).

The combination of soft and hard materials, seen in both vertebrates and invertebrates, is crucial for achieving relative velocity advantages, supporting locomotion, and providing protection. Soft materials damp impulses and vibrations, improve grip, and

enhance stability in rough terrain. In nature, animals generally range from fully soft to semisoft and semirigid bodies, effectively using a mix of soft and rigid parts to suit their specific niches. (Pinski et al., 2022).

Soft roboticists draw inspiration not only from biomechanics but also from living creatures' material properties. Functional materials, similar to those in geckos or water striders, are instrumental in developing miniature soft robots that mimic natural characteristics. Despite challenges in miniaturization, researchers have made progress in producing wireless insect-scale robots, often relying on external stimuli such as light, sound waves, or magnetic energy (Pinski et al., 2022).

The Table 2.1 in the text, not intended to be exhaustive, showcases various bioinspired soft robot designs, highlighting the extensive inspiration drawn from nature. Nature, with its vast range of animals capable of performing diverse tasks, serves as a valuable source of inspiration for soft roboticists. While designs of nature are not necessarily optimal even within their niches, drawing inspiration simplifies the design process compared to direct task-specific design (Pinski et al., 2022).

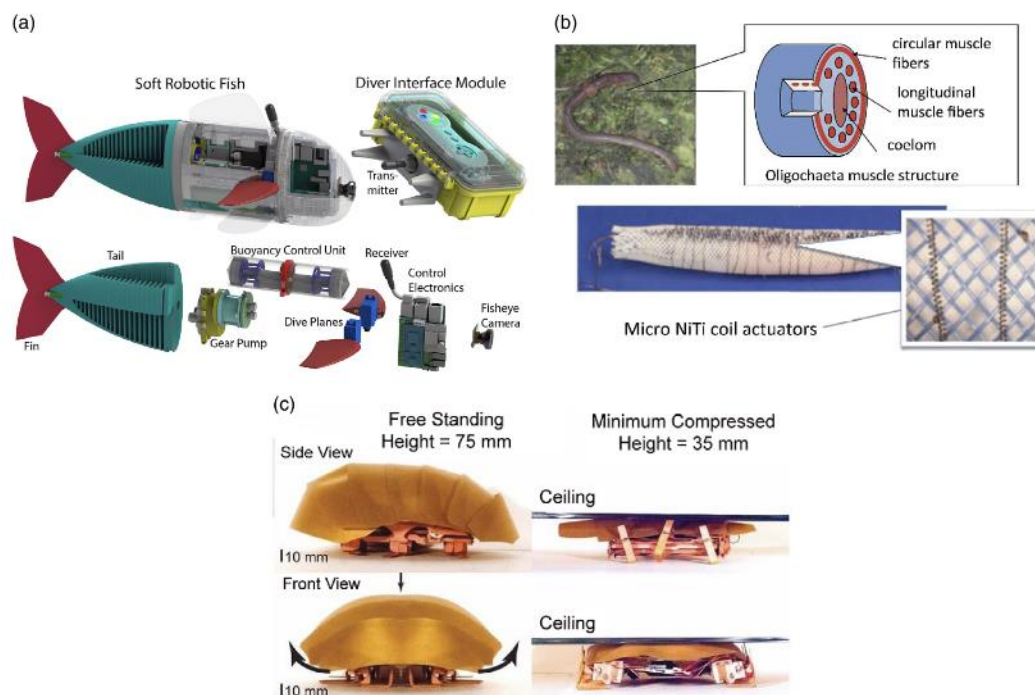


Figure 2.8: Bioinspired soft robots (Pinski et al., 2022).

Table 2.1: Bioinspired soft robot designs (Pinskier et al., 2022).

Animal/Feature	Bioinspiration	Applications	Actuation Principle	Reference
Octopus	Soft body	Soft mobile robots	Fluidic via chemical reaction	(Wehner et al. 2016)
Fish tail	High speed maneuverability of flexible tail	Aquatic mobile robots	Electroactive polymer bending	(Chen et al. 2010)
Fish	Underwater navigation through tail and fin movement	Aquatic mobile robots	Pneumatic bending via synthetic vascular system	(Aubin et al. 2019)
Gecko feet	Passive adhesion caused by directionally compliant microstructures	Climbing mobile robots	Passive adhesion	(Schiller et al. 2019)
Worm	Muscular hydrostatic locomotion through propagating waves	Complex terrain navigation	Braided mesh with radial shape memory alloy	(Seok et al. 2013)
Caterpillar	Ballistic caterpillar rolling dynamics	High-speed mobile locomotion in confined spaces	Longitudinal shape memory alloy	(Lin et al. 2011)
Snake	Climbing locomotion through coiled grasping	Tree climbing	Pneumatic	(Liao et al. 2020)
Turtle	Marine locomotion through flapping flippers	Aquatic locomotion	Shape memory alloy	(Kim et al. 2013)
Jellyfish	Efficient wake based propulsion	Autonomous aquatic surveillance	Shape memory alloy	(Villanueva et al. 2011)
Frog	Synchronous swimming gait	Aquatic locomotion	Shape memory alloy	(Gul et al. 2017)

In the field of soft wearable robots (SWRs), a variety of soft actuators have been developed to address specific support needs and improve targeted movements. Actuator designs in SWRs commonly exhibit patterns such as rotary/bellows, stiffening/extending, tensile/contracting, and bending/curling, as shown in Figure 2.9. These designs are customized to facilitate specific kinds of motion support and deformation approaches. (Thalman & Artemiadis, 2020).

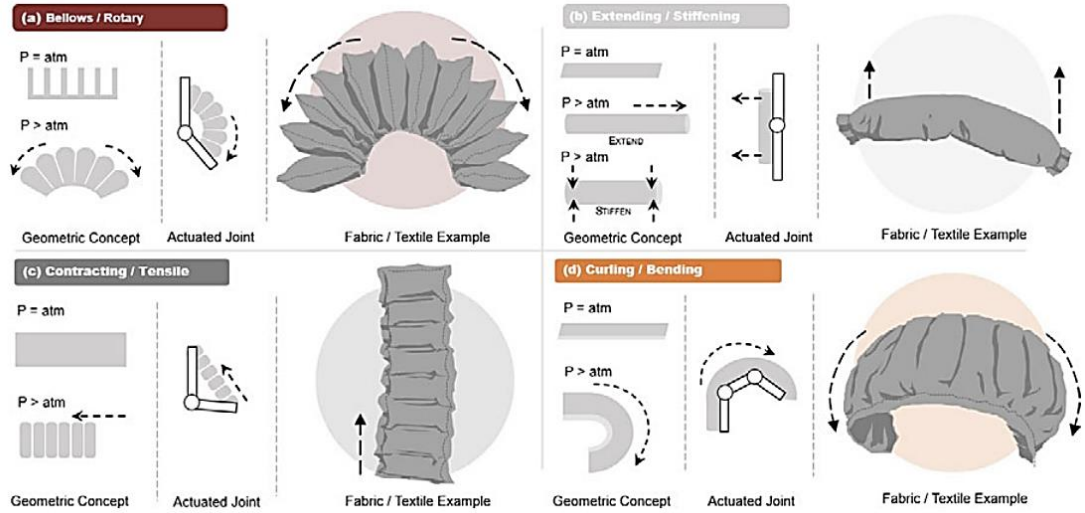


Figure 2.9: Soft actuator actuation motions. (a) Rotary/bellows, (b) stiffening/extending, (c) tensile/contracting (d) bending/curling (Thalman & Artemiadis, 2020).

2.3 Fabrication Methods

Depending on the material and actuator type, different manufacturing processes are employed for soft actuators. Rapid and large-scale production manufacturing technique is crucial in introducing efficient processes for producing soft microfluidic circuits, rigidity-adjustable actuators, and stretchable microelectronics within the field of soft-matter engineering (Majidi, 2013).

2.3.1 Molding

Molding, as a fabrication method, plays a role in shaping soft structures, particularly those crafted from catalyzed polymers like silicone rubbers. This process involves a series of intricate steps, from mixing components to molding operations, each presenting its own set of challenges and innovative solutions (Dong et al., 2022). Figure 2.10 shows various mold designs for fabricating soft robotic grippers.

A considerable amount of soft structures is made from catalyzed polymers like silicone rubbers, which are formed by combining two components before molding. However, the homogenization processes during mixing can introduce air bubbles, potentially weakening the final structure. To address this issue, vacuum degassing is commonly employed to remove bubbles. Additionally, alternative methods such as using

centrifugal forces or strategic vacuum application during injection (vacuum casting) have proven effective (Dong et al., 2022).

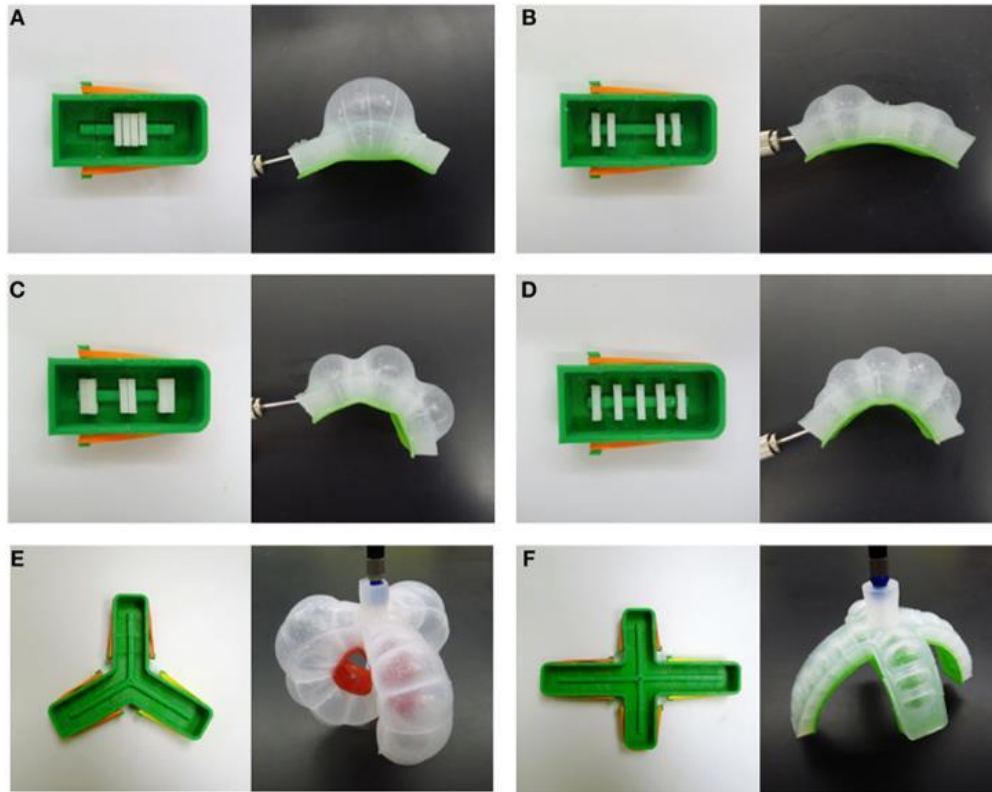


Figure 2.10: Mold designs for soft robotic grippers (Zhang et al., 2017).

When molding thermoplastic materials like paraffin wax, which exhibit high shrinkage, packing pressure during cooling helps to compensate for dimensional inaccuracies. Challenges also arise in multi-step molding, particularly when over-molding components such as actuators or electronics. In such cases, vacuum casting is useful for achieving detailed replication, even at the sub-millimetric scale (Dong et al., 2022).

Manufacturing internal volumes and undercuts in molds can be difficult. Solutions to these challenges include molding in subparts that are then sealed together, adding layers to close internal volumes, and using internal cores that are later removed. For tubular shapes, techniques might involve molding with a removable core, disassembling multipart cores, or utilizing fusible/soluble materials (Dong et al., 2022).

Rotational molding is effective for creating empty internal spaces without a core, while dip coating is suitable for molding internal wall details. Infusion molding, originally

designed for large parts, can also be adapted for smaller soft composites by pulling polymer through fibrous reinforcement (Dong et al., 2022).

Overall, molding methods are diverse, each with its own advantages and limitations. These methods offer various options based on specific requirements, enabling tailored solutions for different soft structure needs.

2.3.2 Bonding

Creating intricate forms with various functional shapes and materials presents a significant challenge in fabrication processes. One effective strategy to address this challenge involves dividing the final system into multiple parts that can be joined later. While numerous solutions are available for bonding rigid components, options become more limited when working with soft materials. This limitation is due to the delicate balance needed at the interface between bonded soft parts, which requires sufficient adhesion without introducing excessive stiffness.

In exploring fabrication methods for soft components, one approach leverages the manufacturing process used for creating soft robotic systems, often involving the curing of polymeric materials. By intentionally slowing the curing process at a specific point, parts can be left in a semi-cured state. These parts exhibit both solid and gel-like properties while retaining their molded shape, facilitating the preparation of the bonding surface. In practice, two distinct soft components can be smoothly joined by applying a thin layer of uncured material, which acts as an adhesive, and then completing the curing process (Marchese et al., 2014). It is important to note that this method is limited to materials that are chemically compatible.

An alternative approach with thermoplastics involves thermal or mechanical fusion. This technique creates pleats or pockets by bonding multiple sheets together through thermal sealing to achieve intricate closed shapes (Niiyama et al., 2014; Nishioka et al., 2017). However, using this method on thicker parts poses challenges due to the poor heat transfer properties of polymers.

Finally, the most prevalent and arguably simplest bonding technique is the use of adhesives. Choosing the right adhesive for a bonding operation can be complex, influenced by various factors such as chemical compatibility, bonding strength, adhesive properties, flexibility, resistance to solvents and temperature, curing duration, viscosity, and the surface texture in contact (Schmitt et al., 2018).

2.3.3 Additive manufacturing

In contrast to traditional subtractive manufacturing methods, such as machining, which involves removing material to shape a workpiece, additive manufacturing (AM) creates the desired shape by locally depositing small amounts of material. This method allows for the fabrication of parts using polymers, elastomers, metals, ceramics, or a combination of two or more materials within a single continuous structure. This versatility supports the integration of electro-conductive materials into mechanical structures, enabling the production of complex parts, including integrated electrical circuits in 2D/3D configurations (Macdonald et al., 2014; Goh et al., 2017). Depending on the method used, components can be produced with dimensions ranging from a few micrometers to several meters. The primary techniques in additive manufacturing involve either the use of powdered substances or the solidification of liquids to achieve the desired shape.

2.3.4 Laser cutting

Laser cutting, as a fabrication method, involves the precise removal of material through the use of lasers, offering unique advantages over traditional cutting techniques. This method is particularly notable for its exceptional precision, high resolution, and minimal wear and tear compared to conventional blade cutting. To optimize the results, various variables need careful tuning (Dezaki et al., 2023; Choudhury et al., 2010).

A key benefit of laser cutting is its ability to work with a wide variety of materials, such as metals and polymers. This versatility makes it a valuable technique in the manufacturing of intricate structures, such as origami and kirigami smart structures or actuators. The precision afforded by laser cutting contributes to the creation of complex and detailed designs with fine edges (Dezaki et al., 2023; Ling et al., 2020).

However, it's essential to note that, like other subtractive manufacturing methods, laser cutting has limitations. One notable constraint is the difficulty in effectively combining a variety of materials in a single fabrication process. Despite this limitation, laser cutting remains a widely used technique for achieving precision in subtractive manufacturing (Dezaki et al., 2023).

2.3.5 Soft lithography

Lithography techniques are employed in the fabrication of various soft robotic structures, with methods like photolithography, ion beam lithography, and electron beam lithography being particularly notable (Acikgöz et al., 2011). These techniques offer versatile applications, including the development of multiresponsive soft actuators. In photolithography, a light-sensitive polymer is illuminated through a patterned mask to form the intended geometric pattern. The resolution, which can reach hundreds of nanometers, depends on the wavelength and optics of the light used. Ion beam and electron beam lithography achieve even higher resolutions (30–50 nm) by irradiating sensitive materials with electrons or ions, without the need for a photomask. Photolithography has been crucial in producing complex three-layer constructs and self-folding tubes with specific geometries for cell adhesion. Although suitable for creating thin films, this method—while capable of producing multilayer structures with various polymers—requires expensive equipment. In photolithography, materials that are cross-linked and either permanently set or removed without using half-tone methods are commonly used. A significant advancement in 2D photolithography involves projecting structured illumination onto dry polymer films, which are photo-cross-linked with the aid of a digital mirror device system. This technique enables the creation of shape-shifting structures, allowing for modifications over time and generating lateral gradients in swelling properties for a range of shape alterations. For photolithography, photosensitive materials are essential, with a preference for photo-cross-linkable active polymers due to their ability to eliminate the need for photoresists, thereby simplifying the manufacturing process (Dezaki et al., 2023; Stroganov et al., 2018; Na et al., 2015).

2.3.6 3D/4D printing

3D printing stands as a groundbreaking and novel technique, revolutionizing the fabrication of highly personalized and multi-material devices, notably soft actuators endowed with exceptional design flexibility and spatial resolution. This technological leap not only unlocks novel possibilities for soft actuators but also harbors the potential to fundamentally reshape the landscape of manufacturing smart Soft-Structured Assemblies (SSAs). In contrast to prevalent conventional production methodologies

in the industry, 3D printing offers enhanced affordability and expedited production timelines (Dezaki et al., 2023).

The limitations inherent in traditional 3D printing become apparent when striving to manufacture soft actuators capable of dynamic shape changes. To tackle this challenge, the emergence of 4D printing has added the dimension of time to the 3D spatial realm, meeting the need for soft actuators that undergo dynamic changes (Dezaki et al., 2023).

External sources of energy, such as heat, UV radiation, pH, or others, serve as the primary initiators for inducing the morphological changes in dynamic products. Reversibility is an additional feature of 4D printing, alongside its capability for one-way transformations. The correct stimulus-responsive materials capable of reacting to both internal and external stimuli is used in order to create intricate and reversible 4D-printed structures. Internal stimuli, such as pH and humidity, contrast with external stimuli like electric fields, light, sound waves, and magnetic fields. Because they can react to stimuli and assume different shape possibilities, smart materials are valuable in many different applications. Recently, 4D printing technology has gained significant popularity in the creation of both micro and macro-scale soft robotics for a range of engineering purposes (Dezaki et al., 2023).

4D printing is an emerging technology that uses advanced materials and 3D printing techniques to create soft actuators. Not all 3D printing methods (Figure 2.11) are utilized for 3D/4D printing. However, several methods are commonly employed, including fused deposition modeling (FDM), direct ink writing (DIW), and stereolithography (SLA). Other techniques used include inkjet printing (IJP), selective laser sintering (SLS), and digital light processing (DLP). Additionally, selective laser melting (SLM), sound printing, and direct laser writing (DLW) are also applied in 3D/4D printing (Dezaki et al., 2023).

SLA and DLP use light-based technology to initiate the photo-polymerization of photo-sensitive materials through UV light sources and laser beams. They are perfect for producing soft actuators because of their fast speed and excellent printing resolution. While DLP creates patterns with an optical mirror to ensure excellent printability, SLA uses photochemical processing to cross-link photosensitive materials to produce extremely precise printed components. Although these methods are not as

precise as lithography methods, projection micro-SLA, a modified version of SLA, is a great way to create multi-material structures like grippers, actuators, and flowers because of its high resolution. Using a virtual photomask and a projector, this technique triggers photopolymerization to create complex soft actuators in various materials and dimensions (Dezaki et al., 2023).

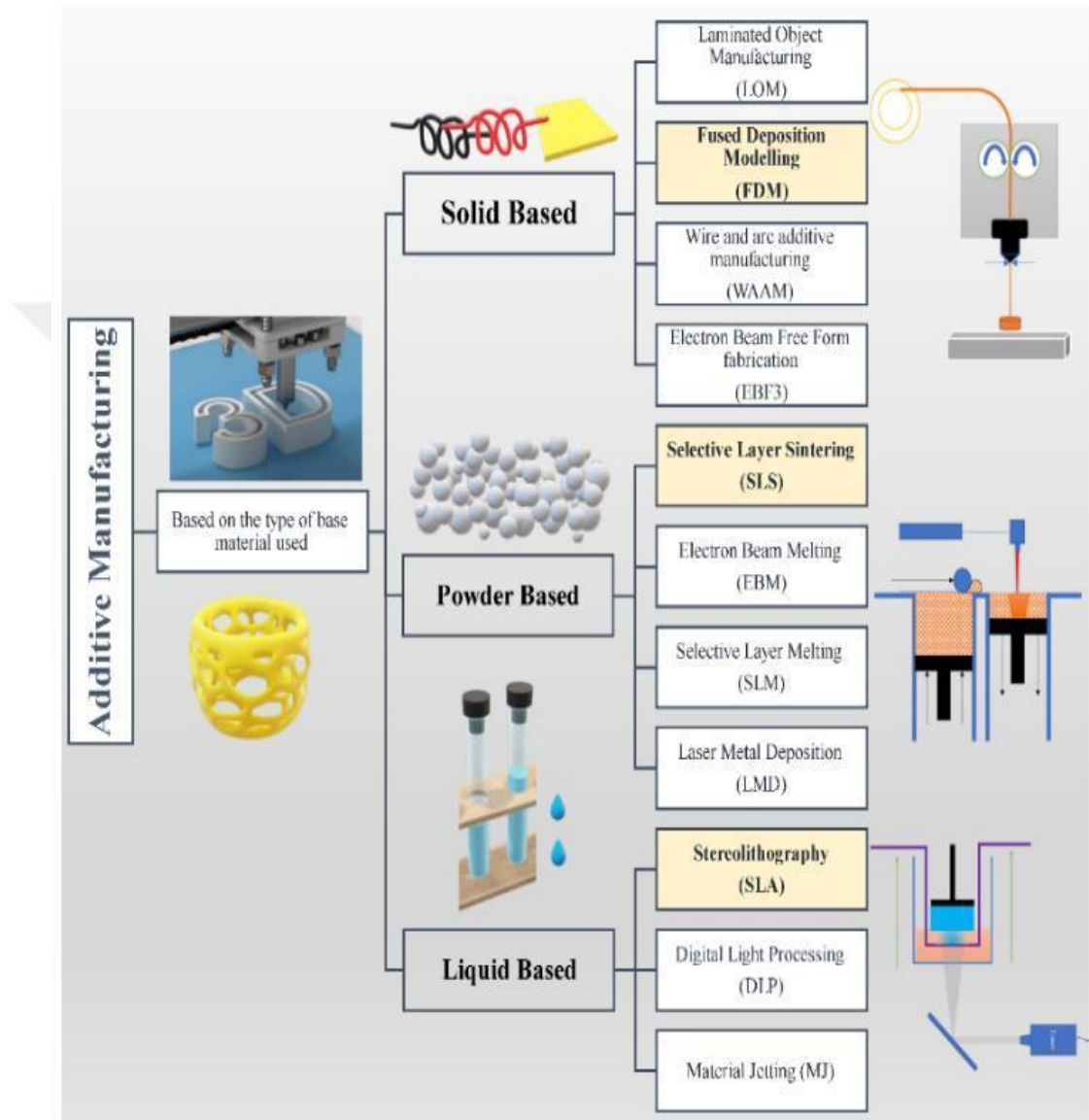


Figure 2.11: 3D printing methods (Kafle et al., 2021).

Among the various available techniques, FDM stands out as the most widely employed, primarily due to its practicality. This method involves applying material onto a surface, which is then solidified to form the final structure. The nozzle moves in the X and Y directions via a motor, while the Z-axis handles the incremental addition of printed layers as the nozzle rises. This iterative process continues until the final

structure is formed. The central component in this type of printing is the 3D printer liquefier. The extruder consists of two sections: one is the cold end, and the other is the hot end. The cold end of the extruder, regulated by a stepper motor, controls the feed rate and draws material from the spool using gears or rollers. This material is then pushed into the hot end, which includes a nozzle and a heating chamber. In the heating chamber, the material is melted. The melted plastic is extruded through the nozzle, which ranges from 0.3 mm to 1.0 mm in diameter, onto the printing surface. The choice of nozzle diameter and heating method depends on the type of material being used. FDM finds frequent application in 4D printing due to its affordability and straightforward maintenance. Ongoing research aims to enhance its efficiency and compatibility with emerging materials. FDM also exhibits the capability to easily produce self-folding and self-coiling metamaterials. Technological progress has enabled the integration of innovative materials into the printing process (Dezaki et al., 2023).

The IJP method, also known as material jetting, creates 3D structures by depositing ink onto a surface through tiny nozzles. Specific requirements regarding the chemical structure of inks, like surface tension, must be met. This technique is particularly advantageous for the development of flexible electronics, optoelectronic components, microfluidic systems, and microrobots. The IJP technique can handle a variety of materials, including less viscous ones, broadening its applicability. It has the ability to print with nanoparticles that remain undissolved, such as metal oxides, ceramics, and organic substances. This technique is highly valued in microfabrication for its accuracy and cost-effectiveness. In polyjet printing, photopolymer ink droplets are sprayed directly onto a printer bed and then solidify, a method frequently employed for producing advanced materials. Presently, polyjet printing is utilized to produce 4D-printed objects responsive to heat. A key benefit of this technique is its capability to print with different materials at the same time by utilizing multiple printheads.

1.1 Similar to FDM, the DIW printing technique uses different viscoelastic ink formulations to build 3D structures by applying high pressure. In this process, a fine nozzle extrudes the viscoelastic ink, which is then deposited in layers. The ability of this technique to accurately control print structures and inks at both meso and microscales is highly regarded. The two main variables that influence printing accuracy and resolution are printing speed and nozzle size. Because of its one-step

creation of multi-material structures, production time, energy consumption, waste, and cost are all reduced while material qualities are preserved. DIW holds promise for 4D printing as well, enabling the development of intelligent materials capable of morphing according to external conditions. Because the three-axis platform, dispenser, and compute are all inexpensive and interchangeable, DIW is a very flexible production method. Recently, DIW has emerged as a reliable method for producing various soft actuators and smart devices. Furthermore, a lot of work is done at the microscale using two-photon polymerization, or DLW, to create incredibly accurate and detailed 3D-printed robots. Multiphoton DLW, utilizing a pulsed femtosecond laser, is a high-resolution additive manufacturing technique that creates 3D photonic devices with resolution at the submicron voxel level. The photoresist undergoes a chemical reaction that is sparked by the laser during the multiphoton polymerization process. DLW technology has enabled the production of various optical components and their related elements, which are essential for tasks like imaging, beam shaping, and integrating photonics. Even though DLW is widely available, its production of microscale optics with intricate structures and shapes is limited by the photoresist's single refractive index. Furthermore, the formation of complex wave guiding photonic networks and compound lenses is limited by the inability of the DLW process to produce free-standing elements. Femtosecond pulsed laser technology enables the creation of structures with sub-micrometer resolution in materials such as hydrogels, liquid crystal elastomers (LCE), and alternative composite materials (Dezaki et al., 2023).

2.3.7 Spinning

Spinning is a form-shaping technique that modifies a material's shape without adding or removing it. However, not every material can be shaped into fibers. The primary requirement for the creation of fibers is that the rate of solidification must be faster than the rate of relaxation of the material. Surface tension forces prevent stretched liquid objects from returning to a more stable spherical form.

There are four main categories of fiber-spinning methods: wet, dry, melt, and gel spinning. These categories are based on how fibers are hardened after spinning. In wet spinning, fibers solidify in a coagulation bath, typically producing fibers with diameters ranging from about 250 to 500 μm (Dezaki et al., 2023; Tamayol et al., 2013).

In contrast, dry spinning involves drying and solidifying fibers using airflow, while melt spinning entails extruding molten polymer and then allowing it to solidify. Gel spinning, on the other hand, involves partially drying and chilling the gel with additional solvents before elongating it to produce fibers. Another technique derived from wet spinning, called microfluidics, yields fibers in the micro range. However, there is a current issue with the mechanical stability of the fibers produced using this technique (Dezaki et al., 2023).

Within the categories of dry and melt spinning, electrospinning is a notable method. It creates fibers with small diameters and high surface areas, ranging from a few nanometers to micrometers, by applying an electrical field to draw them from a solution or melt. Another technique for producing fibers smaller than nanometers is touch spinning. This process begins when the polymer comes into contact with a wire, establishing a fluid link that stretches as the collector rotates and the solvent evaporates (Tokarev et al., 2015; Collins et al., 2012).

Additionally, during the spinning process, fibers are stretched, causing the polymer chains to align with the direction of stretching, which enhances their strength and rigidity. Spinning multiple polymers simultaneously can result in multicomponent fibers. Due to their irregular composition, these fibers are capable of bending and curling (Stoychev et al., 2017). For example, Janus fiber, composed of two materials that soften at different temperatures, can alter its shape when the properties of one polymer change. Melt spinning can be employed to produce these fibers, which may be applied in creating self-guiding structures and multi-responsive soft actuators (Dezaki et al., 2023; Ionov et al., 2017).

2.3.8 Sewing

Inspired by the well-known two-dimensional (2D) cut-and-sew techniques frequently used in the garment industry, three-dimensional (3D) soft actuators represent a soft robotics approach. This new paradigm allows for the integration of sewing fabrication techniques into actuator design, opening the door to complex motions like bending and straightening (Cappello et al., 2018).

Exploiting the anisotropic characteristics present in knit and woven fabrics is a key component of this strategy. These layers of fabric are expertly sewn together, and each one has distinct anisotropic characteristics. An airtight bladder, which is thin and

sturdy, is integrated into the process by placing it in between the layers of knit and woven fabric. The inflated bladder then acts as a trigger to cause the desired soft robotic system actuation (Cappello et al., 2018).

With both knit and woven fabrics being anisotropic, selection of material plays a crucial part in the success of this sewing fabrication technique. A key component in controlling strain under different mechanical loads is the bottom layer, also known as the strain-limiting layer. Selected for this layer are woven textiles, which are known for their complex and anisotropically flexible structures. Knit fabrics are a complementary part of the overall design, adding their own anisotropic characteristics while also improving the actuator's flexibility and responsiveness (Cappello et al., 2018).

The combination of sewing fabrication methods with the intentional use of anisotropic properties in woven and knit fabrics represents a development toward the production of extremely versatile and useful soft actuators. This sewing fabrication method greatly advances the ongoing development of soft robotic systems while also broadening the conventional applications of textiles. The deliberate integration of anisotropic properties from knit and woven fabrics improves the three-dimensional performance of the actuators, expanding the frontiers of soft robotics, as shown in 2.12 (Cappello et al., 2018).

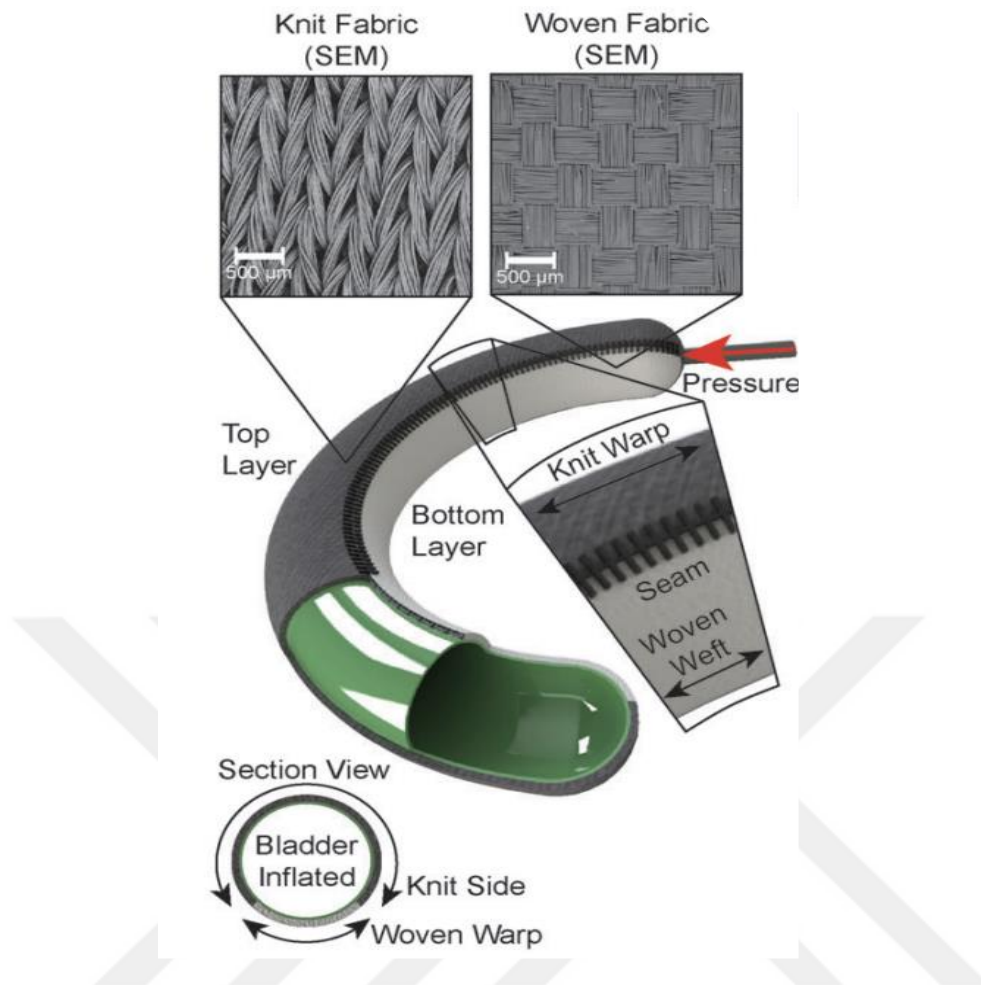


Figure 2.12. Sewing soft textile robot (Cappello et al., 2018).

2.3.9 Braiding

Braiding technology is a well-known textile technique that involves the formation of structures from three or more yarns, typically assembled using machinery that interlaces multiple sets of yarns. These structures resemble woven fabric but are created differently: multiple sets of yarn carriers rotate in circular paths, with one set moving clockwise and the other counterclockwise, intertwining the yarns into the desired structure. Unlike woven fabrics, where yarns intersect at a 90° angle, braids are formed with yarns positioned at various angles, referred to as the "braid angle." This braid angle significantly influences the mechanical properties of the braided structure. As a result, braids are particularly well-suited for forming simple 3D shell shapes, as illustrated in Figure 2.13 (Sanchez et al., 2021).

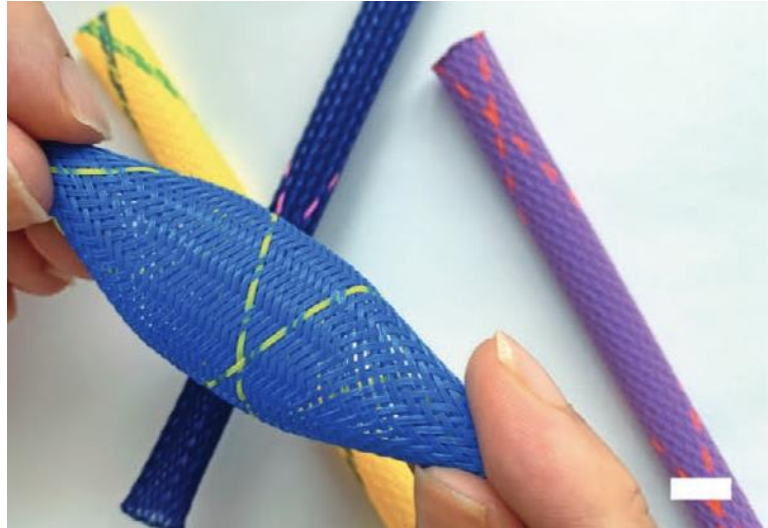


Figure 2.13. Braiding actuator structure (Sanchez et al., 2021).

2.3.10 3D Knitting

One intriguing fabrication technique for integrating wearable assistive devices into clothing is computerized machine knitting. This technology offers a versatile, fully automated end-to-end fabrication method capable of producing precisely tailored deformations in soft textile actuators (see Figure 2.14). Despite the advanced capabilities of industrial machine knitting, which allow for the production of fully shaped clothing with minimal post-processing, its potential for creating wearable assistive soft robotics devices remains largely untapped. (Elmoughni et al., 2021).

The process of knitting involves creating textiles by dividing yarn into columns (wales) and rows (courses) of loops or stitches (Ray, 2012). At its most basic, a knitted structure can be formed from a single continuous piece of yarn. Among machine knitting techniques, flat-bed machine knitting is the most widely used method for producing knitted fabrics, especially for rapid textile prototyping. This technique uses multiple needles arranged in parallel on a flatbed to create intricate knitted structures. The thickness of the fabric produced depends on the machine gauge, which indicates the number of needles per inch on the needle bed. High-gauge machines (12–18

needles per inch) produce finer fabrics, while lower-gauge machines are used for coarser fabrics (Elmoughni et al., 2021).

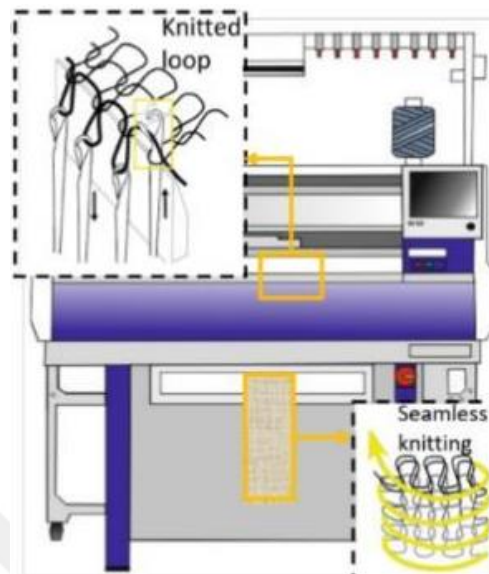


Figure 2.14: Computerized flatbed whole-garment knitting (Elmoughni et al., 2021).

In machine knitting, the coordinated movement of needles and yarn carriers is crucial. Yarn carriers deliver yarn to the needle hook, which forms the stitch by catching the yarn and pulling it through the previously held loop (Spencer, 2001). The natural stretch of knitted materials results from the interlacing yarn structure. Modern, digitally controlled machinery allows precise coordination of both needle and yarn carrier movements. This digital control enables independent knitting of various yarns at predefined settings, facilitating the production of one or more layers with diverse properties. Key parameters affecting the mechanical characteristics of the finished fabric include the type of yarn, stitch density, and needle action.

Advanced computerized knitting machines excel in whole-garment knitting, allowing for the creation of seamless clothing without the need for labor-intensive cutting and sewing processes (McCann, 2016). In summary, computerized machine knitting offers a promising approach for integrating soft textile actuators into wearable assistive devices, combining sophistication with efficiency.

2.4 Soft Robotic Actuation Mechanisms

Different actuation technologies such as pneumatic, chemical, optical, piezoelectric, and magnetic have been developed and are widely in use (Figure 2.15).

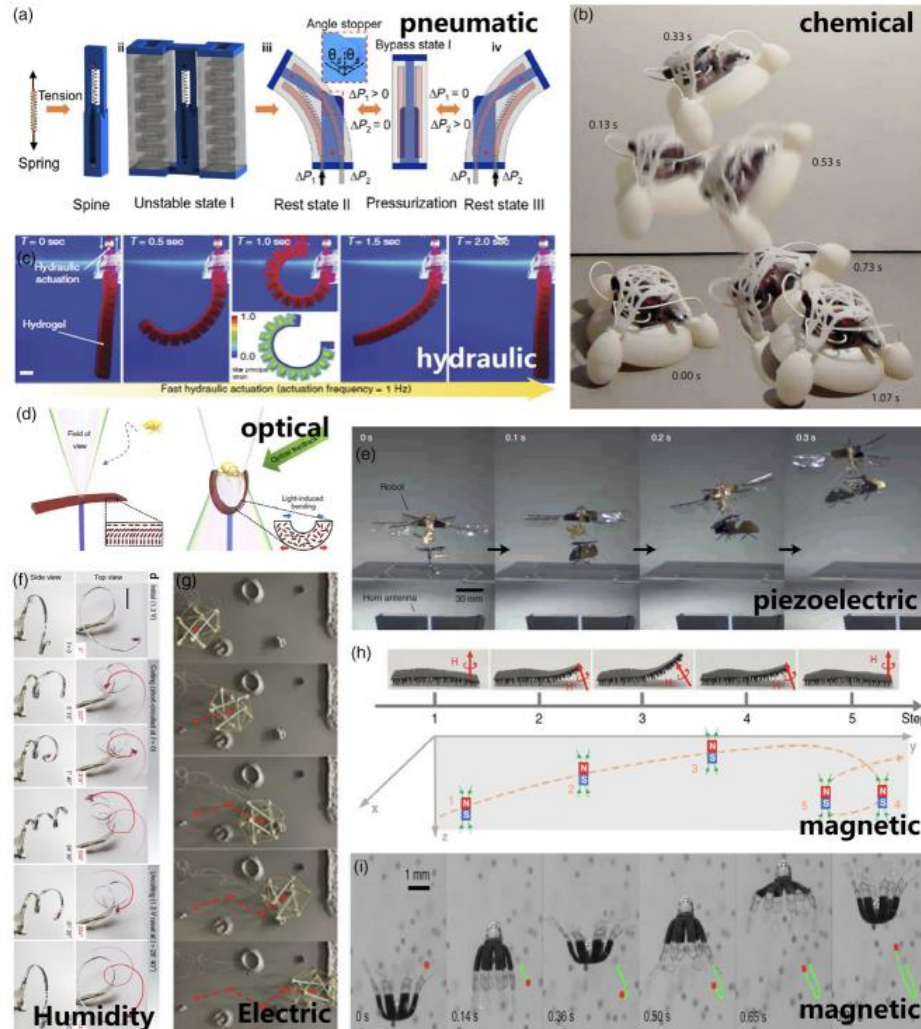


Figure 2.15: Typical actuation methods for soft robotics (Zhang et al. 2022).

2.4.1 Electrically responsive

A variety of materials with properties such as stretchability, softness, and flexibility convert electrical energy into mechanical motion. These materials include memory alloys, liquid metals, polymers, gels, fluids, and carbon-based materials like carbon nanotubes (CNTs). Electronic signals enable easy and rapid modulation of the phase, magnitude, and frequency of these actuators. Furthermore, these actuators can be seamlessly integrated with conventional power sources and electrical controllers, thanks to their compatibility with standard electronic systems. Their potential

applications are vast, including artificial muscles, microrobots, micro-fluidic systems, and microscale object manipulation.

Dielectric elastomer actuators (DEAs) utilize Coulombic forces between two electrodes positioned on opposite sides of a compressible membrane, subjected to a voltage difference (Figure 2.16). DEAs are highly flexible, exhibit high energy density, self-sensing characteristics, and high strains, making them comparable to biological muscles. However, their performance is influenced by the elastomer's dielectric constant, breakdown voltage, and stability. A major drawback of DEAs is the requirement for high operating voltages (measured in kV) and the presence of leakage currents, which can lead to electrical breakdown (Yasa et al., 2023).

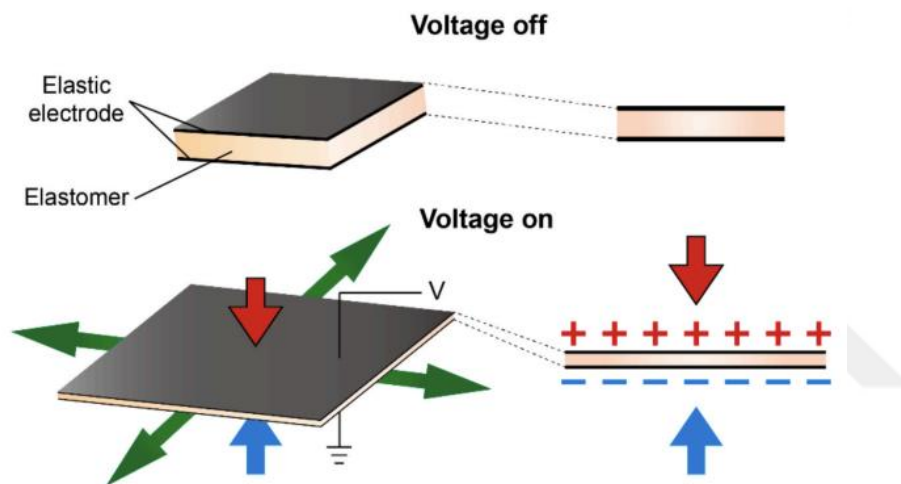


Figure 2.16: Dielectric elastomer operating mechanism (Fu et al., 2022).

Piezoelectric materials generate an electric charge or voltage when subjected to mechanical or vibrational forces. Conversely, applying an electric field to these materials results in mechanical deformation. Despite their potential for actuation, piezoelectric materials used in soft robots typically require high voltages, which can limit their practicality. In practice, polyvinylidene fluoride (PVDF) layers are used to exploit the piezoelectric effect through an alternating current (AC) voltage, enabling the soft robot to expand and contract and thereby change its shape (Yasa et al., 2023).

Although a range of materials responsive to different stimuli have been used to facilitate actuation, employing a servomotor in conjunction with soft components remains one of the most direct and effective methods for achieving actuation through electrical stimulation. However, servomotors have the significant drawback of being

heavy and inflexible, which reduces the overall flexibility and softness of the system (Yasa et al., 2023).

2.4.2 Magnetically responsive

The use of magnetic stimulation is particularly appealing due to the ease with which the intensity and orientation of the magnetic field can be controlled swiftly and precisely, allowing it to permeate a wide range of materials. To enable activation by an external magnetic field, various mediums such as polymers, papers, gels, and fluids have had magnetic particles and fillers embedded within them. When these discrete magnetic fillers are incorporated into soft materials, they create a magnetization profile with varying levels of strength and direction. Under the influence of the magnetic field, these fillers can induce different types of movement, including bending, stretching, and compressing, as they align with the field. These movements generally occur when the spatial gradients of the field interact with the magnetic fillers (Yasa et al., 2023).

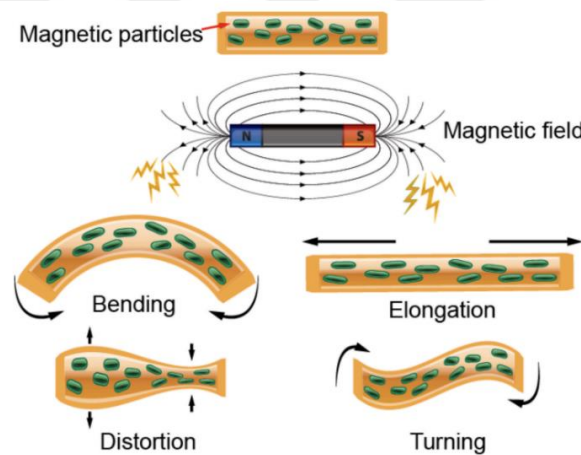


Figure 2.17: Magnetic actuation mechanism (Fu et al., 2022).

2.4.3 Thermally responsive

Thermally responsive actuators are activated by various heat sources such as infrared (IR) light, thermal radiation, near-infrared (NIR) wavelengths, and Joule heating. Additionally, they can be triggered remotely by applying heat, for example, through lasers. In certain applications, especially in biological contexts, thermal stimulation offers a safer alternative to electric fields or ultraviolet light. However, compared to actuators driven by other stimuli, thermally responsive actuators tend to be slower and less efficient. Enhancing their performance can be achieved by using thinner films, increasing energy input, and incorporating heat-absorbing materials. Notable

examples of such materials include shape memory polymers (SMPs), liquid crystal elastomers (LCEs), and shape memory alloys (SMAs).

SMAs are known for their ability to undergo reversible changes in crystal structure, allowing them to be reshaped and revert to their "memorized" form when subjected to mechanical stress and temperature changes. These materials can be composed of various elements, each with its advantages and disadvantages. Iron- or copper-based SMAs, such as Fe—Mn-Si and Cu—Al-Ni, are widely used due to their cost-effectiveness and availability. Conversely, NiTi-based SMAs are preferred for many applications due to their practicality and stability. Typically, these materials have straightforward applications. When subjected to external force, an SMA can assume any shape while in the martensite phase, which has a Young's modulus of 23.2 GPa. As the temperature exceeds a certain threshold, the material shifts to the austenite phase, with a Young's modulus of 49.5 GPa, and then reverts to its original "memorized" shape before deformation. Additionally, the SMA will continuously apply force in an attempt to return to its initial form (Yasa et al., 2023).

2.4.4 Photo-responsive

Soft actuators that respond to light are attractive due to their ability to operate wirelessly and be precisely controlled, regardless of size. Photochromic molecules, which form the basis of photo-responsive materials, absorb light and change their properties accordingly. These molecules can be incorporated into various soft actuators, including gels, polymers, and fluids.

Soft robots designed for efficient operation in natural environments utilize sunlight to activate their actuators, minimizing energy consumption. Currently, many photo-responsive actuators on the market are made from carbon-based materials or liquid crystal polymer networks (LCNs). LCN-based actuators typically exhibit limited deformation but require high light intensities ($>1 \text{ W cm}^{-2}$) (Figure 2.18) (Yasa et al., 2023).

The ability of long-wavelength near-infrared (NIR) radiation to penetrate biological materials with minimal loss has generated increased interest in NIR-responsive soft actuators in recent years. Consequently, NIR has emerged as a leading technique for biocompatible wireless actuation in biomedical applications. However, the effectiveness of NIR-stimulated actuators has been limited by slow actuation rates and

compromised performance due to suboptimal fabrication techniques. Specifically, the development of NIR-responsive soft actuators, such as those using liquid crystal elastomers (LCEs) and polymer-based materials, typically involves incorporating various photothermal agents into polymers. These agents may include substances like graphene, metal nanoparticles, and carbon nanotubes (Yasa et al., 2023).



Figure 2.18: NIR- stimulated soft actuators (Yasa et al., 2023).

Photothermal agents absorb NIR light, converting photon energy into heat, which then modifies the polymers' properties, including swelling, phase changes, and thermal expansion. A significant challenge with this method is the poor solubility of these reagents within the polymers. An insufficient amount of photothermal reagent results in slow actuation speeds, while excessive amounts can cause uneven doping, which weakens the mechanical characteristics of the soft actuator (Yasa et al., 2023).

2.4.5 Fluid-driven

Fluid can be utilized in soft robots to convert pressurized energy into mechanical energy, enabling movement. The core concept involves expanding a soft robot's channel, adjusting the pressure within the fluid chamber, and thereby manipulating the robot's structure to achieve desired deformations. Fluid-based actuation mechanisms

in soft robotics are categorized into three types: pneumatic, hydraulic, and hybrid pneumatic-hydraulic. Fluid actuators are widely used due to their advantages, including easy automation, high output power, and straightforward operation and control.

Soft pneumatic actuation is the most common method for actuating soft robotic structures. Pneumatic actuators are versatile devices that rely on external pneumatic systems such as valves, pumps, and compressors to manage pressurized air (Majidi, 2013). Powered by compressed air, these actuators produce traction and function antagonistically, similar to human muscles. Pneumatic robots, which use air pressure as a driving force, exhibit significant flexibility, excellent safety, and rapid response times. They employ embedded channels and elastic cavities to pressurize gases. The deformation of the robot's structure is caused by stress at the gas-solid interface. It is widely accepted that different pressure levels within the robot's internal cavity will quickly equalize, ensuring consistent pressure distribution throughout the structure. Additionally, achieving full softness and autonomy in robots may involve incorporating soft or miniaturized pumps and valves that do not add elastic rigidity (Majidi, 2013).

Hydraulic actuators, on the other hand, use liquids to flow in specific directions when electric currents are applied. Despite their potential for producing stronger driving forces, their development has been limited by the weight and volume constraints of hydraulic devices (Li et al., 2023).

Hybrid pneumatic and hydraulic systems are predominantly used in underwater robotics. These systems allow a soft robot to absorb or release water, enabling it to sink or float based on changes in internal and external air pressures. Fluid actuators are known for their ability to generate substantial forces and respond more quickly to external stimuli compared to other actuator types. However, external devices are necessary for controlling and operating fluid actuators. Miniaturizing fluid-driven soft robots remains challenging due to the size and weight of the external components. Currently, most fluidic actuators are pneumatically driven and used in semi-automated soft robots, such as grippers, underwater robots, and crawlers. A popular approach involves developing fluidic actuators that can achieve centimeter-scale dimensions, paving the way for fully automated soft robots. (Li et al., 2023).

2.5 Soft Robotic Control Systems

Soft robots possess nearly infinite degrees of freedom (DOFs) and are susceptible to deformation from both external loads and internal driving forces, complicating their control compared to rigid robots. The hyperelastic materials used in these robots exhibit complex behaviors, including hysteresis, nonlinearity, and viscoelastic effects, making precise prediction of their responses challenging. Soft robots employ various actuation mechanisms such as heat, fluid, electric, and magnetic fields, each requiring distinct sensors and control systems. Designing an effective control structure necessitates a thorough understanding of both actuator and sensor characteristics (Wang & Chortos, 2022).

The finite-element method (FEM) is widely recognized as a highly flexible approach for open-loop modeling due to its compatibility with various actuation mechanisms. Nevertheless, open-loop control has inherent limitations as it depends on prior knowledge of the environment and the characteristics of objects that the robot will interact with. In the absence of real-time feedback, minor inaccuracies in material properties can lead to substantial errors in sequential actuation tasks. As a result, even in well-designed environments, achieving precise task execution with open-loop control remains challenging. This lack of precision diminishes the advantages of soft and compliant materials and imposes limitations on future applications. The key distinction in controlling rigid versus soft robots lies in whether their structures are flexible or rigid. Despite this difference, both approaches aim to manage the shape of deformable objects effectively (Lin et al., 2023).

Soft robots require closed-loop control in situations where the task or environment is unpredictable or changing, and the closed-loop control system relies heavily on sensing. In order to achieve autonomy and surpass open-loop control, these soft-bodied systems must incorporate multimodal sensors to offer sensory feedback. In soft robots, closed-loop control relies on sensors that offer feedback regarding both actuator deformations and interactions with the environment. Still, there are numerous obstacles in the way of producing soft robots with perception. Despite substantial efforts to model the statics, motion, and behavior of soft robots, closed-loop control is still developing due to limitations in sensors that hinder real-time updates on the shape of robot (Lin et al., 2023).

The rigidity of traditional sensors in detecting analytes on soft surfaces often results in poor signal transmission. Conventional sensing methods, such as attaching Hall sensors and magnets to soft robots, not only hinder the actuation and deformation of these robots but also introduce unnecessary stiffness. Since the advent of soft robots, significant research has focused on improving sensing capabilities. Advances in soft materials and structures, along with the development of flexible, stretchable sensors, new fabrication techniques, and flexible electronics, have all contributed to these improvements. Stretchable and flexible sensors are crucial in the field of electronics and play a key role in enhancing soft robots with sensing capabilities. The progress in sophisticated materials and integrated systems has notably advanced the development of self-sensing soft robot technology (Lin et al., 2023).

Control systems in soft robotics are impacted by the interplay of actuators, models, sensors, and controllers. Strategies such as open-loop, closed-loop, and autonomous control each play a role in managing these complex systems.

2.5.1 Open-loop control

Predicting motion using information about the robot and its environment is known as open-loop control. Figure 2.19 illustrates how the control diagram for open-loop control utilizes the actuator's mathematical model to map the reference input of the system to the controller's input (u). The controller then adjusts this input (u) for the actuator. Ultimately, the actuator, with its physical characteristics predicted by the model, will be adjusted to reflect its current status, y , in reverse. Controls that lack feedback are generally categorized as open-loop. Therefore, open-loop control strategies are often described as non-model on/off switch controls, which are particularly common in soft robotics. While a single on/off actuator employs a simple control algorithm, coordinating multiple on/off actuators requires a more advanced control algorithm to achieve effective locomotion (Wang & Chortos, 2022; Nguyen et al. 2015).

Open-loop control strategies based on models start with designing the structure and then creating a model to forecast its motion. However, in practical applications, the structure of robot is designed to achieve a particular movement. A significant challenge in this area is solving the inverse problem, which involves designing a robot structure to execute a specified function or motion. The main limitation of open-loop

control is the lack of a feedback mechanism to indicate when the actuator has reached the desired state. Open-loop control is applicable only in situations where the environment and the properties of the objects the robot will interact with are thoroughly understood. Possible changes in environmental conditions include unexpected obstacles or variations in global variables like temperature, which may affect the robot's materials' properties. Examples of challenging robot properties to model include the occurrence of production flaws and the difficulties associated with materials that exhibit complex or variable characteristics. When time-varying material properties are not accurately accounted for, small imperfections can escalate through successive actuation tasks, causing large errors in the absence of feedback. As a result, open-loop control is frequently used for tasks that are either brief or repetitive (Wang & Chortos, 2022; Henke et al. 2017).

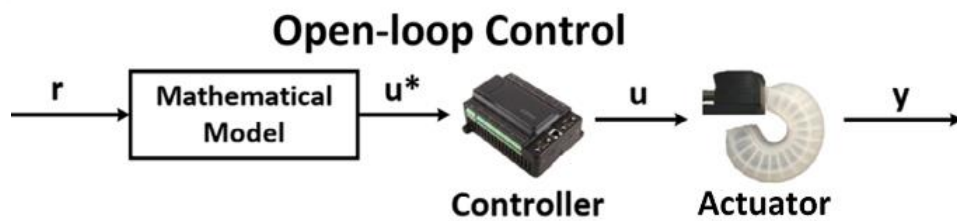


Figure 2.19: Open-loop control diagram (Wang & Chortos, 2022).

2.5.2 Closed-loop control

Effective control systems are essential when dealing with environments or tasks that are variable or unpredictable, such as when an untethered robot navigates new terrain or a gripper handles objects of varying shapes and sizes. In these scenarios, feedback from sensors is crucial for monitoring actuator deformation and interactions with the surrounding environment. The unique actuation mechanisms and structural designs in soft robotics both demand and facilitate the use of a range of sensing technologies (Wang & Chortos, 2022).

In robotics, similar to biological systems, closed-loop control operates on two distinct levels. The first level focuses on using feedback to manage the deformation of each actuator individually. As depicted in Figure 2.20, within this level, actuator stimuli such as pressure, voltage, and temperature are provided, resulting in changes in parameters like angle and length. This level of control targets a specific deformation

of the joint but does not account for the overall deformation of the robot, making kinematic analysis unnecessary (Wang & Chortos, 2022).

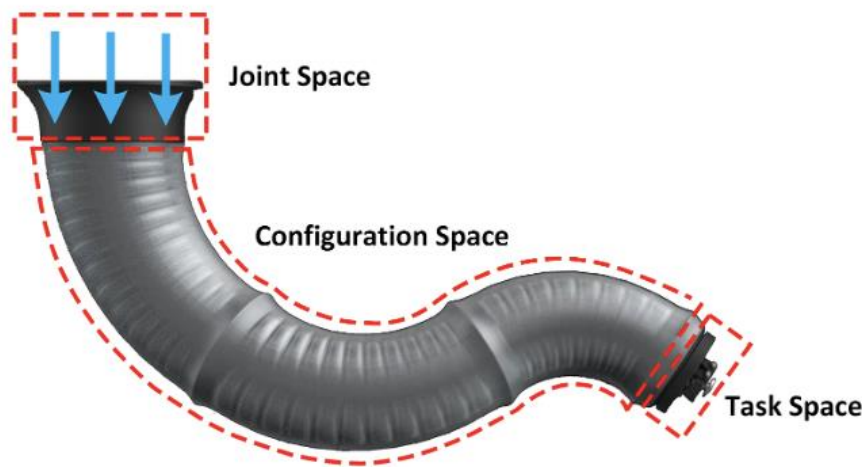


Figure 2.20: Three different spaces of soft robotic (Wang & Chortos, 2022).

These control methods are commonly employed in soft robots with a single actuator. When it comes to robots with multiple actuators, independent systems—such as soft grippers with separate control mechanisms—can achieve their desired functions by focusing on joint-level control, without considering the interactions among the actuators. In Figure 2.20, the forward route operates like open-loop control; however, a sensor within the actuator introduces feedback to the actuator’s reference input prior to its integration into the model. (Wang & Chortos, 2022).

Control at the second level operates within both task and configuration spaces. At this stage, geometric data generated by the first level of control serves as input, allowing the second level to determine the overall geometry of the robot. This level of control involves both the dynamics and kinematics of the robot. The configuration space includes every possible pose the robot can achieve, defined by the movement range and constraints of each joint. Figure 2.21 illustrates how control in this space involves determining the end-effector's position based on the joint configurations. Forward kinematics converts joint data into the configuration space, while inverse kinematics does the opposite. Meanwhile, the task space is concerned with the position, force, and orientation of end-effector. Since these factors are derived from joint configurations,

the task space is considered a more specific subset with fewer variables (Wang & Chortos, 2022).

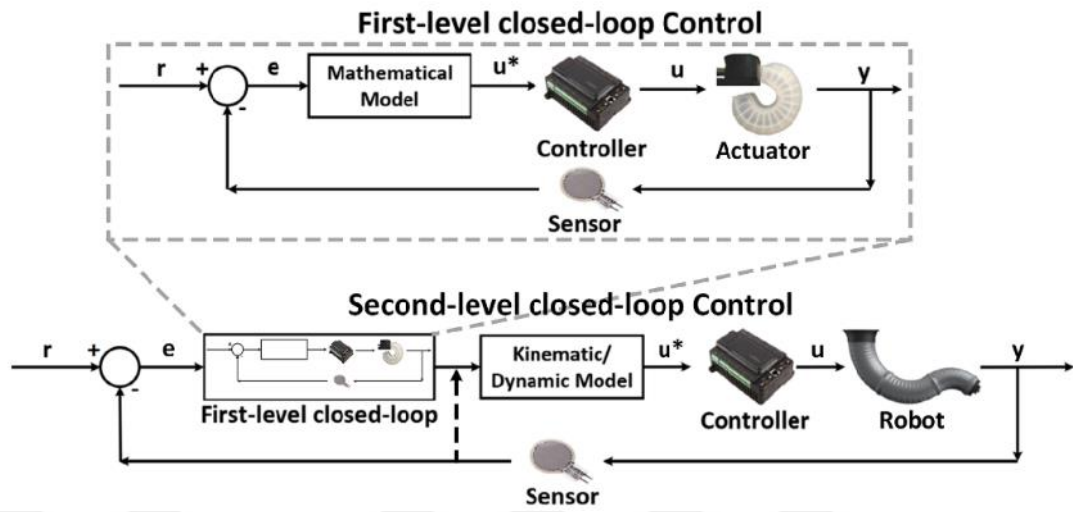


Figure 2.21: Close-loop control diagram (Wang & Chortos, 2022).

Figure 2.21 illustrates a second-level control system that adds an additional layer of oversight and coordination to the first-level control. Here, the reference input first enters the joint space at the lower level, where the output generated then feeds into the second-level control. This higher-level system uses a mathematical model to manage both kinematics and dynamics. Sensor feedback, which monitors the robot as a whole, is integrated before and after the initial control loop. Sensors positioned before this loop are typically placed within the joint space to measure parameters like actuator pressure and voltage. In contrast, sensors tracking end-effector displacement or configuration errors provide feedback after the first-level control has processed the signals (Wang & Chortos, 2022).

After classifying control systems from a robotics perspective, the first-level control is further divided based on sensor technologies. One category focuses on detecting indirect variables related to actuator mechanisms, such as current and voltage for electric actuators or internal pressure for fluid-based actuators. These internal variables often have dedicated sensors, and a model is used to estimate actuator deformation based on them. External variables, like strain, contact force, and angle, offer direct information about the deformation of system but require sensors to be embedded in the robot's structure. Advances in soft sensors and fabrication methods that integrate

sensing capabilities into actuators are making these control systems more feasible for soft robots (Wang & Chortos, 2022).

Second-level control strategies are classified according to the type of model (static or dynamic) and the operational space of the controllers. A common approach involves using a static kinematic model within the configuration or task space, paired with a controller focused on joint movements, providing quicker and more stable responses. Since dynamic models directly relate variables from the joint movements to the task space, their controllers are typically placed there (Wang & Chortos, 2022).

While these control systems offer improvements over open-loop methods, they have limitations. Being model-dependent restricts their applicability, as each model is tailored to a specific soft robot system. Meanwhile, miniaturization is a significant trend in the development of soft robots. As devices shrink, the challenge becomes creating materials and fabrication techniques suitable for tiny, integrated sensors and actuators (Wang & Chortos, 2022).

2.5.3 Autonomous control

The term "autonomous" is often used to describe devices capable of operating independently, without the need for external control or power sources, a concept also referred to as onboard control. This should not be confused with the idea of autonomous control systems, which refers to a controller that is able to predict, adapt, and learn control architectures, models, and parameters on its own. In this context, autonomous control represents an advancement over the earlier discussed strategies. The same control diagrams are applicable, but what sets autonomous control apart is the automatic generation of algorithms within the "Model" and parameters within the "Controller." This automation is achieved through techniques like analytical optimization or machine learning (Wang & Chortos, 2022; Connolly et al., 2016).

Machine learning algorithms are utilized to determine the physical model parameters of sensors and soft actuators in the joint space. Relative adaptive control can then be established using these physical models. Using machine learning (ML) algorithms to obtain dynamic or kinematic models of the entire robot are viewed as an offline autonomous control in the task and configuration space. Autonomous control approaches are divided into two categories: model-free control using machine learning algorithms and model-based control, which includes predictive control and adaptive

control. Trajectory tracking, motion planning, vision-servo, and exploration and adaptation of unfamiliar environments, like complex terrain and random forces, have all been accomplished by these autonomous control strategies (Wang & Chortos, 2022).

Machine learning algorithms are limited by high computational costs, like FEM-based open-loop control. Therefore, lowering the computational complexity of machine learning algorithms while simultaneously increasing their accuracy is one of the field's major challenges. Prediction accuracy largely relies on the quality of the data set, which is often a significant limitation in applying machine learning to soft robots. It is not easy to train a robot to operate in an unfamiliar environment. Furthermore, because machine learning algorithms operate as a "black box" between the control and robot, it is challenging to comprehend the principles of how the design of the robot influences its functionality (Wang & Chortos, 2022).

2.6 Finite Element Analysis of Soft Robotics

Traditional simulation and modeling approaches designed for conventional rigid-bodied robots fall short in adequately characterizing the behavior of soft robots. There is a need for modeling and simulation tools specifically developed to precisely capture the responses of soft materials to external stimuli.

In soft robotics, precise modeling requires simulating how robots deform based on the principles of continuum mechanics, considering forces applied both externally and internally during actuation. Numerical mesh-based modeling involves defining soft robots through parameters such as Young's modulus and Poisson's ratio, along with their geometric shape. The shape of robot is typically divided into a mesh made up of basic geometric units referred to as elements (Coevoet et al., 2017; Du et al., 2021). Additionally, other forms, like particles or regular uniform grids are employed to depict the geometry of the robot. The discretization of geometry of soft robot enables the numerical solution of equations by dividing them into elements and solving for each element separately. A fine mesh is required to accurately capture the behaviors of soft robots within a finite element method-based simulation framework (FEM). In finite element method simulations, the characteristics of soft robots are defined by their material properties and represented using meshes. In this simulation type, the

discretized physical equations are solved after defining the robots and representing them with meshes (Figure 2.22).

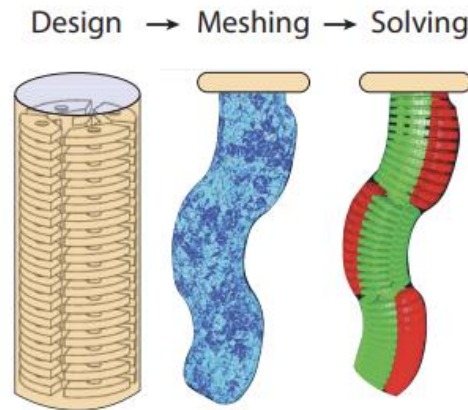


Figure 2.22: Finite element analysis of soft robotics (Yasa et al., 2023).

Soft actuators enable continuous deformation across the entire material, whereas FEM represents the robot using discrete elements. Choosing element sizes that accurately capture continuous deformation without appreciably increasing computational time is a crucial step in creating a suitable FEM model. Despite the fact that FEM is widely used to model various actuator mechanisms, the implementation principles and simulation conditions vary. Enhancing the accuracy of FEM models involves incorporating relevant physics into equations governing each node's behavior. For instance, when simulating elastomer materials in software like COMSOL, ANSYS, and ABAQUS, one can utilize either built-in hyperelastic models or user-defined stress-strain models to create quasi-static models. Viscoelastic property equations must be incorporated into dynamic behavior simulations. Models of fluidic-driven actuators require consideration of solid mechanics; boundary conditions are used to model the effects of fluid stimulation. Similarly, tendon-driven soft robots are indirectly driven by electromagnetic and piezoelectric motors, necessitating consideration of interactions between tendons and robot structure, similar to fluidic-driven soft robots. (Wang & Chortos, 2022).

2.7 Soft Robotic Sensing Technologies

Integrating sensors into soft robots presents a major challenge for effectively carrying out autonomous tasks. Traditional sensors, which are intended for rigid structures, are hard to adapt to the flexible and compliant nature of soft robots. Since soft robots can theoretically exhibit an infinite number of degrees of freedom, they need sensors

capable of detecting gradual changes in their posture, requiring these sensors to offer a wide range of motion, high resolution, and accuracy. These sensors allow precise reconstruction of the overall structure of soft robots when combined with previous knowledge (Yasa et al., 2023).

In soft robotics, proprioception involves the capability to detect the position and movement of the own body of robot. It is an important component in giving feedback control systems for soft robots an accurate picture of their current state. Motion capture systems are frequently used to assess the posture of soft robots, particularly in research focused on modeling and control. This technique uses reflective markers attached to soft robots, which are tracked by infrared cameras to provide precise, real-time posture measurements. However, it depends on an external setup for tracking and is limited by factors like occlusion, which reduces its practicality for real-world interactive tasks. Consequently, efforts have been made to integrate internal proprioceptive sensors into soft robots, enabling posture measurement without the need for motion capture systems (Yasa et al., 2023).

Proprioception is the ability to sense one's movements, whereas tactile sensing is about obtaining information from the environment via touch. Soft robots, with their capacity for compliant interactions with the environment, require the ability to sense when they come into contact with objects. Contact sensing techniques include resistive, capacitive, and magnetic sensors. These technologies often employ a network of sensors across the surface of a robot to collect comprehensive contact data. A novel technique that uses a camera inside a bubble gripper has recently been developed, allowing for the detection of deformations caused by contact.

In soft robotics, a range of sensor technologies is used to enable tactile and proprioceptive sensing abilities. These sensors differ in several aspects such as their capability to identify objects, the kinds of deformation they can measure, and their response to nonlinearity and hysteresis. It is important to evaluate these factors carefully to select the most appropriate sensing technology tailored to the particular design requirements of the soft robot (Yasa et al., 2023).

2.7.1 Resistive sensors

Resistive sensors operate by transforming external signals into changes in resistance. This transformation is calculated by the formula

$$R = \rho l/s \quad (2.1)$$

where R represents resistance, l is length, ρ is the electric resistivity, and s stands for the cross-sectional area. By altering either l or s , the resistance can be modified. Thus, the fundamental concept behind resistive sensors involves converting deformation/force information into alterations in l or s , thereby causing changes in resistance values.

Resistive sensors are made to measure various signals, including stretching, normal force, and shear force, for a variety of structures made of conductive materials. The sensors provide feedback to those forces because the structures can deform in response to particular forces (Yasa et al., 2023). Liquid metal is a highly conductive material used in various resistive sensors. It remains in a liquid state at room temperature and exhibits high conductivity and amorphous properties. When liquid metal fills microfluidic channels, its resistance varies as these channels change shape in response to external forces. By calibrating these resistance changes, various loads can be accurately determined. (Hao et al., 2022).

2.7.2 Piezoelectric sensors

When specific dielectrics are subjected to external forces, a phenomenon known as the piezoelectric effect occurs whereby voltage and charge accumulation occur on both sides of the dielectric (Wu et al., 2021). Piezoresistive sensors function by utilizing the piezoelectric effect, where the electrical resistance of materials varies when subjected to strain or pressure (Yasa et al., 2023). The two types of piezoelectric effects are the inverse and positive piezoelectric effects (Figure 2.23 and Figure 2.24).

The positive piezoelectric effect occurs when a crystal is subjected to force in a specific direction, leading to the generation of electric polarization within the crystal. This results in the accumulation of opposite electric charges on the crystal's surfaces. Once the force is removed, the crystal returns to its original state. The relationship between

the applied force and the amount of generated charge is direct and consistent. Most piezoelectric sensors rely on this effect.

On the other hand, the inverse piezoelectric effect, also known as the electrostrictive effect, takes place when an alternating electric field is applied to a crystal. This causes the crystal to vibrate and deform mechanically. The amplitude of these vibrations increases significantly when the frequency of the alternating voltage matches the crystal's resonance frequency, which is usually related to the crystal's size. This phenomenon is referred as “piezoelectric resonance” (Wu et al., 2021).

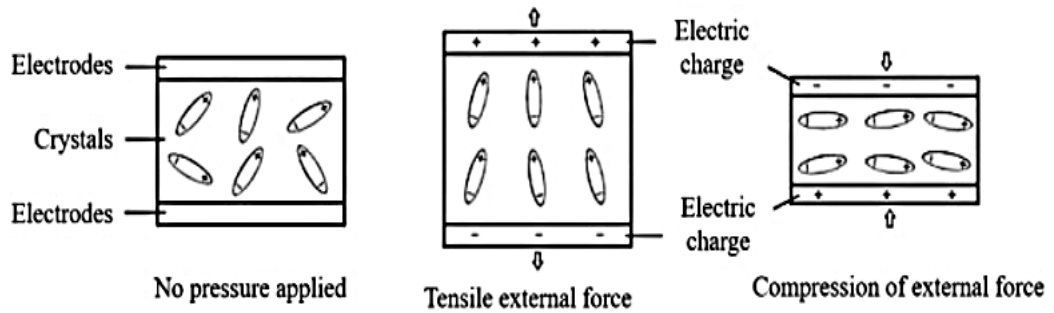


Figure 2.23. Positive piezoelectric effect (Wu et al., 2021).

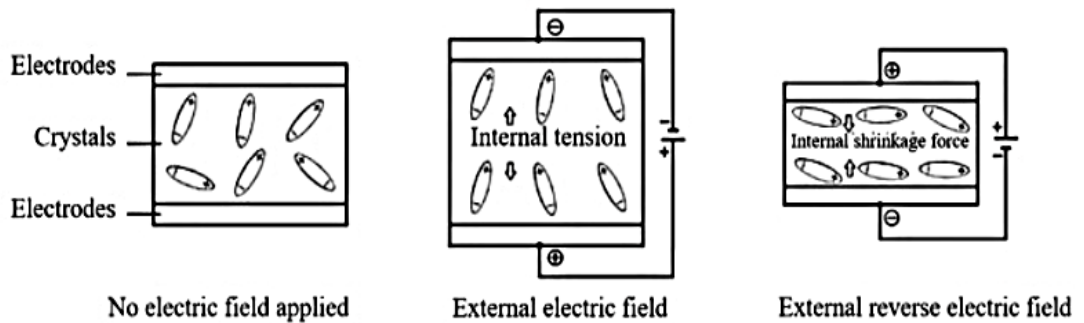


Figure 2.24: Inverse piezoelectric effect (Wu et al., 2021).

2.7.3 Capacitive sensors

Capacitive sensors serve dual purposes in soft robotics: they can measure proprioceptive poses and exteroceptive contacts with the environment. These sensors utilize two primary methods for haptic sensing: one based on self-capacitance and the other on mutual-capacitance. In self-capacitance mode, a single electrode receives an alternating current to identify nearby objects by monitoring variations in the electric fields it creates. (Figure 2.24 (i)). Conversely, mutual-capacitance mode uses a pair of electrodes for both sending and receiving signals. In this mode, a nearby conductive object induces a shielding effect, whereas bringing the electrodes into physical contact

leads to a coupling effect. (Navarro et al., 2020) (Figure 2.24 (ii)). Capacitive sensors have difficulty detecting nonconductive objects, but the coupling effect in mutual-capacitance mode, which based on physical deformation, potentially sense such objects.

Capacitive sensors stand out among various sensor types because of their attractive features, such a simple structure, rapid response times, signal repeatability, low power consumption, and other advantages. (Zhou et al. 2019). Capacitive pressure sensors sense pressure-induced changes in capacitance and convert these variations into electrical signals. The capacitance is described by the following equation.

$$C = \epsilon_0 \epsilon_r \frac{S}{\delta} \quad (2.2)$$

In this context, the capacitance C is defined by the parameters: ϵ_0 representing the permittivity of free space, ϵ_r as the relative permittivity, S as the area of the conductive plates, and δ as the separation between the plates (Zhou et al. 2019; Pignanelli et al. 2019).

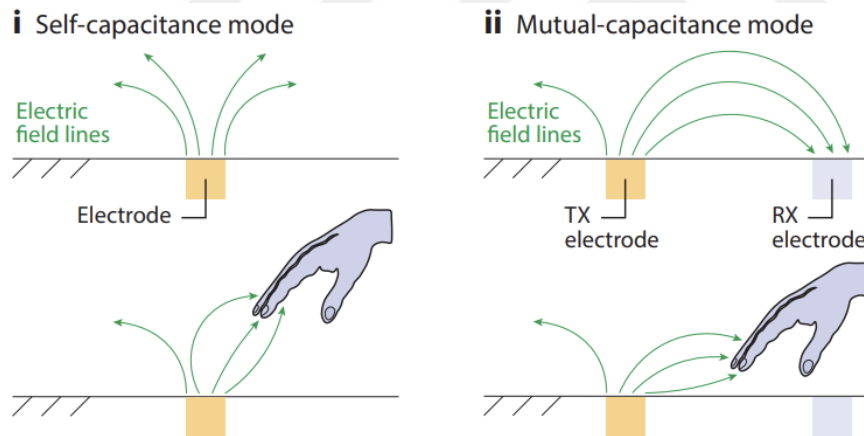


Figure 2.25: Capacitive sensor. (I) Self-capacitance and (ii) mutual-capacitance mode (Yasa et al., 2023).

2.7.4 Optical sensors

Optical fiber sensors with fiber Bragg grating patterns are particularly effective for monitoring the gradual changes in soft robots. These sensors use optical fibers that have periodic gratings at certain intervals, which produce a unique spectral frequency response (Whang et al. 2016). When strain is applied to the grating section, it changes the frequency response, allowing for accurate measurement of the strain at that location. By positioning these gratings throughout the length of the fiber and

integrating multiple fibers, the overall geometry of the sensor array can be reconstructed. Different grating positions and sensor arrangements have been explored to measure continuous curvature accurately, alongside various algorithms for reconstructing the deformation states of soft robots (Zhang et al. 2018; Monet et al. 2020). The fibers' slender design allows for seamless integration into soft robots, though the larger readout equipment necessary for frequency measurement can restrict mobile applications. Although commercially available, fiber Bragg grating systems are relatively costly for widespread adoption. Nevertheless, their compact size and precise curvature measurements make them ideal for critical applications like minimally invasive surgery, where the benefits often outweigh the higher costs and equipment size.

2.7.5 Magnetic sensors

Magnetic sensors have the ability to translate changes in magnetic fields into other forms of information, such as forces and deformation (Hao et al. 2022). The Hall effect is used by magnetic sensors to sense things. Magnetic sensors are less expensive and exhibit less hysteresis compared to resistive sensors. For example, a planar soft robot might incorporate a flexible printed circuit board in its neutral midplane, which houses a small magnet and an integrated magnetic sensor. The magnet moves in relation to the sensor when the robot flexes, changing the magnetic field in a way that can be measured (Ozel et al. 2016). These sensors have compact form factors and hysteresis-free measurements, but they are susceptible to external influences from metal or magnets. Without adequate shielding, magnetic sensors may suffer from interference with adjacent sensors (Walck et al. 2014). However, their accuracy and capacity to function from a distance make magnetic sensing-equipped catheters useful for in vivo tip localization, potentially shortening patient procedure times (Khaykin et al. 2012).

2.8 Textile-based Actuators

Textiles serve not only to reinforce soft actuators but also as active materials for soft robots. They retain traditional textile qualities like flexibility, reliability, and environmental stability while functioning as actuators themselves. This dual role has spurred efforts to develop innovative textile-based soft robots using fibers (like SMA spring fiber, polymer fiber, CNT fiber, hollow fiber, multilayer fiber, etc.), yarns (including CNT yarn, polymer yarn, supercoiled yarn, etc.), and fabrics (such as PAM

fabric, CNT woven, SMA fabric, and knitted fabric, etc.). These type of actuators are activated by diverse stimuli such as pneumatic pressure, heat, vapor, electricity, electrochemical reactions, and light (Fu et al., 2023; Iamsaard et al., 2014).

2.8.1 Fiber actuators

Microscale fibers form the foundational unit of textile materials, providing flexibility and formability to fiber-based materials. These small-scale fibrous actuators can be activated safely using stimuli such as humidity, heat, light, fluid pressure, and low-voltage electric fields (Fu, et al. 2022). Figure 2.26 showcases the work on fiber-based actuators, demonstrating their structure and various applications.

Fiber-based actuators offer diverse functionalities in response to different stimuli. For example, torsional fiber actuators made from spider dragline silk are activated by humidity, achieving deformations exceeding 300°/mm at 70% relative humidity (Liu et al. 2019). However, challenges such as low torque and humidity durability hinder their widespread application. In another study, fiber-based dielectric elastomer (DE) actuators were developed using aligned carbon nanotube (CNT) fibers and flexible films. These actuators exhibit more than 40% directional contraction under minimal electric fields, attributed to the anisotropic mechanical properties of CNT fiber electrodes. Additionally, DE actuators with various fiber configurations facilitate torsion, contraction, rolling, and bending movements. Graphene/polypyrrole fibers, activated by electric fields, exhibit asymmetric responses but is limited in torque output for broader applications. Additionally, polymer and elastomer fiber actuators driven by electric fields, heat, or light display complex movements, necessitating advanced techniques to expand their applications (Fu et al., 2022).

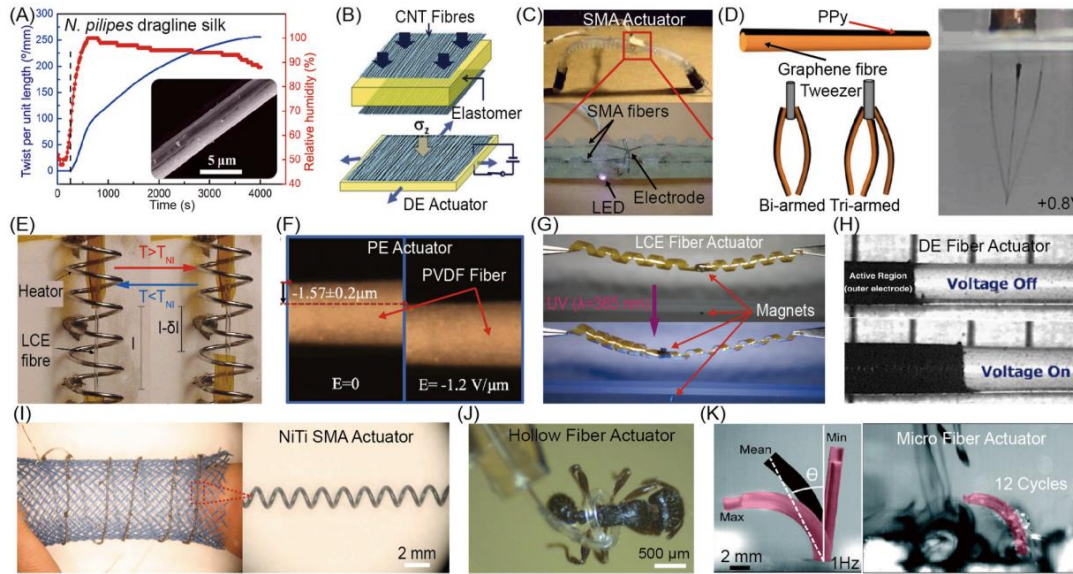


Figure 2.26: Fiber based actuators (Fu et al. 2022).

2.8.2 Yarn-based actuators

Yarn spinning presents considerable potential and opens up new opportunities for yarn-based soft actuators. Techniques like air vortex, ring, and open-end spinning use drafting and twisting to create continuous yarns that are strong and stable. Using these techniques, yarn actuators leverage twisting technology, offering enhanced stability, flexibility, and higher force output compared to fiber-based actuators. This generation of soft actuators demonstrates various motions (contraction, rotation, expansion) and responsiveness to various stimuli (electrochemical, photonic, electrothermal, humidity). Yarn-based actuators are classified into twisted yarn actuators and supercoiled yarn actuators depending on their manufacturing methods (Fu et al., 2022).

CNT twisted yarns are known for their low density, excellent thermal properties, and robust mechanical performance (Jang et al. 2020). During chemical vapor deposition (CVD) spinning, CNT fibers are drawn and twisted to create continuous strands, which are then used for various actuator designs. Electrochemical-driven torsional and contraction actuators based on CNT yarns have been extensively explored, achieving notable results such as 15,000° rotation and 590 twists/min with electrolytes (Guo et al., 2012). However, challenges such as reliance on liquid electrolytes limit their widespread use. Recent developments include integrating CNT yarns with thermoplastic polyurethane (TPU) to create large strain actuators, achieving 13.8% strain and 33 Mpa stress through thermal expansion without additional media.

Overtwist hierarchical architectures have also been employed to enhance performance, demonstrating self-powered rotational actuators with high energy density and stability over 1000 cycles. Hybrid CNT twisted yarns incorporating waxes for thermal expansion have shown promise in generating significant elongation and torsion, albeit with challenges related to wax overflow and reduced durability (Li et al., 2013).

Supercoiled yarn actuators mimic natural helical structures, offering amplified torque and tensile strain capabilities. Initially developed with nylon 6.6, these actuators contract significantly (49%) upon heating, lifting loads over 100 times human muscle capacity. Actuation relies on differential thermal expansion along the yarn's length versus its radial direction, benefiting from less constrained polymer chains in non-crystalline regions. However, reliance on external heat sources limits practicality, mitigated by integrating electric heating systems. Recent advancements include composite yarn actuators with broader temperature ranges, like polyimide/polydimethylsiloxane blends achieving 20.7% tensile actuation from 50 °C to 160 °C. Despite progress, challenges remain such as high production costs for CNT-based actuators and limitations in frequency of activation. Future directions may involve integrating torsional refrigeration into coiled yarns to enhance actuation speed and frequency, with most developments currently confined to lab settings (Fu et al., 2022).

2.8.3 Fabric-based actuators

Numerous fabric-based soft actuators have been developed using diverse textile manufacturing methods. For instance, recent developments feature fluidic-driven muscle sheets made from elastic fabrics, delivering 150 N force and achieving more than 100% strain. By carefully positioning these actuators on the fabric, they facilitate diverse movements and complex 3D shape transformations, such as stretching, compressing, and bending. Additionally, fabric muscles braided from fluidic-driven yarns, such as McKibben muscle yarns, exhibit lightweight, flexible structures capable of significant strain under low air pressures (Kurumaya et al., 2019; Fu et al., 2022).

Electric-driven actuators based on dielectric elastomer fabrics allow for elongation, adhesion, and bending utilizing the fabric's tensile anisotropy to achieve multi-motion patterns. Fabric structural actuators offer amplified output torque and deformation,

exploiting the straight and parallel yarns in plain-weave fabrics for enhanced force, or the looped structures in knitted fabrics designed to accommodate large tensile strains.

Maziz et al. have demonstrated tunable force and strain artificial muscles by integrating electrochemically-driven yarns into knitted and woven fabrics, achieving substantial force enhancement and strain amplification. Another notable example includes a fabric-based actuator made from cotton, polyester, and silver-plated nylon yarns, where silver-plated nylon weft yarns drive the electrothermal actuation of coiled polyester yarns in a 12-warp woven structure capable of lifting up to 3 kg (Fu et al., 2022; Maziz et al., 2017).

Looking forward, integrating novel textile structures such as bifacial fabrics combining knitted and woven patterns holds promise to simultaneously amplify output force and strain of fabric actuators. Furthermore, 3D structures like orthogonal woven fabrics and warp-knitted spacer fabrics offer large specific surface areas and torsional stability, paving the way for function-rich wearable devices that can modify their characteristics based on environmental conditions (Fu et al., 2022).



3. BIAXIAL TEXTILE POUCH MOTORS (CONTRACTING ACTUATOR) FOR FOOT DROP SYNDROME APPLICATION¹

Soft pouch motors (contracting actuators), engineered to mimic the natural movements of skeletal muscles, play a crucial role in advancing robotics and exoskeleton development. However, the fabrication techniques often involve multi-stage processes; they lack soft sensing capabilities and are sensitive to cutting and damage. This work introduces a new textile-based pouch motors with the capacity for biaxial actuation and capacitive sensory functions, achieved through the application of computerized knitting technology using ultra-high molecular weight polyethylene yarn (Spectra®) and conductive silver yarns. This method enables the rapid and scalable mass fabrication of robust pouch motors. The resulting pouch motors exhibit a maximum lifting capacity of 10 kilograms, maximum contraction of 53.3% along the y-axis, and transverse extension of 41.18% along the x-axis at 50 kPa pressure. Finite Element Analysis (FEA) shows closely matches the experimental data. The capacitance signals in relation to contraction motion are well-suited for detecting air pressure levels and hold promise for applications requiring robotic control. Notably, it effectively elevates an ankle joint simulator at a 20-degree angle, highlighting its potential for applications such assisting individuals with foot drop. This study presents a practical demonstration of the soft ankle exosuit designed to provide lifting support for individuals facing this mobility challenge.

Keywords: pouch motors, pneumatic artificial muscles (PAMs), soft robotics, textile robotics, capacitive sensors, soft sensors, wearable robots.

3.1 Introduction

The skeletal muscles within the human body act as dynamic power sources (Frontera et al. 2015) enabling a wide array of movements, from common everyday actions like gripping a glass to the physically demanding activities of walking and engaging in

¹ This chapter is based on the paper “Yilmaz, A.F., Ozlem, K., Celebi M. F., Taherkhani, B., Kalaoglu F., Tuncay Atalay, A., Ince, G., Atalay, O. 2024. Design and Scalable Fast Fabrication of Biaxial Fabric Pouch Motors for Soft Robotic Artificial Muscle Applications, *Advanced Intelligent Systems*, 2300888. DOI: 10.1002/aisy.202300888.”

sports (Groeneveld et al. 2022; Biewener et al. 2016). However, these muscles can lose their functionality due to injuries, traumas, or specific neuromuscular disorders, resulting in numerous challenges for affected individuals in their daily lives (Iolascon et al. 2019; Cohen et al. 2015). In response to these challenges, soft robotic systems have been developed to assist individuals in regaining their independence and improving their quality of life (Yang et al. 2024; Pan et al. 2022; Yilmaz et al. 2022; Thalman et al. 2020; Cianchetti et al. 2018; Polygerinos et al. 2017). These systems, employing soft pouch motor structures, show significant promise in providing assistance to individuals with impaired muscle function by mimicking muscle-like contraction movements (Hiraki et al. 2020; Li et al. 2022; Niiyama et al. 2015; Jang et al. 2023; Oh et al. 2019). Nevertheless, the development of scalable and mass-producible soft pouch motors with integrated sensing capabilities is one of the ongoing challenges in the realm of soft robotics. The automation of robot fabrication, spanning design to assembly, is crucial to reducing prototyping costs and enhancing scalability for mass production. Moreover, the development of cost-effective, efficient, and high-quality mass production methods is imperative to meet the increasing demand for soft pouch motors. It is also important to highlight those novel approaches, like incorporating sensors directly into the framework of motors or devising external sensing systems to enhance these functionalities of motors, have received limited exploration. Additionally, the adoption of more robust materials is needed to enhance the durability and reliability of these motors, particularly in demanding applications.

The process of muscle contraction is a biological phenomenon that depends on the reduction in muscle length, enabling it to produce movement and generate force (Sweeney et al. 2018; Herzog et al. 2023). The force generated by muscles exceeds the opposing force, such as the weight being lifted, resulting in joint movement (Oguntosin et al. 2019; Mirvakili et al. 2018; Ball et al. 2016). Soft pouch motors have emerged as a specialized class of actuators that have garnered considerable attention due to their remarkable ability to mimic this complex motion and functionality observed in natural muscles. These motors have flexible and soft structures, setting them apart from conventional rigid motors, and their softness allows for safe interactions with the environment (Kim et al. 2021; Lee et al. 2020). This type of actuator is fabricated using flexible materials, which exhibit contractile and expansile properties when exposed to various external stimuli, including fluidic pressure (Wirekoh et al. 2019), electrical

stimulation (Yoder et al. 2020), thermal variations (Sanchez et al. 2020), and chemical reactions (Zakeri et al. 2022). One of the standout features of soft pouch motors is their high power-to-weight ratio, making them exceptionally suitable for applications requiring lifting and the generation of substantial force. The combination of high-power output and low-weight properties enables these actuators to efficiently and effectively perform lifting tasks. These unique characteristics enable soft pouch motors to deliver precise and adaptive actuation responses to various conditions and requirements, making them highly suitable for a wide range of applications involving soft artificial muscles, from medical devices to robotic systems and from micro-mechanical mechanisms to automotive applications (Oh et al. 2019; Zakeri et al. 2022).

The fundamental principle behind the contraction motion in soft pouch motors lies in the controlled deformation of their constituent material or structures themselves. The specific mechanism used to accomplish contraction vary depending on the design of the motor and actuation concept. In numerous cases, these actuators achieve contraction through the physical shortening of their structural length. Traditionally, these motors have been recognized for their uniaxial contraction along the y-axis when pressurized fluid is introduced into the motor, causing the material to contract (Li et al. 2022; Kellaris et al. 2018; Tynan et al. 2021). These actuators radially expand in response to changes in gas pressure. The introduction of pressurized air or gas induces the contraction of the flexible material, resulting in a reduction in length and subsequent contraction motion (Tang et al. 2022). While many soft pouch motors predominantly exhibit unidirectional motion along the y-axis, integrating capabilities for movement along both the x and y axes can introduce new concepts.

The effectiveness and capabilities of soft pouch motors depend heavily on the base materials used in their fabrication. Soft pouch motor fabrication commonly relies on materials like film (Li et al. 2022; Niiyama et al. 2015; Kellaris et al. 2018) and textiles (Kim et al. 2021; Sanchez et al. 2020; Nguyen et al. 2020). Film materials possess inherent flexibility, which compromises their mechanical durability. This makes them more prone to deformation or tearing with prolonged or intense usage. Moreover, while polymer film materials offer flexibility, they may not meet the necessary level of comfort required for wearable devices. Comfort and flexibility are crucial for extended wear, and polymer film actuators may fall short of meeting these criteria.

Their sharp edges can cause discomfort or irritation when in contact with the body. Furthermore, the aesthetic suitability and compatibility of polymer film actuators with wearable devices may be limited. Design and style are essential for the acceptance of wearable technology, and these actuators may not align with user preferences. Considering these factors, polymer film actuators are generally not the preferred choice for wearable technology applications. Alternative materials, such as textiles, offer superior comfort, flexibility, and integration capabilities, making them more suitable for wearable device design.

In contrast, textile-based materials offer significant advantages for pouch motors, especially in wearable applications prioritizing flexibility and comfort. Textile actuators integrate into garments, enabling aesthetically pleasing designs. They can be directly embedded into textiles, facilitating the development of smart clothing with integrated sensing and actuation capabilities. Moreover, textile actuators are washable, simplifying maintenance—a critical feature for wearable devices in close contact with the body. Textiles boast several other benefits, including being lightweight, conformal, and resilient against repeated stresses and abrasions encountered during regular use. Unlike flexible polymer films, textiles can withstand wear and tear, ensuring prolonged performance. With their hierarchical structure—from fibers to yarns, and further to fabrics—textiles provide a versatile platform for actuator development. Actuators are engineered at various levels within this hierarchical structure to suit specific functionalities, utilizing appropriate fabrication methods accordingly. For example, at the yarn level, techniques like melt spinning, wet spinning, and electrospinning are employed, while at the fabric level, methods such as weaving, knitting, or braiding fabrication are utilized (Pu et al. 2023). Instead of these technologies, actuators can be produced using cutting, sewing, and bonding methods with commercial woven and knit fabrics (Naclerio et al. 2020; Yap et al. 2017; Nguyen et al. 2019; O'Neill et al. 2022; Seyidoğlu et al. 2024; Yap et al. 2017; Nguyen et al. 2019; Liang et al. 2018; Dávila-Vilchis et al. 2022; Ma et al. 2023). The fabric-based actuator literature predominantly focuses on actuators constructed from commercially available Thermoplastic Polyurethane (TPU)-coated woven fabrics via laser cutting and thermal bonding fabrication methods, and these actuators often lack embedded sensors (Table 3.1) Woven fabrics, compared to knitted fabrics, are less flexible, restricting the motion range of pouch motors and hindering their ability to perform

complex movements (Nguyen et al. 2020). Furthermore, the fabrication process for woven pouch motors is less rapid for mass production. This results in increased production time and costs, while joining woven materials can pose challenges, especially on a larger scale, necessitating additional methods or equipment for material fusion and complicating the manufacturing process. The response to this challenge lies in computerized knitting fabrication. However, current studies indicate that actuators designed and fabricated using computerized knitting machines feature a tubular design, often lacking soft sensing capabilities, and exhibiting sensitivity to cutting and damage. They primarily concentrate on bending and coiling motions. These textile fabric actuators have been summarized in Table 3.1.

Table 3.1: Overview of reported textile fabric actuators.

Works	Material	Fabrication method	Actuation	Sensing	Motion	Comment
(Sanchez et al. 2020)	TPU-coated woven fabric	Laser cutting and heat bonding	Joule heating	Capacitive sensor (not embed)	Contraction	The sensor is integrated with heat bonding to the actuator.
(Thalman et al. 2019)	Woven fabric	Heat bonding	Pneumatic	-	Contraction	-
(Thalman et al. 2020)	TPU-coated woven fabric	Laser cutting, thermal bonding	Pneumatic	-	Contraction	Contraction motion is for compression.
(Sanchez et al. 2019)	TPU-coated woven fabric	Thermal bonding	Pneumatic	-	Contraction	-
(Schara et al. 2022)	TPU-coated woven fabric	Thermal bonding	Pneumatic	Pressure sensor and displacement sensor (not embed)	Contraction	Sensors are rigid and commercially available. 3D printing and bonding fabrication methods are used to integrate of sensor into the actuator.
(Elmoughni et al. 2021)	Lycra yarn, polyamide yarn, melting yarn	Computerized Knitting	Pneumatic	-	Bending	Tubular structure
(Yang et al. 2023)	The boucle of fancy yarns with the core of PU filament and the sheath of twisted PET fibers	Computerized Knitting	Pneumatic	-	Bending, coiling.	Tubular structure

Table 3.1 (continued): Overview of reported textile fabric actuators.

(Luo et al. 2022)	Acrylic yam, elastic yam, conductive yam	Computerized Knitting	Pneumatic	Resistive pressure sensing, swift frequency capacitive sensing (embedding sensor)	Bending	Tubular structure
(Sanchez et al. 2023)	Acrylic yam, shrinking yam, elastomeric yam, conductive yam,	Computerized Knitting	Pneumatic	Resistive sensing	Bending, coiling.	Tubular structure. Only, bending actuator consist of resistive sensing.

In this paper, we present the design and characterization of a novel biaxial soft knitted sensing pouch motor for foot drop and elbow assistance, inspired by the contraction behavior of the human muscle, shown in Figure 3.1 (a)-(b). This study investigates the potential of utilizing textile computerized knitting technology using high-performance Spectra yarn to make it with a cut-resistant feature for the development of soft pouch motors with embedded sensing capability (Figure 1c). Knitting technology provides a seamless, fast, scalable, and mass-production fabrication approach, instead of relying on the assembly of individual parts. The ability of the pouch motor to perform contraction motion, driven by radial expansion and transversal extension, has been thoroughly examined. Addressing the need for improved sensing capabilities and scalable mass production methods is crucial to unlocking the potential of soft pouch motors. It will not only expand their utility but also drive innovation in areas where their unique characteristics can make a difference.

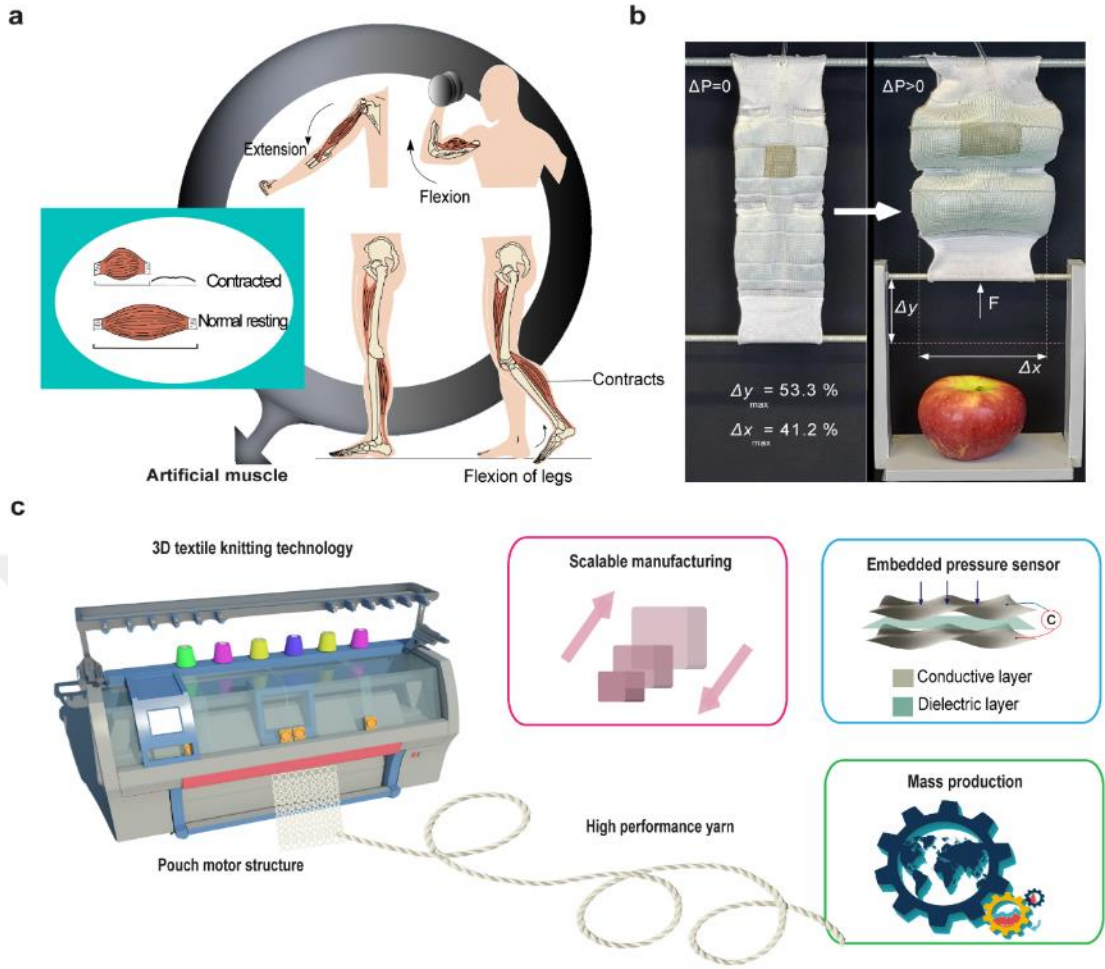


Figure 3.1: The design concept of a soft biaxial sensing pouch motors. (a) Illustration of artificial muscles bioinspiration from human muscles. (b) Prototype of the textile knit-based pouch motors. Δy represents the linear contraction along the y-axis. Δx indicates the transversal extension. (c) The sensing pouch motors are produced using 3D computerized knitting technology, featuring scalable mass production, high-performance yarn, and embedded pressure sensors.

3.2 Experimental Section

3.2.1 Materials

Three types of yarns were used to manufacture the pouch motor sample. The ground structure was created using commercially available 435 dtex ultra-high molecular weight polyethylene fiber (Polat Job Security Industry and Trade Co. LTD, Bursa, Türkiye) and commercial 140/70x2 denier nylon covered spandex yarn (Çombaş Industry and Trade Co. LTD, İstanbul, Türkiye). The sensing structure of the actuator was built using a commercial 235 f/36 dtex 2-ply HC+B silver-plated nylon conductive yarn (Shieldex®, Bremen, Germany). The linear resistance of this conductive yarn was

100 $\Omega \text{ m}^{-1}$, the elasticity was up to 17500 m kg⁻¹, the tensile strength was 46 cN tex⁻¹, and the stretching was up to 15%. To make an air bladder, an impulse sealer machine (PCS 300, Brother, Nagoya, Japan), thermoplastic polyurethane film (Stretchlon 200, Fiber Glast, Brookville, OH, USA), and a polyurethane tube were used.

3.2.2 Fabrication

The sensing pouch motor sample was manufactured using 14-gauge v-bed weft knitting technology (Shima Seiki NSVR 122, Sakata Wakayama, Japan). It is comprised of two rectangular-shaped pouches that are connected to each other. The pouch dimensions were 9 cm in width and 8 cm in height. The contraction line connecting the two pouches is located at the right and left edges of the pouch motor, measuring 1 cm in length and 3 cm in width. There is a central channel between the pouches that allow for the airflow of the air bladder. The pouch motor and electrodes of the sensor structures exhibited a course density of 9 courses per inch and a wale density of 9 wales per inch (wpc), resulting in a stitch density of 81 stitches per square inch (spi). To secure the soft pouch motor to the foot and ankle with Velcro straps passing through, a seamless strap region has been created within the knit structure of the soft pouch motor (Figure 3.2). To create two pouch air bladders, an impulse sealer machine (PCS 300, Brother, Nagoya, Japan), thermoplastic polyurethane film, and polyurethane tube were used. Pouch-shaped films were layered on top of one another, and an impulse sealer was used to create a bond between them at a time setting of 5.5 seconds. A polyurethane tube was inserted into the open end, and a pneumatic system was used to inflate it.

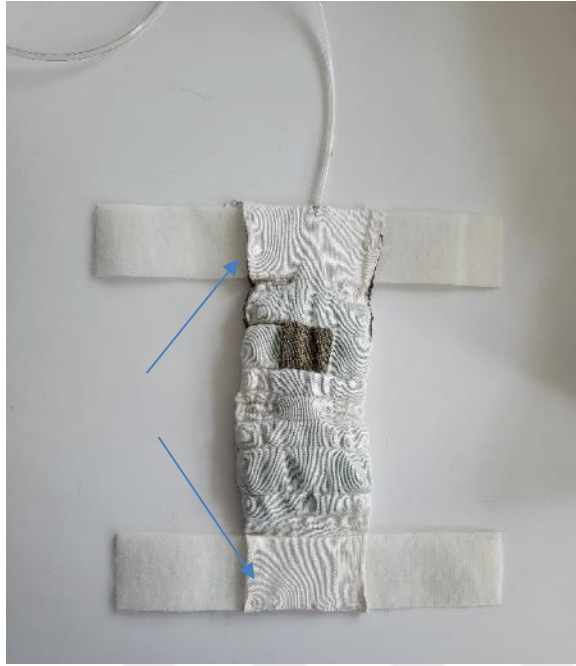


Figure 3.2: Velcro straps: a seamless strap region has been embedded within the knitted structure of the soft pouch motor.

3.2.3 Mechanical and electrical characterizations

The mechanical properties of yarn were tested using yarn grippers at a speed of 250 mm/min with a commercial uniaxial testing machine (Titan 5, James Heal, UK). The knitted samples prepared for modeling and simulation, according to their course and wale orientations, were subjected to mechanical testing using a 5 kN load cell on a uniaxial tensile testing machine (Zwick Roell Z005, Ulm, Germany) at a speed of 100 mm/min. Five 20 cm × 5 cm pieces of knit fabric were manufactured in the course-wale directions. Before testing, the samples were conditioned in a standard atmospheric environment for 24 hours. The extension (mm) and force (N) values were recorded during the tests. The digital microscope was utilized to observe the morphological structure of the yarns.

The static and dynamic experimental characterization of the pouch motors was performed utilizing a motorized horizontal single-axis test stand (ESM 303, Mark-10, Copiague, NY, USA), which was equipped with a single-axis load cell, a pressure regulator, vacuum pump, pressure sensor, linear encoder, a custom amplifier circuit, and a specially designed program for collecting experimental data. One end of the actuator was fixed in a stationary position, while the other end was attached to a weak spring and a magnetic linear encoder. This setup allowed the actuator to easily perform a contraction motion when pressurized air was supplied to it, with the amount of

contraction length being transferred to the computer as data based on the movement of the magnetic linear encoder. The capacitance value was measured using a capacitive touch sensor (MPR121 Proximity Capacitive Touch Sensor Controller, NXP, Eindhoven, Netherlands). Experiments have been conducted in normal atmospheric conditions.

3.2.4 Actuation

Pressurized air was supplied by an air compressor (DN200/8/6, Stanley, Italy) connected to the actuator through a pressure regulator (VPPM, Festo, Germany) and two solenoid valves (2W-025-08, Senya, China), which were used to regulate the pressure level and inflate and deflate the actuator. The air pump and solenoid valve were controlled by the 5 V, 4-channel relay board and Arduino Uno microcontroller. Using an air pressure sensor (MPXHZ6250A, Freescale Semiconductor, USA), the internal pressure of the actuator was measured.

3.2.5 Close-loop control system

A microcontroller (Arduino Uno Atmega328P®, Microchip, USA) as the control unit, a 10-watt power bank as the power source of the control unit, and a portable air compressor (Model 8010A, California Air Tools, USA) as the actuator are used to provide a pneumatic actuation source. The pressure-sensing sock is used for sensor feedback from the control system. The pressure-measuring sock can take on two values: short circuit and open circuit. If the measured resistance value is 120, it means the sensor is in a short circuit state, and if it is 1023, it means it is in an open circuit state. When the sensor is in a short circuit state, it means that pressure is applied to the ball of the foot touching the ground. When it is in an open-circuit state, it means that no pressure is being applied. When the sensor is in a short circuit state, the controller sends a signal for the air compressor to start working, and when it is in an open circuit state, the air compressor stops due to high pressure.

3.3 Design Concept and Fabrication of Knitted Sensing Pouch Motors

In this study, a novel high-performance pouch motors design with sensing capabilities was achieved by seamlessly integrating technical and electrically conductive yarns using computerized weft knitting technology. The classification of our pouch motor as “high performance” originates from the technical properties of Spectra yarn, which are

not typically found in other traditional textile yarns. In the fabrication of soft pouch motors using knitting techniques, Spectra yarn serves as the base material, enabling the transfer of high-performance attributes such as cut resistance and strength to the pouch motor.

The knitted pouch motor design is shown in Figure 3.3(a). Figure 3.4 shows the dimensions and knitted design simulation image of the pouch motor. The design of the knitted pouch motor is universally applicable, facilitated by the utilization of computerized knitting technology. The dimensions of the pouch motor have been optimized considering the foot width, foot and ankle attachment points, as it will be used for foot drop syndrome application. Based on foot width measurements from 10 adult women and men, the actuator width was selected as 9 cm (Figure 3.5 and Table 3.2). The average foot width for women is 9 cm, while for men, it is 10 cm. A 10 cm-wide pouch motor actuator aesthetically appears too broad and protruding for the foot width of women, hence a 9 cm width was chosen. This width also accommodates men's feet adequately. The actuator length is set at 19 cm, chosen as the optimum length required for secure attachment to the foot and ankle (Figure 3.6). Attachment areas for the foot and ankle are set at 4 cm to ensure secure fastening.

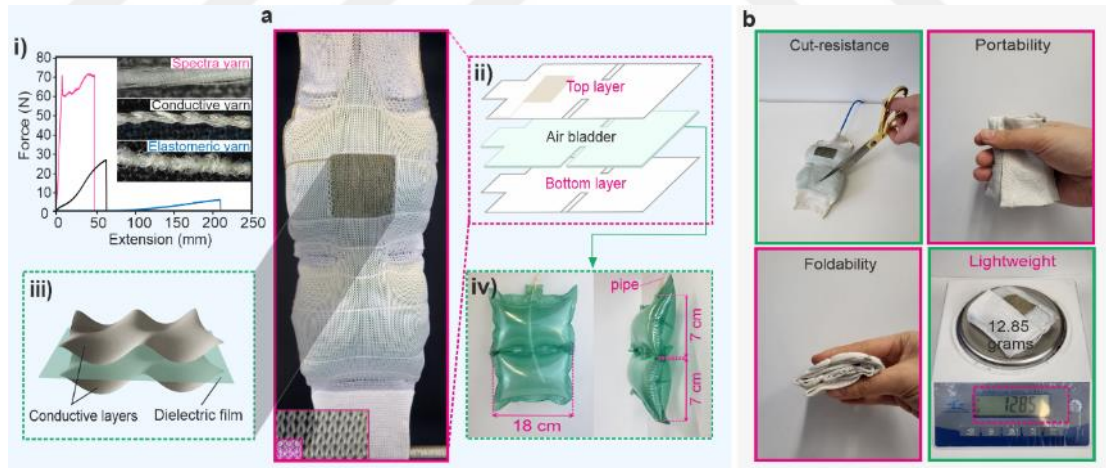


Figure 3.3: (a) Knitted sensing pouch motors. (i) The yarns used in the knitting design of the sensing pouch motors: ultrahigh molecular weight polyethylene yarn, conductive yarn, and elastomer yarn. (ii) Structure of the pouch motor. (iii) Capacitive sensor structure of pouch motors. (iv) The design and dimensions of the air bladder placed inside the pouch motors. (b) Demonstration of the cut resistance, portability, foldability, and lightweight features of pouch motors.

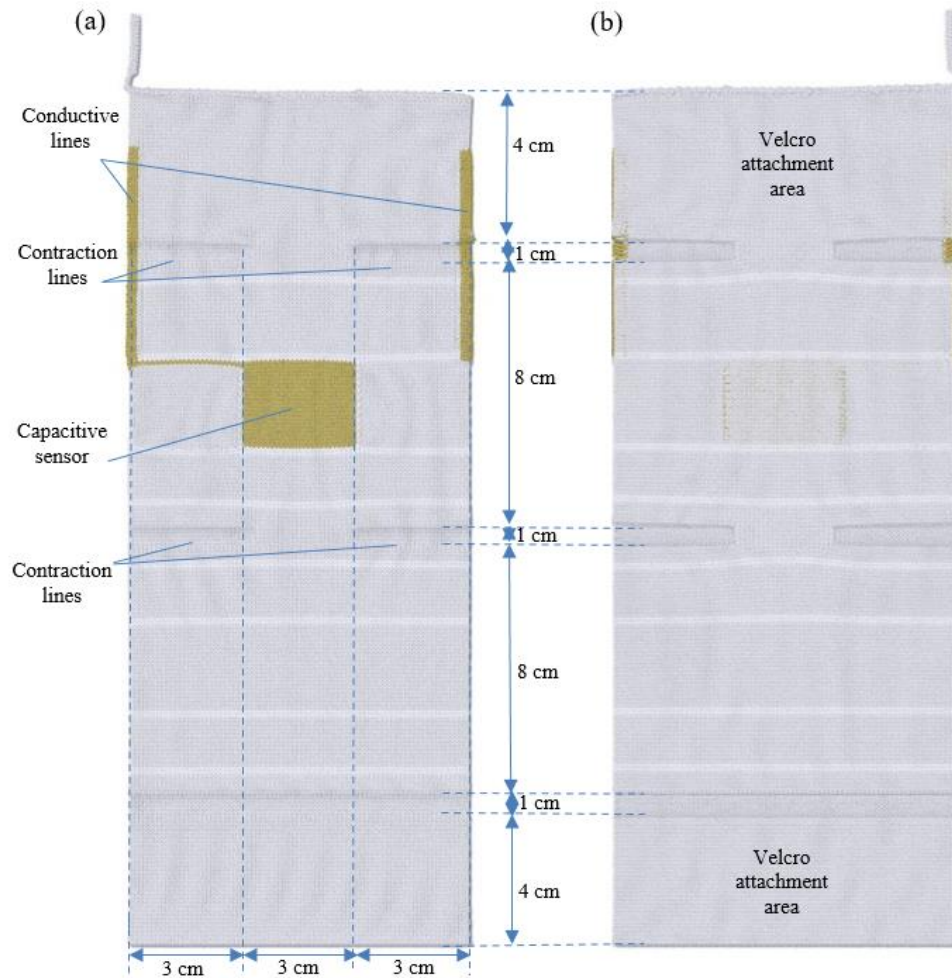


Figure 3.4: Knitted design simulation image and the size of the pouch motor. The yellow loops represent the conductive yarn, the gray loops represent the Spectra yarn, and the white loops represent the elastomer yarn. (a) front side. (b) back side.

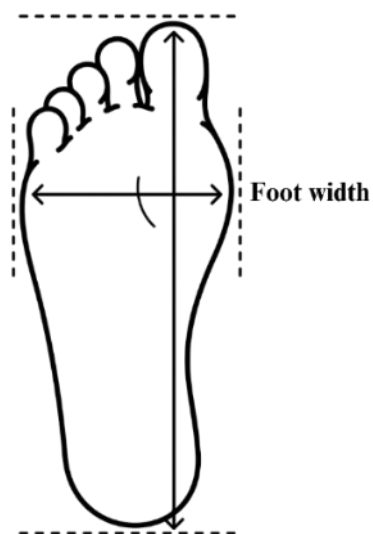


Figure 3.5: Illustration of foot width measurement indicated on the foot.

Table 3.2: Average foot width in humans.

Woman		Man	
Foot width (cm)	Foot size	Foot width (cm)	Foot size
8.5	38	10	44
9	38	10.5	41
9	39	10	43
9.5	38	10	43
9.5	37.5	10	42.5
8	36	10	44.5
9	37	11	45
8	38.5	9.5	40
9.5	38	9.5	42
9	39	10	41
~ 9 cm		~ 10 cm	

**Figure 3.6:** Attachment points of the knitted pouch motor to the foot and ankle.

In the construction of the pouch motors, three different types of textile yarns have been utilized: Spectra, conductive, and elastomeric yarns. These yarns play crucial roles in ensuring the functionality and performance of the motors, with each contributing distinct mechanical, electrical, and elastic properties to the overall design. The results of the tensile strength tests for these yarns are presented in Figure 3.3(a)(I). The high tensile strength exhibited by Spectra yarns, as evidenced by their minimal deformation under load, highlights their exceptional durability and suitability for applications requiring robust mechanical performance. Conductive threads, on the other hand,

demonstrate a balance between strength and flexibility, making them well-suited for use in electrical connections within the pouch motor. Their ability to maintain structural integrity while accommodating various mechanical stresses is essential for reliable electrical connectivity. Elastomeric yarns exhibit notable flexibility, as indicated by their ability to undergo significant deformation and recover to their original state. This property is crucial for applications where the pouch motor needs to adapt to changing shapes and environments, such as in soft robotics. The tensile test results highlight the unique characteristics of these yarns and their contributions to pouch motor technology, emphasizing the importance of selecting the right yarn type for specific design requirements, as shown in Figure 3.3(a)(I).

The base yarn of the pouch motor, Spectra yarn, is known for its exceptional strength, particularly its high tensile strength. This property makes it suitable for applications where the pouch motor needs to withstand significant loads. It has minimal stretch compared to other fibers, which is beneficial for maintaining the desired shape of the pouch motor. It is lightweight and advantageous in weight-sensitive applications such as wearable devices or soft artificial muscle robotics. It is highly resistant to chemicals, making it suitable for use in environments where exposure to corrosive substances may occur. Spectra yarn also boasts good abrasion resistance, contributing to the durability of the pouch motor. Additionally, its UV resistance makes it suitable for outdoor applications (Wang et al. 2021). This yarn offers flexibility while maintaining strength, crucial for achieving desired movements in soft robotics. These properties make Spectra yarn a suitable choice for the development of soft textile pouch motors using weft knitting technology. To impart a recovery feature to the pouch motor, elastomeric yarn is intermittently incorporated. When inflated and deflated, the pouch motor demonstrates the ability to self-recover even after extended cycles. The combination of Spectra yarn and elastomeric yarn empowers the pouch motor with exceptional recovery capabilities. After undergoing numerous inflation and deflation cycles, the motor consistently reverts to its original shape and dimensions. This feature ensures long-term reliability and durability in applications requiring repeated use. Electrically conductive silver-coated yarn is used in establishing and maintaining capacitive pressure sensor and electrical connections within the pouch motor. Conductive yarns enable the motor to transmit and receive capacitive signals effectively, making it responsive to pressure and contraction deformation.

The pouch motor is fabricated through the seamless integration of two layers consisting of upper and lower weft looped knitted fabrics, utilizing a digital knitting machine, as depicted in Figure 3.3(a)(ii). An air bladder is inserted between these layers to allow the pouch motor to inflate.

The main benefits of knitting fabrication technology are mass production and scalability (Elmoughni et al. 2021). In the process of fabricating a knitted pouch motor using a computerized knitting machine, the knit design is initially converted into a digital format compatible with the software of the machine. Then, the machine is programmed to knit pattern using yarns. The machine builds the structure of the pouch motor course by course as it knits, following preprogrammed instructions. The pouch motor is constructed with a knit structure in the form of a double-layered single jersey, while the contraction line is designed with a one-layered single jersey knit structure. The knitting process is executed by electronically controlled knit needles that move according to programmed instructions. These instructions dictate the movement of the needles along with the yarns to create the pouch motor design. The machine operates by feeding yarns through the needles and manipulating them to form loops on the knitting needle bed. As the needles move, they interlock the yarns to create pouch motors structure. Finally, the finished pouch motor is removed from the knitting machine.

The development of flexible and soft pressure sensors holds great significance, especially in soft robotics. A variety of sensing technologies have been explored in prior works (Gerratt et al. 2015; Gong et al. 2014; Viry et al. 2014; Gumus et al. 2022; Pazar et al. 2022; Yilmaz et al. 2023; Mohammed et al. 2017; Qiu et al. 2016; Tao et al. 2017; Park et al. 2010; Dagdeviren et al. 2016; Dagdeviren et al. 2015). Among these, the capacitive sensing technology employing parallel plate structures has gained popularity due to its signal repeatability, insensitivity to temperature, and relative design simplicity, among other advantages (Amjadi et al. 2016; Chortos et al. 2014). Figure 3.3(a)(iii) illustrates the capacitive pressure sensing technology embedded within the pouch motor structure, consisting of conductive electrodes and a dielectric thermoplastic polyurethane (TPU) film. The embedding sensor had dimensions of 3 cm in length by 3 cm in width, with a dielectric thickness of 38.1 μm . During the knitting fabrication process of the knitted pouch motor, the conductive yarns are knitted into the structure of the pouch motor using a technique called intarsia. Intarsia

is a knitting method where different yarns are used to create distinct patterns or designs within the knitted fabric. This integration ensures that the electrodes are seamlessly embedded within the knitted structure of the pouch motor, allowing for efficient electrical conductivity and functionality. By stitching the lower conductive knitted layer and the dielectric layer into the upper conductive electrode, we ensured their secure placement inside the pouch motors. Using a thin thermoplastic film for the dielectric layer resulted in higher baseline capacitance, enhancing sensor robustness against parasitic capacitance in the readout circuitry (Atalay et al. 2018). Furthermore, the conductive connection points from the pressure sensor were embedded within the knitted surface of the electrodes, enabling flexibility, and secure connections for real-life applications. Embedding sensor is inherently more stable and less prone to movement or detachment compared to externally attached sensors. This ensures consistent and reliable data acquisition during operation of pouch motor. Our knitting embedding fabrication approach eliminates the need for additional adhesives or heat press processes, reducing the risk of failure points and enhancing the durability and longevity. Overall, while post-integration of sensors may provide some convenience, the benefits of embedded production, including enhanced stability, seamless integration, and improved durability, make it a more favorable choice for achieving reliable sensing capabilities in soft robotics.

The activation of the pouch motor through air pressure results in contraction, while the use of weft knitting technology imparts it with the ability to deform easily and extend in the course direction. This combination of features enhances the performance of the pouch motor, allowing for both transverse extension and increased contraction. To enable the transverse extension, it is necessary to incorporate an air bladder within the pouch motor with a width twice that of the motor itself, as shown in Figure 3.3(a)(iv). This design choice is crucial in achieving optimal functionality.

The novel pouch motor developed in this study exhibits a set of features, making it a versatile and valuable component in the realm of soft artificial muscle applications, as shown in Figure 3.3(b). The incorporation of Spectra yarn into the pouch motor design provides it with a cut-resistant feature. Its compact and lightweight design makes the pouch motor highly portable, offering ease of transport and integration into various robotic systems. The flexible nature of the pouch motor allows for convenient folding, enabling efficient storage and deployment when needed. With its lightweight design,

the pouch motor maintains ease of use, effectively reducing the overall weight of soft robotic applications.

3.4 Simulation Procedure

For the macro scale simulation, the knitted textile-based material properties were considered as anisotropic hyper-elastic material (Nguyen et al. 2020). Previous numerical studies for soft actuators have concentrated on isotropic hyper-elastic materials (Agarwal et al. 2016; Moseley et al. 2016). However, there are some examples of textile-based soft actuator simulation in the literature review (Nguyen et al. 2016; Connolly et al. 2019). Some of the constitutive models that existed in ABAQUS software for anisotropic material modeling include the Holzapfel-Gasser-Ogden (HGO) and Fung models. The HGO strain energy formula is as follows;

$$U = C_{10}(\bar{I}_1 - 3) + \frac{1}{D} \cdot \left(\frac{(J^{el})^2 - 1}{2} - \ln J^{el} \right) + \frac{k_1}{2k_2} \sum_{\alpha=1}^N e^{k_2 \bar{E}_\alpha^2} - 1 \quad (3.1)$$

$$\bar{E}_\alpha = \kappa(\bar{I}_1 - 3) + (1 - 3\kappa)(\bar{I}_{\alpha\alpha} - 1) \quad (3.2)$$

where κ , k_1 , k_2 , D and C_{10} are temperature-dependent material parameters that are imported into the Abaqus2021 software. N is the fibers families number ($N \leq 3$). I_1 is the first constant of the Cauchy-Green tensor. The material fitting tool permits to define boundary conditions, Poisson's ratio, initial parameters obtained from HGO model and experimental equibiaxial data. Course and wale directions are corresponding to $(\sigma_{\theta\theta}, \sigma_{zz})$. A least-square method for the stress-strain functions in both directions was utilized as follows;

$$\chi = \sum_{i=1}^n \left[\left(\sigma_{\theta\theta} - \sigma_{\theta\theta}^{model} \right)_i^2 + \left(\sigma_{zz} - \sigma_{zz}^{model} \right)_i^2 \right] \quad (3.3)$$

To design the presented pouch motor in Abaqus2021 software, two identical shell plates were used, which are placed at a distance of 0.5 mm from each other (Figure 3.7(a)(I). To fit the boundary conditions appropriate to the experimental work, as shown in Figure 3.7(a)(ii), the surfaces under pressure were defined by partitioning, and the air pressure was uniformly applied to all internal regions of the pouch motor. The mesh used for this simulation, according to Figure 3.7(a)(iii) is C3D10M, and its

number is 1421. The simulation of the front surface of the pouch motor is presented in Figure 3.7(b). The simulation image of the lateral side of the knitted pouch motor, illustrating radial expansion, is depicted in Figure 3.7(c). The experimental data and the simulation of knitted pouch motor both exhibited similar contraction behavior, as shown in Figure 3.7(d). The simulation explains the experimental results with a 4% margin of error.

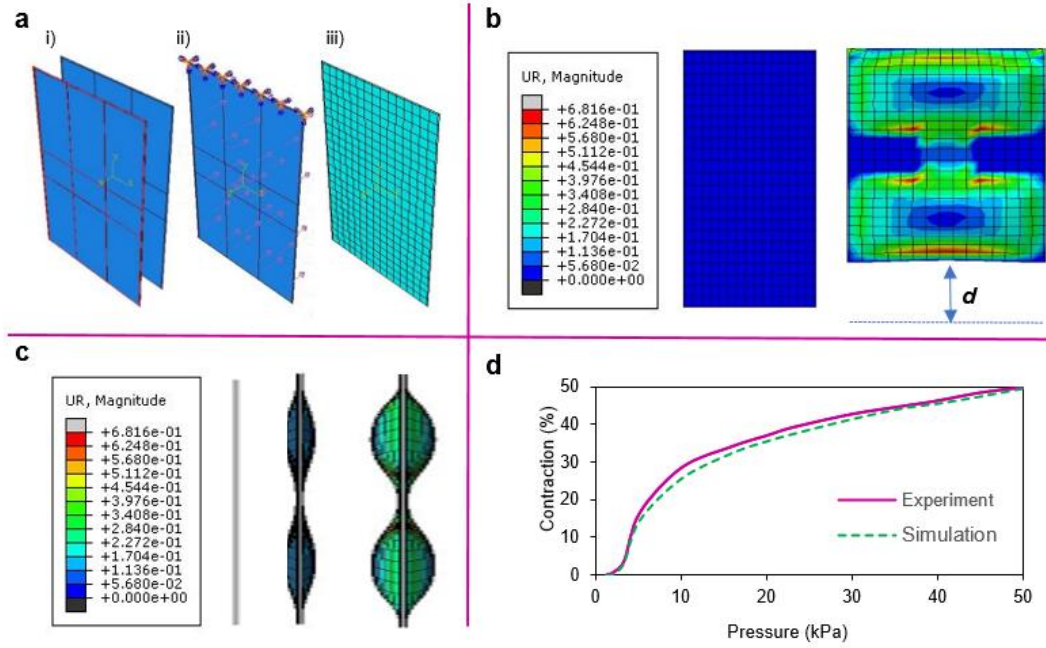


Figure 3.7: Simulation procedure of soft knitted pouch motor. (a) I) Pouch motor structure with the distance of 0.5 mm between each surface, ii) boundary conditions, and iii) mesh of the pouch motor. (b) Numerical images in the frontal view. (c) Numerical images in the lateral view. (d) Comparison of contraction behaviour: simulation v.s. experimental results.

3.5 Results

3.5.1 Mechanical characterization

We experimentally characterized the pouch motor by utilizing an air compressor for pneumatic actuation and a precision regulator for pressure adjustment. Upon inflation through the application of pressure, our pouch motor demonstrates features, including radial expansion and transverse extension, as illustrated in Figure 3.8(a) and Figure 3.8(b). The transverse extension deformation sets it apart from traditional pouch motors. The knitted pouch motor demonstrates both radial expansion and transversal extensions, leading to a contraction ratio of approximately 53.3%. The behavior of up to 41.18% extension along the x-axis can be attributed to the structure of the knitted

fabric, which allows the loops to expand laterally. Notably, with increasing pressure, we observe a corresponding increase in contraction, highlighting the sensitivity of our design to pneumatic changes. The pouch motor functions as a specialized mechanical artificial muscle actuator designed to exert forces for inducing motion in objects. Its primary function is to convert pneumatic power into pulling force, allowing it to exert forces and induce motion.

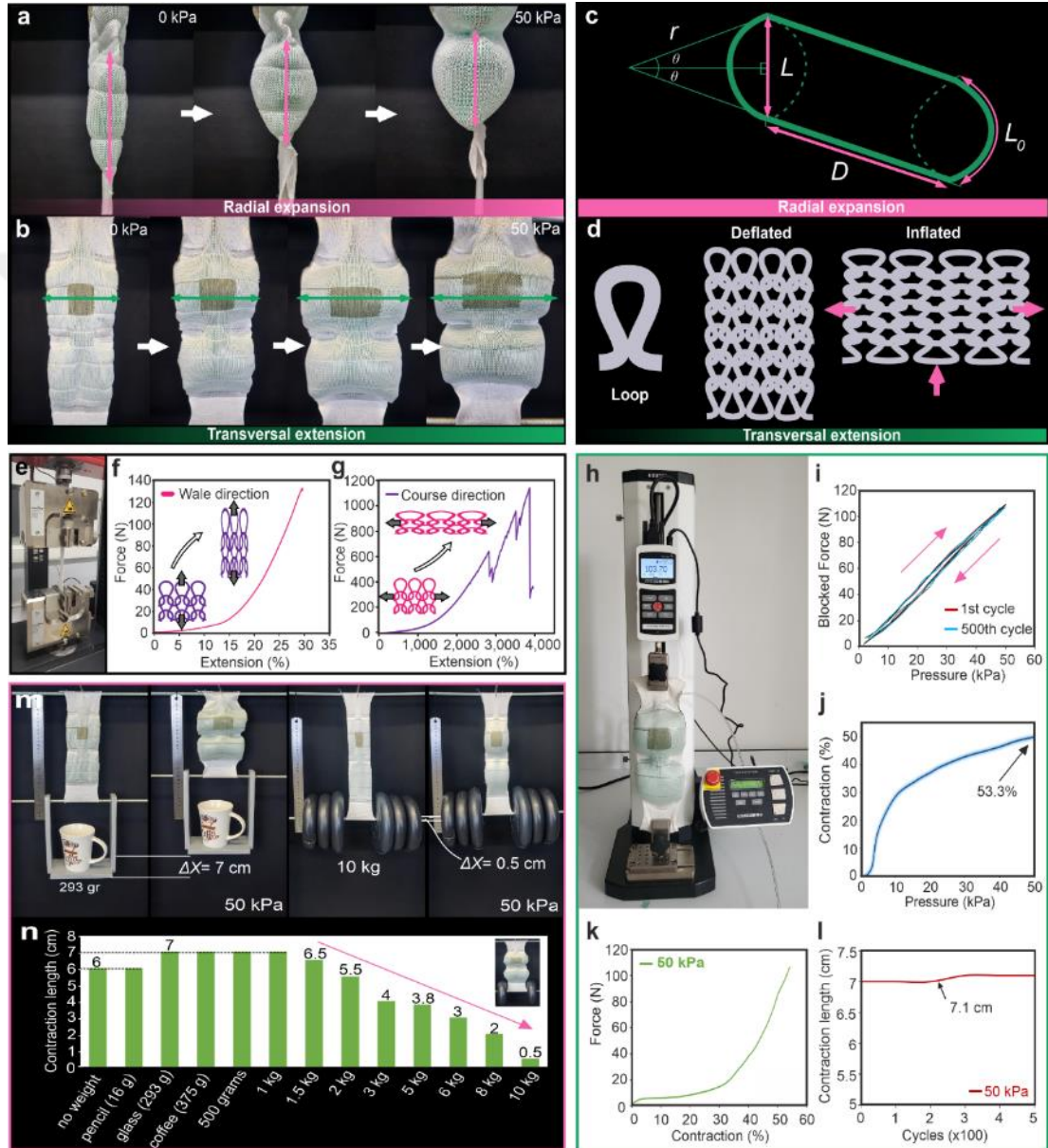


Figure 3.8: The contraction actuation mechanism of soft knitted pouch motor. (a) Radial expansion of the pouch motor. As the air pressure increases, the radial expansion of the motor also increases. (b) Effect of increasing air pressure on the transversal extension of the pouch motor. This deformation is based on the sliding of the knit loop structure in the weft direction. (c) Theoretical model of the pouch motors. (d) Loop structure of the knitted pouch motor in deflated and inflated states.

Figure 3.8 (continued): (e) Universal testing machine. (f) Tensile test of Spectra knitted fabric sample in the wale direction. (g) Tensile test of a Spectra knitted fabric sample in the course direction. (h) Experimental setup. The pouch motor is connected to an air tube and pressure sensor. Here, displacement, force, and air pressure are recorded. (I) Blocked force (N)- pressure (kPa) relationship during 500 cycles at pressures ranging from 0 to 50 kPa. (j) Maximum % contraction at pressures in the range of 0-50 kPa. (k) Force (N) – contraction (%) relationship at 50 kPa. (l) Change in contraction length (cm) during 500 cycles. (m) Showing that the 3D knitted sensing pouch motor exhibits the ability to lift up to 10 kilograms of weight under 50 kPa. (n) Contraction length (cm) of the pouch motor under various weights at 50 kPa pressure.

The theoretical contraction ratio for traditional pouch motors, assuming the surfaces of the pouch are cylindrical (Figure 3.8c), we can obtain equations to relate parameter of the pouches as

$$L_0 = 2r\theta \quad (3.4)$$

$$r \sin\theta = \frac{L}{2} \quad (3.5)$$

where L_0 is initial length of the pouch before deformation, r is a radius of the curve, L is the length of the inflated pouch, θ is the central angle of the circular segment,

$$A = 2r^2\theta - Lr\cos\theta \quad (3.6)$$

where A is the cross-sectional area of the pouch.

The volume of the pouch V can be derived as

$$V(\theta) = AD = \frac{L_0^2 D}{2} \left(\frac{\theta - \cos\theta \sin\theta}{\theta^2} \right) \quad (3.7)$$

where D is a width of the pouch. The length L can then be derived from the geometry as

$$L(\theta) = L_0 \frac{\sin\theta}{\theta} \quad (3.8)$$

The energy conservation equation derived from the equilibrium between input work dW_{in} and dW_{out} output work, is given by

$$-FdL = PdV \quad (3.9)$$

where F is the tension force, P is the inner pressure of the pouch, dL and dV are the displacements in length and volume. The force as a function of the angle can then be derived as

$$F(\theta) = -P \frac{dV}{dL} = -P \frac{\frac{dV}{d\theta}}{\frac{dL}{d\theta}} = L_0 DP \frac{\cos \theta}{\theta} \quad (3.10)$$

L_e is defined as the ratio of total deformation to the initial length of the longitudinal edges L_0 as

$$L_e = \frac{L_0 - L}{L_0} = 1 - \frac{\sin \theta}{\theta} \quad (3.11)$$

The theoretical maximum contraction ratio of the linear traditional pouch motor is $L_e(\pi/2) = \frac{\pi-2}{\pi} \approx 0.363$ (36.3%). However, pouch motors are not able to reach this theoretical value due to the force decreasing significantly in the later part of the contraction as the angle θ reaches 90° and the edges of the pouch not being able to deform in a circular shape. Thus, the practical maximum contraction ratio of the linear traditional pouch motors is closer to 30% (Oh et al. 2019). But, it can vary depending on parameters such as design, material, and fabrication technique. Our pouch motor is noted as having a high strain due to surpassing the contraction ratio of traditional pouch motors. This is attributed to the inherent mechanical characteristics of knit structure, as depicted in Figure 3.8(d). Knitting involves interlocking loops of yarn, which offer inherent flexibility, allowing for greater transverse extension compared to other manufacturing methods like weaving or braiding. In our study, we inserted an air bladder into the knitted pouch motor, twice as large as the pouch motor itself, enhancing the opening of the knitting loops and facilitating increased transverse extension. This combination of features enhances the performance of pouch motor, allowing for both transverse extension and increased contraction.

The knitted structure of the pouch motor, characterized by its course (the horizontal rows of loops) and wale directions (the vertical columns of loops), plays an important role in its actuation performance. For this reason, we analyzed the structural integrity of Spectra base fabric of the pouch motor by subjecting it to uniaxial tensile testing using a mechanical testing machine, as shown in Figure 3.8I. The fabric sample exhibits a 32% extension at 138 N in the wale direction (Figure 3.8(f)) and 2800% extension at 620 N in the course direction, as shown in Figure 3.8(g). After achieving a 2800% extension at 620 N, a decline in the graph was observed due to the loop breakage. Knitted structures are known for their construction, which involves interlocking loops of yarn in both the course and wale directions (Gong et al. 2011).

The interlocking loops in both directions distribute forces evenly, ensuring that the fabric can withstand the stresses associated with the contraction and extension cycles of the motor. From these perspectives, when additional weight is applied to the pouch motor, it tends to contract along the y-axis without significant extension, even at lower internal air pressure, making it easily deform in the transverse direction.

The knitted pouch motor was subjected to actuation tests as isotonic (constant load) and isometric (constant length). The measurements were performed under static conditions. Isometric tests were used to investigate the relationship between tensile force and pressure. The isometric tests consisted of each soft pouch motor being pretensioned to 0.5 N (chosen to minimize slack in embedded fibers while also reducing effects on actuator performance and pressurized to 50 kPa (chosen to avoid failure), as shown in Figure 3.8(h). This was performed for three trials. The actuator can generate a maximum blocked force of $107 \pm 2.2\text{N}$ when pressurized up to the maximum operating pressure of 50 kPa (Figure 3.8(i)). Due to the limited pressure threshold of the air bladder, pressures exceeding 50 kPa were not applied. The hysteresis of the pouch motor, exposed to 500 cycles of inflation and deflation, is not significant. This decrease in hysteresis is attributed to the strategic placement of elastomeric yarns in the course direction. Experiments demonstrate that the output force of the pouch motor increases with input air pressures. Isotonic tests were used to investigate the maximum contraction with increasing pressure. Typical pneumatic contraction actuators can deliver a maximum contraction of around 25–35%, for example, McKibben muscle and other pouch motors (Daerden et al. 2002; Niiyama et al. 2015). Our pouch motor has exhibited a maximum contraction behavior of up to 53.3% with increasing pressure (Figure 3.8(j)).

Figure 3.8(k) shows the force–contractile relationship at a constant 50 kPa maximum pressure. The pouch motor exhibits a 53.3% contraction, corresponding to a reduction in length of 7 cm. After subjecting the pouch motor to 500 inflation and deflation cycles at 50 kPa, it was observed that its contraction increased to 7.1 cm after 235 cycles, as shown in Figure 3.8(l). This demonstrates the remarkable durability of the pouch motor, as repeated inflation and deflation did not result in structural degradation. This data underscores resilience of the pouch motor and stability over multiple inflation and deflation cycles, making it a reliable component for various

applications. The minimal change in its contraction behavior indicates its robust design and suitability for long-term use.

By first subjecting the pouch motor to rigorous mechanical testing, we gained insight into its baseline capabilities. However, it was also crucial to examine how it would perform under more realistic conditions that it might encounter in everyday use. The 50 kPa test was conducted to simulate the kinds of loads it could face in practical applications, allowing us to assess its functionality and reliability in scenarios that align with its intended use. The contraction length of the muscle structure was measured while loads varied from 125 grams to 10 kilograms, as shown in Figure 3.8(m)-(n). There was a general trend for the contraction length of the muscle structure to be reduced as the load it carried was increased. At a pressure of 50 kPa, a maximum contraction of 7 cm has been measured. To ensure the pouch motor reaches its full length, it is necessary to apply a lightweight load, such as a 293-gram (glass weight), as depicted in Figure 3.8(m). Knitted structures shrink or curl after production (once removed from the knitting machine) due to unbalanced forces generated by the yarn loops. In their unstressed or relaxed state, knitted fabrics typically exhibit a non-fully stretched configuration. This phenomenon arises due to the inherent looped structure and the elastic nature of the constituent yarns. The inherent gathering observed in relaxed knitted fabrics stems from the ability of the yarn loops to adjust and move within the overall fabric structure. Therefore, applying tension is essential to counteract these tendencies and achieve full extension of the pouch motor. This tensioning process serves the purpose of mitigating the inherent gathering within the fabric. By doing so, it facilitates a more uniform alignment of the yarn loops. This tensioning technique aids in revealing the actual size and shape of the knitted pouch motors. As a result, this approach ensures that the pouch motor is not only theoretically sound but also practically viable.

3.5.2 Sensor characterization

The soft capacitive pressure sensor of knitted pouch motors consists of conductive knitted layers to serve as electrode layers and thermoplastic polyurethane film dielectric layer, illustrated in Figure 3.9(a). We employed an Ag-coated polyamide yarn to knit the conductive electrode surface. Figure 3.9(b) illustrates an optical microscopy image of the loops in the conductive knitted layer. The incorporation of a

capacitance pressure sensor into a knitted pouch motor allows for the precise calculation of capacitance variations in direct reaction to changes in both the air pressure delivered to the pouch motor and contraction motion. This sensor integration provides real-time monitoring and feedback, offering valuable insights into the interplay between internal air pressure and pouch motor deformation and how it influences the behavior of the sensor.

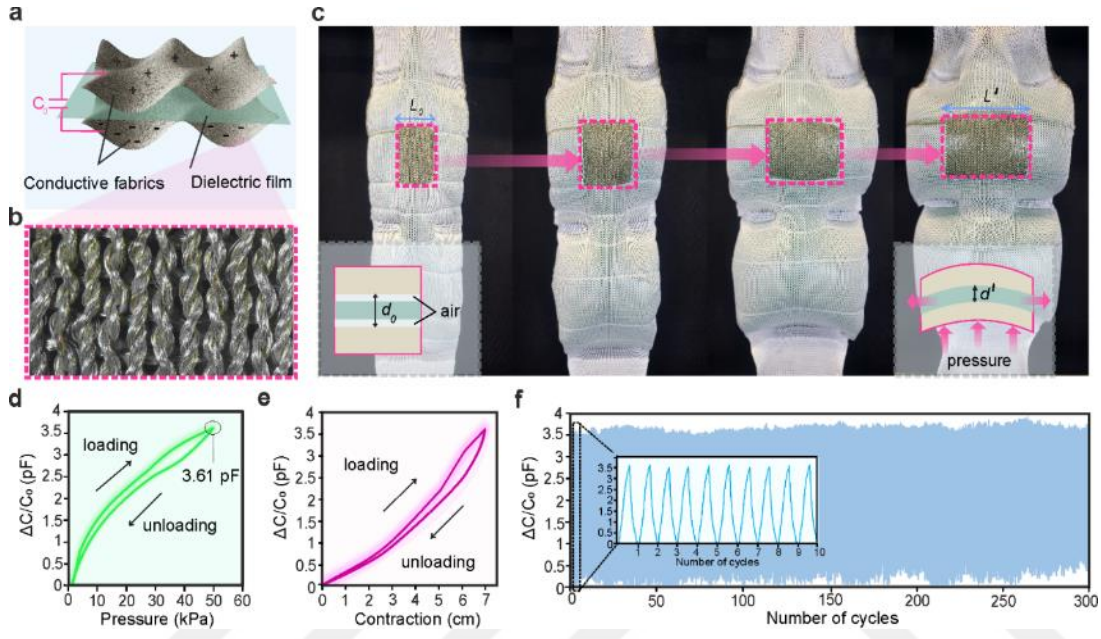


Figure 3.9: Capacitive pressure sensing of knitted pouch motor. (a) Cross-sectional view of the capacitive sensor comprising conductive electrodes at the top and bottom, separated by a dielectric film. (b) Optical microscopy image of the loop structured sensor electrode (c) Actual images of the sensor increasing air pressure. (d) Relative change in capacitance during the loading/unloading process under 50 kPa. (e) Relative capacitance change of sensor with increasing and decreasing contraction length (cm) of the pouch motor. (f) Sensor repeatability test.

To assess the electrical response of these sensors to applied air pressure, we designed an experimental setup for the synchronized collection of mechanical and electrical data, employing a mechanical tester and a capacitance meter. The capacitance of the sensor (C_{sensor}) can be understood through several parameters, including electrode area (A), dielectric thickness (d), the dielectric permittivity of a vacuum (ϵ_0), and the relative permittivity of the dielectric (ϵ_r). Equation (1) quantifies the changes in capacitance attributable to variations in dielectric layer thickness and electrode area.

$$C_{sensor} = \epsilon_0 \epsilon_r \frac{A}{d_0} \quad (3.12)$$

Pressure application causes the conductive knitted area to stretch, leading to an expansion in the surface of the electrode (Figure 3.9I). This stretching results in an increased capacitance of the electrode due to the larger surface area, enabling better overlap between the conductive layers. The width of the sensor exhibits a 100% increase when the pouch motor is inflated. When the fabric is in its unstrained state, the closely spaced knit loops of the sensor create numerous conduction paths, resulting in a low initial resistance. As the fabric undergoes stretching, the morphology of the loop changes, primarily due to yarn slipping at the interlooping points. This change reduces the contact areas between the knitting loops, thereby improving the contact resistance ($R_{contact}$). As $R_{contact}$ increases, the capacitance of the sensor also increases because of the expanded surface area of the electrode caused by stretching. Consequently, the connections between the arc segments of the knitting loops recede, leading to visible gaps and open circuits, which further raise the resistance of the knit sensors. Besides, as the pouch motor receives internal air pressure, the air gaps between the conductive layers and the dielectric film gradually close. This process leads to an increase in capacitance, enhancing the sensitivity of the sensor. The decrease in air gaps acts like a secondary dielectric layer, leading to a more noticeable change in capacitance when the sensor experiences mechanical deformation or changes in pressure.

In Figure 3.9(d), we observe the electrical response of the sensor under applied pressure levels, ranging from increasing to decreasing, up to 50 kPa. Notably, the change in capacitance is most pronounced when subjected to the maximum pressure. The sensitivity (S) of the pressure sensor can be calculated as $S = \Delta C/C_0/P$, where P represents the applied pressure and ΔC and C_0 signify the change in capacitance and baseline capacitance, respectively. The pressure sensitivity of the sensor is determined to be $722 \times 10^{-4} \text{ kPa}^{-1}$. The relationship between the output electric signals (normalized capacitance change, $\Delta C/C_0$), and the contraction is depicted in Figure 5e. We observed that as the pouch motors contracted, the relative capacitance changed the it increased with increasing pressure. In the pressure unloading phase, the relaxation of stress within the material leads to a partial recovery of its original configuration. However, deformations and hysteresis persist, especially within the pressure range between 50 kPa and 30 kPa, and as the contraction decreases. Below 30 kPa, the decreasing hysteresis indicates a notable transition, potentially corresponding to the

saturation of deformations or the establishment of a quasi-equilibrium state within the material. As a result, the influence of pressure variations on the capacitive sensor becomes less pronounced, leading to reduced hysteresis. Overall, the observed hysteresis behavior reflects the intricate interplay between material properties, structural dynamics, and sensor characteristics in the textile-knitted pouch-based pressure sensing system.

To evaluate the stability of the pressure sensors concerning pressure sensitivity, we conducted a repeated loading/unloading cyclic test, as shown in Figure 3.9(f). The sensor demonstrated both long-cycle stability and satisfactory robustness after 300 loading and unloading cycles at 50 kPa of air pressure.

These results signify that the soft pressure sensor is well-suited for detecting air pressure levels during the contraction process and holds promise for applications requiring robotic control. The stable and reproducible signal affirms the potential of the sensor for long-term usage. Therefore, the designed pressure sensor meets the requirements for effectively monitoring actuation and contractions in the realm of soft robotics.

3.5.3 Application demonstration

The high contraction ratio and high output force exhibited by pouch motors make them an ideal choice for incorporation into soft artificial muscle robots. In our study, we have selected to demonstrate the exercise and walking application of pouch motors in the context of an exoskeleton robot designed to address foot drop syndrome. In this robotic design, as depicted in Figure 3.10(a), the system featured an electro-pneumatic control unit, as shown in Figure 3.10(a)(i) that could be comfortably secured around the waist, conductive wires transmitting signals from the heel to the pneumatic control system (Figure 3.10(a)(ii), pressure-sensing socks, and our pouch motor easily attachable to the foot and ankle (Figure 3.10(a)(iii)). Within the control system worn around the waist, there is a pneumatic pump, a battery, and an Arduino Uno microcontroller board. These components collectively contribute to the functionality and operation of the system.



Figure 3.10: Application demonstration of the soft pouch motor in assistive robotics. (a) Showing the concept behind the soft ankle-foot orthosis exosuit. (b) Phases of the human gait. (c) Functionality and application of the textile-based resistive pressure sensing sock. (d) Dorsiflexion motion of the simulated ankle joint by soft pouch motor. (e) Close-loop control block diagram. (f) Deflated pouch motor fastened to a human foot. (g) Dorsiflexion of the human foot using pouch motors that is inflated.

Healthy individuals naturally perform the “heel strike,” “stance,” “heel off,” and “swing” walking phases while walking (Figure 3.10(b))(Awad et al. 2020). These phases involve generating an ankle dorsiflexion moment in the swing phase of each limb to lift the foot and facilitate ground clearance. However, when it comes to exoskeletons, concerns such as rigidity, high development costs, portability, alignment complications with the biological joint they are trying to assist, and comfort over extended periods of use arise (Thalman et al. 2018). By using our soft pouch motor, developed through knitting technology, we introduce valuable addition to the field of assistive artificial muscle devices. Its adaptability, convenience, lightweight nature, cost-effectiveness, and comfort in both robot and human interactions make it a good fit for wearable applications, enabling prolonged daily usage.

The soft pouch motor securely attaches to the foot and ankle using textile straps to generate torque for lifting the simulated ankle joint. Our assistive wearable device

consists of a textile-based resistive pressure sensor (Atalay et al. 2018) (Figure 3.11) designed to be placed on the heel of the sock and a soft pouch motor. The soft pouch motor is controlled with a single resistive pressure sensor, specifically a heel contact sensor, which detects gait timing. As the swing walking phase initiates, the ankle dorsiflexes, raising the toes to clear the ground for the upcoming gait cycle that begins at the heel strike (Perry et al. 2010). The input received from the heel activates the pneumatic system of the actuator, causing it to expand and subsequently inducing a contraction motion, resulting in dorsiflexion of the foot. Dorsiflexion involves an increase in the joint angle and an upward movement of the toes. The presence-absence resistive sensor placed on the heel of the sock is connected using thermoplastic-coated conductive threads for both positive and negative connections (Figure 3.10(c)). As a result, the soft pouch motor automatically adapts to changes in the gait speed of the wearer, as the pressure sensor detects when the heel is on the ground and pressure should be applied to the pouch motor. Tests have indicated that the pouch motor has the potential to provide dorsiflexion assistance, as evidenced by the simulated ankle achieving a dorsiflexion torque of 20° at 50 kPa air pressure, as shown in Figure 3.10(d). This indicates the potential effectiveness of the motor in supporting ankle dorsiflexion. The response time is approximately 1 second. Optimizing the equipment constituting the pneumatic control system has the potential to further reduce response time. Proper design, sizing, and configuration of valves, pressure regulators, pipes, and powerful pumps in pneumatic systems are crucial for achieving faster response times. In the future, by focusing on the design and engineering of the pneumatic system, we will achieve even faster response times of the pouch motors.

The schematic diagram of the closed-loop control system illustrating the operational principle of our soft robotic system is presented in Figure 3.10(e). After evaluating the dorsiflexion torque capability on the simulated ankle joint, the ability of the pouch motor to apply torque on the human foot was also tested. Figure 3.10(f) indicates the deflated pouch motor securely attached to a human foot, showcasing its initial state. The dorsiflexion of the human foot is demonstrated through the inflated pouch motor, as shown in Figure 3.10(g). It successfully applies approximately 35 degrees of dorsiflexion torque to the human foot at 50 kPa pressure. This depiction highlights the dynamic functionality of the pouch motor in facilitating dorsiflexion, underlining its potential as a valuable component for supporting walking and foot drop exercises.

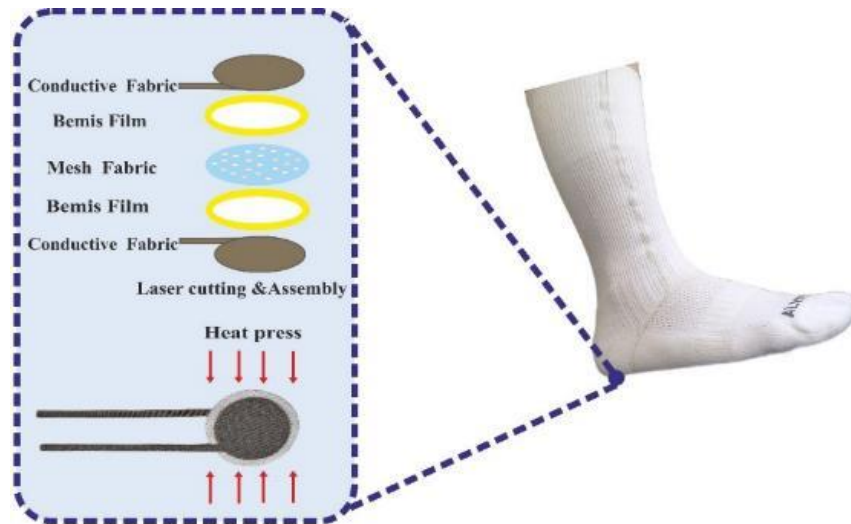


Figure 3.11: Textile-based resistive pressure sensor assembly in exploded view.

The pouch motor is anchored at the ankle and foot, ensuring the inflation region – the part that transversal extension and radial expansion – doesn’t touch the foot itself. This targeted inflation focuses solely on lifting the foot, minimizing any potential contact-induced discomfort. The device utilizes a securing element (strap, band, or Velcro) that allows users to adjust the tightness around the ankle and toes. This personalization feature ensures a comfortable and secure fit, preventing the pouch motor from slipping or causing irritation due to excessive tightness. In simpler terms, this soft pouch foot lift assist is designed to be gentle on your foot. It inflates only where needed for lifting, and the pressure and tightness can be adjusted for your comfort. Furthermore, in general, the duration of the dorsiflexion phase in a walking cycle covers a short period. Therefore, there will be no comfort issues associated with it.

3.6 Discussion

In Table 3.3, we compare the performance metrics of existing pneumatic pouch motors studies with knitted pouch motors, focusing on parameters such as contraction, force, pressure, and sensor sensitivity. However, it’s essential to note that our primary objective is not to assert the superiority of our pouch motors over existing works in terms of specific performance metrics. Instead, the novelty of our work lies in demonstrating the utilization of textile computerized knitting technology for the design and fabrication of sensing fabric pouch motors. By employing textile knitting technology, we aim to enable rapid and scalable manufacturing of these motors. While our knitted pouch motors may exhibit similar average values for contraction, force,

and pressure compared to those using film and TPU-coated materials, it's crucial to consider the longevity and durability factors. The utilization of film and TPU-coated materials in other studies may restrict their durability and render them less resilient in real-world applications. Our soft knitted pouch motor, integrating high-performance Spectra base yarn, effectively leverages its outstanding features, including cutting resistance and high strength. This attribute contributes to the overall durability and reliability of knitted pouch motors, making them suitable for practical artificial muscle applications.

Table 3.3: Comparison of pneumatic pouch motors.

Work	Material	Max. contraction ratio (%)	Max. force (N)	Pressure (kPa)	Sensor type and sensor sensitivity
Pouch (Niiyama et al. 2015)	Film	28	100	40	-
Flat film PAM (Kwon et al. 2020)	Film	44	300	30	Capacitive sensor* (Not embed)
Origamic Pouch (Li et al. 2022)	Film	40.6 (Series) 55.9 (Parallel)	175.2	30	-
Paired Pouch (Oh et al. 2019)	TPU-coated woven commercial fabric	41.9	100	90	-
Gusseted Pouch (Jang et al. 2023)	TPU-coated woven commercial fabric	42.6	100	40	-
CRAM (Xie et al. 2021)	TPU-coated woven commercial fabric	48.3	33.1	100	Capacitive sensor* (Not embed)
X-PAMs (Feng et al. 2023)	TPU-coated woven commercial fabric	0.92	134.7	150	-
Knitted sensing pouch motors (This work)	Knitted fabric	0.53	107	50	Embedded capacitive sensor $722 \times 10^{-4} \text{kPa}^{-1}$

* These data are not found in the article.

3.7 Conclusions

Our muscle-inspired study has utilized 3D textile knitting technology to digitally fabricate soft and robust pouch motors, incorporating pneumatic-driven contraction motion programmed within their knit loop architecture. The soft pouch motor we have developed addresses the challenges of scalability and mass production while also positioning itself as a promising solution in the field of soft robotic artificial muscles. Our soft knitted pouch motor, integrating high-performance Spectra yarn, effectively leverages its outstanding features, including remarkable cutting resistance, lightweight design, and high strength, which set it apart from other film-based and woven fabric-based pouch motors. It displayed a high contraction ratio under 50 kPa pressure, with a maximum lifting capability of 10 kilograms a remarkable 53.3% contraction along the y-axis, and a transverse extension of 41.18% along the x-axis.

One noteworthy advantage of this compact design is the transverse extensibility provided by the knitting technology, resulting in a significantly improved contraction rate when compared to conventional woven fabric and film-based pouch motors. This enhanced performance has broad implications for various applications. Furthermore, the transverse extensibility has increased the area of the embedded capacitive sensor, leading to an enhanced capacitance change in pouch motor sensing technology.

The primary function of the motor is to offer dorsiflexion support, with the potential to address foot drop symptoms, although further empirical validation is needed. Furthermore, our research underscores its potential to drive advancements in powered orthoses. The inherent compliance and flexibility of the design facilitate the development of soft robotic devices that closely mimic the natural form and movement of the human body.

The pouch motor offers practical benefits, including enhanced user mobility, making it suitable for daily use and easy to put on. It is expected that forthcoming human subject trials will provide concrete evidence of these advantages. In this context, the work makes a valuable contribution to the field of soft robotic artificial muscle technologies. Furthermore, knitted pouch motors embedded within a wearable device or clothing during social touch and interactions can help people feel more connected to each other, whether in person or on digital platforms. Additionally, in the world of VR gaming, pouch motors can contribute to a heightened sense of touch and feedback.

They can simulate the feel of virtual objects and environments, adding depth and realism to the gameplay. With their potential to provide lifelike sensations, knitted pouch motors can have the power to revolutionize the gaming experience, bringing players closer to their virtual worlds. The integration of pouch motors in haptic applications can offer exciting possibilities for enhancing the way we interact with digital environments and each other.



PRELIMINARY WORKS

4. CAPACITIVE SENSING TEXTILE-BASED ACTUATORS²

The use of textiles in soft robotics is gaining popularity because of the advantages textiles offer over other materials in terms of weight, conformability, and ease of manufacture. The purpose of this research is to examine the stitching process used to construct fabric-based pneumatic bending actuators as well as the effect of segment types on the actuators' properties when used in soft robotic glove applications. To impart bending motion to actuators, two techniques have been used: asymmetry between weave and weft knit fabric layers and mechanical anisotropy between these two textiles. The impacts of various segment types on the actuators' grip force and bending angle were investigated further. According to experiments, segmenting the actuator with a sewing technique increases the bending angle. It was discovered that actuators with high anisotropy differences in their fabric combinations have high gripping forces. Textile-based capacitive strain sensors are also added to selected segmented actuator types, which possess desirable properties such as increased grip force, increased bending angle, and reduced radial expansion. The sensors were used to demonstrate the controllability of a soft robotic glove using a closed-loop system. Finally, we demonstrated that actuators integrated into a soft wearable glove are capable of grasping a variety of items and performing various grasp types.

Keywords: soft robotic; soft actuator; sensing actuator; textile-based actuator; wearable robot.

4.1 Introduction

Recent years have seen an increase in the study of soft robotics, with the goal of ensuring the safe interaction of robot technologies with humans and the environment (El-atab et al., 2020; Wang et al., 2018). Textile materials are favored in these investigations due to their lightweight, softness, conformability to various shapes, and

²This chapter is based on the paper “Yilmaz, A.F., Khalilbayli, F., Ozlem, K., Elmoughni, H.M., Kalaoglu, F., Atalay, A.T., Ince, G., Atalay, O. 2022. Effect of Segment Types on Characterization of Soft Sensing Textile Actuators for Soft Wearable Robots, *Biomimetics*, 7, 249. DOI: 10.3390/biomimetics7040249.”

comfort properties (Wang et al., 2018; Sanchez et al., 2021; Xiong et al., 2010; Connolly et al., 2019). As a result, terminology such as “robotic textiles”, “wearable robots”, and “textile-based robots” began to appear in the literature, and textiles became a component of new generation robots. Naturally passive textiles gain the ability to activate in a number of ways and become dynamic. Textile actuators can be powered by cable-driven (or tendon-driven) systems (Popov et al., 2016; Kim et al., 2019; Xiloyannis et al., 2019; In et al., 2015; Awad et al., 2017; Yang et al., 2019; Schmidt et al., 2017), hydraulic or pneumatic fluid systems (O’Neill et al., 2020; Bryant et al., 2014; Naclerio et al., 2020; Cappello et al., 2018; Elmoughni et al., 2021; Polygerinos et al., 2013; Ge et al., 2020; Zhu et al., 2020), or shape-memory polymers (Granberry et al., 2019; Park et al., 2020; Kim et al., 2009). However, fluid-driven actuation is one of the most prevalent and rapidly growing types of actuation in the soft robotics field for developing assistive devices (Pan et al., 2021). To create fabric-based fluidic actuators capable of applying forces and defining motions, layers of materials with opposing mechanical properties are joined to form anisotropic inflated pouches. Technologies such as ultrasonic welding (Cappello et al., 2018), thermal welding (Connolly et al., 2019; Ge et al., 2020; Feng et al., 2021), and overlock sewing (Cappello et al., 2018) have been used to construct anisotropic actuator shells by combining fabric layers with different mechanical properties. Soft actuator shells are then inflated with air-fluid to produce the necessary force and motion. The creation of mechanical anisotropy between fabric layers is essential to obtaining the bending motion of the pressurized fabric actuator (Cappello et al., 2018). However, a thorough investigation into how the high or low mechanical anisotropy differential of the fabric layers that make up the actuator might affect the actuator’s force characterization is still lacking.

Prior experiments employing silicon actuators have indicated that segmented actuators are advantageous for high energy consumption, low energy density, and delayed response time problems (Polygerinos et al., 2013; Yang et al., 2020; Mosadegh et al., 2014; Galloway et al., 2016; Wang et al., 2019). The main goal of this research is to determine how different segment types created by sewing affect the characteristics of fabric-based actuators. Therefore, we explored how different segment types affected the actuators’ grasping forces and bending angles. To accomplish this, we first combined commercially available woven and weft knit fabrics with an asymmetry and anisotropy approach, followed by demonstrating the design of the soft bending

actuator using sewing technology. We evaluated the influence of varying anisotropies between layers using two distinct knit and woven textiles. To show the actuators' suitability for wearable applications, they were employed to make a soft robotic glove. With the expansion of soft robotics into more complex and demanding applications, sensor data become critical for obtaining high task performance levels. Thus, we combined our previously textile-based capacitive sensors (Atalay et al., 2017) into optimally characterized actuators and showed their use in a wearable exoskeleton glove using a closed-loop system design.

4.2 Materials and Methods

4.2.1 Fabric materials

Two woven and two weft knit textile fabrics with varying structure properties were used in the experiments. Table 4.1 lists the properties of knit fabrics that are coded as K1 and K2, while Table 4.2 lists the properties of woven fabrics that are coded as W1 and W2.

Table 4.1: Properties of knitted fabric samples.

Properties of Fabrics	Knit Fabric 1 (K1)	Knit Fabric 2 (K2)
GSM (g/m ²)	180	235
Course per cm	41	50
Wale per cm	35	26
Thickness (mm)	0.58	0.48
Fiber Type	Polyester/Elastane	Polyamide/Elastane
Knit Structure	Single Jersey	Single Jersey

Table 4.2: Properties of woven fabric samples.

Properties of Fabrics	Woven Fabric 1 (W1)	Woven Fabric 2 (W2)
GSM (g/m ²)	195	165
Warp density (ends/cm)	52	34
Weft density (picks/cm)	35	24
Thickness (mm)	0.45	0.41
Fiber Type	Polyester	Polyester
Weave Structure	Coated Plain Weave	Plain Weave

4.2.2 Fabrication of soft fabric actuator

Figure 4.1 depicts the fabrication method of textile actuators. The actuators are made by combining knit fabric on the top layer and woven fabric with a strain-limiting function on the bottom layer using a Brother CS 6000i sewing machine. The sewing is performed with 301 lock stitch at four tension settings. For sewing thread, 100 percent polyester Nm 60/2 thread was used. Table 4.3 shows that segment types, sample numbers, and fabric combinations of 28 different actuators were created. Actuators are made up of six different segment types that are A, B, C and 3S, 5S, 7S using two different knit (K1–K2) and two different woven fabrics (W1–W2). The fabric combinations in Table 4.3 define which woven fabric is used in the bottom layer of the actuator and which knit fabric is used in the top layer of actuator. These actuators have asymmetry due to the difference in width-wise length (woven fabric width: 1.5 cm, knitted fabric width: 4.5 cm) and anisotropy due to the inherent elasticity difference (Figure 4.1(a)). We discovered that the joining seam strength of the actuator made of woven and knitted fabric cut asymmetrically is more durable than the joining seam strength of the actuator cut symmetrically.

To make the actuator without adding segments, the woven fabric was cut into strips 15 cm long by 1.5 cm wide, and the knitted fabric was cut into strips 15 cm long by 4.5 cm wide, as shown in Figure 4.1(a) and Figure 4.1(b). The woven fabric was then reversed on the knit fabric and aligned to its right edge. On the right edge, the aligned knitted and woven fabrics were sewn with a straight stitch. After that, the same sewing process was repeated, but this time the woven fabric was aligned to the left edge of the knit fabric. After straightening the knit strip so that it was in the center of the woven strip, the upper end of the actuator was also sewn with a straight stitch, and the actuator sample was closed on three sides. Finally, the actuator's front face was turned out. Woven and knit fabrics were cut into strips to begin the production of segmented actuators. Across the width of the knit fabric, segment stitches were made Figure 4.1(c). The joining process of woven fabric and segment stitched knit strip was completed in the following steps of the production of non-segmented actuators. In our study, we labeled segment types as A, B, and C, as well as 3S, 5S, and 7S. The A, B, and C segment types indicate stitch spacing between the lower and upper width-wise stitches. The joints in the human finger were taken into consideration to create the 3S,

5S, and 7S segments. The codes 3S, 5S, 7S refer to the number of stitches created separately in the upper and lower parts of the knit fabric.

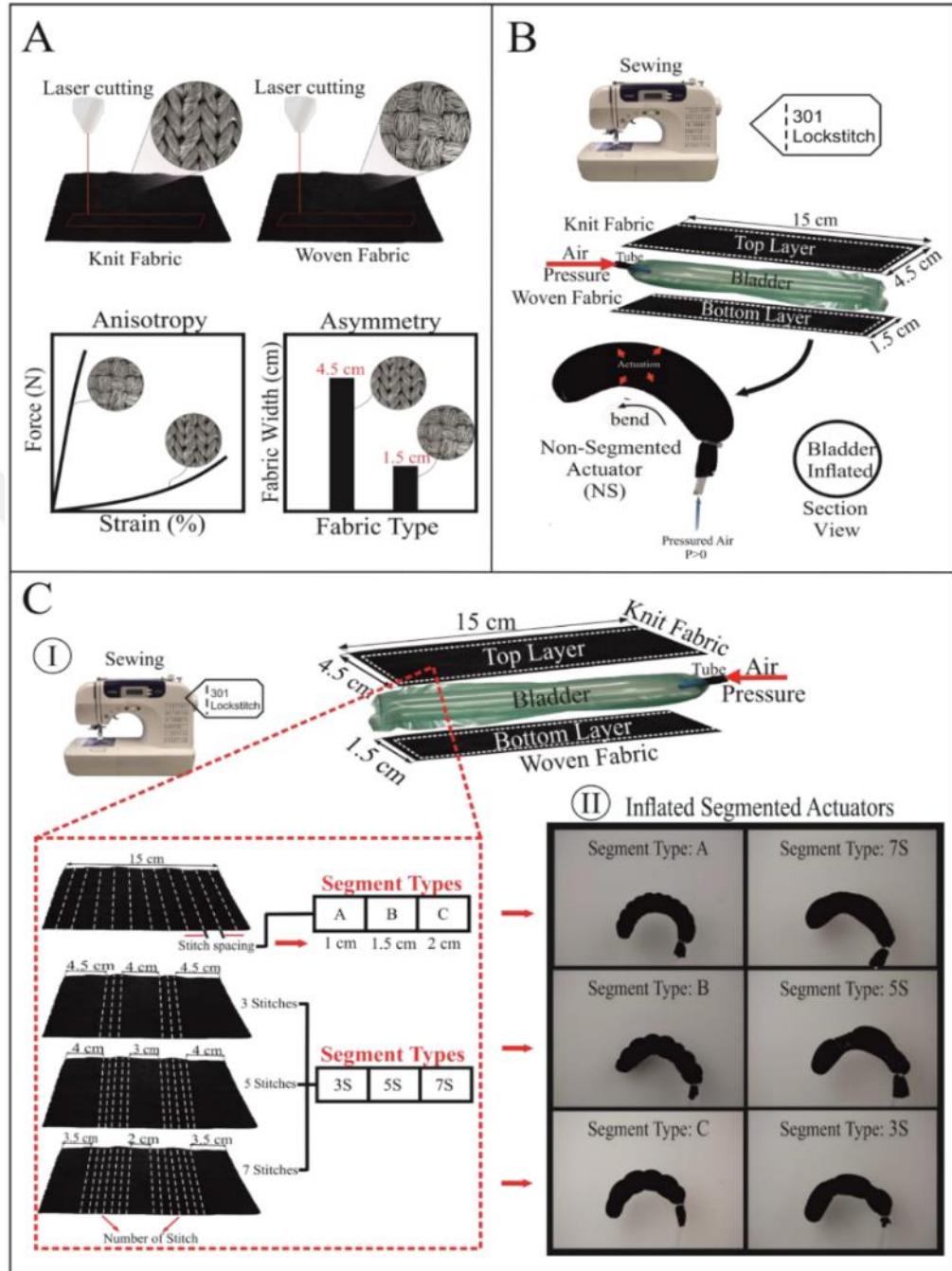


Figure 4.1: Fabrication steps of non-segmented and segmented fabric-based actuators. (a) Laser cutting of knit and woven fabrics, showing mechanically anisotropy and asymmetry approaches. (b) Construction and sewing of non-segmented actuator, demonstrating the bending motion of the inflated non-segmented actuator. (c) Construction of segmented actuators. (I) Sewing of segment types (A, B, C and 3S, 5S, 7S) on knit fabric. (II) Showing of pressurized states of segmented actuators.

Table 4.3: Segment types and fabric combinations of actuator samples.

Segment Types	Sample	Fabric Combinations
Non-Segmented (NS)	1	K1W1
	2	K2W1
	3	K1W2
	4	K2W2
A	5	K1W2
	6	K1W1
	7	K2W2
	8	K2W1
B	9	K1W1
	10	K1W2
	11	K2W2
	12	K2W1
C	13	K2W1
	14	K1W1
	15	K2W2
	16	K1W2
3S	17	K2W1
	18	K2W2
	19	K1W1
	20	K1W2
5S	21	K2W2
	22	K1W2
	23	K1W1
	24	K2W1
7S	25	K2W2
	26	K1W2
	27	K1W1
	28	K2W1

4.2.3 Fabrication of thermoplastic air bladder

The air bladder was manufactured using an impulse sealer machine (PCS 300, Brother, Nagoya, Japan), thermoplastic polyurethane film (Stretchlon 200, Fiber Glast, Brookville, OH, USA), and polyurethane pipe. The impulse sealer machine was set to the 5.5 s time setting in order to form a bond between two rectangular cut films that were stacked on top of one another. When all three sides of the rectangle cut TPU sheet were closed, the bonding procedure was complete. By inserting a polyurethane tube into the open end, air was forced into the bladder via a pneumatic system, inflating it. The actuators in our study were composed of a single pocket produced by two layers of fabric, and a tpu bladder of 18 cm in length and 2.8 cm in width was inserted into the actuator's pocket.

4.2.4 Sensor integration to actuator

Based on our previous study, we prepared textile-based capacitive strain sensors made of conductive silver-plated knit fabric as electrodes and silicone elastomer a dielectric (Atalay et al., 2017). The capacitive sensor was bonded using flexible glue to the knit fabric, (the actuator's upper layer) and dried, as shown in Figure 4.2. This procedure was performed for five actuators, which correspond to the five fingers of a wearable robotic glove. This sensor measures the elongation of the actuator during bending motion; consequently, we measured the change in capacitance and defined the corresponding bending angles of the actuators created for five fingers. The actuators were then permanently attached to the fingers of a wearable glove.

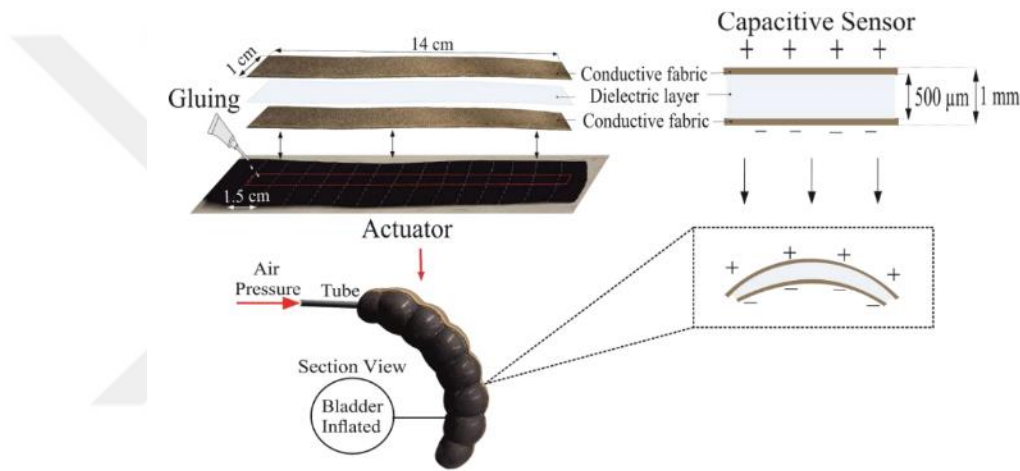


Figure 4.2: Sensor integration to actuator.

4.2.5 Tensile test

The “uniaxial test method” or the force effect method in only one direction is used to determine the anisotropic tensile properties of fabrics. In this investigation, we used the James Heal Titan Universal Testing Machine to conduct uniaxial tensile tests in accordance with the EN ISO 13934-1 test standard (Figure 4.3). Five strips of 20 cm × 5 cm were cut in the weft–warp directions and the course–wale directions of woven and knit fabrics, respectively. All fabrics were conditioned for 24 h prior to the test under typical atmospheric conditions. The average of five samples was used to produce the force–extension graph. The speed of the test is 100 mm/min. The goal of this test is not to measure the fabric’s strength but to determine the direction of extension and to demonstrate the differences in mechanical anisotropy between woven and knit materials. This test is critical because the bending movement of an inflated actuator is

obtained when the high extension direction of the knit fabric is used in the longitudinal direction of the actuator.

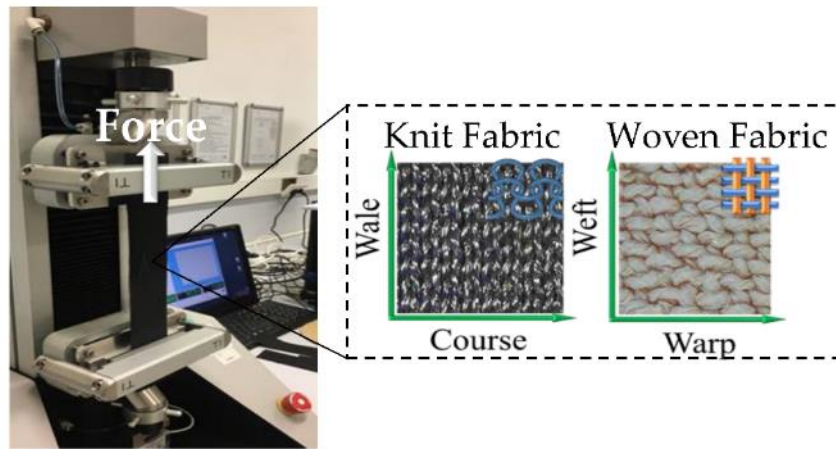


Figure 4.3: Uniaxial tensile test of knit fabric and woven fabric.

4.2.6 Grip force-pressure test

The soft actuators were characterized in order to understand how grasping force varies with actuator pressure using the grip force test setup demonstrated in our study (Elmoughni et al., 2021). The gripping range of each actuator was determined by the amount of pulling force applied by the actuator to the hollow rectangle attached to the dynamometer.

4.2.7 Bending angle-pressure test

To better understand the bending behavior of the single chamber soft actuator, the change in its bending angle in relation to the applied pressure is recorded for each actuator as it is gradually inflated. To provide consistency between actuator samples and to facilitate understanding, bending angle is widely utilized in comparison with the curvature value (Cappello et al. 2018) when measuring the actuators' bending motion.

To eliminate the variation in brightness caused by the lighting conditions in the room, the actuator was placed in a closed platform that included a camera, an installation fixture, and a single-channel test rig. An air pump, a vacuum pump, an inflate valve, a deflate valve, a vacuum valve, a 4-channel relay board, an air pressure sensor, an MPR121 capacitive touch sensor controller, manual switches, and a power supply comprise the single-channel test setup (Elmoughni et al. 2021). Using manual switches, the test rig can inflate, deflate, or vacuum the actuator's bladder. Due to the

nature of TPUs, vacuum is the state of full suction of the air inside the bladder, which cannot be obtained when utilizing the deflate command. The test equipment can monitor and communicate bladder air pressure and actuator capacitive sensor values to the computer. During the tests, the proximal end of the actuator was secured to the installation fixture to eliminate any unwanted motion, while the distal end moved freely in a circular motion.

A digital camera (Microsoft LifeCam HD-3000, Microsoft, Beijing, China) positioned perpendicular to the actuator's platform captured the bending action of the actuator. Three color markers were attached to the neural axis of the actuator, and their location was fixed in accordance with the finger knuckles to establish the bending angle. As a result, the extreme points are the bottom of the proximal phalanx (M1), the middle of the medial phalanx (M2), and the top of the distal phalanx (M3).

By using automated contour detection and circle-fitting algorithms operating in real time, the coordinates of each marker's centroid in each frame of the captured video are identified. Thus, the angle formed by M1, M2, and M3, namely angle A , is calculated by the Cosine formula:

$$A = \cos^{-1} \left(\frac{b^2 + c^2 - a^2}{2bc} \right) \quad (4.1)$$

where b is the distance between M1 and M2, c is the distance between M2 and M3, and a is the distance between M1 and M3. The bending angle is calculated as the conjugate angle to the central angle that sub-tends to the inscribed angle, A .

To demonstrate the experiment's repeatability, the actuator's inflation and deflation processes were repeated six times sequentially. Due to the fact that the number of frames collected per second and the pressure values obtained were varied, these values were matched using their timestamps. To produce more stable results, the initial cycle of pressure application and withdrawal was omitted. After obtaining the matched data, just the inflation component was retrieved, as only the inflation component contained valuable information on the bending motion. The average pressure value corresponding to each bending angle was calculated. This procedure was followed for all actuator types.

4.2.8 Torque-pressure test

To determine the twisting force exerted by the actuator around its own proximal end, the value of the exerted torque was recorded at various bending angle configurations. To replicate the range of finger motion, the bending angle was set between 0° and 75° in multiples of 15°. The actuator's distal end was inserted into a hollow cylinder created using a three-dimensional (3D) printer and affixed to the top of the dynamometer to apply a pulling force during the experiments. The distal end was fastened in a solid 3D-printed object and relocated for the purpose of collecting torque values at various bending angle configurations. During the torque experiment, the actuator was inflated and deflated four times sequentially with the same static pressure speed, and the related statistical variables were calculated. The torque test was conducted in the same manner as the grip force test in terms of data collecting and post-processing. To determine the torque value, the actuator with the best grip force and bending angle was chosen and included in the experiment setup. To calculate the net output torque, τ , the product of the dynamometer pressure value (F) and the actuator–dynamometer distance in mm ℓ was used.

$$T = r \cdot F \quad (4.2)$$

4.2.9 Radial expansion test

In unrestricted designs, radial expansion of the actuator walls results in an increase in its diameter and a decrease in bending angle over a wide range of pressure levels. The radial expansion of two distinct actuators is determined, and their performance is compared in relation to the applied internal pressure. To accomplish this, the actuator was put in an isolated area that was internally illuminated in order to maintain a static lightning state during the experiment. A rectangular object with a defined width and height and a different color than the actuator was positioned beneath the actuator, and the camera installed at the top of the experiment environment captured the actuator's motion over the object. Due of the color-based method used, the experiment area was intended to contrast with the object. The outside contours of the viewable parts of the item were generated using image processing techniques. As observed in Figure 4.4, the object looked to be divided into three sections from the camera as a result of the actuator being placed on it. The regions covered by the right and left sections can be identified based on the object's color. However, the region of the middle part cannot

be detected because it is beneath the actuator. Given the shape of the object, the region it covers may be determined by adding the upper and lower lines of the right and left sections.

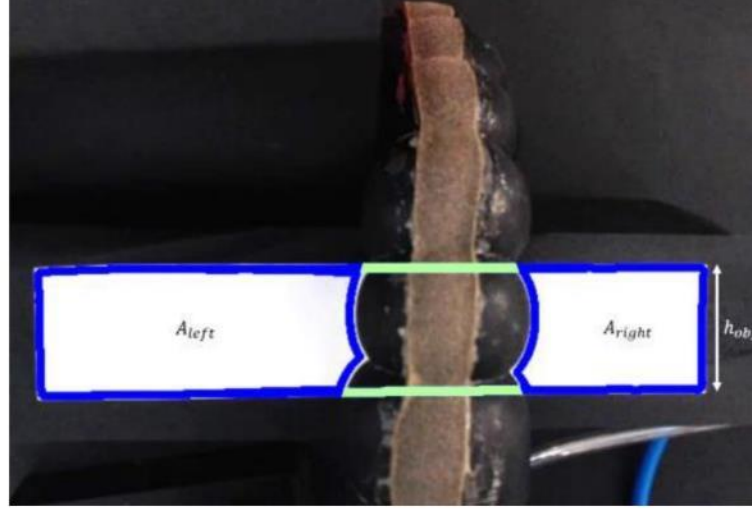


Figure 4.4: Camera view of the radial expansion test setup.

The number of pixels in the region occupied by the object indicates the area of the object in the image. Using the formula in Equation (3), the pixel per square cm ($PPcm^2$) value in the image is found using:

$$PPcm^2 = \frac{A_{obj}}{\hat{A}_{obj}} \quad (4.3)$$

where A_{obj} is the area of the object in cm^2 and $\hat{A}_{obj}$ is the number of pixels in the region occupied by the object. In other words, $\hat{A}_{obj}$ is the pixel area of the object in the image. The region underneath the actuator provides information about the actuator's diameter. The pixel area of the region underneath the actuator is calculated as:

$$\hat{A}_{under} = \hat{A}_{obj} - \hat{A}_{right} - \hat{A}_{left} \quad (4.4)$$

where A_{hidden} is the pixel area of the region hidden by the actuator, A_{right} is the pixel area of the right part of the object, and A_{left} is the pixel area of the left part of the object. Then, real area of the region underneath the actuator can be calculated using $PPcm^2$ and A_{hidden} as below:

$$A_{under} = A_{hidden} \cdot PPcm^2 \quad (4.5)$$

Furthermore, the actual area of the region hidden by the actuator can be calculated as below:

$$A_{under} = \bar{d}_{act} \cdot h_{obj} \quad (4.6)$$

where $\bar{d}_{act}$ is the average diameter of the actuator, and h_{obj} is height of the object. Using both formulas, the average diameter of the actuator can be calculated as below:

$$\bar{d}_{act} = \frac{\hat{A}_{under} \cdot PPcm^2}{h_{obj}} \quad (4.7)$$

Actuator radial expansion and the air pressure data are collected simultaneously in a real-time manner.

4.2.10 Capacitance measurement

The constant DC charge approach was utilized in this work to measure capacitive sensors. This technique charges the sensor with a constant current value over a constant time period. Thus, capacitance stores a charge, which may be calculated using Equation (4.8):

$$Q = I \cdot t \quad (4.8)$$

where Q is charge amount, I is the current of the charge, and t is the duration of the charge. After the charging process, the voltage information of the sensor can be measured, and the capacitance value can be calculated using Equation (4.9):

$$Q = C \cdot V \quad (4.9)$$

where C is the capacitance value of the sensor, and V is the voltage value of the sensor after the charging. Using both equations, the capacitance value is calculated as follows:

$$C = \frac{I \cdot t}{V} \quad (4.10)$$

It is possible to increase the sensitivity of capacitance measurement by changing the current and charging time parameters in this technique.

Capacitance is measured using the MPR121: proximity capacitive touch sensor controller. The integrated circuit's primary role is to detect the body capacitance using the electrodes produced for the button and keypad. The capacitance of the human body fluctuates between 50 pF and 250 pF (Ott et al., 2009), and capacitive sensors produced

with textiles do not surpass this value. As a result, this integration can also be used in capacitive sensors based on textiles. Charge current and time values can be modified in software on this integrated circuit, allowing for more precise measurement of capacitances across a wide range. Additionally, the integrated circuit's two-layer digital filter reduces noise during capacitance measurements. This integrated circuit is capable of measuring up to 12 electrodes/sensors.

The system is powered by a 12V 16A power supply. This power supply also feeds the microcontroller, relays, and valve drivers. The pressure sensor and MPR121 are fed with appropriate voltages through the voltage regulator connected to the microcontroller. Due to the voltage difference between the microcontroller and the power supply, it is given to the microcontroller after the voltage is reduced to the appropriate level with the adjustable voltage regulator.

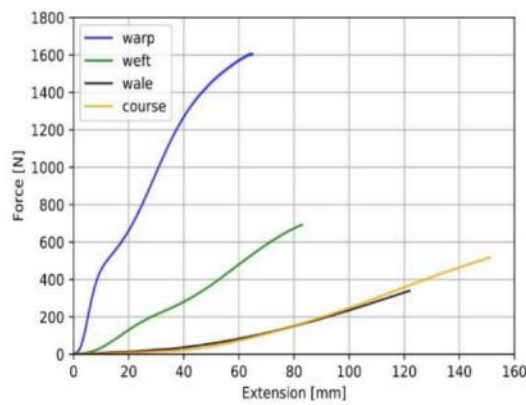
4.3 Results and Discussion

4.3.1 Uniaxial tensile characteristic of woven and knit fabrics

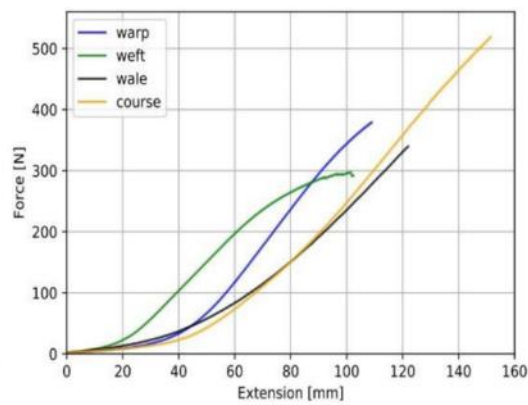
When inflated with air, fabric actuators elongate and deform in various directions. The anisotropic behavior generated by the variation in elongation of the textiles is employed by the actuator to perform the bending movement. In this study, to determine how anisotropy difference of textile materials affects actuator performance, a comparison of the tensile characteristics of the woven and knit fabrics that make up the actuator structure was made.

The results of the force–extension test of combinations of knit fabrics and woven fabrics are given in Figure 4.5. The extension until failure for woven 1 (W1) fabric in the warp direction was 65 mm at 1600 N, and in weft direction, 83 mm at 700 N; for woven 2 (W2) fabric in warp direction was 110 mm at 390 N, and in weft direction, 100 mm at 300 N. The extension until failure for knit 1 (K1) fabric in the course direction was 150 mm at 530 N, and in wale direction, 125 mm at 340 N; for knit 2 (K2) fabric in course direction was 188 mm at 198 N, and in wale direction, 150 mm at 260 N. According to the results of the uniaxial tensile test of textile fabrics, an anisotropy comparison was made in two main directions, warp–weft for woven fabric and course–wale for knit fabric. Knit and woven fabrics exhibited different deformations as a result of fiber content, linear density, fabric geometry, yarn

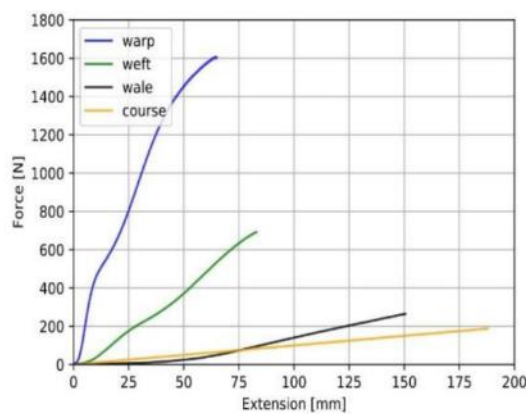
properties, and related Poisson effects in response to applied loading. Knit fabrics showed more deformation than woven fabrics due to their loop structures and elastane yarn content. Due to the elongation of the course direction of knit fabrics and the warp direction of woven fabrics, the longitudinal placement of the actuator was made in these directions. The woven 1 fabric was more rigid than the woven 2 fabric due to its coated structure, that is, it showed a low elongation tendency when high force was applied. In addition, it was concluded that the anisotropy difference between the warp direction of the woven 1 fabric and knit fabrics (K1 and K2) was very high. Among the fabric combinations, K1W1 and K2W1 had the highest anisotropy difference between woven and knit layers, and the lowest anisotropy difference was noted for K1W2.



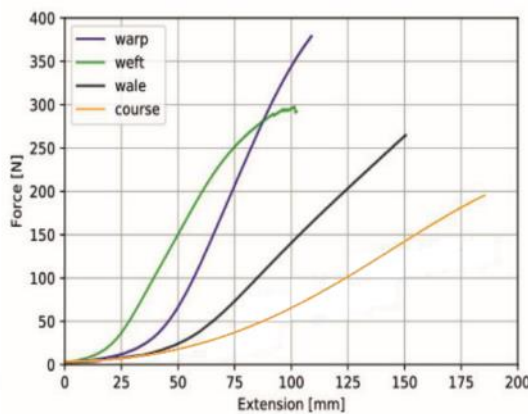
(a) K1W1



(b) K1W2



(c) K2W1



(d) K2W2

Figure 4.5: Results of uniaxial tensile test of textile fabrics.

4.3.2 Characterization of fabric-based actuators

The effect of segment types on the gripping force of the actuator was investigated. The graphs of the applied pressure versus the grip force of the segmented and non-segment actuators in all fabric combinations are given in the Figure 4.6. The non-segmented sample 2 (K2W1) had the maximum gripping force compared to all actuators (4 N at 160 kPa). Sample 1 (K1W1) and sample 2 (K2W1) combinations, which showed the highest anisotropy difference, achieved the highest grip force. It has been found that actuators with K1W1 fabric combination generally produce high gripping force with low pressure change. Forming A, B, C and 3S, 5S, 7S segment types decreased the grip force in K1W1 and K2W1 samples that have a high anisotropy difference. Creating different segment types in samples with a low anisotropy difference resulted in unstable behavior on grip force. This is because the uncoated woven 2 fabric structure can affect the complicated nature of the textile's strain deformation.

The bending angles of all segmented and non-segmented actuators in the K1W1 fabric combination against pressure are given in Figure 4.7(a). Segmented and non-segmented actuators exhibited bending behavior; however, a higher bending angle was obtained with segmented samples. At 170 kPa, the non-segmented actuator had a maximum 110 degree bending angle. It was noticed that inflating the actuator to a pressure greater than this value had no effect on the bending angle. All segmented actuators can withstand pressures more than 170 kPa and have bending angles between 150 and 200 degrees. As a result, it was determined that increasing the number of segments increased the bending angle. It is believed that creating stitches in the width-wise direction on the actuator's knit fabric increases the bending angle by preventing the actuator from expanding radially. The actuator with the greatest bending angle was determined to be a 7S segment type K1W1 specimen. However, due to the radial expansion irregularity between the non-segmented parts without stitching and the segmented parts with stitching, it was determined that this actuator would not be suitable for using in the application of wearable gloves. As a result, the B segment type (1.5 cm stitch gaps) K1W1 actuator was chosen, as it had the second highest bending angle.

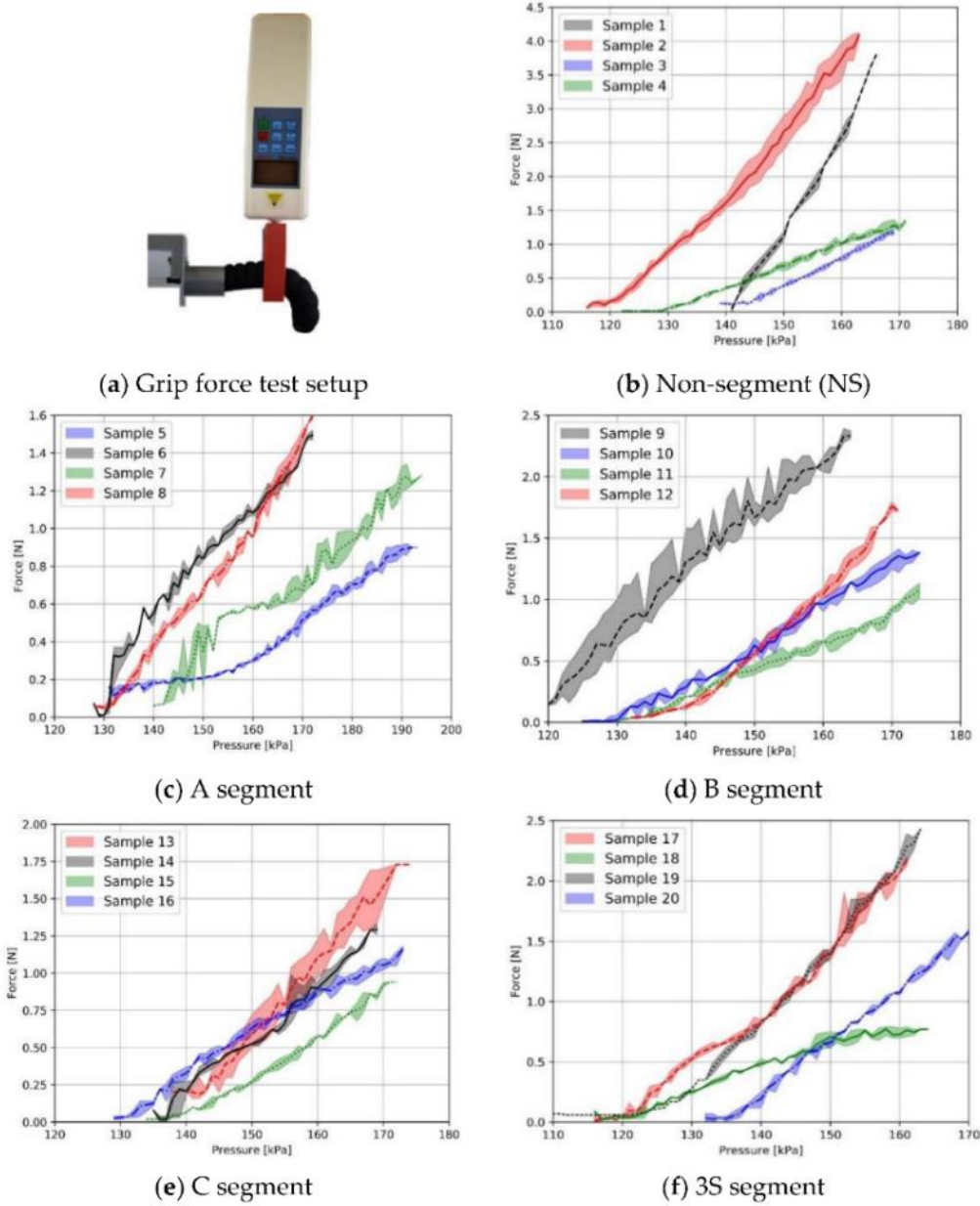


Figure 4.6: Grip force-pressure test.

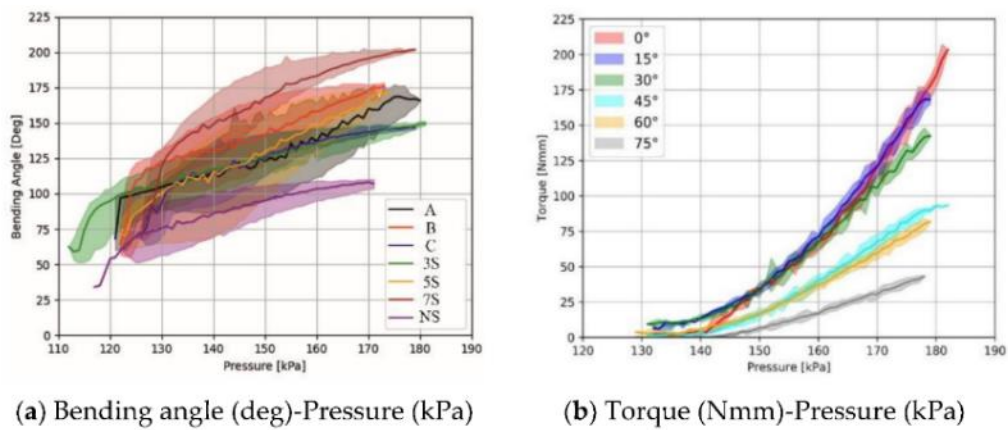
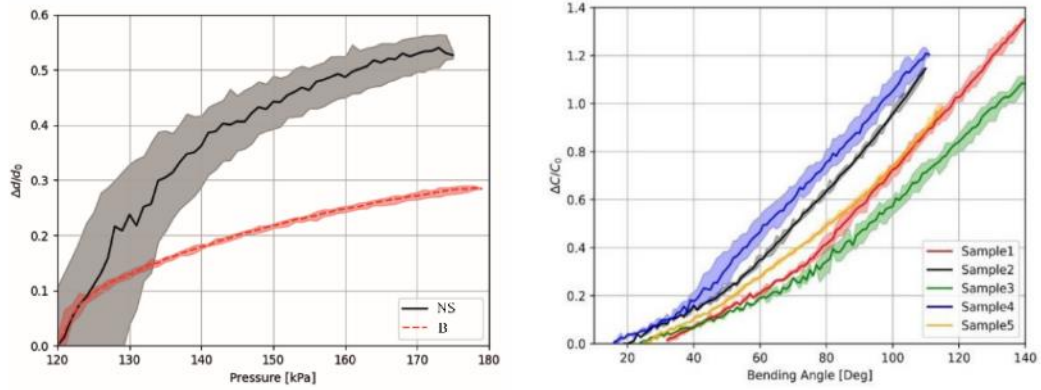


Figure 4.7: The experimental results of actuators.



(c) Radial expansion-Pressure (kPa) (d) Capacitance change-Bending Angle (deg)

Figure 4.7 (continued): The experimental results of actuators.

The experimental results of the torque measurement are shown in Figure 4.7(b). The reported results show that the B segmented approach produces the highest torque with a maximum of 210 N.mm at 0 degrees bending when a pressure of 183 kPa is applied. It was found that as the bending increased, the torque produced by the fabric actuator decreased. This result is consistent with the torque results in our previous work (Elmoughni et al., 2021).

The radial change experimental results are shown in Figure 4.7(c). Fabric actuators initially are the two-dimensional (2D) and expand radially with a given pressure increase. The non-segmented actuator inflates as a cylindrical tube, while the segmented actuator exhibits a knobby appearance. A radial change of 0.28 mm of the segmented actuator was achieved at the maximum pressure of 175 kPa, while the non-segmented approach achieved a radial change of 0.53 mm at the same maximum pressure. It was observed that the non-segmented actuator had high radial expansion due to the tendency of the weft-knitted fabric to elongate in the width-wise and longitudinal directions. It is not aesthetically pleasing to place an actuator that highly inflates in the radial direction as an exoskeleton on top of the fingers. In addition, compressed air contributes to the inflating of the actuator, not its bending. When comparing the segmented actuator created by adding 1.5 cm stitch gaps (B) and the non-segmented actuator, it was found that the radial expansion was reduced by approximately 50%.

Figure 4.7(d) shows capacitance change–bending angle graph of five identical actuators with integrated textile-based capacitive strain sensors. These actuators have

B segment structure and K1W1 fabric combination, which depicts the best performance according to bending angle and grip force. As can be seen from the results, the capacitance change and bending angle show positive correlation. The sample results are approximately linear. Although the sensitivity of identically produced actuators is different according to the bending angle, they present similar behavior.

4.4 Control Strategy

Figure 4.8 shows the block diagram of the developed control system. The control system consists of air flow components, control components, data components, and power components.

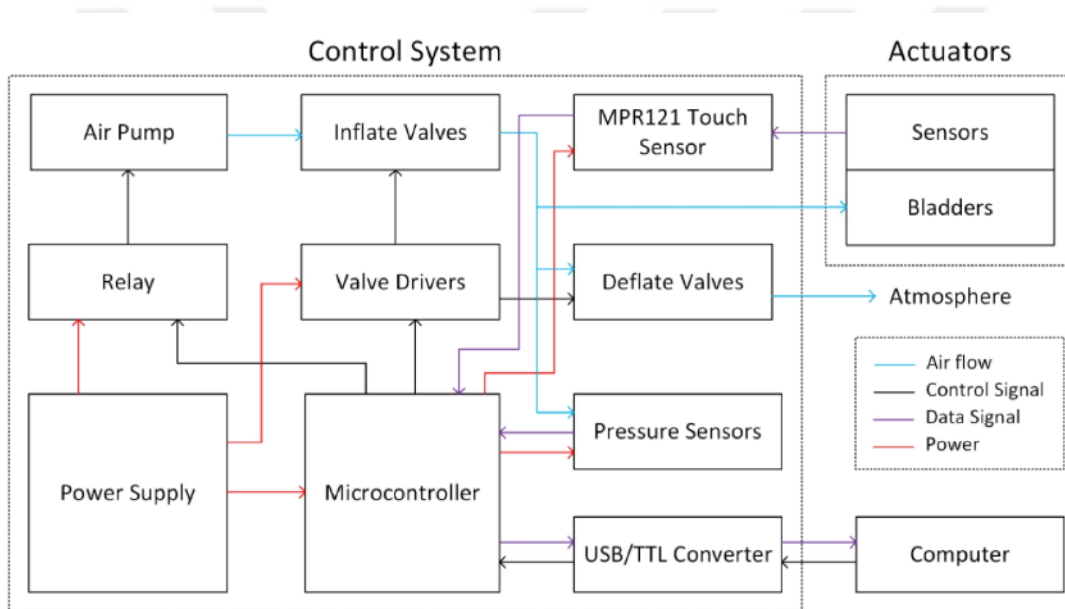


Figure 4.8: Control system of sensorized soft robotic glove.

Components of airflow include an air pump, inflate valves, deflate valves, and pressure sensors. To initiate the actuators' bending motion, the air pump is activated, and the inflate valve is opened. The generated air is directed to the bladders via the inflate valves, and the actuator is bent. While the actuator is bending, the deflate valve is in the closed position. It is worth noting that no two air bladders or actuators are completely identical due to manufacturing conditions. When non-identical air bladders were filled simultaneously, a homogeneous bending action in all fingers was not observed. As a result, the actuators are inflated sequentially with a 200 ms inflation duration apiece, while the entire glove forms the closing movement. If all actuators meet the stop condition, no additional air is provided to the actuator that meets the stop

condition, and the air pump is shut off. The air pump and inflate valves remain closed during the relax movement of the glove, while the deflate valves are simultaneously opened. Thus, the air in the air bladder flows toward the atmosphere because its pressure exceeds that of the surrounding air. When the glove provides a stopping condition for the sensors-measured relax motion, the deflate valves are closed.

The control system consists of the following components: a relay, valve drivers, a microcontroller, a USB/TTL converter, and a computer. The microcontroller controls the actuator by receiving opening and closing signals from the computer. Additionally, it controls whether the actuator is closed or opened in response to sensor input. A USB/TTL converter connects the computer and the microcontroller. When the air pump is functioning, the microcontroller may control it through the relay, and it operates at full power. Valve drivers are used to regulate valves, as a heating problem develops when the valves are left open with full power for an extended period of time; thus, the valves are opened with maximum power for 10 milliseconds and then operated with low energy to maintain the open state.

The MPR121 touch sensor, pressure sensor, microcontroller, USB/TTL converter, and computer are the signal components. When capacitive sensors are used, the noise in the sensor values increases as the distance between the measurement circuit, and the capacitive sensor grows due to changes in the line capacitance. Thus, noise can be minimized by positioning the measuring circuit as close as feasible to the sensors (Ozlem et al., 2019). To minimize the noise, the MPR121 touch sensor was placed closest to the actuators. Capacitive sensors generate feedback signals, while the actuators carry out the given commands, and the system is controlled by a closed-loop control system. According to the results in Figure 4.7(d), the capacitive sensors show approximately linear behavior with respect to the bending angle. In this way, with the upper and lower threshold values determined for the sensor values, it can be decided whether the actuator is in the closed or open state. By scaling the upper and lower thresholds, the actuator can be closed at different angles. According to the results in Figure 4.7(d), capacitive sensors on 5 actuators show similar behavior but operate with different sensitivity. For this reason, when the system is started, all actuators are calibrated one by one, and separate upper and lower threshold values are determined for each. These obtained upper and lower limits constitute the bending and relax stop conditions of the actuators. When an actuator reaches its upper limit in inflation, it

meets the stop condition and is no longer supplied with airflow. Similarly, when the capacitive sensors reach the lower limit in the relax state, the deflate valves are closed. Pressure sensors are used to control the air pressures in the actuators and provide a backup feedback signal in case any problem occurs with the capacitive sensors. Both capacitance and pressure sensor values are collected by the microcontroller, and control signals are generated according to these sensors' data. At the same time, the sensor data are transferred to the computer via USB/TTL converter and used to visualize the system data.

4.5 Application Demonstration

To demonstrate the application of the sensorized fabric-based pneumatic actuator, it was integrated into a wearable glove. The glove was made of lycra/polyester fabric and was stretchable and compliant. To demonstrate the glove's actual holding capability without human intervention, the glove was worn by a hand model. As shown in Figure 4.9(a), all fingers were respectively given a closing motion and represented by the numbers 1-2-3-4-5 to prove the separate controllability of the actuators that are integrated into all five fingers of the glove. By operating the control system of the developed soft robotic glove, the flexion movement of the actuators was enabled to hold various objects at 160–180 kPa. Actuator fingers were inflated to create different grasp types according to the shape of the objects. As seen in Figure 4.9(b), the objects that can be found in daily life were selected to be different sizes and weights, including: screw-wrench (336 g), plastic water glass (219 g), banana (150 g), apple (129 g), red pepper (93 g) and lemon (51 g). Some objects had a slippery surface, causing then to be difficult to hold. Therefore, it is recommended to develop approaches that will create friction between the glove and the object.

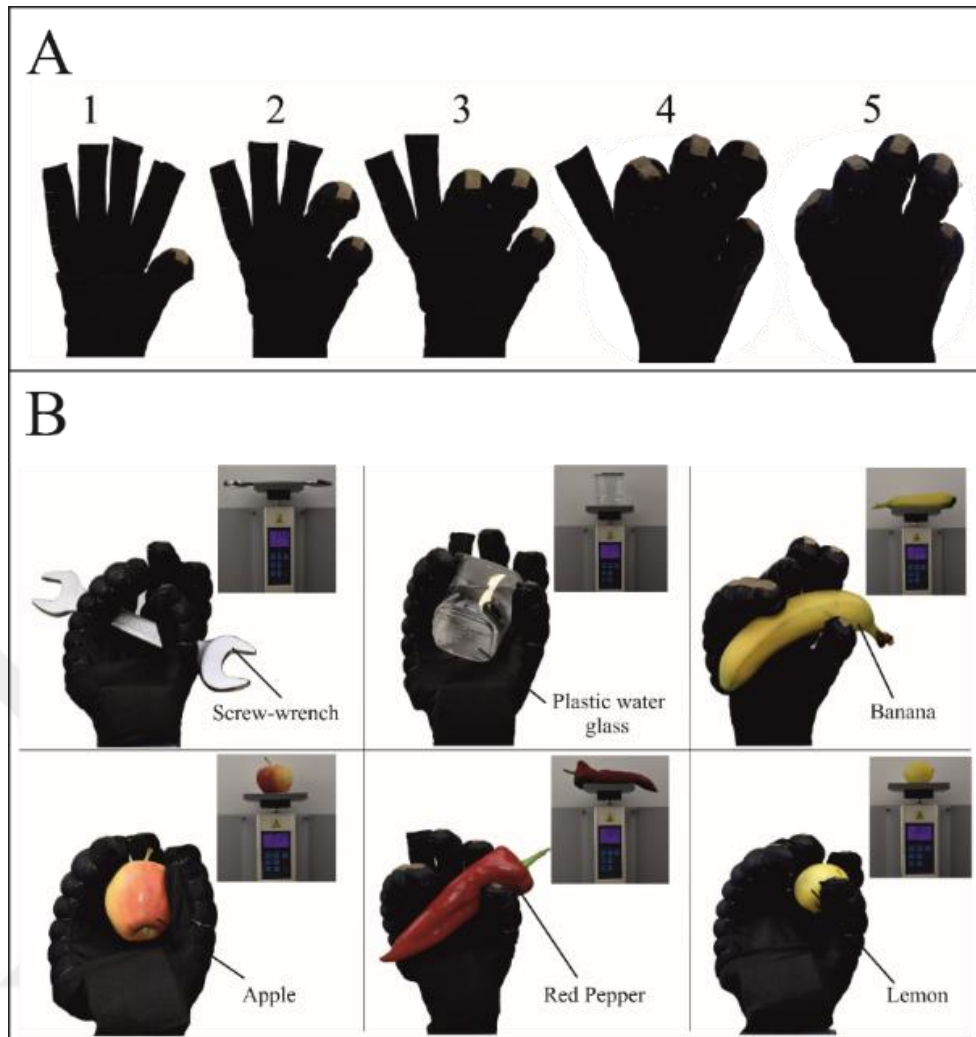


Figure 4.9: Application of soft robotic glove. (a) Demonstrating how each of the five fingers on the robotic glove can be controlled separately. (b) Holding several objects of various shapes and weights by soft robotic glove.

4.6 Conclusions

The stitching technique was used to create segmented fabric-based bending actuators in this study. The influence of six distinct segment types was tested on the actuators' grip force and bending angle. Four different combinations of knit-woven materials with varying degrees of mechanical anisotropy were selected to produce actuators. It was discovered that actuators with a large anisotropy difference have a greater grip force than actuators with a small anisotropy difference. Segmentation by adding width-wise stitches reduces the grip force in samples with a large anisotropy difference. By adding segments, the actuator's bending angle is increased, while actuator's radial expansion tendency is decreased. It is also recommended to employ coated woven fabric in actuators made of knit-woven fabric to achieve repeatable results. The

capacitive sensors demonstrated the controllability of the soft robotic glove using a closed-loop system. The developed sensing soft robotic glove can provide sufficient force for objects weighing up to 336 g and of different shapes due to the wide range of bending angles and grip forces achieved. This demonstrates the wearability and application of the glove as an exoskeleton device for people who want to perform daily life activities.



5. RESISTIVE SELF-SENSING TEXTILE-BASED ACTUATOR³

Designing advanced soft robots with soft sensing capabilities for real-world applications remains challenging due to the intricate integration of actuation and sensor capabilities, which require diverse materials and complex procedures. This paper introduces a fabric-based robotic technology featuring an “all textile-based self-sensing pneumatic actuator” and a low-cost resistive strain sensor created through simple sewing techniques. The novel approach eliminates the need for additional strain-limiting woven fabric, simplifying the manufacturing process. It also enables the development of bioinspired motions such as bending, twisting, and snake-like movements. The electromechanical behaviors of the sensor and bending actuator are tested for their performance under positive air pressure. Through mathematical modeling, we accurately estimate the actuator’s sensing capacity, providing precise feedback for pressure and position control. Different closed-loop controller types, including On-Off and Proportional Integral Derivative (PID) control, are evaluated for their effectiveness. Furthermore, the practical application of the sensing actuator is demonstrated by integrating it into a wearable glove, showcasing its enhanced sensing capabilities for finger-like soft wearable robotic applications. This research tackles the challenges associated with designing advanced soft robots with integrated sensing capabilities, offering a promising fabric-based solution that can drive significant advancements in real-world applications.

Keywords: self-sensing actuators, soft actuators, soft robotics, sensors, resistive strain sensors, textile-based actuators, bioinspired soft robotics.

5.1 Introduction

Soft robotics has achieved remarkable progress in emulating various organisms found in nature, including humans, fish, worms, and flowers, through the careful selection

³This chapter is based on the paper ” Yilmaz, A.F., Ozlem, K., Khalilbayli, F., Celebi, M.F., Kalaoglu, F., Atalay, A.T., Ince, G. And Atalay, O. 2023. Resistive Self-Sensing Controllable Fabric-Based Actuator: A Novel Approach to Creating Anisotropy. *Advanced Sensor Research* 2300108. DOI:10.1002/adsr.202300108.”

and construction of appropriate soft materials (Ilami et al., 2021; Kim et al., 2013; Ren et al., 2021; Das et al., 2023; Dong et al., 2022; Stella et al., 2023; Ahmed et al., 2022). Elastomers (Franke et al., 2020), hydrogels (Lee et al., 2020), shape memory alloys (Lee et al., 2019), and self-healing polymers (Roels et al., 2022) have been utilized to create fundamental bioinspired kinematics, encompassing bending (Jing et al., 2022; Ke et al., 2022), extending (Azami et al., 2019), and twisting motions (Li et al., 2023; Ahn et al., 2019). The bioinspired kinematics devised for specific application areas are based on the design, mechanical deformation, and straining range capabilities of the chosen materials. Textile materials are highly suitable for constructing soft actuators due to their lightweight, compliant, low-cost, hierarchical structure, and compatibility with the human body (Fu et al., 2022; Xiong et al., 2021). While most research on textile-based actuators has predominantly focused on bending motion (Cappello et al., 2018; Suulker et al., 2022; Yap et al., 2017; Ge et al., 2020; Nguyen et al., 2020; Connolly et al., 2019), the ability to design various motions for textile-based soft robotics holds the potential to expand the scope of new application scenarios.

Fabric-based bending actuators often entail intricate design elements such as folding, pleating, or the construction of double-layered fabric structures. The technique of mechanical anisotropy is employed to induce bending motion in these double-layered fabric designs, which consist of two different textile layers, including elastic and strain-limiting fabric (Cappello et al., 2018; Suulker et al., 2022; Yap et al., 2017; Ge et al., 2020; Nguyen et al., 2020). However, this approach has inherent limitations, such as the requirement of separate fabric panels for strain limitation and elasticity, susceptibility to failure at weak points during inflation, and the occurrence of shrinkage at the seams, compromising the mechanical properties of engineered structures.

Moreover, various welding technologies have been employed to bond fabric layers in the fabrication of fabric actuators (Yap et al., 2017; Ge et al., 2020; Nguyen et al., 2020; Connolly et al., 2019). Nonetheless, these bonding methods exhibit limitations, such as the inability to use non-thermoplastic materials and the challenge of achieving a robust molecular bond in areas where chemically incompatible thermoplastics converge. On the other hand, knitting technology is limited in its availability due to

the high initial investment costs and the need for extensive professional expertise in actuator design.

Before textile-based actuators can be effectively utilized in real-world controllable applications, compliant sensing properties must be incorporated into their stretchable structures. Integrating sensors into the design of these actuators provides valuable information about their motion or position (Amjadi et al., 2016; Cheng et al., 2019; Thuruthel et al., 2019). To ensure that the actuation motion is not impeded, the sensors must possess stretchable, adaptive, lightweight, and compliant characteristics, akin to the actuators themselves.

While numerous fabrication techniques exist for producing sensors (Jansen et al., 2020; Atalay et al., 2014; Seyedin et al., 2019; Sadeqi et al., 2018; Tolvanen et al., 2018; Du et al., 2016) and actuators (Fatahillah et al., 2020; Han et al., 2017; Feng et al., 2021; Fei et al., 2019; Nassour et al., 2020; Tuyboyov et al., 2023) separately, it is crucial to focus on the method of sensor integration into the actuator. Coating and printing processes using conductive polymers or pastes, as well as chemical bonding, can be employed to incorporate sensors onto stretchable actuator bodies (Seyedin et al., 2019). However, these methods are time-consuming and often result in an inhomogeneous distribution of electrically conductive polymers, slippage issues, and poor interfacial adhesion between the sensor structure and actuator. Thus, achieving complete interfacial attachment and material compatibility between the soft actuator and sensing element is of paramount importance for accurately capturing the actuator's true motion and preventing delamination at connection points during actuation.

To overcome the aforementioned challenges, we present, for the first time, a resistive self-sensing fabric-based pneumatic actuator fabricated entirely using low-cost sewing technology. In this paper, we provide comprehensive insights into the design, fabrication, sensing, characterization, and control of this self-sensing actuator. Additionally, utilizing the same fabrication technique, we demonstrate the creation of bioinspired soft robots capable of mono-directional twisting and snake-like movements. Following sensor and actuator characterization, we mathematically model the sensing behavior of the bending actuator to showcase its controllability. Furthermore, we systematically evaluate and compare the performance of ON-OFF and PID closed-loop controllers.

5.2 Experimental Section

5.2.1 Starching process

The corn starch (15 grams) and cold water (300 mL) were mixed until the clumps were gone. The resulting starch solution was then heated until it thickened to the desired consistency. After allowing the starch solution to cool down, a rib-knit fabric was immersed in the solution, ensuring it was fully coated. The fabric was carefully removed from the solution and left to dry on a flat surface.

5.2.2 Fabrication of stitched sensor and textile-based actuator

The 1×1 rib knit fabric, with a thickness of 0.3 mm and dimensions of 2 cm x 13 cm, was cut using a laser cutting machine (VLS 2.30, Universal Laser Systems, Scottsdale, AZ, USA). The sensor and actuator components were then created using a sewing machine (Brother CS-6000i, Brother International, Nagoya, Japan). The actuator and sensing capability were built using commercially available rib knit fabric (65% lycra, 35% polyamides), a commercial silver-plated nylon conductive yarn (Shieldex 235 f/36 dtex 2-ply HC+B), and sewing thread (100% polyester Nm 60/2). The linear resistance of this conductive yarn was $100 \Omega \text{ m}^{-1}$, the elasticity was up to $17\,500 \text{ m kg}^{-1}$, the tensile strength was 46 cN tex^{-1} , and the stretching was up to 15%. The sensor was created on knit fabric using 304 zigzag stitch geometry, with the conductive thread in the bobbin thread area, and polyester stitch thread in the needle thread area of the sewing machine. 301 lockstitch, polyester thread in the bobbin, and needle threads were used to make bending anisotropy stitches. The seam that was superimposed was created for stitching the actuator. The air bladder was then inserted into the actuator.

5.2.3 Fabrication of thermoplastic air bladder

An impulse sealer machine (PCS 300, Brother, Nagoya, Japan), thermoplastic polyurethane film (Stretchlon 200, Fiber Glast, Brookville, OH, USA), and polyurethane tube were used to make the air bladder. Two rectangular cut films 2 cm x 14 cm were layered on top of one another, and an impulse sealer was used to create a bond between them at a time setting of 5.5 s. The welding process was finished when all three edges of the TPU sheet with the rectangle cut-off were closed. A

polyurethane tube was inserted into the open end, and a pneumatic system was used to inflate it.

5.2.4 Characterization of mechanical properties of fabric

The mechanical characteristics of knit fabric were tested at a speed of 100 mm min⁻¹ using a commercial uniaxial testing machine (Titan 5, James Heal, UK) following the EN ISO 13934-1 test standard. Five 20 cm × 5 cm pieces of knit fabric were cut in the course-wale directions. The fabric was treated for 24 h in a typical atmospheric environment before the test. Data for both the extension (mm) and force (N) were recorded. Using the mean of five samples, a force-extension graph was made to identify the direction of greater fabric extension.

5.2.5 Electromechanical characterization of the strain sensor

The electromechanical properties of the stitched-strain sensor were evaluated using a vertical tensile tester (ESM 303, Mark-10, Copiague, NY, USA). This testing apparatus allowed for precise measurements of the response of the sensor to mechanical strain, providing valuable data on its performance under various conditions. For each strain experiment, strain velocity was adjusted at 1000 mm min⁻¹. The resistance value of the actuator was measured using Keysight 34465A Digital Multimeter. Strain and resistance values were collected and synchronized by a computer. The resistive strain sensor works by measuring relative changes in:

$$R = \rho \frac{L}{A} \quad (5.1)$$

where R is the electrical resistivity of the conductive yarn, the resistivity ρ of the conductive material, L is the length of the strain sensor, and A is its cross-sectional area. Experiments were conducted in normal atmospheric conditions.

4.2.6 Actuation

An air pump, valve, relay, pressure sensor, and microcontroller were all parts of the airflow system. An air pump motor (DC 12 V/370-02PM-SKU-5000, Makeblock, Shenzhen, China) was used to actuate the textile actuator. The air pump and solenoid valve (12 V 2W-025-08, Senya) were controlled by the 5 V 4 channel relay board and Arduino Nano microcontroller. Using an air pressure sensor (MPXHZ6250A, Freescale Semiconductor, USA), the actuator's internal pressure was measured.

5.2.7 Characterization of sensing actuator

The sensing actuator was fastened and coupled to a pneumatic-valve control system that included a pressurized air supply and a pressure sensor. The input pressure was adjusted between 0 and 195 kPa to evaluate the connection between air pressure and normalized peak electrical resistance during actuation. As with strain sensor characterization, the electrical resistance was measured using a digital multimeter (34465A, Keysight, California, USA) connected to two ends of the resistive sensor. To eliminate any sort of undesired motion, the probes were fixated on the test setup. The extracted resistance values and corresponding timestamp data were transmitted to, recorded, and observed on the computer in a real-time manner. To better investigate the change in resistance of the actuator concerning its bending behavior, the resistance, and bending angle values were recorded while the actuator was pressurized and depressurized six consecutive times. Out of the six pressurization and depressurization cycles, the first one was eliminated in all of the conducted experiments to obtain stable results by avoiding the possible dislocations of the actuator in the initial cycle. While conducting the experiments, one end of the actuator was fixated on a custom-made test rig, while the other end followed a circular motion without any restraint to overcome the aforementioned undesired dislocation problem. Also, the pressure range in each cycle was kept constant that is the minimum and maximum pressure capacity of the actuator to have comparable results. While the actuator was inflated and deflated by the control system (Yilmaz et al., 2022), the bending motion was recorded via a camera located on the plane of the actuator. Both the actuator and the camera were placed in a secluded area to achieve stable lighting conditions. By implementing several image processing techniques such as contouring on the three color markers attached to the extreme points of the actuator, the markers' center of mass coordinates were calculated. The bending angle value was then computed according to these coordinates. In the experiments, the locations of the extreme points were set to mimic the knuckles of a finger. At each frame of the captured video of the actuator's motion, the bending angle value and its corresponding timestamp were obtained. Since the amount of data obtained per second from the multimeter and the number of extracted bending angle values from frames of the captured video per second were different, these values were then matched up according to their timestamps in such a way that the resistance values were coupled with the bending angle value with the closest

timestamp. The resistance values were represented as the change in the resistance concerning the initial resistance value. The mean bending angle value through all cycles corresponding to the same resistance value was calculated. The same method was utilized for matching the pressure data obtained from the control system with the bending angle results. Here, the mean and the range of the pressure data were calculated for each corresponding bending angle value.

To analyze the gripping capability of the soft sensing bending actuator, using the grip force test setup established in the previous work (Elmoughni et al., 2021), the exerted grip force according to the applied pressure was recorded by utilizing a digital dynamometer (SH-50, Geratech, Istanbul, Turkey).

5.3 Results and Discussion

The actuation structure in textile-based actuators is crucial to controlling and generating motion with textile materials. In previous studies, a two-layered construction consisting of stretch knit fabric and non-stretch, strain-limiting woven fabric has been commonly employed to provide bending motion in textile-based actuators (Cappello et al., 2018; Suulker et al., 2022; Yap et al., 2017; Ge et al., 2020; Nguyen et al., 2020). In contrast, this work aims to eliminate the need for an additional non-stretch woven fabric by introducing a novel approach. Instead, we use stretch knit fabric that is commercially available as the only material for the actuator's body and incorporate strain-limiting capabilities using sewing technology to achieve anisotropy. To demonstrate the feasibility of our anisotropy method, we showcase soft actuators capable of bending like human fingers, twisting like the human body, and mimicking snake-like biomotion (Figure 5.1). This is made possible by strategically placing stitches on the knit fabrics in individually designed patterns for each specific motion. Rather than relying on woven textiles, we harnessed the flexibility of knit fabric through a stitching technique, slightly reducing its natural stretchiness to a level comparable to woven textiles. This strategy for producing anisotropy highlights the possibilities for adaptable, affordable soft robotic systems and emphasizes the value of programmable stitches for a range of applications.



Figure 5.1: The novel method provided to create bio-inspired bending, snake-like, and twisting actuators.

The primary objective of this research is to develop a self-sensing pneumatic bending actuator that incorporates a stitched-based resistive sensor to enable direct sensor feedback from the actuator's stretching surface for precise control. The high elasticity of the lycra substrate utilized in the actuator provides the stretchable fabric with exceptional strain-sensing capabilities. Before sensor integration, we determine the stretch direction of the knit fabric using a uniaxial tensile machine. The knit fabric is cut using laser cutting in both the course and wale directions, as depicted in Figure 5.2(a). The fabric sample exhibits a 100 mm extension at 32 N in the course direction and a 100 mm extension at 90 N in the wale direction, as illustrated in Figure 5.2(b).

The actuation performance of textile-based actuators is significantly influenced by factors such as the thickness and knit structure of the fabric. The knit structure plays a crucial role in determining the actuator's stretchability and range of motion. For applications requiring specific movements or deformations, selecting an appropriate knit structure is essential. The choice of knit structure has a profound impact on stretchability and the extent of achievable motion. We used the 1×1 rib knit structure, which results in significantly higher strain values in the course direction compared to the wale direction. This is especially important for sensing actuator applications that demand precise and tailored movements. Besides, thicker knit fabrics tend to resist deformations, which is particularly important when aiming for precise and controlled movements. Thicker fabrics require higher pressure levels or airflow rates to achieve specific motions compared to thinner fabrics. The selection of fabric thickness should be a deliberate design choice, tailored to the specific requirements of the application. We found that the 1×1 rib knit fabric with a thickness of 0.3 mm is the optimum choice for our application.

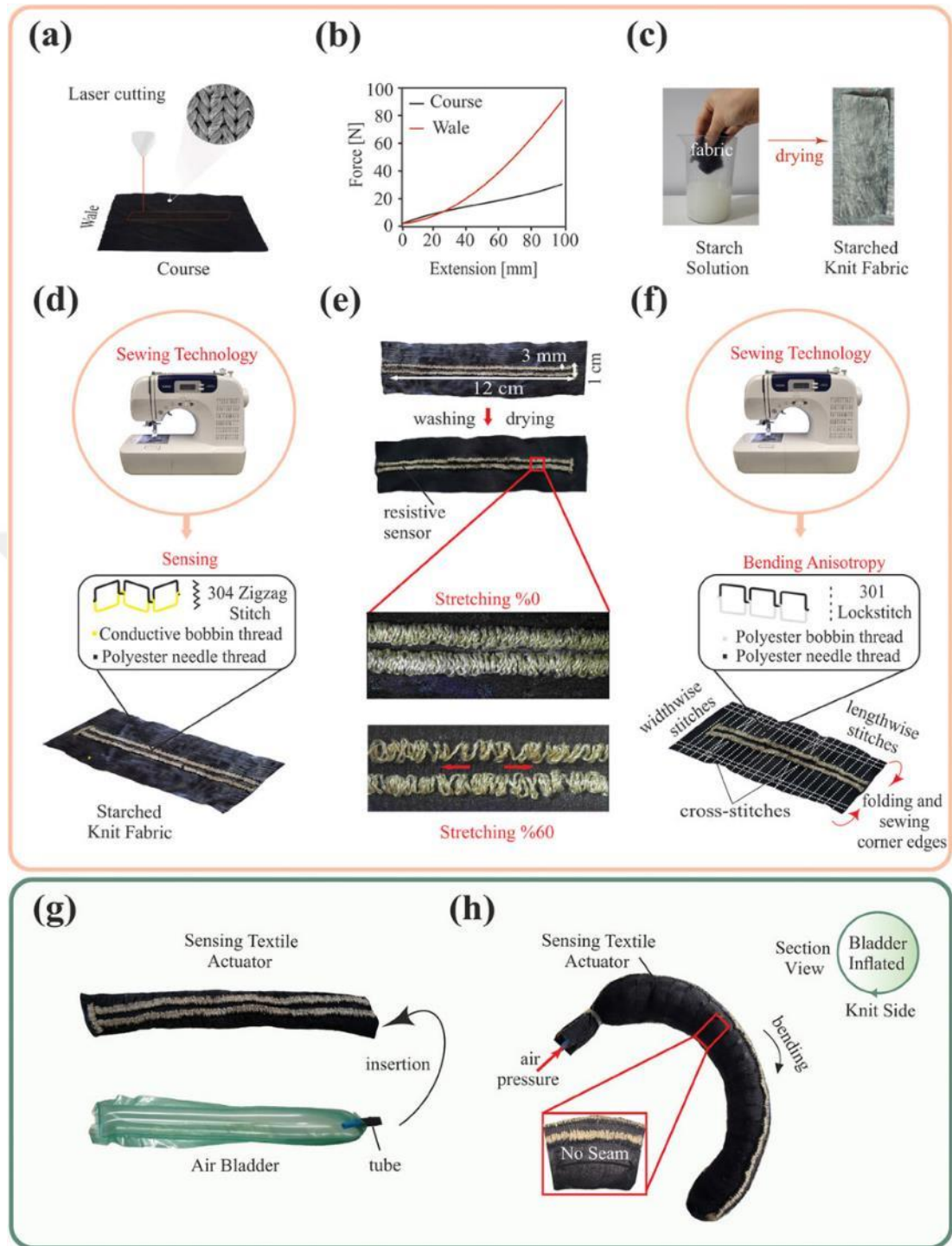


Figure 5.2: The fabrication process of the stitched-based sensor with electrically conductive yarn and bending textile actuator. (a) Laser cutting of the knit fabric. (b) Tensile testing of the knit base fabric to determine the strain direction. (c) Starching process of the knit fabric to stiffen it. (d) Stitching process to fabricate the sensor using a flexible zigzag stitch type on the starched knit fabric. (e) Washing and drying of the starched resistive stitched sensor and stretching of the stitched sensor. (f) Creation of bending anisotropy utilizing sewing technology, followed by folding and stitching of the corner edges to form a bending textile actuator. (g) Insertion of a bladder within the 2D textile bending actuator. (h) Demonstration of the inflated sensing textile actuator with no visible seams.

In the context of the rib knit structure's loop pattern, the knit fabric demonstrates significantly higher strain values in the course direction compared to the wale direction. Therefore, the integration of the sensor is carried out along the course direction to ensure substantial changes in electrical signals and enable rapid bending deformation even at low air pressure. This strategic placement of the sensor facilitates enhanced sensitivity and responsiveness in capturing the motion of the actuator. By leveraging the remarkable properties of the lycra substrate and carefully aligning the sensor integration along the course direction, our self-sensing pneumatic bending actuator achieves remarkable strain-sensing capabilities.

The utilization of a zigzag stitch with a high stitch density presents challenges in the fabrication process, including the potential puncturing of the knit fabric due to its flexible and looping nature, as well as the risk of breaking the machine needle. To effectively address these problems, a simple strategy is employed, involving the immersion of the knit fabric in starch to enhance its stiffness, sewing performance, and suitability for high-density zigzag stitching (Figure 5.2©). In the construction of the sensor, we employ a conductive thread that offers a range of desirable properties, including lightweightness, softness, durability, and resistance to deformation. Through the application of sewing techniques, the sensor is integrated at the top of the bending actuator, enabling precise sensing capabilities. The sensor is meticulously fabricated using the 304 zigzag stitch geometry, as depicted in Figure 5.2(d). This stitch type is specifically chosen for its remarkable stretchability, allowing unrestricted motion of the actuator and preserving the inherent flexibility of the fabric to the greatest extent possible. By immersing the knitted fabric in a starch solution and utilizing a conductive thread in the fabrication of the sensor, we overcome the challenges associated with the zigzag stitch, ensuring the integrity and longevity of the actuator.

In the construction process, the conductive thread is specifically employed in the bobbin thread region of the sewing machine, while a polyester stitch thread is utilized in the needle thread area. This strategic use of materials ensures optimal performance and functionality. Once the fabrication of the sensor is completed, the fabric undergoes a rinsing process with warm water to remove any residual starch, followed by thorough drying (Figure 5.2(d)). By combining the conductive yarn with the knit fabric through stitching, we achieve an inherent stretchability in the sensor. When the flexible and stretchable sensor is subjected to strain from one or two sides, the adjacent conductive

threads undergo separation, resulting in a discernible change in resistance (Figure 5.2©). This mechanism allows for precise sensing capabilities, enabling the actuator to accurately detect and respond to external stimuli. Through the integration of conductive threads and the utilization of stitching techniques, we have successfully developed a versatile and adaptable sensor that enhances the functionality of the fabric-based actuator. The resulting stretchability and the ability to detect resistance changes contribute to the actuator's controllability and responsiveness, further solidifying its potential for a wide range of real-world applications.

We present a straightforward and cost-effective approach for fabricating a sensor-integrated, mechanically bending anisotropy actuator using sewing technology, as depicted in Figure 5.2(f). By employing 301 lockstitches at four tension settings, we stitch widthwise, longitudinal, and two cross-stitches to impart the desired bending characteristic to the textile fabric.

The actuator's widthwise and longitudinal lines are sewn at regular 0.5 cm intervals, with a width of 2 cm and a length of 13 cm. The longitudinal stitches serve to relieve strain in the knitted fabric, mimicking the properties of the woven fabric used in earlier studies (Cappello et al., 2018; Yilmaz et al., 2022).

Meanwhile, the widthwise lines are sewn together to prevent radial expansion of the actuator. To emulate the joints in a human finger, two cross-stitches are incorporated, effectively enhancing the bending angle of the actuator. Although the human finger possesses three joints – the distal interphalangeal joint (DIP), the proximal interphalangeal joint (PIP), and the metacarpophalangeal joint (MCP) (Abdelhafiz et al., 2023) – we find that three cross-stitches actually reduce the bending angle of the actuator. Thus, our actuator accurately replicates the soft-sewn distal interphalangeal and metacarpophalangeal joints. Furthermore, the inclusion of two cross-stitches significantly enhances the controllability of the sensing actuator's electrical feedback, preventing electrical signals from rapidly saturating.

After completing the stitching of the bending anisotropy threads, the stitched fabric is transformed into a tubular actuator. An airtight thermoplastic polyurethane bladder is inserted into the actuator, and controlled air pressure is applied, as depicted in Figure 5.2(g). In the development of pneumatic actuators, it is crucial to ensure actuation stability and the actuator's ability to maintain its bending shape over an

extended period without gas leaks affecting its performance. To address these concerns, we selected a high-quality thermoplastic polyurethane (TPU) film (Stretchlon 200, Fiber Glast, Brookville, OH, USA). Additionally, the thermoplastic polyurethane film undergoes thorough cleaning to prevent welding problems caused by dust or dirt. It should be wiped with a non-linting soft cloth or sponge. The welding thickness is set at 0.5 cm to minimize the risk of the welded region suddenly opening under air pressure. To assess the impermeability of the air bladder and detect any adhesion problems, an air leakage test is conducted by immersing the air bladder in water. It's important to note that the successful creation of a high-quality air bladder is indicated by the absence of bubbles when air pressure is applied to the bladder submerged in water. The actuator, consisting of a single continuous piece of knit fabric, has no seams along its sides, as illustrated in Figure 5.2(h). This design ensures structural integrity and optimal performance.

5.3.1 Electromechanical characterization

The limited availability of flexible, elastic, compliant, and self-recovering integrated sensors on soft actuators has created significant barriers to the progress of soft robotics. In this study, we present an approach that involves the design of a stitched strain sensor with resistive sensing capabilities. The sensor employs conductive yarn as the sensing element, while the non-conductive knit fabric imparts elasticity and durability to the system. When the conductive threads make contact, the electrical length of the structure decreases, resulting in a decrease in resistance. Conversely, when the conductive stitches are separated, the electrical length increases, leading to an increase in resistance. However, accurately predicting how the stitching parameters influence resistance change proves to be a complex task. The yarn, consisting of filaments and staple fibers, coupled with the structural design, introduces the possibility of contact or non-contact of the fabric's looped structure during straining. While the conductivity of the electrically conductive yarn exhibits linearity, the introduction of curvature and mechanical stresses during manufacturing may induce non-linear behavior when the yarn is applied to a textile-knitted structure. To gain a comprehensive understanding of the conductive yarn's properties, conductivity measurements are conducted. Figure 5.3 provides an in-depth electromechanical characterization of the stitched-based strain sensor and sensing actuator, showcasing their performance and behavior in detail.

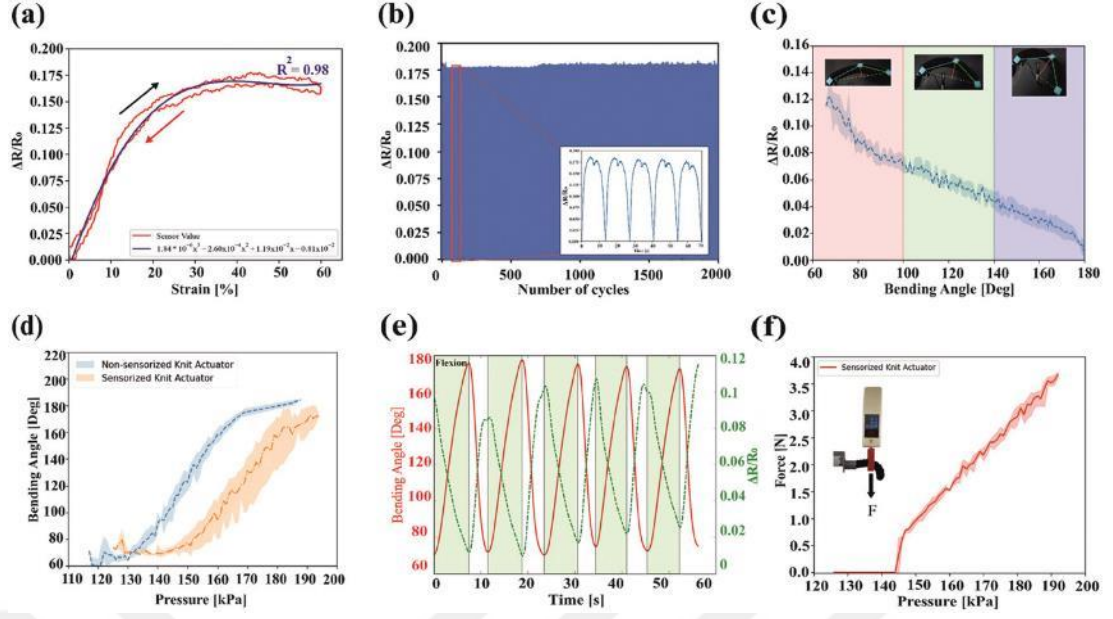


Figure 5.3: Electromechanical characterization of the stitched-based strain sensor and sensing textile actuator. (a) Sensitivity of the sensor. (b) Electrical response under 60% loading and unloading strain for 2000 cycles, demonstrating the durability and stability of the sensor with low creep. (c) Resistivity changes with bending straining. (d) Comparison of bending angle-pressure between the non-sensorized and sensorized actuators. (e) Bending angle-resistance change-pressure relationship of the sensing actuator. (f) Gripping force-pressure relationship of the sensing actuator.

When the actuator undergoes its maximum bending deformation, the sensor exhibits an extension of $\approx 60\%$ of the actuation strain. To assess the sensitivity of the sensors, they were subjected to 2000 cycles of testing using a 60% strain level and a 60% cyclical load. Figure 5.3(a) illustrates the sensor's relative shift in resistive signal, providing insight into its electrical properties under a 60% mechanical strain. The electrical response sensitivity of the sensor is represented by a fitted function with an R^2 value of 0.98, following a third-order polynomial function that enables calibration through an electrical circuit. The strain sensor demonstrates a gauge factor (GF) of 0.27. The response of the sensor to stretching reveals an increasing resistance change with higher strain levels, accompanied by low hysteresis. Figure 5.3(b) displays a loading-unloading graph depicting 2000 cycles at strain levels ranging from 0% to 60%, with minor fluctuations observed in the relative resistance change across the five loading-unloading cycles. Following 2000 cycles of stretching, the variation of R/R_0 remains virtually constant in each cycle. These minor changes could be attributed to stitch readjustment and the sliding of conductive yarn within the

knit structure during sensor recovery. The sensor's stability, repeatability, and sensitivity contribute to the accurate detection of actuator bending motion.

Sensor-based closed-loop control plays a crucial role in the field of soft robotics. It involves collecting data through tests conducted on the sensing actuator, followed by modelling (Rich et al., 2018; Polygerinos et al., 2015; Bilodeau et al., 2018). Previous studies have utilized adhesive techniques to integrate rigid sensors, commercially available flexible sensors (Elgeneidy et al., 2018), and textile capacitive sensors (Bilodeau et al., 2018). In contrast, our approach involves the complete integration of a stitched strain sensor into the body of the actuator, ensuring reliable data representation of the actuator's dynamics. Our compliant flexible stitched-based sensor, unlike polymer-based sensors, exhibits excellent durability, remaining intact even when subjected to expansion over time. By utilizing a flexible stitch-based resistive sensor, the angular motion of the actuator is accurately measured, with the resistance altering proportionally to the degree of bending. Figure 5.3© demonstrates the relationship between the sensor's relative resistance change (R/R_0) and the associated bending angle, obtained through position feedback. The relative resistance varies as the sensor geometry reacts to the actuator's bending, pressure, and strain effects. Notably, during the actuator's 180° bending motion, the sensor's resistance decreases almost linearly. This decrease is attributed to the separation of conductive yarn contact points resulting from the combined effects of strain, bending, and radial expansion. Remarkably, the stitched actuator achieves a maximum bending angle of 180°, showcasing the sensing element's responsiveness and its ability to accurately detect various bending angles. The sensor exhibits remarkable resilience in the presence of substantial bending deformation, unlike flexible sensors used in other studies that exhibit adverse effects on sensing properties due to the diverse mechanical properties of constituent materials. Figure 5.3(d) compares the bending angle characterization of the sensing and non-sensing pneumatic actuators during inlet pressure measurements ranging from 110 to 195 kPa. As the actuator is initially 2D before inflation, the bending angle is computed through image processing after reaching an internal pressure of 120 kPa. The results demonstrate that integrating the stitched sensor into the actuator has minimal impact on the maximum 180° bending angle. However, at pressure values of 150–195 kPa, the bending angle of the sensor-integrated actuator increases, potentially due to the higher pressures required to

overcome the limiting influence of the sensor stitching. Figure 5.3© displays five complete cycles of the bending actuator, including both inflation and deflation. Throughout these cycles, the relative resistance decreases with bending motion and returns to its initial value as the bending angle decreases. Moreover, the bending angle remains constant over the actuation cycles. The actuator inflates within 7.5 s at an actuation strain rate of $8\% \text{ s}^{-1}$, while deflation takes 4.5 s to reach the maximum bending angle of 180° . The deflation cycle is faster than the inflation cycle, likely due to the opposing forces of atmospheric pressure and the recovery of the actuator's textile structure. Figure 5.3(f) illustrates the nearly linear relationship between grip force and applied pressure for the actuators. During testing, our actuator exhibits a maximum blocking force of 3.8 N at 195 kPa, providing sufficient strength to enable bending similar to the human finger.

5.4 Sensing Finger Glove Application

Textile actuators offer several advantages for robotic hand applications, including their softness, comfort, breathability, and wearability compared to rigid and other soft materials. These characteristics make them suitable for safe human-machine interaction, resembling human body tissues (Chen et al., 2021). However, for effective control and manipulation of a soft robotic hand, it is essential to incorporate a sensing mechanism that enables the hand to perceive its posture and movements (Rakhtala et al., 2022).

To demonstrate the capabilities of our sensing textile actuator, we integrated the actuator onto the outer surface of a wearable finger glove, specifically designed to assist the index finger. The fabric of the glove was carefully selected to provide a secure grip, offer stretchability, avoid finger injury by preventing excessive squeezing, and maintain a lightweight design to facilitate finger flexion. The robotic glove weighs only 15 grams due to the lightweight nature of the textile material and the simplicity of the design.

The sensing mechanism of the actuator glove functions in response to bending, straining, pressure, and finger support, as depicted in Figure 5.4(a). The actuator is securely fixed to the glove using stitching, and the sensor's response to finger flexion and relaxed motions is measured, as shown in Figure 5.4(b). Experimental tests were conducted to examine finger bending with and without the assistance of the actuator

(Figure 5.4(c)). The results indicate that the relative resistance change generally decreases during unassisted finger bending, while increasing during assisted finger movement. Conversely, when the finger is relaxed, the results exhibit the opposite behavior. The integration of the actuator into the glove capitalizes on the natural support provided by healthy human fingers from beneath. This support results in a counterforce applied to the actuator, thereby limiting its full actuating potential. Notably, the actuator's activation range was wider before it was integrated into the glove.

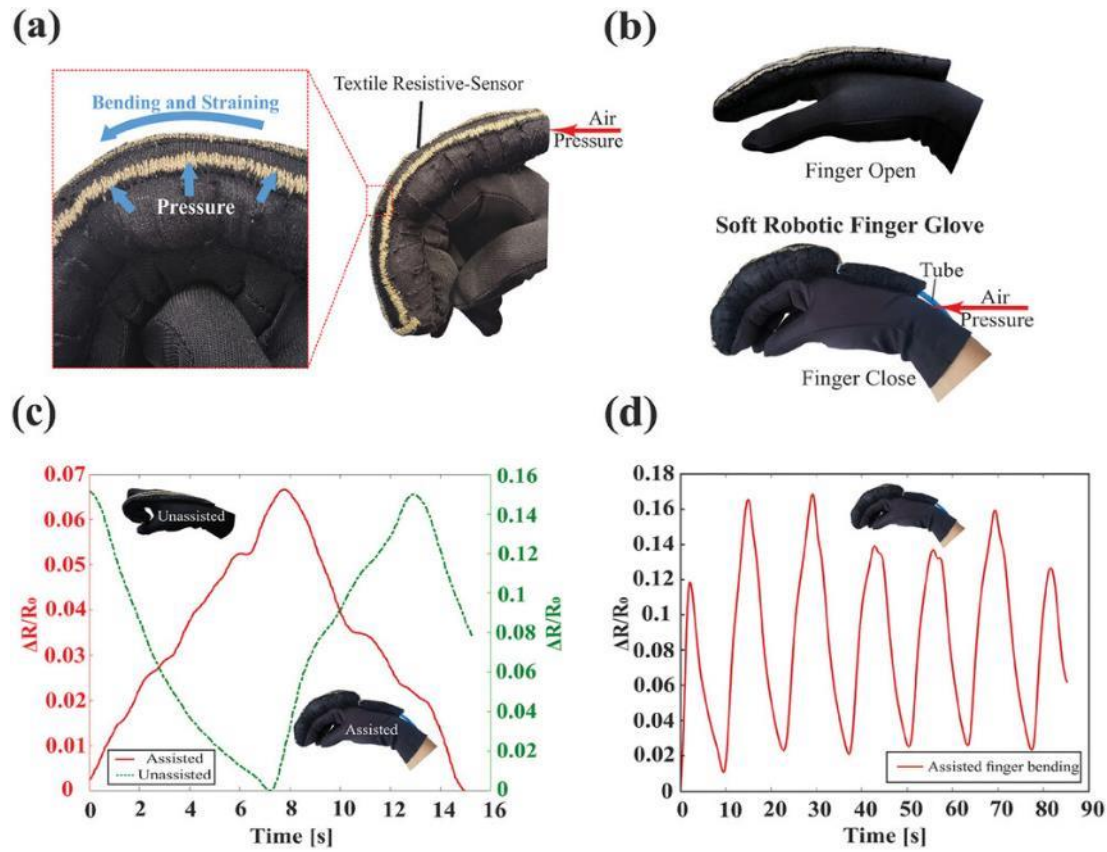


Figure 5.4: Demonstration application of the self-sensing actuator. (a) Image of bending, straining, pressure effects, and finger support on the sensing actuator. (b) Images showcasing the soft robotic finger gloves in open and closed positions. (c) Comparison of the resistance change ($\Delta R/R_0$) during unassisted and assisted finger bending. (d) Electrical signal representation of the assisted finger bending over 7 cycles.

It is worth noting that the behavior of the sensor differs when the actuator is not integrated into the glove (Figure 5.4©) compared to when it is integrated into the human hand. As the fingers provide support to the actuator from underneath, the contact points of the sensor stitches remain in contact, and the conductive threads experience increased contact due to the pressure effect. Figure 5.4(d) illustrates the

repeatability of the sensor's behavior during assisted finger-bending action over seven cycles.

The conducted experiments demonstrate that the soft finger glove is capable of sensing the bending angle at pneumatic pressure intervals ranging from 0 to 195 kPa. This showcases the effectiveness of our sensing textile actuator in enabling precise finger motion detection and control.

5.5 Modeling and Close-Loop Control of Textile Bending Robot

Using the MATLAB System Identification Toolbox, we employed the unit-step response of the sensing actuator in its non-integrated state to identify the transfer function and state space equation, as well as to assess the system's stability. The estimated transfer functions and state space functions, along with simulated response comparisons, are presented for both the inflation and deflation modes of operation. The positive signs of the denominators in the transfer functions indicate stability, as the poles are negative. These system identification and controller design studies serve the purpose of demonstrating the system's stability and providing valuable insights for future research directions.

5.5.1 Modeling of resistance (ω) - pressure (kPa)

The transfer function models and simulated response comparisons, along with the fitting percentage of the acquired data and predicted model, are presented in Equation 1 and Equation 2, respectively.

$$\left| \frac{\Delta R}{\Delta P} \right|_{inflation} = e^{-1.07s} \frac{0.003595s + 0.01957}{s^2 + 0.474s + 0.03196} \quad (5.2)$$

$$\left| \frac{\Delta R}{\Delta P} \right|_{deflation} = e^{-1.07s} \frac{1170s^2 + 1402s + 1407}{s^3 + 2091s^2 + 2533s + 1722} \quad (5.3)$$

As observed from the transfer functions, both inflation and deflation modes have a delay of 1.07 seconds. The fitting percentage of the estimated transfer function model with the acquired data is calculated as 91.01% for inflation and 97.81% for deflation, as depicted in Figure 5a and b. The estimated state-space equations for the inflation mode are as follows.

$$\frac{dx(t)}{dt} = -0.045 x(t) + 0.134 \times 10^{-3} u(t) + 0.184 e(t) \quad (5.4)$$

$$y(t) = 164.7x(t) + e(t) \quad (5.5)$$

The estimated state-space equations for deflation mode are obtained by

$$\frac{dx(t)}{dt} = 0.026x(t) + 1.085 \times 10^{-5} u(t) - 0.155 e(t) \quad (5.6)$$

$$y(t) = -194.7x(t) + e(t) \quad (5.7)$$

where $y(t)$ represents resistance in Ohms, $x(t)$ is a stretch state variable of the sensor, $u(t)$ is the pressure in kPa, and $e(t)$ is the disturbance. The fit between the estimated model and the experimental results is calculated as 95.18% for inflation and 78.29% for deflation. Despite the delay exceeding 1 second, the estimated model is highly suitable for periodic reference tracking applications.

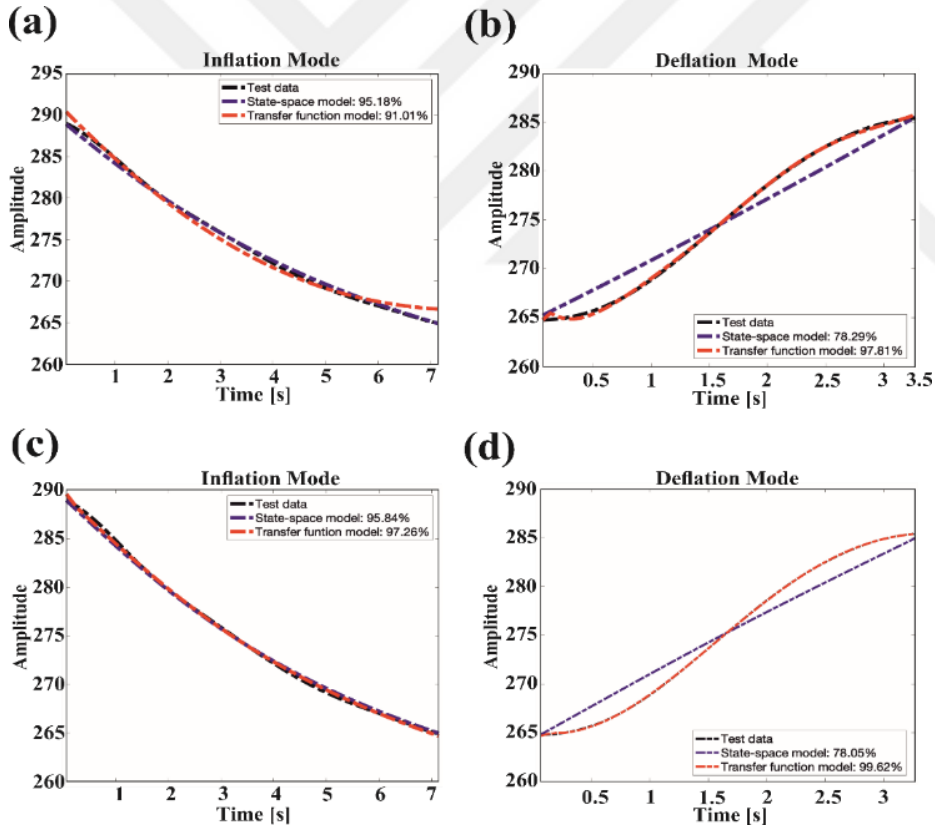


Figure 5.5: (a) Inflation mode of resistance-pressure model prediction versus robot behavior. (b) Deflation of resistance-pressure model prediction versus robot behavior. (c) Inflation mode of resistance-bending angle model prediction versus robot behavior. (d) Deflation mode of resistance-bending angle model prediction versus robot behavior.

5.5.2 Modeling of resistance (ω)-bending angle ($^\circ$)

The resistance-bending angle relation of the actuator is estimated and modeled for both inflation and deflation modes of operation, with a minimal delay of only 0.2 seconds. The transfer function and simulated response comparison are given

$$\left| \frac{\Delta R}{\Delta \theta} \right|_{inflation} = e^{-0.2s} \frac{0.02615}{s + 0.02416} \quad (5.8)$$

$$\left| \frac{\Delta R}{\Delta \theta} \right|_{deflation} = e^{-0.2s} \frac{0.0113s + 0.2011}{s^2 + 0.6322s + 0.02416} \quad (5.9)$$

The estimated state-space equations for inflation mode are

$$\frac{dx(t)}{dt} = -0.024x(t) + 5.162 \times 10^{-5} u(t) + 0.06 e(t) \quad (5.10)$$

$$y(t) = 506.6x(t) + e(t) \quad (5.11)$$

The estimated state-space equations for deflation mode are

$$\frac{dx(t)}{dt} = 0.0173x(t) - 2.709 \times 10^{-5} u(t) - 0.0746 e(t) \quad (5.12)$$

$$y(t) = -440.5x(t) + e(t) \quad (5.13)$$

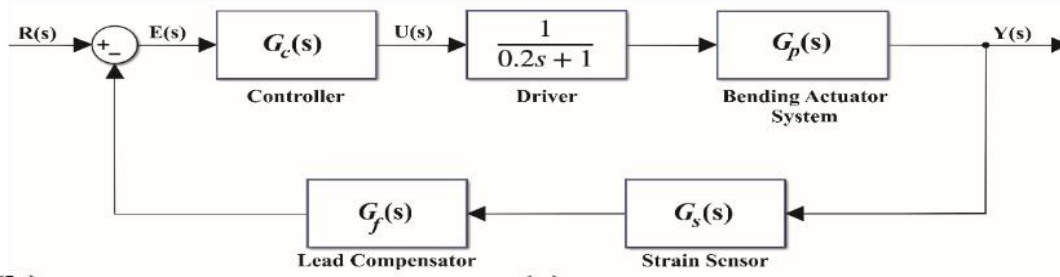
where $y(t)$ represents resistance in Ohms, $x(t)$ is a stretch state variable of the sensor, $u(t)$ is the pressure in kPa, and $e(t)$ is the disturbance. The fit of the transfer function models with the acquired data is determined to be 97.26% for inflation and 99.62% for deflation of the actuator. Additionally, the fit of the state-space models with the acquired data is calculated at 95.84% for inflation and 78.05% for deflation, as depicted in Figure 5c and 5d, respectively. Due to the estimated computational costs of controllers in real microcontroller operations, higher-degree state-space models were not computed. Instead, transfer function models are deemed sufficient and more suitable for implementation in real microcontroller operations using the basic inverse Laplace transform and Newton-Raphson method.

5.5.3 Closed-loop control simulation

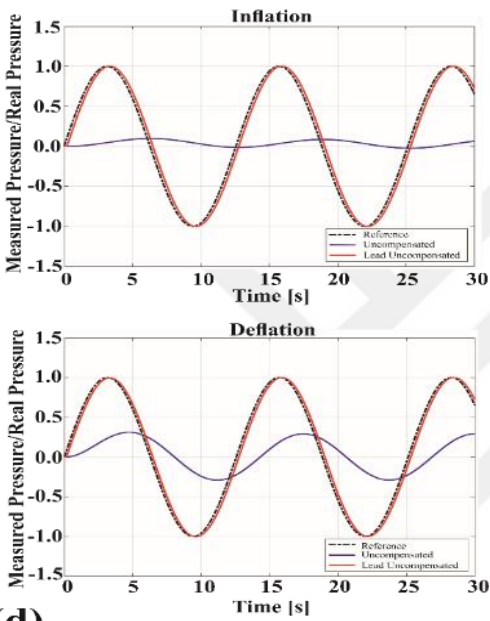
To simulate the closed-loop control for the bending angle application, the provided control block diagram in Figure 5.6(a) is utilized. The simulation process involves system identification of the relay driver model actuator block and the air pressure and

bending actuator system model plant block. Following this, the actuator and plant models are computed for further analysis and evaluation.

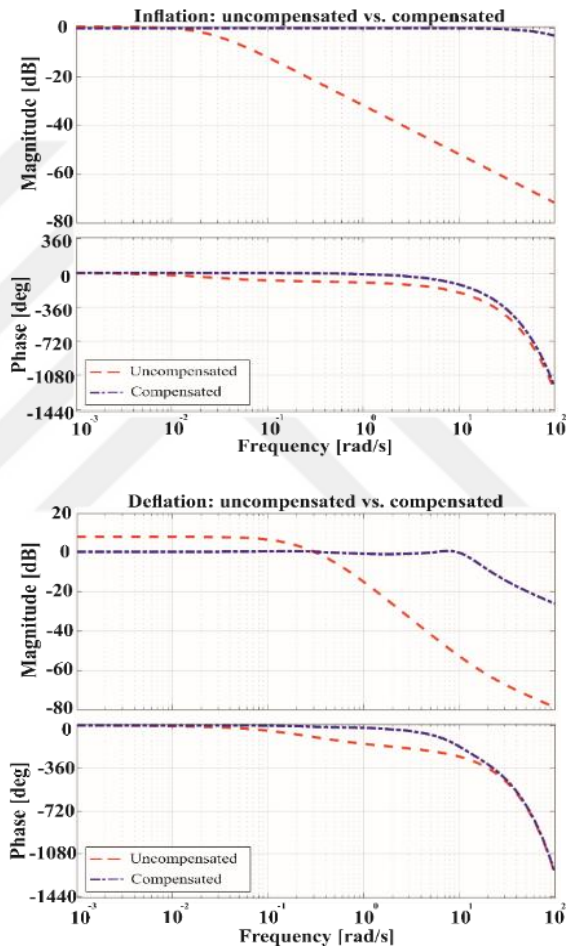
(a)



(b)



(c)



(d)

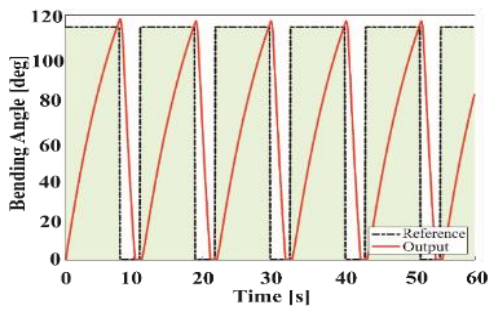


Figure 5.6: (a) Schematic control block diagram ($G_c(s)$, $G_p(s)$, $G_s(s)$, $G_f(s)$). (b) Comparison of the sinusoid response of the sensor with and without compensator. (c) Bode diagrams with and without compensator. (d) Bending angle control simulation result.

Inflation bending actuator model is

$$G_p(s) = \frac{200}{8.8s+1} \quad (5.14)$$

The deflation bending actuator model is

$$G_p(s) = \frac{180}{3.7s+1} \quad (5.15)$$

A phase delay and a drop in amplitude are seen when a sinusoidal input is supplied to the sensor model. This results from hysteresis between the actuator's inner and outer kinematics. As a result, two distinct lead compensators for the inflation and deflation phases are created.

The general formula of “lead compensator” is $0 < \alpha < 1$ as follows

$$G_f(s) = K_f \frac{s + \frac{1}{T}}{s + \frac{1}{\alpha T}} \quad (5.16)$$

For the inflation phase, $K_f = 3830$, $T = 41.67$, and $\alpha = 0.00024$

$$G_f(s) = K_f \frac{s + \frac{1}{T}}{s + \frac{1}{\alpha T}} = 38.3 \frac{s + 0.024}{0.01s + 1} \quad (5.17)$$

compensator model is used. Since the deflation phase sensor dynamics degree is higher, a higher-order compensator design is done as follows

$$G_f(s) = 4.34 \frac{s^2 + 0.77s + 0.1}{0.01s^2 + 0.1s + 1} \quad (5.18)$$

The lead compensator is designed for our operating frequency between 0-16 Hz (0-100 rad/s). The lead compensator will not amplify the noises when the sensor is used, as the noises generated will be at higher frequencies. Table 1 shows the designed PID closed-loop controllers for inflation and deflation phases, where K_p , K_i , and K_d are controller parameters.

Table 5.1. Comparison of PID controller variants.

Phase	K_p	K_i	K_d
Inflation	0.1	0.03	0.03
Deflation	0.038	0.006	0.012

The sinusoidal response of the system with a controller is presented in Figure 5.6(b), demonstrating the effect of the lead compensator on the output signal. The Bode diagrams in Figure 5.6(c) provide insights into the frequency range of the designed controller, indicating its suitability for the applied reference signals. It is worth noting

that the ON-OFF and tuned PID controllers produce identical control signals. The simulation results of the bending angle control model (Figure 5.6(d)) align well with the experimental data. In the simulation, a reference pressure of 114 kPa is used for the inflating mode, while a reference pressure of 0 kPa is applied for the deflation mode. Two separate controllers are designed for the sensor, considering its different transfer functions when used as a pressure sensor and a bending angle sensor. The controller's performance is evaluated against selected references with close amplitudes (60 kPa and 100 degrees) during a simulation period of 11 seconds, resembling the experimental conditions for data collection.

5.6 Conclusions

This study has successfully demonstrated the integration of a textile-based resistive sensor into a fabric actuator, showcasing its design, fabrication, characterization, modeling, and control. By utilizing standard sewing technology, we have achieved the combined sensing and mechanical capabilities without the need for extensive training or costly investments. This approach streamlines the manufacturing process, eliminating the need for additional processing in both sensor and actuator production. Experimental evaluations have revealed remarkable performance, with the actuator achieving bending angles of up to 180 degrees at pressures of 195 kPa, generating a maximum blocking force of 3.8 N. Notably, the stitched sensor exhibited no adverse effects on the actuator's straining ability, ensuring its reliable functionality. The developed transfer function models have proven highly effective in estimating both pressure (91.01% for inflation and 97.81% for deflation) and bending angle (97.26% for inflation and 99.62% for deflation) of the sensing actuator.

In the performance analysis of different controller variants, the simplicity of the ON-OFF controller emerged as the preferred choice. This finding emphasizes the feasibility and practicality of our approach in developing closed-loop control systems for soft robotics. Moving forward, our research will focus on refining the modeling, calibration, and control of the actuator specifically on the human hand, as the sensor's behavior may vary within the finger glove assembly.

Furthermore, we envision further advancements of this sensing actuator in applications such as grasping, assistive robotic wearables, and human rehabilitation. These

promising avenues will be explored to unlock the full potential of our technology. We believe that our study will inspire fellow robotics researchers to embark on the development of simple yet highly effective sensing solutions for soft robot technologies. By sharing our findings, we aim to foster innovation and drive progress in the field of soft robotics.





6. MACHINE-KNITTED SEAMLESS TEXTILE ACTUATOR⁴

Computerized machine knitting offers an attractive fabrication technology for incorporating wearable assistive devices into garments. In this work, we utilized, for the first time, whole-garment knitting techniques to manufacture a seamless fully knitted pneumatic bending actuator, which represents an advancement to existing cut-and-sew manufacturing techniques. Various machine knitting parameters were investigated to create anisotropic actuator structures, which exhibited a range of bending and extension motions when pressurized with air. The functionality of the actuator was demonstrated through integration into an assistive glove for hand grip action. The achieved curvature range when pressurizing the actuators up to 150 kPa was sufficient to grasp objects down to 3 cm in diameter and up to 125 g in weight. This manufacturing technique is rapid and scalable, paving the way for mass-production of customizable soft robotics wearables.

Keywords: soft robotics; knitted actuators; wearables, assistive devices.

6.1 Introduction

Soft wearable robotic technologies have seen tremendous research efforts in the past decade as an attractive solution for human mobility assistance and rehabilitation (Thalman et al., 2020; Cianchetti et al., 2018; Polygerinos et al., 2017). The use of soft materials that conform to the human body and are compliant when exposed to external forces has led to the gradual advancement from rigid exoskeletons to lighter weight soft wearable alternatives (Yap et al., 2017; Jung et al., 2019; Yang et al., 2020; Zhong et al., 2019; Sun et al., 2020). Namely, garment-like textile-based fluidic actuators demonstrated promising potential towards increased user comfort and safety (Sanchez et al., 2021; Persson et al., 2018; Belforte et al., 2014). Unlike elastomeric and tendon

⁴ This chapter based on the paper "Elmoughni, H.M., Yilmaz, A.F., Ozlem, K., Khalilbayli, F., Cappello, L., Tuncay Atalay, A., Ince, G., Atalay, O. 2021. Machine-Knitted Seamless Pneumatic Actuators for Soft Robotics: Design, Fabrication, and Characterization. *Actuators*, 10(94). DOI: 10.3390/act10050094."

actuators, which are heavier and bulkier, textile-based actuators can be easily concealed thanks to their reduced weight and volume. Various methodologies have been presented to date to create pneumatic bending textile-based actuators, which translated successfully into low-cost wearable assistive devices (Cappello et al., 2018; Yap et al., 2017; Low et al., 2017; Al-Fahaam et al., 2018; Connolly et al., 2019; Visan et al., 2012). The efforts in this context have mainly focused on creating anisotropic structures through combining a highly extensible top material with an inextensible base layer to form the inflatable bending textile pouches. The contrasting mechanical properties of the combined layers cause the actuator to exhibit bending motions upon pressurizing with compressed fluid such as air (Yap et al., 2017; Cappello et al., 2018). The techniques used to connect the layers follow a cut-and-sew approach and rely heavily on manual assembly and fabrication steps. The process is not only time consuming and labor intensive, but it also presents other challenges including inconsistencies and the possible failure of the actuator during inflation. Another major drawback of the process is that the actuator behavior is determined by off-the-shelf textile material's properties, which are usually controlled at the mass-production scale, limiting systematic iterations and fine-tuning. Computerized machine knitting offers an alternative end-to-end automated fabrication technology that can be leveraged to produce soft textile actuators with the desired deformations. Despite the advanced capabilities of industrial machine knitting to produce fully shaped garments with minimal post-processing, this technology is seldom explored as a fabrication technology for wearable assistive soft robotics devices. In this work, we manufactured a proof-of-concept fully knitted seamless bending actuator using machine knitting. The knitting parameters were varied to produce four tubular 3D structures with different stretch properties at the top and bottom layers to create anisotropy. Experimental results showed that the actuators exhibited a range of bending behaviors comparable to previously reported cut-and-sew textile actuators. Finally, to demonstrate the potential of the developed seamless knitted actuator, five actuators were used to construct an assistive glove, which was capable of gripping and holding various objects at pressure range up to 150 kPa.

6.2 Machine-Knitted Actuator Fabrication and Design

Knitting is a textile fabrication process based on forming a yarn into rows (courses) and columns (wales) of loops or stitches (Ray et al., 2012). In its most basic form, a knitted structure can be formed from a single continuous length of yarn. Flat-bed machine knitting is the most widely used mechanical process for knitted fabric manufacturing and is considered by far the most accessible for rapid textile prototyping. The machine forms a knitted structure through a sliding action of multiple needles arranged in parallel on a flat bed. The machine gauge defines the number of needles per inch on the needle bed; therefore, it determines the fabric thickness that can be produced. Finer fabrics can be knitted on high-gauge machines (12–18 needles per inch), while coarser fabrics can be knitted on lower gauge machines. In machine knitting, the needles' action is synchronized with yarn carriers that provide yarn to the needle hook, which grabs the yarn to form the stitch and pulls it through the previously held loop (Figure 6.1(a)) (Spencer et al., 2001). This structure of inter-looped yarn gives knitted fabrics their inherent stretch property. Digitally controlled machines enable controlling the needle action and the movement of multiple yarn carriers simultaneously. This allows knitting of different yarns independently at digitally pre-set knitting parameters to produce single or multiple layers with different properties. The type of yarn used, stitch density, and needle action selected are all knitting machine parameters that determine the mechanical properties of the produced fabric. Advanced computerized knitting machines are also capable of whole-garment knitting, which allows for manufacturing seamless garments without the need for the labor-intensive cutting and sewing processes (Mccan et al., 2016). In this work, we leveraged computerized knitting, employing a 10-gauge SHIMA SEIKI whole-garment knitting machine to manufacture seamless knitted actuators. The basic actuator structure consisted of a knitted pouch construction with two chambers. For the purposes of this work, bending was the desired deformation; therefore, an anisotropic actuator fabric structure was designed. The stitch density and the type of yarn constituted the two knitting parameters that were varied to control the extensibility of the top and bottom actuator fabric layers. Four types of actuators were manufactured, each with different yarn type combinations for the top, middle, and bottom layers, as listed in Table 6.1, and according to the structure parameters listed in Table 6.2. A plain knitted structure, which was lightweight and less bulky, was selected as the base structure for all the

actuators with the same dimensions (14 cm length and 2.5 cm width). To create contrasting material properties between the top layer and the other two layers (middle and top), the number of courses per centimeter (cpcm) of the former was selected to be higher than the latter ones. This higher course-to-wale ratio between the top and bottom layers created a more extensible top layer due to the added extra rows of loops, which took the form of gathers at the top layer of all the actuators, as can be seen in Figure 6.1(b). The use of yarn combinations of a highly extensible yarn such as Lycra with a less extensible yarn such as plied yarn for the top and bottom layers, respectively, was expected to create a range of anisotropy for the different actuators produced.

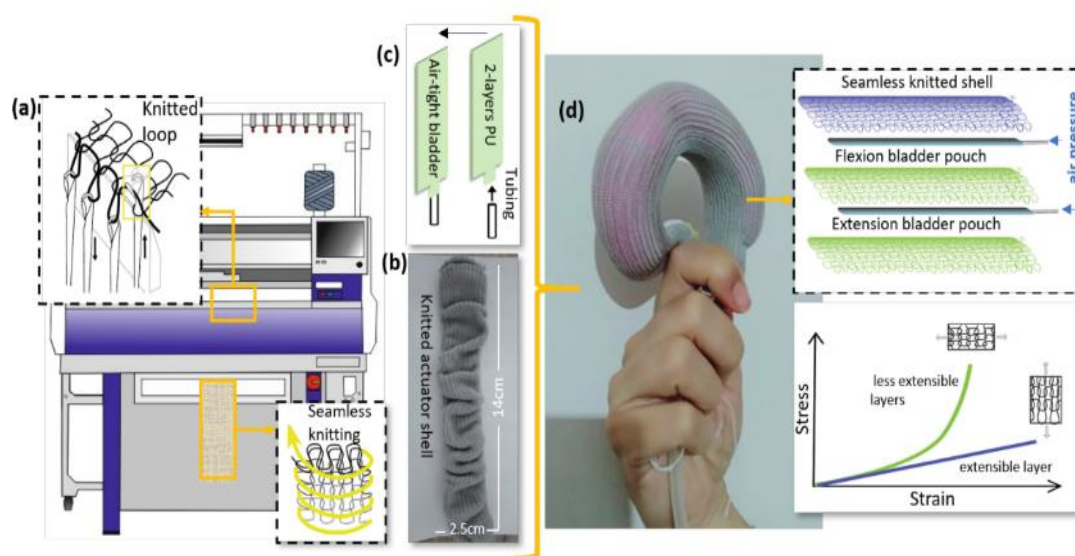


Figure 6.1: (a) Computerized flatbed whole-garment knitting. (b) Machine-knitted seamless actuator. (c) Polyurethane air-tight bladder assembly. (d) Bending motion of the knitted actuator under air pressurization and a construction principle based on an extensible top layer and less extensible middle and bottom layers.

Table 6.1. Yarn combinations of actuator layers for each actuator type.

	Top Layer	Middle and Bottom Layer
Actuator Type 1	Lycra	Lycra
Actuator Type 2	Lycra	3-ply Polyamide Yarn
Actuator Type 3	Lycra	Melting Yarn
Actuator Type 4	2-ply Polyamide Yarn	3-ply Polyamide Yarn

Table 6.2. Knitted structure parameters of the three actuator layers (common to all actuator types).

	Top Layer	Middle and Bottom Layer
Courses per cm (cpcm)	15	10
Wales per cm (wpcm)	5	5
Stitched density (S)	75	50
Course-to-wale ratio	15:5	10:5

To create an inflatable actuator, airtight tubes were fabricated using thermoplastic polyurethane stretchy film (Stretchlon 200, Fiber Glast). Each bladder was manufactured by laser cutting two identical (17×2.5 cm) rectangles, which were welded using an impulse sealer (PCS 300, Brother) from three edges. A polyurethane tube with a 6mm outer diameter was attached to the open edge of the bladder to connect it to the compressed air line. The tube was securely attached to the bladder with Globe PVC black tape in order to prevent any air leakage (Figure 6.1(c)). Finally, two identical bladders produced with the aforementioned technique were inserted in the top and bottom chambers in order to achieve flexion and extension motions, respectively, when inflated (Figure 6.1(d)).

6.3 Actuator Characterization

6.3.1 Curvature test

The change in curvature values with respect to the applied pressure was recorded for each actuator type using a webcam (Microsoft LifeCam HD-3000, Microsoft, Beijing, China), which was positioned in alignment with the actuator plane. During the test, one end of the actuator was fastened to a stable stand, while the other end moved freely in a circular motion. Each actuator was continuously inflated up to 150 kPa and deflated six times consecutively. Since a color-based approach was implemented, the actuator was placed in a secluded area that was internally illuminated by LED strip lights, in order to avoid brightness variations along the actuator surface. To locate the actuator in each video frame, a marker-based solution was developed. Markers were placed on the extreme points along the actuator length, namely the bottom of the metacarpophalangeal (Marker 1), the top of the distal interphalangeal (Marker 2), and the middle of the proximal interphalangeal (Marker 3) joints (Figure 6.2(a)). In each captured frame, the RGB values were first converted into HSV to achieve better color-based image segmentation. To sooth the noise, dilation and erosion were applied to the

resized and blurred frame. To detect the markers, outer contours and their respective center-of-mass covering the color range of the placed markers were located in the given frame. After identifying the intersection coordinate of Marker 3 and the line connecting Markers 1 and 2, the angle formed by Markers 3, 1, and the intersection pixels was determined. The radius of the possible circle created by the actuator movement (rr) was calculated to be:

$$r = a \cdot \cot(2x) + k \quad (6.1)$$

where a is the distance between Marker 2 and intersection pixels, x is the aforementioned angle, and k is the distance between Marker 3 and intersection pixels. Curvature I was obtained from the equation $c = 1/r$. To represent the curvature value in terms of its actual length instead of pixels, an object with a known width and height was placed in the platform.

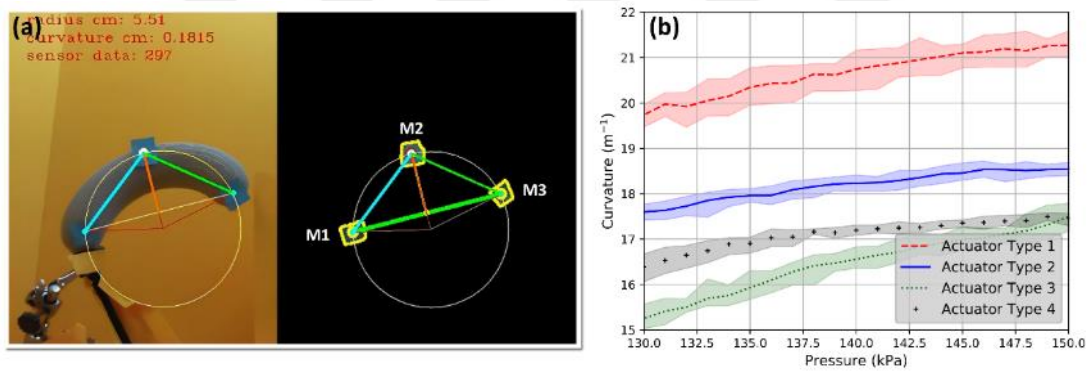


Figure 6.2: (a) Curvature measurement using a video frame. (b) Curvature of the seamless knitted actuators at different pressures.

6.3.2 Tip Force- grip force and torque

A digital dynamometer (Geratech SH-50) was used in order to measure the forces and torque of the seamless knitted actuators. Data were transmitted to the computer via an RS-232 cable. Experiment oriented shapes were designed and fabricated using a 3D printer (Ultimaker 2+, Ultimaker, Zaltbommel, Netherlands) and placed on top of the dynamometer (Figure 6.3). Prior to starting the experiment, the actuators were fully pressurized and depressurized five times consecutively in order to eliminate any fabric or bladder relaxation and to fit the actuators to the custom test rig. One end of the actuator was fastened to a custom-made board, while the other end moved freely in a circular bending motion, to avoid any undesired movements, which would result in noise. While being pressurized, the free end of the actuator was applying a pushing

force on the cup-shaped object and a pulling force on the hollow rectangle attached to the dynamometer to measure tip and grip forces, respectively. For torque measurement, the actuator was placed in a hollow cylinder connected to the dynamometer. The actuator was pressurized up to 150 kPa and placed from the other end at angles between 0° and 120° subsequently, in multiples of 15 (Figure 6.4). Output torque was calculated as the product of the pressure value obtained from the dynamometer and the distance between the actuator and the dynamometer at each angle.

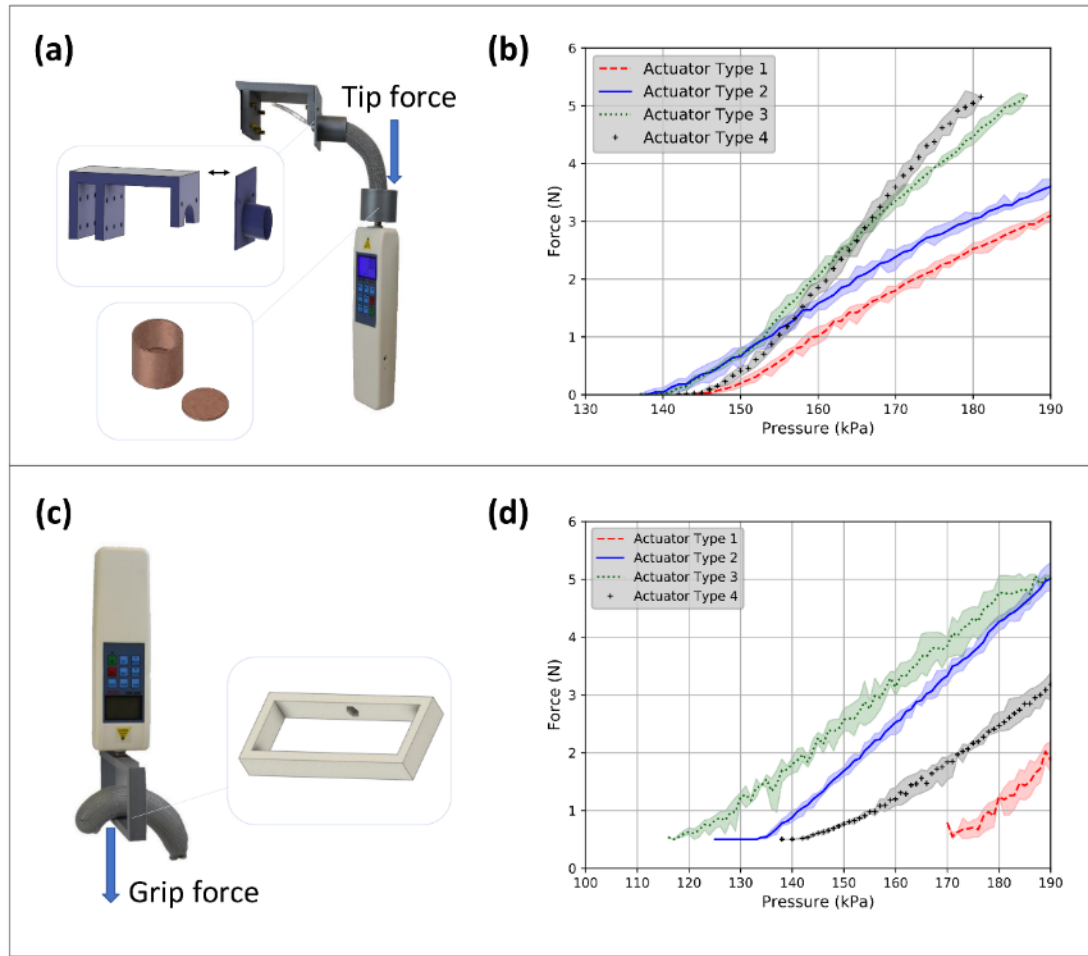


Figure 6.3: (a) Tip force test setup. (b) Tip force-pressure characteristics of all actuators. (c) Grip force test setup. (d) Grip force-pressure characteristics of all actuators. € Torque test setup. (f) Output torque of Actuator Type 3 at different bending angles.

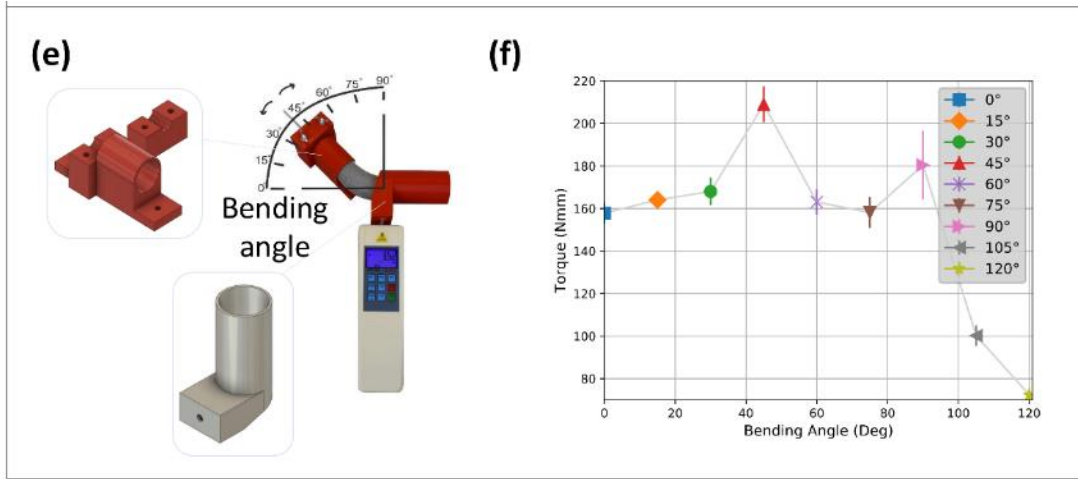


Figure 6.3 (continued): (a) Tip force test setup. (b) Tip force-pressure characteristics of all actuators. (c) Grip force test setup. (d) Grip force-pressure characteristics of all actuators. € Torque test setup. (f) Output torque of Actuator Type 3 at different bending angles.



Figure 6.4: Output torque measurement setup.

6.4 Results and Discussion

First, the actuator was pressurized continuously up to 150 kPa using an air pump to achieve bending motion. The change in curvature values with respect to the applied pressure was recorded using a digital camera. To determine the actuator curvature in each video frame, an automated method based on edge detection and a circle fitting algorithm was used (Figure 6.2(a)). The detailed steps for calculating the curvature are discussed in Section 6.3.1. This procedure was carried out six times for each actuator

type, and as shown in Figure 6.2(b), the knitted actuators exhibited consistent bending behavior when pressurized, and an approximately linear relationship between curvature and pressure was observed. It was clear that the different knitting parameters used to manufacture the actuators resulted in distinctively different bending behaviors. For example, Actuator Type 1 showed a maximum curvature of 21 m^{-1} (reciprocal of the SI unit for distance) at the maximum of 150 kPa of pressure applied due to the Lycra yarn used for knitting the whole actuator combined with the higher number of courses at the top layer. Although Actuator Types 3 and 4 showed the same curvature of 17.5 m^{-1} at a maximum pressure of 150 kPa, the initial curvature values for those actuators were different. It was also clear from the results that Actuator Type 4 exhibited the lowest curvature due to the absence of Lycra yarn in all layers of the actuator.

Second, in order to deduce the force capacity of the knitted actuators, pressure values were correlated with the values of tip force, grip force, and output torque. To carry out the force measurements, experiment-oriented shapes were designed and fabricated using a 3D printer and placed on top of a digital dynamometer. While being pressurized, the free end of the actuator was applying pushing force on a cup-shaped object (Figure 6.3(a)) and a pulling force on a hollow rectangle (Figure 6.3(c)) attached to the dynamometer to measure tip and grip force, respectively. A torque test was carried out by placing the actuator in a hollow cylinder connected to the dynamometer (Figure 6.3(e)). The detailed steps for carrying out the tests are discussed in Section 6.3.2. As the results in Figure 6.3(b) and Figure 6.3(d) show, an approximately linear relationship was observed between tip and grip forces and the applied pressure for all four actuator types except for the dead-band region in Figure 6.3(d), which occurred due to the actuator not applying any pulling force to the hollow rectangle attached to the dynamometer at the beginning of the pressurization. However, it was observed that the actuator types fell into different orders when the measured forces and curvature results at different pressures were compared. This indicated that the actuator with the higher curvature at a given pressure did not necessarily exert higher forces. For example, Actuator Type 1, which showed the highest curvature across the range of pressure applied, gave the lowest tip and grip forces compared to the other actuators. On the other hand, Actuator Type 3, which showed the lowest curvature, gave the highest tip force (5.3 N) and grip force (5 N), at the maximum pressure applied,

compared to the other actuators. Actuator Type 3 was also tested for torque, given that it had the highest tip and grip force values. According to Figure 6.3(f), our soft actuator was able to apply a torque that gradually increased up to bending values of about 45°, after which it started decreasing. One possible reason is the occurrence of the buckling phenomenon, which might negatively affect its performance. In fact, it is known that buckling dramatically reduces the mechanical properties of a thin beam, leading to its failure for stresses much lower than those that might cause failure in a thicker beam. As the bending angle of the actuator increased, the compressive stresses in the side of the compressed fibers increased, causing a reduction in the maximum torque that it can apply. Nevertheless, this actuator exhibited a maximum torque value of 210 Nmm.

The reported values above for the actuator curvature, grip and tip forces, and output torque were comparable to previously reported values measured for cut-and sew textile-based actuators at the 150 kPa applied pressure range (Correia et al., 2020; Zhou et al., 2019; Yap et al., 2016; Ge et al., 2020). However, in contrast to existing fabrication processes of textile-based actuators, the proposed seamless knitting approach had a number of value-added features including; rapid, automated, and customizable manufacturing, less bulk and weight, robustness, and lower cost.. Furthermore, the single actuator can be incorporated into wearable structures for different body parts including hand, foot, or knee utilizing whole-garment knitting. Such an advancement would replace the use of multiple separate actuators as attachments on already-made garments into garment-like robotic structures. This would result in further reduction of bulk and weight. Endless machine knitting parameter combinations can be further explored in order to fine-tune the desired range and type of deformations. It must be highlighted that the parameter combinations chosen to produce the actuators in this study were arbitrarily selected to demonstrate the functionality of this manufacturing approach and provide a benchmark for a more in-depth investigation of seamless machine knitted actuators for various applications. Furthermore, higher gauge machines could be investigated as they would allow further reduction in the actuator form factor. A finer knitted fabric structure would also have a higher level of elasticity, which would ensure repeatable performance with multiple flexing and would be more compliant, therefore requiring lower pressure to achieve the desired deformation. All the aforementioned possible enhancements demonstrate

the versatility of machine knitting and its potential for the development of wearable soft robotics structures.

6.5 Air pressure control system

A portable control system was developed in order to characterize the bending motions of the actuators. The system consisted of: (1) microcontroller, (2) relay card, (3) air pump, (4) valve driver cards, (5) solenoid valves, and (6) pressure sensors to inflate and deflate the actuators (Figure 6.5). Each valve controlled the inflation and deflation of each air bladder in order to achieve actuator bending and extension. The actuator motion was automatically controlled via a microcontroller using the on-off controller principle.

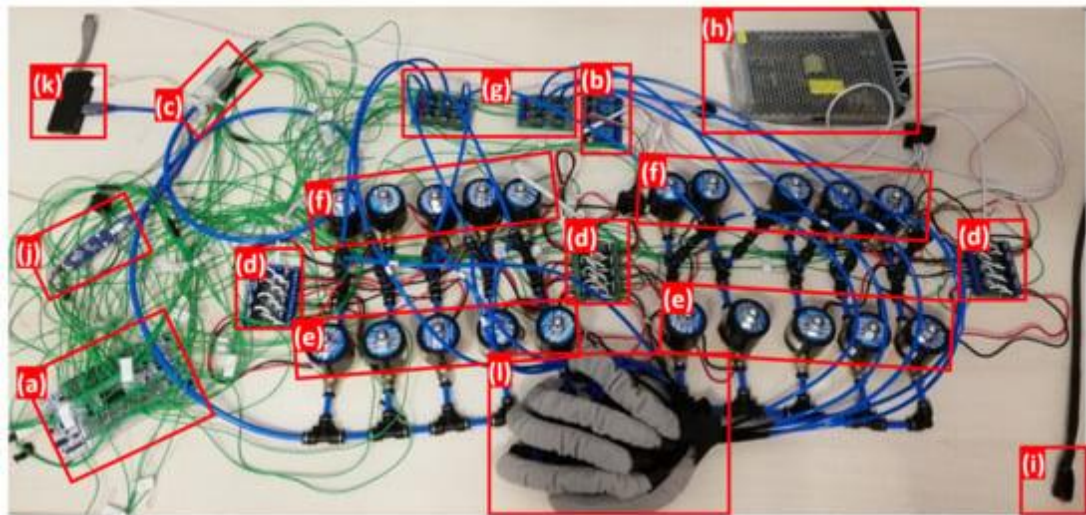


Figure 6.5: Air pressure control system components, which include: (a) Microcontroller. (b) Relay card. (c) Air pump. (d) Valve driver cards. (e) Inflate solenoid valves. (f) Deflate solenoid valves. (g) Pressure sensors. (h) Power supply. (i) Emergency stop switch. (j) USB to TTL converter. (k) USB hub. (l) Soft robotic glove.

Real-time pressure values of each bladder were visualized through a graphical user interface via a computer. When the inflation button is pressed, air is pumped to inflate the bladder through the inflation valve. When the inflation valve is released, the current to the air pump and inflation valve is cut off, and the inflation of the actuator is stopped. The same procedure was conducted for the deflation operation. To achieve the bending motion of an actuator, the inflate valve of the flexion bladder and the deflate valve of the extension bladder are activated, which ensures that the flexion bladder is inflated while the extension bladder is deflated. When the bladders reach maximum inflation

pressure, the air pumping stops. The system was scaled up for glove actuation using a total of 10 inflation and 10 deflation valves.

6.6 Application

In order to demonstrate the potential of the seamless knitted actuators in wearable assistive device applications, they were integrated into an adjustable glove. Actuator Type 3, which exhibited the highest tip and grip forces, was selected. Five identical actuators were mounted on the top surface of the glove using Velcro belts and straps (Figure 6.6(a)). The test setup, detailed in Section 6.5, for inflating and deflating the actuator was developed to control the five actuators via a computer according to preset air pressure values. In order to evaluate the functionality of the glove, a range of flexion and extension actuator motions was set to allow grasping of different objects, as shown in Figure 6.6(b). The results showed that the glove was capable of grasping objects, of different weights and sizes (up to 125 g), at the applied pressure range (up to 150 kPa).



Figure 6.6: (a) Wearable assistive glove prototype based on a seamless knitted actuator. (b) Achievable motions with the glove prototype for grasping objects of different weights and sizes.

In order to evaluate the assistive action of the glove, muscle activation was compared with and without the glove, while performing a sequence of hand actions. The sequence of actions included: (1) relaxing the hand, (2) closing the hand, (3) relaxing the hand again, and (4) opening the hand. To provide a reference point, these actions were then repeated without the glove while exerting maximal force in order to obtain the maximum voluntary contraction (MVC) percentage of the muscular activity, which can be defined as the maximum muscle strength. We avoided exerting any force in conducting the actions while wearing the glove. Two EMG sensors (Advance

Technologies MyoWare Muscle Sensor) with a sampling frequency of 50 Hz were placed on the flexor digitorum superficialis (FDS) and extensor digitorum communis (EDC) muscles (Figure 6.7(a)). The detected signal was later filtered with a second-order Butterworth filter with a critical frequency of 2 Hz. When worn, the glove was pressurized up to 150 kPa to complete the hand closing action and depressurized to relax the hand again in alternate sequence. As Figure 6.7(b) indicates, the maximum voluntary contraction (MVC) of both muscles while wearing the glove was at the baseline EMG activity. A significant muscle activity change was noted from 66.81% to 23.12% of MVC in the flexor muscle and from 35.49% to 21.33% of MVC in the extensor muscle, while closing and opening the hand. The results indicated that the user relied on the glove's auxiliary force to perform the actions.

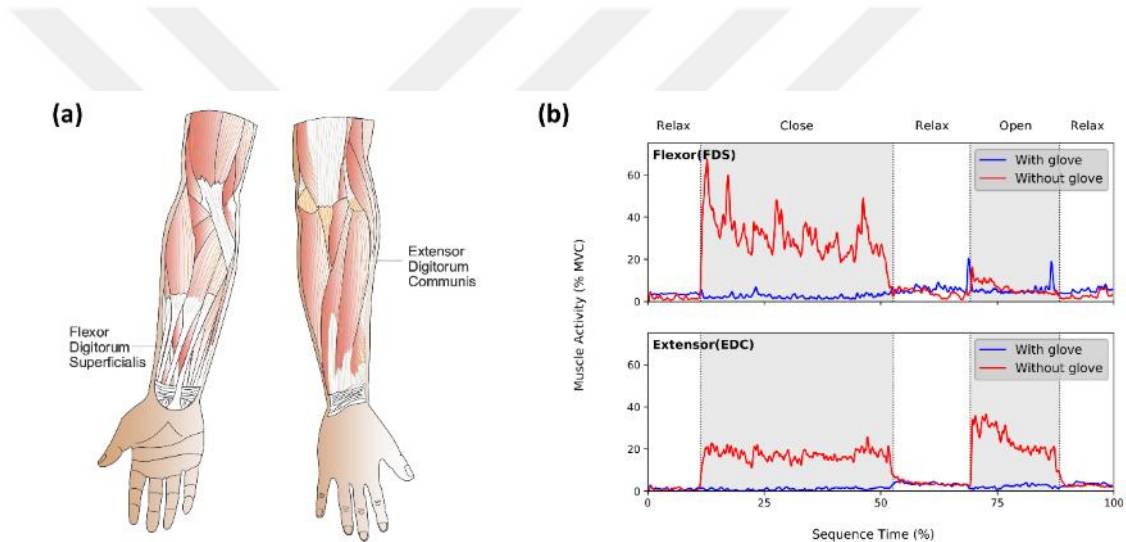


Figure 6.7: (a) EMG sensors' placement on arm muscles. (b) Muscle activity comparison with and without the powered glove.

6.7 Conclusions

In this work, we leveraged advanced computerized knitting to manufacture seamless pneumatic knitted actuators. An anisotropic fully knitted actuator structure was realized through combinations of machine knitting parameters. For the purposes of demonstrating the viability of the approach for manufacturing bending actuators, arbitrarily selected knitting parameters, including stitch density and yarn type variations for the top, middle, and bottom actuator layers, were investigated. The actuators were experimentally tested showing a range of bending curvatures, as well as grip and tip forces up to 5 N at a maximum 180 kPa air pressure value. The above-

mentioned actuators were used to construct a wearable soft robotics glove, which aimed at assisting hand grasping motion. This application demonstrated the capability of the fully knitted actuators to exert sufficient force for grasping objects up to 125 g in weight at a minimal air pressure (150 kPa), comparable to existing cut-and-sew textile actuators. We believe that this cutting-edge approach, which to the best of our knowledge has not been presented before, will push the boundaries of garment-like wearable soft robotics manufacturing towards viable mass-production. Computerized whole-garment knitting, as demonstrated in this work, is an accessible technology for rapid iterations of textile actuators, which can be customized to different users. Further work will be carried out for investigating various combinations of knitting parameters in order to achieve higher ranges of actuator curvature and exerted forces at minimal pressure. The process will also be scaled up to manufacture a fully knitted glove and more complex garment geometries, which can be customized as assistive devices for different body parts. Another compelling potential advancement offered by this technology is the integration of textile-based sensors during the knitting process, which enables a two-way interaction between the user and the actuator through implementing closed-loop control strategies. All such advances would pave the way for complete systems of soft robotics garments.

7. HIGHLY STRETCHABLE TEXTILE KNITTED INTERDIGITAL SENSOR FOR KNEE BRACE APPLICATION⁵

Wearable technology applications have experienced remarkable development and advancements, with soft and stretchable strain sensors playing a significant role in this progress. Despite the promising potential of combed-shaped interdigital capacitive strain sensors in wearable electronics, several challenges exist, including limited stretchability, universal mass fabrication, and seamless integration into diverse clothing parts. In this study, we present a textile knitted interdigital capacitive sensor that incorporates stretchable conductive yarn, produced using textile twisting technology, to achieve stretchability and adaptability, allowing seamless conformation to human body movements and textile materials. The fabrication process involves embedding the interdigital electrodes and interconnections directly into the fabric through textile knitting technology, ensuring robust integration. Furthermore, our work presents opportunities for commercializing the stretchable interdigital strain sensor through a low-cost and mass production strategy. Electromechanical characterization demonstrates exceptional performance with high stretchability ($\sim 230\%$), excellent linearity ($R^2 = 0.997$), a gauge factor of -0.68 representing relative capacitance change, and a rapid response time of 66 ms. To validate the usability of sensors in wearable technology, a knee brace application is employed to investigate capacitance changes during walking and cycling exercises. This approach will accelerate the accessibility of wearable stretchable interdigital sensors for all.

Keywords: (Interdigital sensors, capacitive strain sensors, soft sensors, textile-based sensors, knitted sensors, stretchable conductive yarns, wearable electronics.)

7.1 Introduction

Interdigital capacitive sensors have emerged as a technology with various applications, ranging from human motion detection (Atalay et al., 2018; Yuan et al., 2023; Zhang

⁵ This chapter is based on the paper "Yilmaz, A. F., Ahmed, I. A. K., Gumus, C., Ozlem, K., Cetin, M. S., Atalay, A. T., Ince, G., & Atalay, O. (2024). Highly Stretchable Textile Knitted Interdigital Sensor for Wearable Technology Applications. *Advanced Sensor Research*, 3(2), 2300121. DOI: 10.1002/adsr.202300121."

et al., 2022; Kim et al., 2017; Wang et al., 2022; Kumar et al., 2023; Rahman et al., 2016; Liu et al., 2017) and touch sensing (Kanaparthi et al., 2017) to soft tactile robotics (Fan et al., 2022) and industrial automation (Afsarimanesh et al., 2020). They have a fast dynamic reaction, allowing them to detect and respond to capacitance changes quickly (Qin et al., 2021). They are useful in applications that require real-time measurements and quick sensing capabilities (Afsarimanesh et al., 2020). Moreover, their sensitivity allows them to detect even the most minute variations in the measured quantity, enhancing accuracy and precision (Kim et al., 2017). These characteristics make interdigital capacitive sensors suitable for applications requiring precise measurements or the detection of motion changes in human activities. Nevertheless, the fabrication of flexible interdigital capacitive sensors has challenges and limitations that require effective solutions to achieve seamless integration in wearable technologies (Liu et al., 2018).

The production of mechanically flexible interdigital capacitive sensors faces several key challenges, primarily concerning the employed fabrication strategies. The selection of electrode materials assumes paramount importance in this context (Yu et al., 2017). Also, achieving precise and uniform electrode patterns on flexible substrates poses a significant obstacle. For instance, flexible interdigital capacitive sensors often incorporate materials with distinct and limited stretchable mechanical properties, such as conductive inks or thin metal films on polymer substrates. Ensuring compatibility and adhesion between these materials becomes indispensable to maintaining the electrical behavior of sensors and their reliability across diverse operating conditions (Su et al., 2022; Rivadeneyra et al., 2020; Zhang et al., 2022; Rachmanita et al., 2019; Roy et al., 2021; Helseth et al., 2018; Liu et al., 2023). Generally, these sensors have been manufactured on limited flexible substrates, typically mounted on flat surfaces. However, with the increasing demand for wearable electronics, there is a need for stretchable and repeatedly bendable sensors. The ability of stretchable sensors to conform to complex shapes and deformations makes them ideal for applications in wearable devices and soft robotics (Fan et al., 2022; Cholleti et al., 2018; Rogers et al., 2010; Wagner et al., 2012; Park et al., 2014; Cheng et al., 2015; Yao et al., 2015; Wang et al., 2016; Mccoul et al., 2016; Harris et al., 2016; Amjadi et al., 2016). This not only enhances user comfort but also allows the sensors to mimic natural mobility (Zhang et al., 2022). Furthermore, their stretchable property empowers them to be

applied to various shapes and surfaces, enabling direct integration into garments or attachment to body parts, thereby offering design flexibility for numerous wearable electronic applications.

The development of stretchable sensors involves a multitude of intricate challenges that demand careful consideration. Among these challenges, the primary focus is on ensuring the durability and long-term performance of these sensors. They must demonstrate the ability to withstand repetitive stretching and deformation without compromising their functionality or precision, particularly in situations involving continuous mechanical strain or stress (Erlenbach et al., 2023). The selection of materials that can maintain their electrical or sensing properties while undergoing stretching and deformation poses a substantial obstacle. These materials must exhibit the qualities of flexibility, stretchability, and durability to endure repeated stretching without experiencing degradation. Additionally, it is other important challenge to achieve cost-effective and scalable manufacturing of these sensors. Rapid prototyping is a critical tool in addressing the challenge of cost-effective stretchable sensor mass production (Song et al., 2021; Heo et al., 2020; Heikenfeld et al., 2021; Souri et al., 2020; Fan et al., 2020; Homayounfar et al., 2020; Ullah et al., 2022).

Nonetheless, embedding sensing elements on flexible and stretchable substrates presents significant technical challenges. Establishing soft reliable electrodes is of utmost significance to ensure long-term functionality and durability (Teyeme et al., 2020; Wu et al., 2019; Yu et al., 2017; Vervust et al., 2012; McCan et al., 2019; Dias et al., 2015; Atalay et al., 2015; Huang et al., 2017; Shyr et al., 2014; Gibbs et al., 2005; Capineri et al., 2015; Atalay et al., 2013; Shanbeh et al., 2015). Interdigital capacitive sensors have been integrated using various textile production methods such as weaving (Martínez-Estrada et al., 2023) and embroidery (Martínez-Estrada et al., 2018; Martínez-Estrada et al., 2019) technologies. These interdigital sensor production approaches, however, do not impose stretchability constraints and completely support the different body proportions and movement requirements of wearable technologies. Furthermore, these approaches are insufficiently rapid and cost-effective for high-volume production. As a result, efficient and stable textile manufacturing methods for large-scale manufacture of stretchy interdigital strain sensors are required.

In this study, we address these challenges by presenting a novel textile knitted interdigital capacitive strain sensors in wearable technologies. By incorporating

stretchable conductive yarn manufactured with twisting technology into the sensors, we achieve high stretchability and adaptability in the interdigital capacitive strain sensor, enabling them to seamlessly conform to body movements and the natural flexibility of textile materials. Leveraging the capabilities of textile knitting technology, we seamlessly embed these electrodes of sensor and connection lines directly into textile products, integrating them into the fabric itself. This strategy allows users to effortlessly and comfortably utilize the sensors in their everyday lives, bringing additional functionalities to their daily experiences. Furthermore, the utilization of knitting technology enables mass production, ensuring rapid and cost-effective manufacturing of high quantities of interdigital sensors. With increased accessibility, these stretchable conductive yarns, produced through the direct twist method, coupled with the integration of knitting technology, emerge as an effective approach for the fabrication of interdigital capacitive sensors in wearable technologies.

7.2 Experimental Section

7.2.1 Materials

The homogeneity of the structure of a knitted sensor plays a critical role in achieving the desired sensor characteristics, including high sensitivity and durability, while also expanding its potential applications. The uniform stretchability along the sensor structure directly impacts its linearity, signal stability, and operating range. To ensure homogenous stretchability, it is necessary to match the elastic cores of the hybrid conductive and dielectric yarns, including their yarn counts and materials (140 denier Spandex for both cores). The stretchable conductive yarn production involved using a twisting machine (DirecTwist 2C®, Ağteks, Istanbul, Turkey) with silver-plated nylon conductive yarn (235/36 dtex HC+B, Shieldex®, Germany) and Spandex monofilament (140 denier, Creora®, Turkey) based on the specifications provided in Table S1, Supporting Information. The interdigital sensors were manufactured using the N.SVR 122® V-bed flat knitting machine (Shima Seiki, Sakata Wakayama, Japan). The dielectric base stretchable yarn (140/70*2 denier spandex/nylon, Combas®, Turkey) was selected as the equivalent to the elastomeric core of the hybrid conductive yarn. The sensor structure exhibited course density of 48 courses per inch and wale density of 40 wales per inch (wpc), resulting in a stitch density of 1920 stitches per square inch (spi), with a weight of 12.5 grams. The manufacturing

parameters of the sensor on the Shima Seiki N.SVR 122® V-bed flat knitting machine have been provided in Figure S9-10-11, Supporting Information.

7.2.2 Electromechanical characterization

A test rig for conducting strain tests was constructed, as depicted in Figure S4, Supporting Information. The design of the test rig involved the utilization of two clamps to secure the knitted specimens on a platform. One clamp remained fixed at one end, while the other clamp was movable. The movable clamp was attached to a threaded power shaft connected to a stepper motor. Once the specimens were securely positioned, strain test data was collected based on the number of rotations driven by the motor, which were controlled by commands from a microcontroller (Arduino Uno Atmega328P®, Microchip, USA). Simultaneously, the capacitance value was measured using a capacitive touch sensor (Arduino MPR121®, NPX, Netherlands).

7.3 Results and Discussion

7.3.1 Fabrication of stretchable conductive yarn and knitted interdigital sensors

The first step in creating a textile knitted interdigital capacitive sensor was to make stretchy conductive yarn. To achieve this, we employed the DirecTwist®2C twisting machine, as depicted in Figure 7.1(a), to wrap electrically conductive yarn around an elastomeric core yarn. The elastomeric core provided the yarn with its stretchable properties, while the conductive yarn enabled its electrical conductivity.

During the direct twisting process, the elastomeric core and conductive yarns are carefully aligned and subjected to twisting. During the direct twisting process, the conductive yarn was wrapped around the elastomeric core, and the twisting action involved rotating the yarns around their longitudinal axes. This process securely bound the conductive yarns with the elastomeric core, creating a stretchable continuous conductive yarn.

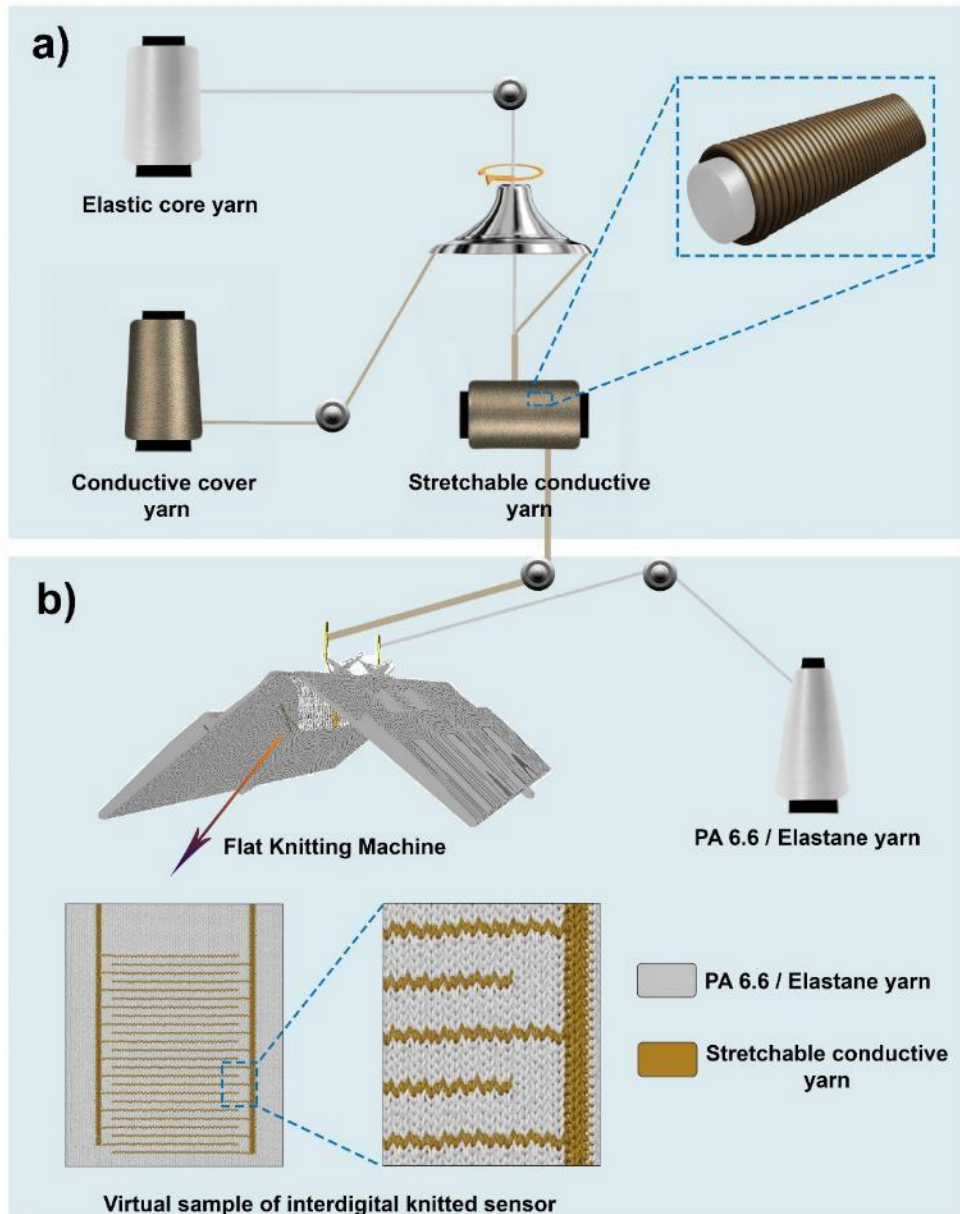


Figure 7.1: Fabrication of stretchable conductive yarn and interdigital capacitive knitted sensor. (a) Twisting of elastic core yarn and conductive cover yarn to fabricate stretchable conductive yarn. (b) Flat weft knitting of stretchable conductive yarn and PA 6.6/elastane yarn to fabricate interdigital knitted sensor.

The direct twisting process demanded precise control over various twisting parameters to achieve the desired characteristics of the conductive yarn. These parameters directly influence the stretchability, mechanical strength, and electrical conductivity of twisted stretchable conductive yarn. To determine the optimal production parameters, we conducted multiple trial sets, aiming to achieve an optimum cover ratio of the conductive yarn while minimizing tension within the elastomeric core. These trials were documented in Table 7.1.

Table 7.1: The required parameters needed for the production of the stretchable conductive yarns utilizing the conventional and non-conventional methods.

Trial methods	Tr.m ⁻¹	E%
Conventional	650, 700, ..., 1100	35, 40, ..., 60
Nonconventional	250, 300, 350	85, 90

The number of turns per meter ($Tr.m^{-1}$) played a crucial role in determining the cover ratio of the conductive yarn around the elastomeric core. Similarly, the elastane feeding ratio ($E\%$) defined the proportion of elastane relative to the cover yarn during the direct twist process, allowing us to comprehend its influence on the inner tension of the twisted yarn and its overall mechanical properties. Ensuring a sufficient covering ratio and yarn tension were critical to ensuring the usability of the stretchable conductive yarn for creating sensors in knitting technology. By optimizing the parameters of the direct twisting yarn fabrication, we successfully produced stretchable conductive yarn, which serves as a key component in our knitted interdigital capacitive sensor.

After the successful production of stretchable conductive yarn, the manufacturing stage of the knitted interdigital sensor has been initiated. Various knit pattern designs were created using the APEX4 software of flat weft knitting technology to fabricate comb-shaped interdigital capacitive sensors. The interlock knit structure (Figure 7.2), was chosen as the basis for the knitted interdigital sensor design. The interdigital sensing design consisted of a combination of two rows of comb electrode areas and eight rows of separator dielectric areas of weft knitted loops. This design was preferred to obtain a high capacitance value of the sensor in the unstretched state because the separator dielectric areas created a smaller area where the electrodes were close to each other, hence increasing the capacitance. In addition, the separator dielectric areas improved the reliability of the sensor by helping to prevent the electrodes from touching each other. The production of knitted interdigital capacitive sensors was carried out on the Shima Seiki N.SVR 122[®] flat weft knitting machine. Fabricated stretchable conductive yarn was used for the conductive electrodes, while 140/70*2 denier PA 6.6/elastane Combas[®] yarn was employed for the dielectric layers of the capacitive sensor. These yarn materials were carefully selected for their compatibility with the knitting process and their ability to provide the necessary electromechanical properties for the functionality of sensor. The flat knitting production process of the interdigital capacitive sensor, showcasing the successful integration of the stretchable

conductive yarns and dielectric layers into the final sensor design, is presented in Figure 7.1(b). By incorporating interlock knit pattern design and stretchable conductive and dielectric yarn materials, the production of comb-shaped interdigital capacitive sensors using knitting technology was accomplished. These sensors not only exhibit high functionality and stretchability but also can be seamlessly integrated into various wearable electronics and smart textile applications.

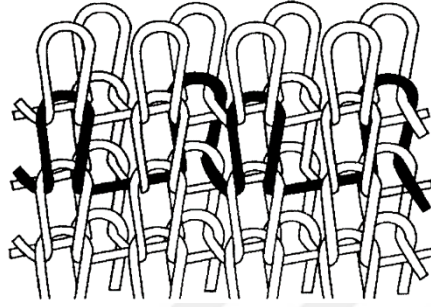


Figure 7.2: Schematic of interlock loop structure.

7.3.2 Electromechanical theory

The fabricated sensor is characterized as a planar two-dimensional interdigitated capacitive sensor, which calculates the capacitance using Equation 7.1.

$$C_L = (n - 1) \frac{\epsilon_r \epsilon_0 W t}{d} \quad (7.1)$$

In this equation, C_L represents the measured capacitance value. ϵ and ϵ_r correspond to the permittivity of free space and the dielectric layer, respectively. W represents the overlapped length of electrodes, d denotes the distance between the two electrodes, t indicates the thickness of the conductive electrode, and n signifies the number of interdigital electrodes within the structure. For our knitted sensor, there are 24 electrodes with an overlapped length W of 50 mm, a thickness t of 1.4 mm, and a distance d of 2.4 mm, and the relative permittivity of free space ϵ_r is set to 8.85×10^{-12} F/m. The capacitance value obtained from Equation 1 provides essential information about the electrical behavior of interdigital sensor. It reflects the interplay between various geometric parameters, such as the number of electrodes, their dimensions, and the distance between them. Moreover, the dielectric properties of the yarn material surrounding the electrodes influence the capacitance reading. Understanding these factors helps in designing and optimizing stretchable interdigital knitted sensors that are both sensitive to stretching and tailored to meet specific capacitance requirements.

The reason for selecting a separation distance of $d=2.4$ mm between the electrodes was to ensure that they could be positioned as close to each other as possible without causing a short circuit. This specific value of 2.4 mm was determined based on the results of fabrication trials, where it was found to correspond to 8 loops set during the weft knitting process. Maintaining this separation distance was crucial because anything less than 2.4 mm in an interlock structure would result in the electrodes coming into contact with each other when the sensor was stretched. By choosing this design parameter, the sensor was able to preserve its functionality and capacitance even when subjected to stretching, ensuring reliable performance.

Our sensor is used in a knee brace application, and because of the dynamic nature of knee movements during various activities in the knee region, accurately detecting knee bending and motions is of paramount importance. Therefore, the deliberate choice of designing the sensor with a 50 mm width specific to this region is aimed at ensuring precise detection of these movements.

Figure 2a displays the structural configuration of the textile knitted interdigital strain sensor and its response under transversal and longitudinal strains. Additionally, Figure 7.3 illustrates the electrical field between loop-based knitted electrodes in both relaxed initial and strain-induced states. Knitted textile sensors, comprising interconnected loops, have the capability to modulate capacitance allows the sensor to be tailored for different applications and optimized according to the specific parameter to be measured. Each loop acts as a fundamental unit, significantly impacting the overall capacitance of the sensor. The spacing between the loops plays a critical role in capacitance modulation, with closer arrangements fostering enhanced electrical interactions and resulting in amplified capacitance levels. The dielectric permittivity directly impact capacitance values. The structure and geometry of the sensor are critical factors affecting capacitance variations.

The direction of tensile strain influences the capacitance changing as negative or positive in a stretchy interdigital knitted sensor. Stretching the two-dimensional knitted interdigital sensor in two directions, the course and wale directions, is possible. The horizontal rows of loops in a knitted fabric are referred to as the course direction. The wale direction in a knitted fabric refers to the vertical columns of loops. Tensile force in the course direction of the stretchable electrodes causes the dielectric loops between them are compressed, reducing the distance between them while stretching and

elongating the electrodes, resulting in an increase in their effective surface area. Conversely, when a force is applied in the wale direction, the dielectric loops between the electrodes are decompressed, increasing the distance between the electrodes. The ability to modulate the capacitance changing of a stretchable interdigital knit-based sensor by applying tensile strain direction is a valuable property for a variety of applications.

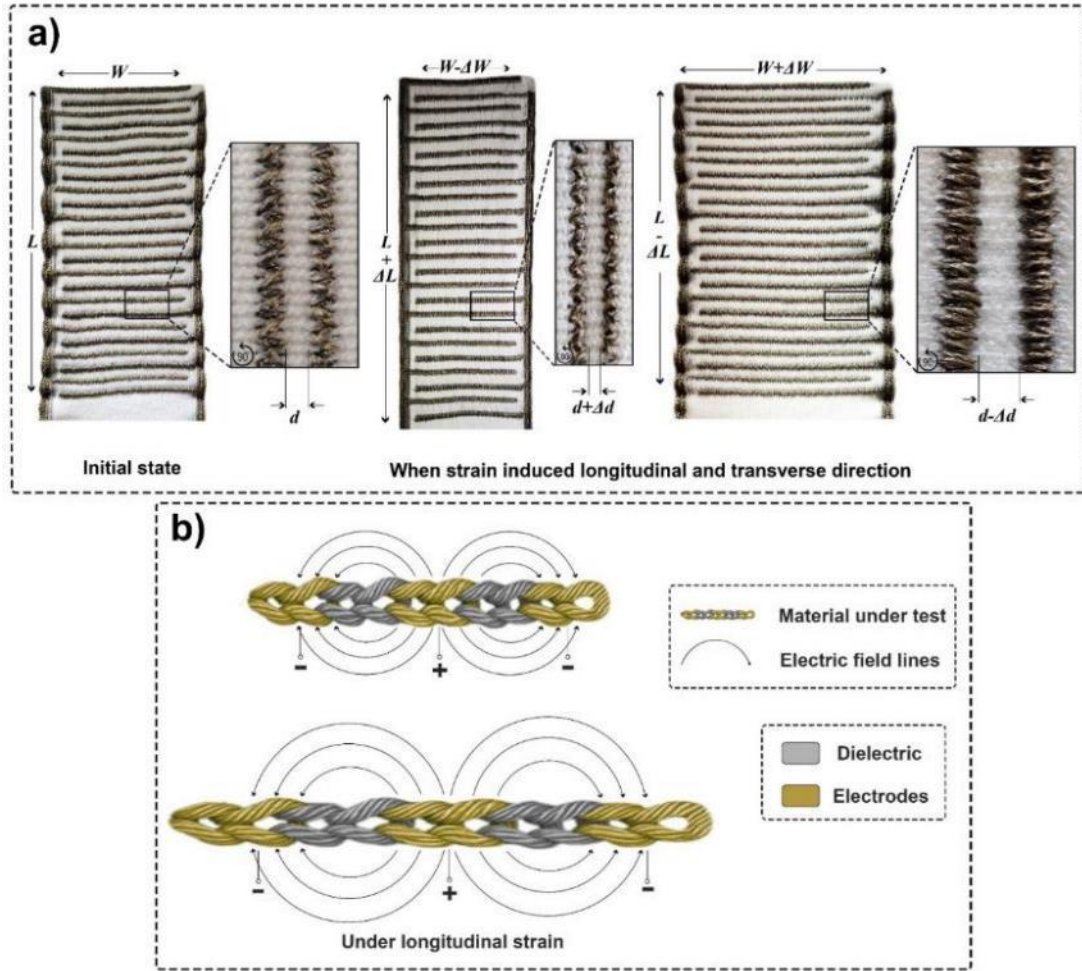


Figure 7.3: (a) Photographs of the states of the knitted interdigital sensor under longitudinal and transversal strains. (b) Visualization of the electrical field between loop-based knitted electrodes relaxed and strain induced states.

7.3.3 Electromechanical performance of sensor

To facilitate the electromechanical performance of the knitted interdigital sensor, we utilized a specially designed tensile test rig and graphical user interface (GUI) (Figure 7.4 and Figure 7.5). After evaluating various knit structures, the interlock knit structure was selected as the most suitable choice due to its excellent recovery properties after being stretched. We fabricated an interdigital sensor design with dimensions of 6 cm

width and 8 cm length, consisting of a total of 24 electrodes. The conductive electrodes included 2 rows of knitted loops, while the dielectric area comprised 8 rows.

A graphical user interface (GUI) was developed to facilitate real-time monitoring and display of the test rig results. The interface allows for immediate input of the desired distance in millimeters and steps, enabling forward and backward movement of the test system. The strain test can be initiated, paused, and terminated using the interface. Real-time information displayed includes the current distance, capacitive sensor value, step count, remaining distance in the tested direction, direction of movement, remaining steps in the tested direction, cycle count, speed, and the number of switch clicks on the limit sensor. During the strain test, the interface automatically saves the test results using a file name that includes the start time. With a data transmission frequency set at 50 Hz, 50 data points per second are recorded. To facilitate data analysis and comparison of test results, appropriate visualization programs were developed. These programs enable automated visualization of the recorded test data, allowing for efficient comparison and analysis.

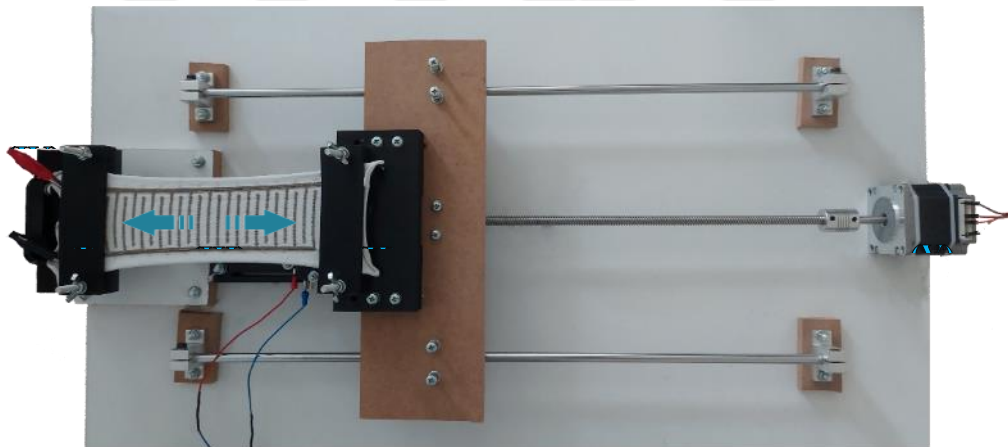


Figure 7.4: Operation of the electromechanical characterization test setup, featuring (I) the fixed clamp, (II) the movable clamp, (III) the stretched sensor specimen during testing, (IV) crocodile jaws for the capacitance measuring circuit, and (V) the stepper motor.

During the strain testing, the sensor was evaluated in two directions, termed the "positive" and "negative" samples. The positive sample was stretched in the transversal (course) direction, whereas the negative sample was stretched longitudinally (wale). This enabled us to evaluate the effect of testing direction on capacitance variations. A strain level of 50% was chosen to fulfill the requirements for sensing human body

posture and movement. Each positive and negative sample consisted of three replicates, and the tests were conducted for 100 cycles, reaching a strain level of 50%.

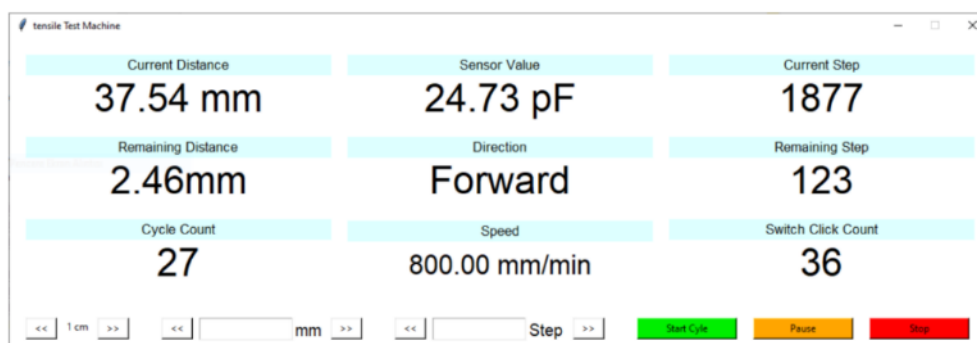


Figure 7.5. Tensile test interface.

The sensor exhibited greater stretching capability ($\sim 230\%$) in the transversal direction, as demonstrated in Figure 7.6. When the sensor is extended in the positive direction in the course direction, the dielectric yarn loops between the stretchable electrodes are squeezed. When the distance between these electrodes is shortened, causing capacitance to increase. Also, the knitted electrodes are stretched and extended, increasing their effective surface area and contributing to the increase in capacitance. The dielectric loops between the electrodes, on the other hand, are decompressed in the negative direction. This effect causes the distance between the electrodes to rise, resulting in a decrease in capacitance. Furthermore, the knitted electrodes may experience compression and contraction, resulting in a decrease in capacitance. Each of the design configurations has been tested on the tensile tester fitted with a loading cell of a 250 N, both designs exhibited excellent stretching capability.

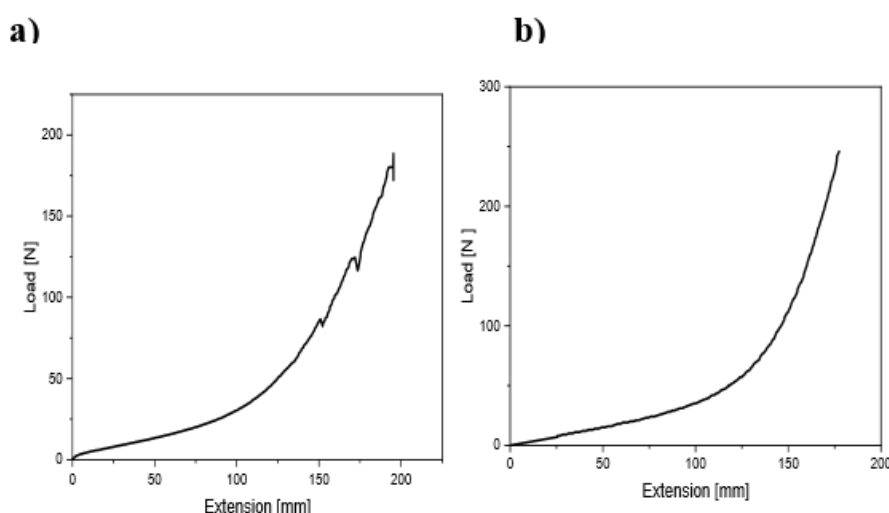


Figure 7.6: (a) Tensile test in the transversal direction.
(b) Tensile test in the longitudinal direction.

Sensitivity is a crucial characteristic that determines a performance of sensor in measuring the intensity of tested physical phenomena. Sensitivity is typically quantified using the gauge factor (GF), which represents the relative change in the reported signal compared to the initial stationary value. For capacitive sensors, the GF is calculated as $(\Delta C/C_0)/\epsilon$, where ΔC is the capacitance change, C_0 is the initial capacitance value, and ϵ is the applied strain. To determine the GF of different sensor designs, the sensors were extended up to 45 mm for the negative design and 35 mm for the positive design, equivalent to a 50% strain, surpassing the required range of ~35-45% for human applications (Atalay et al., 2018).

Figure 7.7 illustrates the GF and working range of the sensors. The positive sample in Figure 7.7(a) achieved a peak GF of 0.46. In Figure 7.7(b), the negative sample exhibited a peak GF of -0.68, consistent with previous studies on capacitive-based strain sensors ranging from 0.7 to 1 (Kim et al., 2018). Both sensor types maintained their peak GF values within the strain levels required for human applications, demonstrating their suitability for practical use. The results provide valuable insights into the GF and optimal working range of the sensor, highlighting its high sensitivity to dimensional deformation.

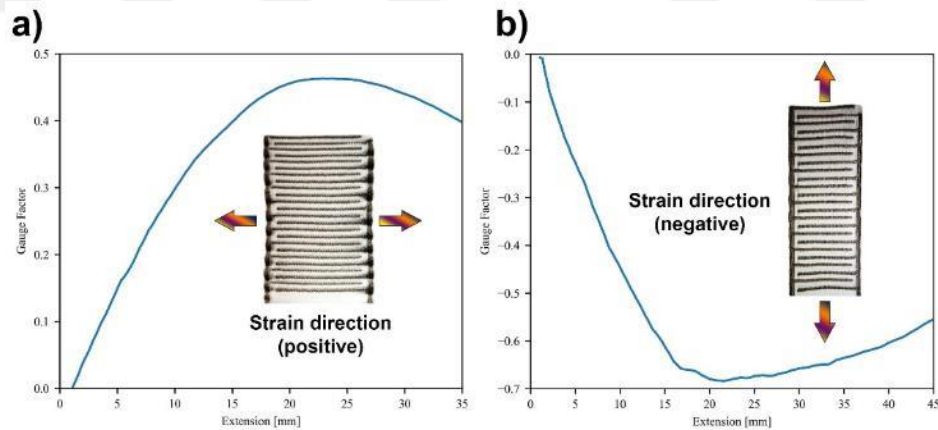


Figure 7.7: Sensitivity of the interdigital knitted capacitive sensors under 50% strain. (a) Positive-strained sensor. (b) Negative-strained sensor.

Another important characteristic of the sensor is its response time, which determines the speed and accuracy of detecting changes in the tested physical phenomena. A quicker response time ensures higher accuracy in detecting shifts. On the other hand, signal drift is an undesirable feature where the signal magnitude fluctuates under constant intensity. The response time of the negative design was measured to be 66 ms (Figure 7.8(a)), while the positive design exhibited a response time of 68 ms (Figure

7.8(b)). These response times indicate the delay between mechanical stimulation and the sensor signal when it rises three times above the standard deviation of the baseline signal magnitude. Comparing these response times to the motion frequencies of the human body, the sensor can effectively monitor human movements since human limb reflexes rarely exceed frequencies of 10 Hz. In the next section, the successful monitoring of knee movements will be demonstrated to further validate the suitability of the sensors for human applications.

The linearity of the negative design, as shown in Figure 7.8(c), was calculated to be $R^2 = 0.997$, consistent with a previous study using a different interdigital design. Likewise, the linearity of the positive design was calculated as $R^2 = 0.994$ (Figure 7.8(d)), demonstrating a high degree of linearity.

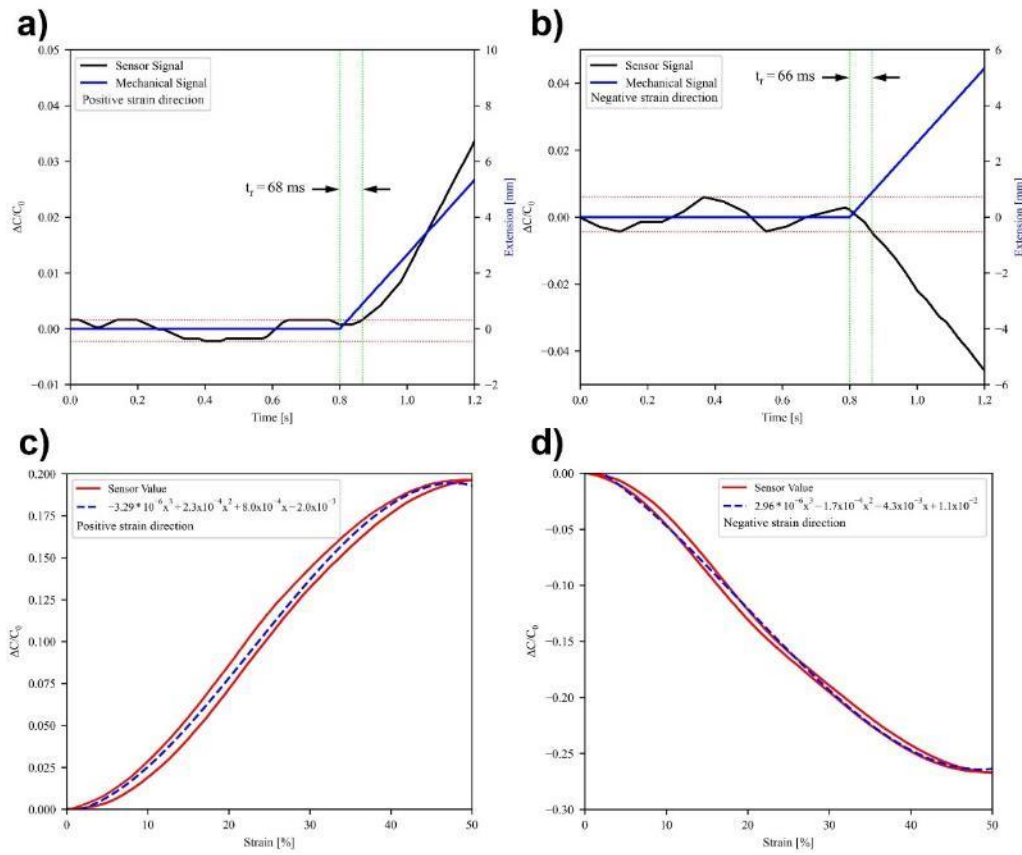


Figure 7.8: Response times of interdigital capacitive sensors. (a) Positive strained sensor. (b) Negative strained sensor. (c) Linearity of capacitance values for the positive strained sensor as a function of strain. (d) Linearity of capacitance values for the negative strained sensor as a function of strain.

To assess the drift values of the sensor signal, strain levels of $\epsilon = 0.125$, 0.25, 0.375, and 0.5 were applied and held for 10 seconds to observe the effect of static loading on signal drift. Figure 7.9(a) illustrates the electrical response changes of the negative

design under constant strain values. The drift values for the negative sample were measured as 2.4%, 1.8%, 1.3%, and 1.6% for $\varepsilon = 0.125, 0.25, 0.375$, and 0.5 strain levels, respectively. Similarly, the drift values for the positive design were determined as 1.8%, 1.6%, 1.6%, and 1.3% for the corresponding strain levels (Figure 7.9(b)). These values can be attributed to the relaxation of the knitted loops in a stressed position.

In wearable electronic applications, the durability of sensor structures is a crucial characteristic. Figure 7.9(c) presents the outcomes of a cyclic strain test performed on a negative sample, where the sample was subjected to 50% strain and then relaxed for 100 cycles. Similarly, Figure 7.9(d) displays the results of the positive sample subjected to the same test. These results indicate that both designs exhibit negligible changes in the $\Delta C/C_0$ ratio, signifying the exceptional stability of the knitted interdigital structure under repetitive stretching. This remarkable durability can be attributed to the uniform interconnected loops that form a secure conductive network within the knitted fabric structure.

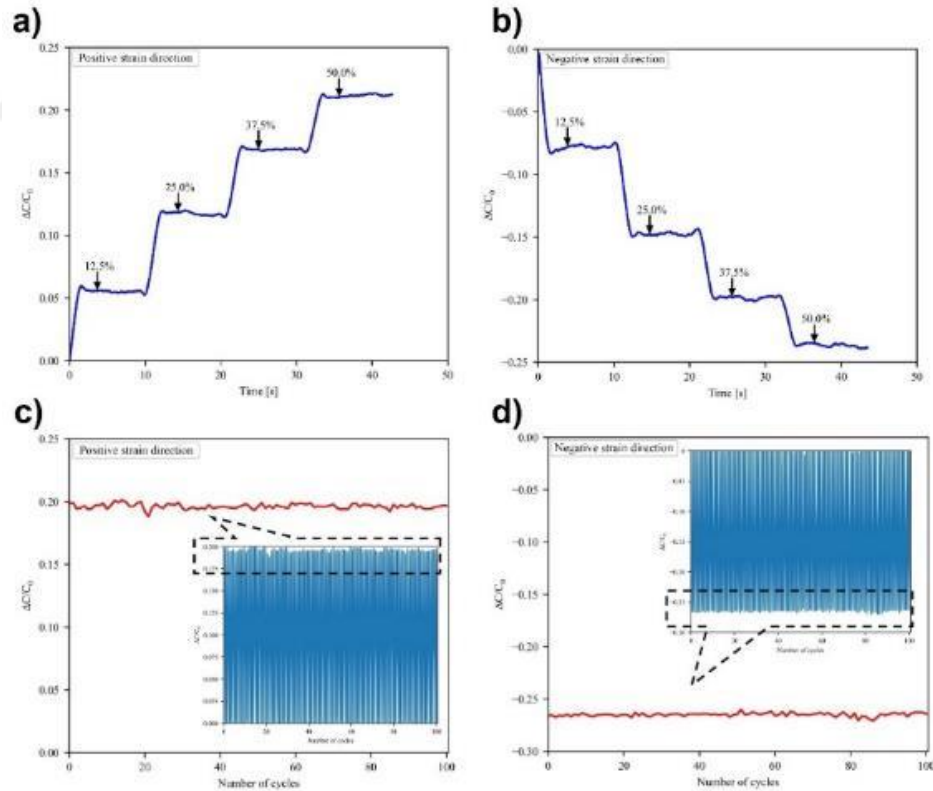


Figure 7.9: Drift signals under constant strain levels. (a) Positive strain direction sensor. (b) Negative strain direction sensor. Durability test with 50% cyclic strains. (c) Positive strain direction sensor. (d) Negative strain direction sensor.

7.4 Knee Brace Application

To assess the applicability of the textile knitted interdigital sensor in human motion applications, we modified the knitted base fabric of the sensor to tightly enclose the knee area of the subject, as demonstrated in Figure 7.10. This adaptation enabled a comfortable fit on the human body while facilitating the collection of data related to knee movement.

Figure 7.10(a) demonstrates the snug fit of the sensor fabric around the knee area, facilitating close contact with the skin and thereby enhancing accuracy and sensitivity. The findings presented in Figure 7.10(b) and Table 7.2 reveal distinct levels of strain applied during different knee bending activities. During walking, the knee undergoes slight bending, resulting in a relatively small stretch in the knitted fabric and subsequently a lower signal magnitude. In contrast, running involves moderate knee bending, while deep-squatting imposes the most significant stretch on the soft sensor structure, leading to the highest signal magnitude. Regarding the knee brace, it exerts a more pronounced effect on transversal stretching rather than longitudinal stretching. This was expected since knitted fabrics exhibit greater elasticity along their course direction, particularly flat knitted fabric, which readily stretches in the transversal direction. Consequently, in the application testing for different exercises, the increase in capacitance outweighed the decrease in capacitance.

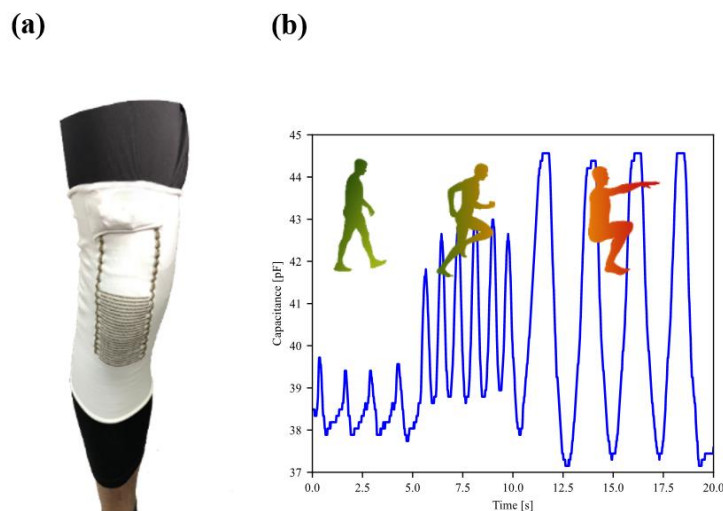


Figure 7.10: (a) The sensor fabric tightly fitted around the human knee.(b) Sensor signals corresponding to various movements.

Table 7.2: Stretching of knee brace interdigital sensor in various exercises.

Exercise type	Overlapping length (mm)	ΔW	Electrodes distancing Δd (mm)
	Increasing (positive effect)		
Walking	2		0.2
Fast-paced walking	5		0.6
Running	11		0.9

To enable wireless data collection in real-life scenarios, we utilized the DFRobot Beetle BLE® device from Shichuan, China, along with an Arduino Uno equipped with Bluetooth 4.0. By measuring the relative change in capacitance, we captured the data wirelessly, eliminating the need for cumbersome wired connections. The compact circuitry design required a small portable battery and consumed minimal energy, while efficiently collecting and transmitting data through low-power Bluetooth technology. During the experiment, which included consecutive movements of walking and cycling exercises (Figure 7.11(a) and Figure 7.11(c)), we recorded the real-time data. The walking tests were performed at 1 km/h, 3 km/h, and 6 km/h speeds. The recorded data revealed a clear relationship between the intensity of the exercises and the corresponding sensor signal magnitude, as shown in Figure 7.11(b) and Figure 7.11(d).

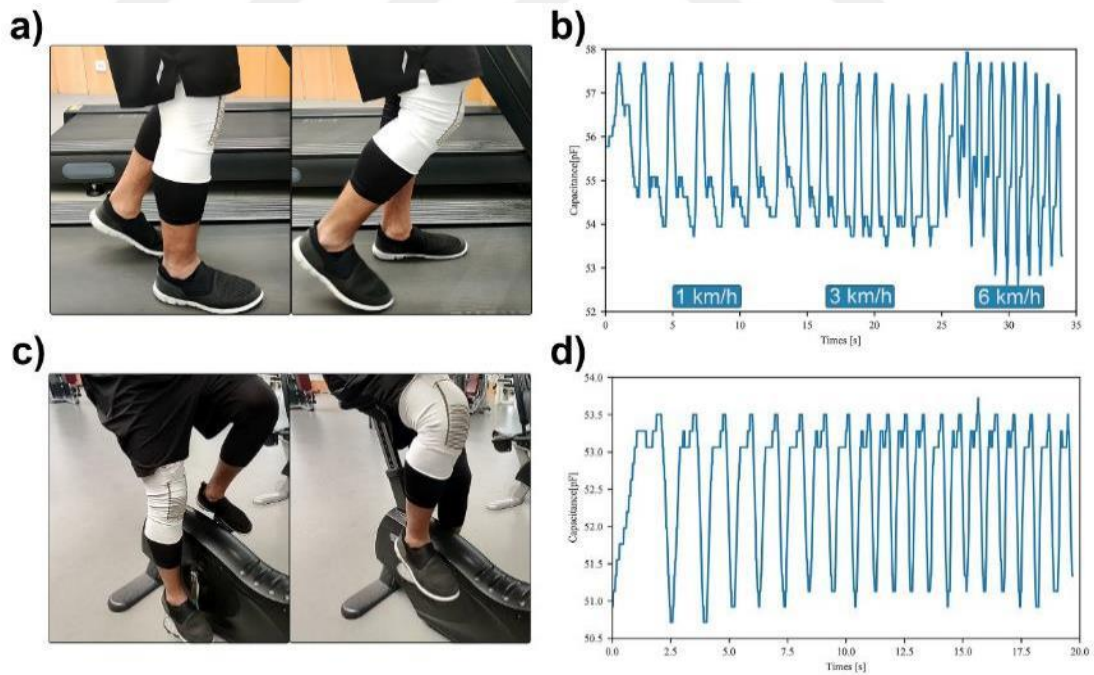


Figure 7.11: (a) Photograph of walking activity on a treadmill. (b) Sensor capacitance signals corresponding to walking at different speeds. (c) Photograph of cycling exercise. (d) Sensor capacitance signals corresponding to cycling exercise.

Specifically, we observed increasing capacitance values during both walking and cycling exercises. This indicates that our stretchable knitted interdigital capacitive

sensor effectively captures and quantifies the dynamic changes associated with different levels of physical activity. These findings highlight the versatility and potential applications of our capacitive sensor technology in monitoring and analyzing various types of human knee motion, providing valuable insights for gait analysis, sports performance monitoring, and rehabilitation.

Although interdigital sensors are adaptable in a wide range of applications, it is important to recognize that the environmental circumstances in these applications are dynamic. However, the characteristics of sensor remain unchanged after a 6-month period, with no electrical changes (Figure 7.12). In terms of exhibiting the same electrical sensor characteristics in both negative samples from 6 months ago and more recent ones, it indicates the long-term stability and reliability of the sensor. This shows the sensor's durability to environmental conditions and variables. Considering that factors like temperature and humidity did not adversely affect the performance of sensor, it can be confidently stated that this sensor can be used in various application areas.

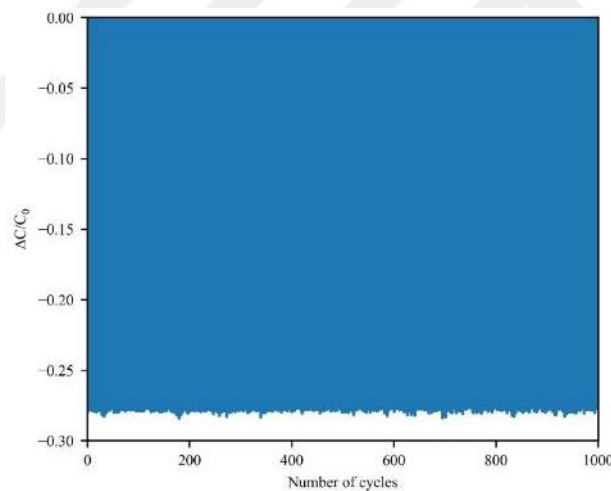


Figure 7.12: 50% strain 1000 cycles test on negative samples after six months.

7.5 Conclusions

This study has introduced a universal mass fabrication methodology for advancing wearable technology applications through the utilization of textile knitted interdigital capacitive strain sensors. The successful fabrication and thorough characterization of these sensors have demonstrated their exceptional stretchability, high linearity, and rapid response time. Through the incorporation of stretchable conductive yarn with

textile knitting technology, these sensors have exhibited outstanding adaptability and wear-comfort to knee movements. The direct integration of knitted sensors into fabric has ensured a robust and fully functional integration. Furthermore, the utilization of knitting technology has facilitated the rapid, reliable, reproducible and economical production of interdigital capacitive sensors. The capacitance change performance of sensor has been effectively demonstrated through its application in knee braces during walking and cycling exercises, showcasing remarkable repeatability across multiple cycles. These obtained results serve as concrete proof of the enhanced electromechanical performance and functionality of interdigital capacitive strain sensors in wearable technologies. In summary, this study offers a substantial contribution to the realm of wearable technology through an effective approach for the advancement of stretchable interdigital capacitive sensors in a wide range of applications such as healthcare monitoring, sports performance analysis, soft robotics, entertainment applications, and human-machine interfaces. Future studies may focus on exploring additional functionalities, employing sustainable textile materials, and exploring novel applications.



8. CONCLUSIONS AND RECOMMENDATIONS

In this thesis, the development and validation of a novel textile-based soft robotic actuator designed to assist individuals with foot drop were presented. The actuator, inspired by the contraction behavior of human muscles, utilizes high-performance Spectra® yarn and conductive silver threads, produced using computerized knitting technology. This approach aims to address the limitations of current assistive devices and provide a scalable, durable, and comfortable solution for individuals with impaired mobility.

The key findings of this research can be summarized as follows:

Material and Design Innovation: The use of Spectra® yarn significantly enhances the durability and performance of the actuator. The computerized knitting technology allows for seamless, rapid, and scalable production of the actuators.

Functional Performance: The soft pouch motors demonstrated impressive actuation capabilities, including a maximum lifting capacity of 10 kg, a 53.3% contraction ratio along the y-axis, and a 41.18% elongation along the x-axis at 50 kPa pressure. These results indicate the actuator's potential to effectively assist in lifting the foot during the dorsiflexion phase of walking.

Sensing and Control: The embedded capacitive sensors provided reliable pressure sensitivity ($722 \times 10^{-4} \text{ kPa}^{-1}$), facilitating the development of a feedback control mechanism. This integration ensures consistent and accurate performance, essential for applications requiring precise control, such as assistive exosuits.

Application in Assistive Devices: The practical application of the developed actuator was demonstrated through its integration into a soft exosuit designed for individuals with foot drop. The exosuit effectively assisted in dorsiflexion, improving the user's walking pattern and reducing the risk of stumbling.

Scalability and Production Efficiency: The use of knitting technology for actuator production proved to be efficient and scalable, addressing the need for mass production without compromising on quality or performance. This approach significantly reduces

production costs and time, making the technology more accessible and viable for widespread use.

Based on the findings and conclusions of this research, several recommendations for future work and potential improvements are proposed:

Advanced Sensing Integration: The development of more sophisticated sensing systems, such as multi-modal sensors capable of detecting various physiological signals, could enhance the functionality and responsiveness of the soft robotic actuators.

Comprehensive Clinical Trials: Conducting extensive clinical trials with a diverse group of users will be crucial to validate the developed exosuits. These trials should focus on long-term usage and quality of life.

Optimization of Control Algorithms: Improving the control algorithms to better interpret sensor data and provide real-time adjustments will enhance the performance of the actuators. Machine learning techniques could be employed to develop adaptive control systems that learn and respond to individual user patterns.

Exploration of Additional Applications: While this research focused on foot drop assistance, the developed technology has potential applications in various other areas, such as rehabilitation for other neuromuscular disorders, enhancement of athletic performance, and general mobility aids. Exploring these applications could expand the impact and utility of the technology.

In conclusion, this thesis has demonstrated the feasibility and potential of textile-based soft robotic actuators in providing effective assistance for individuals with foot drop. The integration of advanced materials, innovative design, and scalable production techniques represents a significant step forward in the development of next-generation assistive technologies.

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