

Development of Capacitive Wearable Sensors for Limb Volume Measurement Towards
Swelling Management

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Lymphedema represents a chronic medical condition characterized by progressive limb swelling due to compromised lymphatic drainage, affecting millions of people globally and necessitating continuous monitoring for effective clinical management. Current assessment methodologies rely predominantly on infrequent clinical measurements and subjective evaluations, creating substantial gaps in patient care protocols and treatment optimization strategies. This research addresses these critical limitations through the development of an advanced wearable sensing system utilizing highly stretchable capacitive strain gauge (HSCSG) technology for continuous limb volume monitoring applications in people living with lymphedema.

The investigation employed a systematic methodological approach encompassing comprehensive literature review, advanced fabrication technique optimization, multiphysics simulation modeling, and extensive experimental validation protocols. Following thorough comparative analysis of available sensing modalities, capacitive sensing utilizing interdigitated electrode (IDE) array configurations was selected based on superior linearity characteristics, minimal drift properties, and enhanced compatibility with wearable electronics applications. Direct ink writing (DIW) fabrication processes were systematically optimized for IDE sensor production, incorporating thermoplastic polyurethane (TPU) substrate materials selected for their advantageous mechanical properties in wearable electronics implementations ([Chapter 3](#)). A novel sensor generation software platform was developed to enhance fabrication precision and manufacturing repeatability, while comprehensive COMSOL Multiphysics simulation studies provided detailed design space optimization guidance ([Chapter 4](#)).

The research successfully developed optimized HSCSG sensors demonstrating linear sensing response capabilities extending to 25% mechanical strain while approaching theoretical gauge factor sensitivity limitations. Extensive characterization protocols confirmed exceptional durability performance under high elongation conditions and cyclical loading environments ([Chapter 5](#)). A novel limb volume phantom model (LVPM) incorporating pneumatic artificial muscle technology was developed for comprehensive sensor calibration and validation procedures, enabling precise assessment of circumferential monitoring capabilities with minimal calibration requirements ([Chapter 6](#)).

This comprehensive study established significant contributions to the field of soft robotic sensing both scientifically and technologically. These contributions include: i) enhanced understanding of IDE capacitive sensor behavior under large mechanical deformations, ii) innovative DIW fabrication protocols optimized for stretchable electronics applications, and iii) practical validation methodologies for wearable sensing system implementation, which collectively provide a robust foundation for future clinical deployment in lymphedema monitoring applications.

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List of Abbreviations

CIJ	Continuous Inkjet
CNT	Carbon Nanotube
DOF	Degrees of Freedom
DIW	Direct Ink Writing
DOD	Drop-on-Demand
FEM	Finite Element Analysis
IDE	Interdigitated Electrode Array
R2R	Roll-to-Roll
μCP	Microcontact printing
SCARS	Strain-mediated Contact in Anisotropically Resistive Structures
PDMS	Polydimethylsiloxane
TPU	Thermoplastic Polyurethane
LVPM	Limb Volume Phantom Model
HSCSG	Highly Stretchable Capacitance Strain Gauge
LSHSCSG	Laser Cut Highly Stretchable Capacitive Strain Gauges
MTPA	Multi-threaded Python Application
PAM	Pneumatic Artificial Muscle

1. Introduction

1.1 Background

The development of wearable health monitoring systems is inherently interdisciplinary, drawing upon principles from biomedical engineering, electrical engineering, materials science, and human physiology. This thesis builds upon the convergence of these fields to address the practical and clinical challenges of real-time limb volume monitoring. Such a system demands not only an understanding of biological phenomena—such as fluid retention, tissue expansion, and musculoskeletal structure—but also expertise in soft electronics, sensor materials, and mechanical integration into garments suitable for dynamic human use.

Historically, wearable health technologies have evolved from rigid instrumentation used in clinical or laboratory settings to more recent systems aimed at ambulatory and continuous monitoring. Early sensing systems, typically focused on vital signs such as heart rate or motion, relied on accelerometers, photoplethysmography, or simple resistive strain gauges. While valuable, these technologies offered limited sensitivity or specificity when applied to conditions involving progressive morphological changes, such as lymphedema or peripheral edema. In these cases, a primary clinical need is the detection of subtle, localized volume changes that can occur over time and may require therapeutic intervention.

Limb volume measurement itself is not new; established techniques include water displacement volumetry, tape-based circumference measurements, and optical perometry. However, these methods are inherently limited by their episodic nature, reliance on operator precision, and inapplicability to continuous use. As healthcare shifts toward decentralized, preventative, and home-based care, there is a growing demand for non-invasive, low-profile, and intelligent sensing systems capable of long-term deployment outside clinical environments.

Advances in materials and manufacturing techniques have enabled the integration of thin, stretchable sensors into wearable substrates such as textiles and elastomers. These sensors, including capacitive, resistive, and piezoelectric types, can be engineered to detect strain, pressure, or deformation across body surfaces. Yet, the transition from lab-scale prototypes to reliable, field-deployable systems necessitates a rigorous approach to fabrication repeatability, electrical and mechanical robustness, and meaningful signal interpretation in physiological contexts.

In this work, the sensing application—monitoring changes in limb circumference and volume—presents a unique set of requirements: high compliance to soft tissue, low mechanical impedance, sensitivity to distributed deformation, and integration with a data acquisition system that can operate unobtrusively. Addressing this challenge requires coordination across disciplines, from sensor design and materials processing to signal conditioning, hardware architecture, and biomechanical modeling. Each element must be optimized in concert to ensure that the final system is capable of producing reliable, interpretable data under real-world conditions.

Thus, the context of this thesis lies not only in solving a specific clinical measurement problem but in exemplifying a multidisciplinary engineering process that integrates physiology, materials, electronics, and computation. The broader implications of this work extend to other wearable technologies in rehabilitation, sports science, and chronic disease management, where accurate, long-term biomechanical monitoring is essential.

1.2 Motivation

Despite significant advances in health monitoring technologies, the management and surveillance of progressive limb swelling conditions—such as lymphedema and peripheral edema—remain clinically underserved. These conditions are often characterized by subtle volumetric changes in the limbs over time, which, if detected early, can inform therapeutic strategies and improve patient outcomes. However, access to continuous, quantitative data on limb volume remains limited, particularly outside of specialized medical facilities. The absence of affordable, wearable solutions for longitudinal volume tracking restricts the clinician’s ability to monitor disease progression or response to treatment in real-world contexts.

Existing methods for limb volume quantification are highly constrained by environment, cost, and user dependency. Techniques such as water displacement and tape measurement are inexpensive but manual and episodic. Optical methods and bioimpedance analysis, while more sophisticated, require stationary setups, power sources, and often trained personnel. These systems are unsuitable for continuous use, lack adaptability to patient-specific anatomy, and are frequently inaccessible to individuals without consistent medical oversight. Consequently, many patients with early or mild symptoms go unmonitored until conditions escalate, delaying intervention and increasing long-term morbidity.

Moreover, technological solutions currently available in the wearable sector tend to prioritize general-purpose physiological metrics—such as heart rate, activity tracking, or respiration—rather than targeted biomechanical signals. The challenge in limb volume sensing lies in the mechanical compliance required to detect changes in soft tissue under dynamic and non-uniform strain conditions. While some commercial systems aim to address compression therapy management, they often fail to provide granular, high-resolution volume data in a format suitable for clinical decision-making.

This gap highlights a broader issue: the disconnection between sensor design and application-specific biomechanics. Designing sensors for generic strain or motion is insufficient when the sensing objective is tied to specific anatomical changes or physiological markers. In this context, a wearable sensing system tailored to track limb volume must account for tissue compliance, complex deformation patterns, and variable placement on the body. It must also incorporate robust signal conditioning and data acquisition infrastructure, as well as intuitive integration into garments or sleeves that can be worn comfortably for extended periods.

From a clinical perspective, the need is not only for accuracy but for accessibility. In many public health systems, particularly in decentralized or resource-constrained environments, regular access to specialists and diagnostic equipment is limited. A low-cost, passive, and robust monitoring system could enable general practitioners, physical therapists, or even patients themselves to collect data relevant to limb swelling and recovery. Such systems would allow for earlier detection, better treatment adherence, and more personalized care pathways.

The motivation for this thesis stems from this intersection of technical challenge and clinical need. The development of a wearable system that can reliably detect and quantify limb volume changes—without the limitations of existing technologies—requires innovations in materials, fabrication, electronics, and data interpretation. By addressing these needs in an integrated manner, this work aims to contribute to both the field of wearable biomedical sensing and the broader effort to make healthcare monitoring more accessible, personalized, and effective.

1.3 Thesis Objectives and Contributions

The objective of this thesis is to develop a complete, end-to-end wearable sensing system for monitoring volumetric changes in human limbs, with specific relevance to clinical conditions such as lymphedema and edema. The work integrates design, fabrication, modeling, and testing of stretchable sensor arrays capable of capturing circumferential strain and correlating this signal with limb volume. This is achieved through innovations in capacitive strain gauge development, robust mechanical characterization, system-level integration, and custom experimental modeling.

Research Objectives and Methodology Overview

This research aims to investigate advanced wearable sensor technologies for limb volume monitoring with specific focus on:

1. **Characterizing and optimizing direct ink writing processes** for interdigitated electrode capacitive strain gauge fabrication
2. **Developing multiphysical modeling frameworks** to guide sensor design optimization and performance prediction
3. **Creating novel calibration platforms** using pneumatic artificial muscle systems for controlled sensor validation
4. **Integrating fabrication, modeling, and validation** within a comprehensive wearable sensing framework

1.3.1 Methodological Approach

Fabrication and Materials Development:

- Systematic characterization of direct ink writing parameters and material properties
- Development of novel sensor generation software for enhanced manufacturing precision
- Investigation of substrate materials and post-processing techniques using laser patterning

Modeling and Simulation:

- Multiphysical finite element modeling using COMSOL Multiphysics 6.3
- Steady-state capacitance analysis and parametric geometric optimization
- Mechanical deformation response prediction under varying loading conditions

Experimental Validation:

- Construction of pneumatic McKibben muscle-based limb volume phantom model
- Implementation of precision control systems with silhouette imaging feedback
- Comprehensive sensor performance evaluation under physiologically relevant conditions

Key Technical Contributions

The first major contribution of this work is the formulation of a reproducible and mechanically robust fabrication process for flexible capacitive sensors using direct ink writing techniques. Building on principles from microelectromechanical systems (MEMS) and printed electronics, interdigitated electrode (IDE) geometries were optimized and implemented through systematic parameter characterization. Attention was given to material compatibility, substrate performance under strain, and long-term durability. The fabrication protocol includes critical developments in conductive ink deposition, novel sensor generation software, and laser-based post-processing techniques.

To ensure sensor performance meets the mechanical and physiological demands of limb deformation, extensive multiphysical modeling was conducted using COMSOL Multiphysics 6.3. Finite element analysis incorporating steady-state capacitance calculations and mechanical deformation responses was used to establish design guidelines and optimize sensor geometries. A parametric study of design variables—such as electrode gap, width, and substrate material—was conducted through systematic geometric sweeps to refine signal response and improve accuracy under varying mechanical conditions.

Recognizing the lack of standardized tools for evaluating sensor response to limb swelling, a second contribution of this thesis is the design and implementation of a controllable pneumatic McKibben muscle-based limb volume phantom model. This apparatus mimics biological soft tissue expansion using pneumatic artificial muscles and enables controlled, repeatable inflation of an artificial limb segment. The model incorporates precision control systems with silhouette imaging feedback, serving as ground truth data for sensor calibration and enabling testing of complete wearable systems in laboratory settings.

Finally, this thesis contributes a complete experimental framework for validating the wearable system through integration of optimized fabrication processes, multiphysical design guidelines, and controlled testing platforms. This includes comprehensive sensor characterization protocols, performance evaluation under dynamic conditions, and systematic comparison with established measurement techniques.

Summary of Objectives and Contributions

- **Characterization and optimization** of direct ink writing fabrication processes for interdigitated electrode strain gauges, including development of novel sensor generation software and systematic material property analysis
- **Multiphysical modeling and simulation** of stretchable capacitive sensors using COMSOL Multiphysics, incorporating steady-state capacitance analysis and parametric geometric optimization studies
- **Design and fabrication** of highly stretchable and durable wearable strain gauges through systematic geometric optimization, substrate material characterization, and laser processing integration
- **Development of pneumatic artificial muscle-based limb volume phantom** for controlled sensor calibration, featuring precision control systems and silhouette imaging feedback for accurate expansion control
- **Comprehensive experimental validation** of integrated sensing systems, including long-term stability assessment, dynamic response characterization, and clinical relevance evaluation
- **Implementation of complete wearable sensing framework** integrating fabrication, modeling, and validation methodologies for practical limb volume monitoring applications

1.4 Thesis Structure

This thesis is organized into seven chapters, each addressing a distinct aspect of the development, characterization, and integration of a wearable system for limb volume monitoring.

- **Chapter 2:** Conducts comprehensive analysis of lymphedema pathophysiology and the importance of limb volume sensing, examining current measurement methods and identifying critical gaps in existing approaches. Reviews the potential for wearable sensors to improve diagnosis, treatment and health monitoring of the condition. Summarizes current state-of-the-art wearable sensing techniques, modalities, architectures, materials and fabrication processes.
- **Chapter 3:** Details characterization and optimization of the direct ink writing process for interdigitated electrode capacitive strain gauges for wearable sensing applications. Presents systematic analysis of DIW materials and parameters, introduces novel sensor generation software to improve sensor fabrication precision and repeatability.
- **Chapter 4:** Presents multiphysical simulation of stretchable IDE capacitive sensors to develop a design space that guides sensor fabrication and optimization. Utilizes COMSOL Multiphysics 6.3 for steady-state capacitance analysis and sensor performance evaluation over parametric sweeps of geometries and imposed mechanical deformations.
- **Chapter 5:** Documents design and optimization of highly stretchable and durable wearable strain gauges for limb volume measurement. Develops highly repeatable fabrication processes, investigates sensor performance over a range of geometries, characterizes performance using different substrate materials, and implements optimization utilizing laser cut post processing. Demonstrates optimal sensor showcasing linearity, durability and form factor.
- **Chapter 6:** Details development of a novel limb volume phantom model (LVPM) to aid in the calibration and assessment of developed wearable sensors and systems for accurate limb swelling monitoring. The model utilizes pneumatic artificial muscles (PAMs) to

create a safe and soft test platform that provides highly accurate expansion across a large linear region. Presents control system development for precise feedback control allowing accurate diameter setting using silhouette imaging techniques. Includes validation of preliminary wearable sensors on LVPM over the goal range and long-term use evaluation.

- **Chapter 7:** Summarizes the research findings and technical contributions of the thesis. Reflects on system performance, limitations, and the path to clinical implementation. Concludes with recommendations for future work and potential applications beyond limb volume monitoring.

2. Literature Review

2.1 Lymphedema and Edema

The lymphatic system plays a critical role in interstitial fluid regulation, lipid absorption, and immune surveillance. It operates parallel to the vascular system, draining lymph—a protein-rich extracellular fluid—through a network of lymphatic capillaries, vessels, and nodes. Lymphatic transport is powered by intrinsic contractility of lymphatic vessels and assisted by extrinsic forces such as skeletal muscle activity. Unlike the circulatory system, the lymphatic system lacks a central pump; thus, mechanical obstructions or damage can significantly impair its function. When lymph drainage becomes insufficient relative to lymph production, protein rich interstitial fluid accumulates, resulting in a pathological condition known as lymphedema. This chronic condition manifests primarily as progressive swelling in the extremities and is often accompanied by pain, restricted mobility, and risk of infection due to the stagnation of bacteriophilic lymphatic fluid [1].

Lymphedema is typically classified as either primary or secondary, depending on its etiology. Primary lymphedema results from congenital or hereditary malformations of the lymphatic vasculature, including hypoplasia, hyperplasia, or aplasia of lymphatic vessels. It is less common, with onset often occurring in adolescence or early adulthood. In contrast, secondary lymphedema arises from acquired damage to an otherwise intact lymphatic system. Causes include surgical lymph node dissection, malignancy, radiotherapy, recurrent infection, and parasitic diseases such as filariasis [1]. The incidence of secondary lymphedema is especially high among cancer survivors; for instance, more than 20% of women undergoing axillary lymph node dissection for breast cancer will develop lymphedema [2]. In Canada, this equates to tens of thousands of affected individuals annually, given there are approximately 84 new breast cancer diagnoses per day [3].

The physical progression of lymphedema is clinically staged, with a commonly used classification system being the International Society of Lymphology (ISL) criteria. This system categorizes patients into one of 4 classifications, Stages 0-III, ranging from subclinical accumulation of lymphatic fluid (Stage 0) to irreversible fibrotic tissue changes (Stage III). Patients with Stage 0 lymphedema do not have any visible swelling but do have known impaired lymph transport or changes in tissue fluid or symptoms. Patients may stay in Stage 0 for years before progressing to visible edema. Stage I lymphedema involves the early accumulation of protein-rich fluid, which improves with elevation of the limb. In Stage II, permanent accumulation of fats and proteins is seen. Elevation of the affected limbs will not reliably reduce tissue swelling, and pitting- temporary indentations of the skin when the area is pressed- is common. However, as the patient progresses through Stage II, pitting may no longer occur due to fibrosis and subcutaneous fat. Patients with Stage III lymphedema have severe swelling known as lymphostatic elephantiasis, where pitting is completely absent and skin changes such as alterations in tissue compliance, dermal thickening, and deposition of adipose and fibrosis. Within each stage, the ISL criteria further categorizes patients based on a severity assessment, which compares the volume of

the affected vs non-affected limbs. In the case a patient presents with bilateral lymphedema, this assessment is less valuable. Patients with minimal severity show 5-20% increase, moderate show 20-40% increase, and severe show >40% increase in limb volume comparatively when measured against non-affected limb. A major drawback of the ISL criteria is that it relies solely on physical/qualitative traits of the limbs. Staging criteria based on qualitative factors such as pathogenesis, genetics, and imaging are lacking and could be the future of lymphedema staging [4].

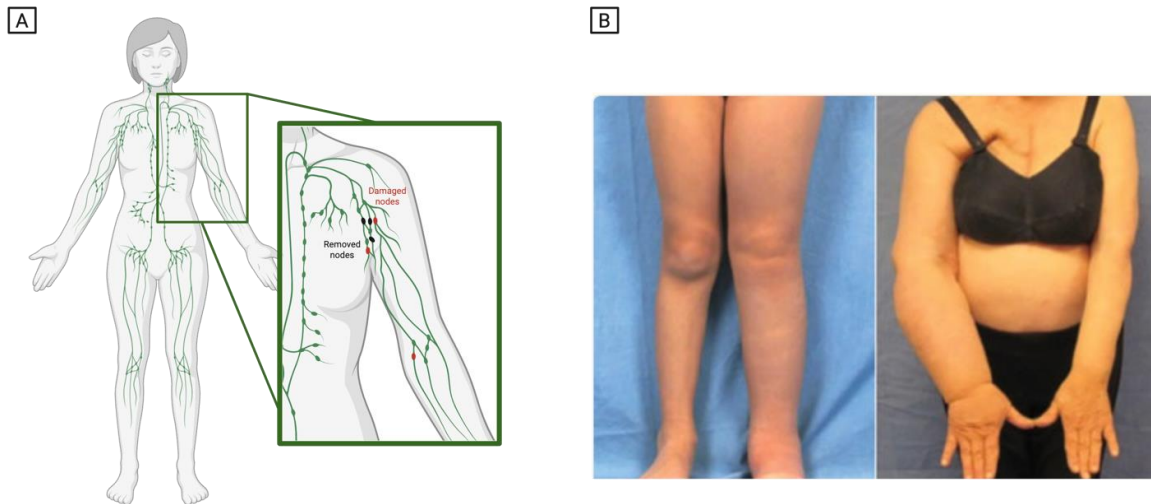


Figure 1. A) Anatomical diagram of lymphatic vasculature in the upper limb and chest. B) Patients presenting with lower extremity lymphedema (left) and upper extremity lymphedema (right) adapted from [5].

From a global health perspective, lymphedema affects an estimated 140–250 million individuals [6], with both high- and low-income countries experiencing increasing prevalence due to cancer survivorship, surgical interventions, and chronic venous insufficiency. The economic burden is significant, with lifetime management costs for breast cancer-related lymphedema ranging from CAD \$14,887 to \$23,167 per patient beyond standard cancer treatment expenditures [7]. These costs encompass physician visits, compression garments, physical therapy, specialized consultations, and hospitalization in cases of infection. Furthermore, indirect costs—such as reduced work productivity and long-term disability—exert additional socioeconomic pressure.

The current standard of care focuses on management rather than cure. The most widely accepted treatment approach is Complex Decongestive Physiotherapy (CDP), which consists of manual lymphatic drainage (MLD) performed by a trained physiotherapist, and is done in addition to other techniques such as compression therapy, exercise, skincare, and patient education. MLD is a technique that uses gentle, rhythmic manual pressure to direct lymph flow from the extremities toward functional lymph nodes. This method is effective in early stages but is time-consuming, labor-intensive, and requires trained clinicians for optimal delivery. Compression therapy, in the form of multilayer bandaging or elastic garments, is used to maintain volume reduction achieved by MLD and prevent further accumulation [4]. Patients are often transitioned to daily use of compression sleeves, which provide static pressure but lack adaptability to physiological or anatomical changes over time.

The effectiveness of compression therapy depends on accurate pressure application, garment fit, and user compliance. Traditional sleeves exert uniform pressure across the limb and cannot dynamically respond to fluctuating volume or localized swelling. Consequently, they are more effective for maintenance than for active reduction of lymphatic load. This has led to increased interest in Intermittent Pneumatic Compression (IPC) systems that use timed inflation of air bladders to create a sequential gradient moving in a distal-to-proximal direction, simulating the effects of MLD [4]. Commercial IPC systems can reduce limb volume and enhance lymphatic drainage; however, their utility is limited by factors such as upfront cost, device bulk, wall-tethered power supplies, and inflexible form factors. Many systems rely on electromechanical solenoid valves to control individual bladders, which increases the size, energy consumption, and mechanical complexity of the control units. Portable IPC devices exist at lower price points (~USD \$299), but these often employ a reduced number of actuated bladders, resulting in diminished therapeutic effectiveness [8].

2.2 Limb Volume Measurement

Accurate quantification of limb volume plays a central role in the diagnosis, surveillance, and therapeutic evaluation of lymphedema. Clinical evidence shows that small changes in volume—on the order of 3–5%—can indicate early disease progression, particularly in breast cancer-related lymphedema (BCRL) [9]. Objective measurement supports longitudinal tracking, allows for timely treatment adjustments, and provides standardized outcome metrics for therapeutic interventions. However, across clinical practice, several methodologies and subsequent instrument selection exist, resulting in variability in diagnoses and treatment efficacy.

When it comes to understanding the fluctuation of limb volume in a healthy individual, there exists limited data and no clinical guidelines. A study done by Matthews et al. observed the normal fluctuations in upper limb volume in healthy women between seasons (~3-month periods) and showed that there is a non-significant change in limb volume at these intervals [10]. Another study completed by Park et al. examined the correlation of limb volume increases and increased difficulty with performing activities of daily living (ADLs) in breast cancer patients 12 months after surgery. This study showed that at the 12-month mark, 105 of the 136 (77%) participants exhibited <5% limb volume change from baseline, 22 of 136 (16%) showed 5-10% limb volume change, and 9 of 136 (7%) showed >10% limb volume change[11].

The available data begins to suggest that limb volume fluctuations are minimal or non-significant in healthy individuals, and even small limb volume changes may be indicative of lymphedema. This supports the idea that regular limb volume measurements can help better detect and improve treatment outcomes of those with or at risk of developing lymphedema. With small changes in limb volume compared to baseline detected earlier on, conservative interventions can be implemented, likely reduce the chance of progression of the disease, and lifelong cost savings[4]. Additionally, the non-significant natural fluctuation of limb volume reduces the chance of mistakenly diagnosing or identifying progression of lymphedema, as any changes can be

associated with the disease alone. However, the data is scarce, and further research is needed into natural limb volume fluctuations in healthy individuals over shorter time frames, including monthly, weekly, and throughout the day, to better understand the progression of lymphedema, and aid in its diagnosis.

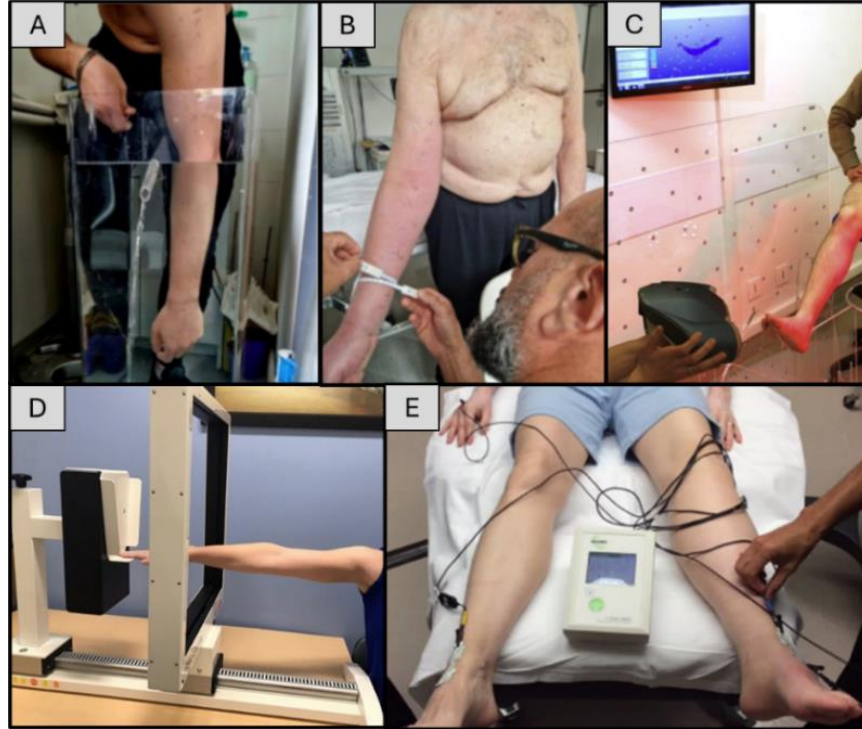


Figure 2. Overview of limb volume measurement techniques: A) Water displacement, B) tape measurement, C) 3D scanning, D) perometry, E) bioimpedance spectroscopy adapted from [12], [13], [14], [15]

In the clinical setting, limb volume is most frequently estimated using circumferential tape measurement, optoelectronic perometry, or water displacement volumetry. Tape-based measurement, while inexpensive and broadly accessible, is highly susceptible to inter-operator variability. Inconsistencies in tape tension, anatomical landmark selection, and limb orientation contribute to measurement error, particularly for small volume changes [16], [17]. Tape-based methods are also susceptible to non-reproducible results when non used by non-specialists or patients themselves. Limb volume calculations are typically performed using geometric approximations such as the frustum or truncated cone model, which assume limb symmetry and smooth curvature—assumptions often violated in pathologic swelling [18].

Optoelectronic perometry employs infrared sensor arrays to scan limb cross-sections and reconstruct volume using voxel-based integration. Studies show superior reproducibility and sensitivity of perometry relative to tape-based methods, particularly in detecting subtle volume changes associated with early-stage lymphedema [18], [19]. However, perometry systems are expensive, require frequent calibration, and are largely confined to specialist clinics due to size and operational constraints. Water displacement, considered a retired gold standard, is labor-intensive, non-hygienic, and rarely used outside of controlled research environments [20].

Table 1. Comparative summary of limb volume measurement techniques: accuracy, repeatability, usability, cost, and suitability for clinical or home deployment with personal scoring applied.

Metric	Tape Measurement	Water Displacement	Perometry	Bioimpedance (BIS)
Accuracy (1-5 Scale)	2 (1-8% RACC)	5 (0.3% RACC)	4 (Average SE 23.23)	3 (Diagnostic accuracy ~85% but high false positives)
Repeatability (1-5 Scale)	2 (1-6% SD)	5 (SD up to 0.9%)	4 (Cronbach's alpha 0.90-0.99 for practitioners)	2 (High false positives, limited correlation with volume changes)
Operator Dependence (1=High, 5=Low)	1 (High)	5 (None)	4 (Low, due to automated process)	4 (Low, due to automated process)
Equipment Cost (1=High, 5=Low)	5	4	1	3
Suitability for Home vs. Clinic Use (1=Clinic Only, 5=Both)	5 (Both, practical and low-cost, but better in clinic with trained staff)	1 (Clinic only, requires specific apparatus and patient cooperation)	1 (Clinic only, due to expensive equipment)	1 (Clinic only, requires specific device)
Descriptive Assessment	Practical, low-cost, but highly operator-dependent and prone to variability.	Highly accurate and repeatable, considered a "gold standard" for accuracy., time-consuming	Highly accurate, reliable, and efficient. Reduces human error. High upfront cost.	Non-invasive, measures extracellular fluid. Promising for early detection but prone to high false positives.

In clinical practice, objective measurements are often supplemented or replaced with qualitative evaluation, including visual inspection and patient-reported symptoms such as heaviness, tightness, or functional impairment [4]. This introduces substantial variability across clinical providers and jurisdictions, and in many cases leads to diagnostic delay or under-diagnosis. A key issue is the lack of universally accepted diagnostic criteria. Some institutions define lymphedema using absolute thresholds (e.g., >200 mL volume increase), while others use relative change formulas such as the Relative Volume Change (RVC) equation:

$$RVC = \frac{A_2 \cdot U_1}{U_2 \cdot A_1} - 1 \quad (1)$$

where A_1 and A_2 are arm volumes at baseline and follow-up untreated arm volumes are U_1 and U_2 denote affected and unaffected limb volumes at times 1 and 2, respectively. The absence of

consensus on cutoff values—ranging from 5% to 10% increases—complicates inter-study comparisons and limits the generalizability of clinical trials [17].

When not in a clinical setting, patients are tasked with regular self-monitoring via tape measurement. While accessible at home, this practice is hampered by poor reproducibility and risk of error due to anatomical inaccuracy, resulting in low sensitivity to small limb volume changes. Most home methods lack the resolution to track dynamic fluctuations, such as diurnal swelling patterns or post-exertional volume changes. Consequently, clinical decisions are based on episodic, sparse data rather than continuous or personalized trends.

Advanced methods such as bioimpedance spectroscopy (BIS) offers a physiologically grounded approach to volume measurement by inferring extracellular fluid content through frequency-dependent impedance profiles. BIS can detect early-stage interstitial fluid accumulation before visible swelling appears and is used in some specialized centers for BCRL screening [9]. However, this technique requires user training and calibration, and is sensitive to electrode placement, limb positioning and variation in tissue conductivity [21]. Imaging-based techniques, including MRI and CT scanning, offer detailed volume and tissue composition data but are limited by accessibility, cost, and the impracticality of repeated use for longitudinal tracking in the current healthcare climate [22], [23]. 3D structured light and laser scanning systems are increasingly being explored for limb volumetry, with high resolution and contactless operation, though work is still needed to be done in terms of limb volume accuracy [24].

Additional experimental approaches have emerged in research contexts. One such method involves plethysmographic measurement using strain sensors, such as rubber-liquid metal or carbon-nanotube elastomers, adhered circumferentially around the limb. These sensors function by correlating mechanical strain to electrical impedance changes, which are then calibrated to volume through geometric models. Systems such as the Electrically Calibrated Plethysmograph (ECP) have demonstrated precise volume quantification under controlled conditions and have been used to investigate limb blood flow and fluid redistribution in response to external compression[25].

In the context of lymphedema therapy, reliable volume monitoring enables assessment of disease progression, treatment efficacy, and early identification of exacerbation events. The existing body of evidence highlights a persistent gap in the limb volume measurement ecosystem. Technologies with sufficient accuracy (e.g., perometry, BIS) are too expensive or complex for decentralized or self-managed use. Many require precise sensor alignment, are not robust to motion artifacts, and lack real-time wireless data transmission. In contrast, accessible methods (e.g., tape, visual inspection) lack precision and standardization. This dichotomy results in reduced diagnostic confidence, variability in treatment outcomes, and poor alignment between clinical monitoring and patient self-care strategies. There is significant need for non-invasive, wearable systems capable of accurately capturing localized volume changes in real-time under dynamic conditions. Such

systems must offer high sensitivity, mechanical conformity to soft tissue, and integration with textile or garment-based platforms without interfering with user mobility or comfort.

Recent trends in wearable electronics [26] and soft sensors suggest a viable path forward for limb volume measurement. Textile-integrated strain gauges, printed capacitive arrays, and flexible pressure sensors can be conformally attached to the body and offer real-time, localized strain data. These data streams, if appropriately fused and modeled, can serve as proxies for regional or total limb volume. The success of these systems will depend on sensor resolution, material repeatability, mechanical coupling to soft tissue, and the ability to reject noise due to motion or environmental interference. Though not yet commercialized, such systems present a promising opportunity to resolve the limitations outlined above: enabling accurate, repeatable, and accessible limb volume monitoring at the point of care and in the home setting.

2.3 Wearable Sensing (on-the-go assistive technology)

Wearable flexible sensors have emerged as transformative technologies in biomechanics and health monitoring, offering unprecedented capabilities for continuous, non-invasive physiological assessment. This comprehensive review examines the fundamental principles, materials, fabrication methods, and applications of highly stretchable strain gauges specifically designed for assistive devices. The transition from rigid, laboratory-based sensing systems to flexible, wearable platforms presents significant challenges in balancing sensitivity, mechanical robustness, and seamless integration with the human body. This review provides a systematic analysis of current sensing modalities, including resistive, capacitive, piezoelectric, and inductive approaches, with particular emphasis on their suitability for assistive device applications. Advanced materials including highly stretchable substrates and conductive components are examined, alongside fabrication techniques ranging from traditional photolithography to emerging additive manufacturing approaches.

2.3.1 Introduction to Wearable Sensing and Flexible Sensors

A. Fundamental Concepts and Definitions

Wearable flexible sensors represent a paradigm shift in human-centered monitoring technologies, facilitating seamless and intelligent interactions between individuals and their surrounding environments. These devices are characterized by their inherent mechanical compliance, enabling integration onto nonplanar surfaces without impeding natural motion, thereby allowing soft machines and wearables to respond dynamically to environmental stimuli [27]. The fundamental distinction between conventional rigid sensors and flexible wearable systems lies in their ability to conform to the complex geometry of the human body while maintaining measurement accuracy and reliability over extended periods of operation.

The concept of flexibility in wearable sensors encompasses multiple dimensions: mechanical flexibility allowing bending and deformation, stretchability enabling accommodation of large strain variations, and electrical flexibility maintaining signal integrity under mechanical

stress. These characteristics are essential for applications ranging from soft manipulation and skin-mounted electronics to wearable robotics and assistive devices [28]. The integration of these sensors into everyday life requires careful consideration of biocompatibility, durability, and user comfort, representing a significant departure from traditional sensor design paradigms.

B. Recent Trends and Growing Interest

The field of wearable sensing has experienced unprecedented growth driven by several converging factors. A primary catalyst is the recognized need to overcome fundamental limitations of traditional muscle strength assessment techniques, including manual muscle testing (MMT) and isokinetic dynamometry. Conventional methods are often discrete, subjective, and costly, proving impractical for continuous, real-world monitoring applications [29]. The capacity for continuous monitoring without constraining range of motion or requiring adaptation to specific hardware configurations offers significantly richer and more comprehensive datasets for clinical and research applications.

Contemporary trends in wearable sensing are characterized by the integration of flexible sensing components with high-performance, low-power traditional silicon integrated circuits (ICs). This hybrid electronics approach enables efficient signal conditioning and transmission while optimizing overall system performance [30]. The increasing demand for disposable sensing components, particularly in medical screening and athletic monitoring applications, necessitates consistent performance across individual sensor units to minimize calibration overhead. This requirement is critical for the practical viability of wearable prototypes transitioning from controlled research environments to widespread commercial deployment [30].

The paradigm shift from controlled laboratory environments to ubiquitous, "on-the-go" monitoring in unconstrained, real-world settings represents a fundamental transformation in wearable sensor development. This transition mandates a comprehensive re-evaluation of sensor design priorities, extending beyond idealized performance metrics to encompass practical considerations such as washability, resilience to impacts, and ease of donning and doffing [28], [29]. This evolution profoundly influences research and development trajectories, necessitating innovations in inherent environmental resilience of materials, self-calibration capabilities, and robust, user-friendly packaging solutions.

Table 2. Comparison of state-of-the-art soft sensors for wearable and human monitoring applications.

<i>Authors</i>	<i>Type & Mechanism</i>	<i>Material Composition (Substrate / Conductor)</i>	<i>Sensing Modality</i>	<i>Sensitivity (Gauge Factor, GF)</i>	<i>Working Range (% Strain)</i>	<i>Safety & Wearability Notes</i>
<i>Sun et al., 2022 [31]</i>	Piezoresistive; Microcrack	TPU / CNTs & AgNWs /	Piezoresistive	691 (0-102%)	0–171%	TPU. Durable for

<i>Pan et al., 2019 [32]</i>	Piezoresistive; Mechanically Heterogeneous Substrate	PDMS (mechanically heterogeneous) / Gold (Au) film /	Piezoresistive	Tunable from 3.3 to 75.8	Up to 50%	PDMS.
<i>Araromi et al., 2020 [33]</i>	Piezoresistive; SCARS	TPU / Carbon Fibre Polymer Composite / TPU with Silicone	Piezoresistive (Ohmic Contact)	>9,000 (R ² >0.98); >85,000 (R ² >0.96)	<5% for high sensitivity	Extremely robust and washable
<i>Aksoy et al., 2022 [34]</i>	Capacitive Force Sensor; Shielded	Silicone Foam / Silver-filled / PDMS	Capacitive	Force Sensitivity: 2.77 mN/FF (normal), 0.23 mN/FF (shear)	>20 N force	Fully shielded from EM/proximity effects, integrated into gloves/robotic hands.
<i>Ma et al., 2024 [35]</i>	Capacitive; Wavy Structure	Silicone / FPCB (Copper on Polyimide)	Capacitive	0.52 (stretch); 1.54 (compression)	33% (stretch); 14% (compression)	Dragonskin-20 is non-toxic/harmless
<i>Yilmaz et al., 2024 [36]</i>	Capacitive; Knitted Interdigital	PA 6.6/Elastane Yarn / Silver-plated Nylon on Spandex Core	Capacitive	-0.68 (longitudinal)	~230%	Fully textile-based
<i>Katanić et al., 2024 [37]</i>	Capacitive; Interdigital on Fabric	Elastic Textile / Conductive Cu/Ni Fabric /	Capacitive	Sensitivity reported as pF/mm: 0.087	(~18%)	Sewn onto a standard elbow sleeve.
<i>Yong & Aw, 2022 [38]</i>	Capacitive; Shielded Interdigital (LIDC)	Ecoflex 00-30 / Carbon Black-Ecoflex Composite / Ecoflex 00-30	Capacitive	Sensitivity reported as pF/mm: 0.15 pF/mm	Up to 50%	Shielded to reduce interference; retrofitted to a robotic hand.

2.3.2 Applications of Advanced Wearable Sensors

A. Assistive Device Integration

The healthcare and rehabilitation applications of wearable strain gauge technology demonstrate substantial potential for revolutionizing patient care through continuous, objective monitoring of physiological parameters and therapeutic progress. In rehabilitation contexts, these sensors enable quantification of muscle activity, joint range of motion, and movement patterns, providing clinicians with detailed data to optimize treatment protocols and track recovery progress over time. Muscle strength assessment using soft strain sensors offers advantages over traditional manual muscle testing and isokinetic dynamometry through continuous monitoring capabilities that detect subtle changes in muscle function not apparent during discrete clinical assessments, with the

correlation between skin deformation and muscle force output providing non-invasive quantification of muscle strength and recovery monitoring [29].

The current generation of wearable strain gauges has successfully addressed many fundamental challenges that previously limited their practical application. The development of SCARS technology represents a significant breakthrough in achieving simultaneously high sensitivity (gauge factors exceeding 85,000), excellent mechanical robustness, and insensitivity to off-axis deformations [28]. This achievement demonstrates that the traditional trade-offs between sensitivity, durability, and wearability can be overcome through innovative sensor architectures and materials engineering.

The fabrication landscape has matured considerably, with roll-to-roll gravure printing demonstrating the capability for mass production of consistent, high-quality sensors suitable for disposable medical applications [30]. The achievement of 150,000 electrodes produced in 30 minutes on 150-meter web rolls represents a significant milestone in manufacturing scalability. Advanced printing techniques, including direct ink writing and multi-material inkjet printing, have enabled the creation of complex, three-dimensional sensor architectures that were previously impossible to fabricate.

Materials development has progressed toward inherently safe and biocompatible solutions, with the explicit avoidance of potentially harmful materials like carbon nanotubes in favor of safer alternatives such as carbon black [39].

C. Challenges in Wearable Sensor Design

Despite significant technological advances, several fundamental challenges persist in wearable sensor development. A pervasive design dilemma involves the inherent difficulty in simultaneously optimizing high sensitivity, mechanical robustness, and seamless wearability. This complex trade-off often requires application-specific compromises where advancements in one attribute may compromise performance in others. For instance, while high strain sensitivity is crucial for detecting subtle biological signals, maintaining this sensitivity frequently conflicts with the robustness required to withstand unpredictable mechanical and electrical stresses of daily use [27], [28], [29].

Capacitive sensors, despite their promising characteristics, demonstrate significant susceptibility to electromagnetic interference (EMI) and proximity effects, historically limiting their application to controlled laboratory environments due to inadequate shielding [27]. This susceptibility prevents reliable discrimination between actual pressure (contact) and mere presence of nearby objects (proximity), which is critical for safe human-robot interaction applications [27]. The implementation of electromagnetic shielding in soft capacitive sensors introduces additional complexity through parasitic capacitance variations between shields and sensing electrodes during sensor deformation, complicating stable signal compensation [27].

Wearable sensors must withstand diverse mechanical stresses including high bending, torsion, and pressure loads. The ability to decouple or reject unwanted off-axis deformations is crucial for accurate measurements in dynamic environments [28]. Devices operating in unconstrained environments face vulnerability to impacts, punctures, and over-extension, particularly during donning and doffing of clothing-integrated systems [28]. Ultra-sensitive soft strain sensors can exhibit significant performance variability based on precise body placement, influenced by complex muscle anatomy and individual physiological differences where minor positioning shifts can substantially impact measurement correlation [29].

Emerging Challenges and Technical Limitations

Despite significant progress, several fundamental challenges remain unresolved. The susceptibility of capacitive sensors to electromagnetic interference continues to require sophisticated shielding solutions that introduce complexity and potential performance compromises [27]. The varying parasitic capacitance in deformable shielded sensors represents a particularly challenging technical problem that requires continued innovation in circuit design and signal processing.

The transition from controlled laboratory environments to real-world applications has revealed additional challenges related to sensor drift, calibration stability, and environmental robustness. The need for consistent performance across manufacturing batches, particularly important for disposable medical devices, requires continued advancement in quality control and process optimization [30]. The integration of sensors with existing healthcare infrastructure and the development of standardized communication protocols remain significant hurdles for widespread adoption.

User acceptance and practical implementation issues, including sensor attachment methods, washing procedures, and long-term wearability, require continued attention. The development of truly invisible and maintenance-free sensor systems remains an aspirational goal that will require significant advances in materials science and system integration [40], [41].

2.3.3 Sensor Review - Working Principles, Materials and Properties

A. Overview of Flexible Sensor Technologies

Flexible sensors for wearable applications encompass a diverse range of sensing modalities, each designed to capture specific physiological parameters or mechanical deformations. The primary categories include strain gauges for measuring mechanical deformation, pressure sensors for detecting contact forces, electrocardiography (ECG) sensors for cardiac monitoring, electromyography (EMG) sensors for muscle activity assessment, and biochemical sensors for sweat analysis. Each modality presents unique advantages and limitations in terms of sensitivity, dynamic range, power consumption, and integration complexity.

Strain gauge sensors represent a fundamental category within flexible wearable systems, designed to quantify mechanical deformation through various transduction mechanisms. These sensors convert mechanical strain into measurable electrical signals, enabling continuous

monitoring of body movement, muscle activity, and joint flexion. Strain Gauges were selected as the architecture of choice to estimate the change in limb volume based on localized strains on the outer circumference of the wearable garment. This is believed to provide greater robustness to the measurements in systems placed on varying body physiology and regions. The selection of appropriate strain gauge technology depends on specific application requirements including sensitivity range, mechanical durability, and environmental operating conditions.

B. Strain Gauge Sensors: Operating Principles and Classifications

1. Fundamental Operating Principles

Strain gauge sensors operate on the fundamental principle of converting mechanical deformation into measurable electrical signals through changes in electrical properties of sensing materials. The basic relationship governing strain gauge operation involves the correlation between applied mechanical strain and resultant electrical parameter variations, typically resistance, capacitance, or voltage generation. The sensitivity of strain gauge sensors is commonly characterized by the gauge factor (GF), defined as the ratio of relative change in electrical property to the applied mechanical strain. For resistive strain gauges, the fundamental relationship is expressed as:

$$\text{Gauge Factor (GF)} = (\Delta R/R_0)/\epsilon \quad (2)$$

where ΔR represents the change in resistance, R_0 is the initial resistance, and ϵ is the applied strain. High gauge factors indicate greater sensitivity to mechanical deformation, though this parameter must be balanced against other performance criteria including linearity, hysteresis, and mechanical robustness.

The operation of strain gauge sensors in wearable applications involves complex interactions between mechanical deformation, electrical transduction, and signal conditioning. The sensors must maintain consistent performance across varying environmental conditions including temperature fluctuations, humidity variations, and electromagnetic interference. Additionally, the mechanical coupling between sensor and target surface significantly influences measurement accuracy, requiring careful consideration of adhesion methods and substrate compliance.

2. Classification of Strain Gauge Sensors

Strain gauge sensors can be classified according to their transduction mechanism, with four primary categories dominating wearable applications: resistive/percolation, capacitive, piezoelectric, and inductive sensors. Each category exhibits distinct characteristics in terms of sensitivity, dynamic response, power requirements, and fabrication complexity.

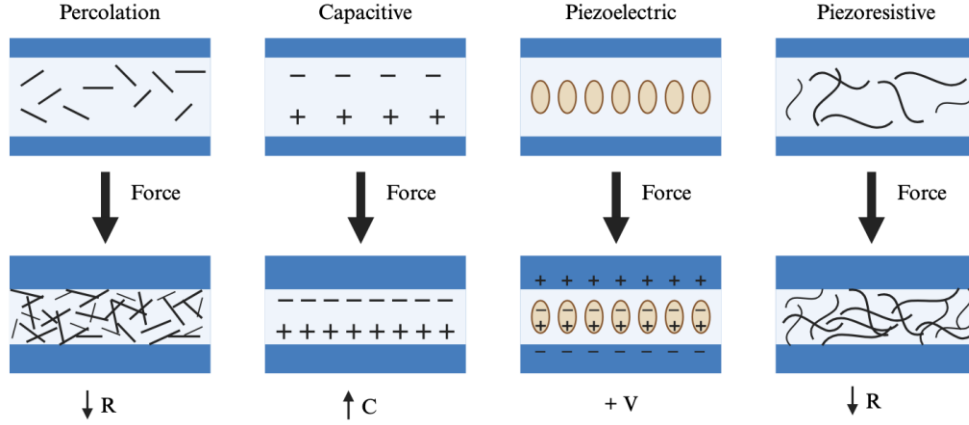


Figure 3. Schematic illustrations of different wearable sensing modalities operating principles. Show casing sensing modalities investigated Percolation conductive networks, Capacitive systems, Piezoelectric and Piezoresistive materials.

C. Resistive and Percolation-Based Strain Sensors

1. Working Principles

Resistive strain sensors convert mechanical deformations into electrical signals through alterations in electrical resistance responding to applied strain [40]. When composite structures experience stretching, microstructural changes within conductive sensing films produce corresponding variations in electrical resistance. Upon strain release, sensing films revert to original states, recovering initial electrical resistance values [40].

Beyond conventional piezoresistivity, highly stretchable resistive sensors utilize innovative mechanisms including disconnection between sensing elements, crack propagation in thin films, and tunneling effects. These mechanisms become dominant at high strain levels where traditional geometrical changes and intrinsic material piezoresistivity exhibit limited influence [40]. The disconnection mechanism, observed in conductive thin films composed of nanomaterial networks, involves loss of overlapped area and electrical connection between nanomaterials during stretching, resulting in increased resistance. This phenomenon is attributed to nanomaterial slippage due to weak interfacial binding and substantial stiffness mismatch between nanomaterials and stretchable polymers [40]. The tunneling effect, predominantly found in carbon nanotube (CNT) or graphene-polymer nanocomposites, involves modification of tunneling resistance through unfolding of entangled elastic nanomaterials during stretching. This mechanism differs from disconnection by relying on elastic nanomaterial deformation rather than physical separation of rigid components [40]. Crack propagation occurs in brittle thin films coated on soft polymer layers, where stretching initiates and propagates microcracks, consequently increasing resistance. These microcracks typically originate at stress-concentrated areas, with high-density microcrack generation yielding ultra-high sensitivity [40].

2. Advanced Resistive Technologies

A notable advancement in resistive strain sensing is SCARS (Strain-mediated Contact in Anisotropically Resistive Structures) technology, offering high-sensitivity strain detection with remarkable mechanical resilience [28]. SCARS operates on changes in Ohmic contact between stiff, micro-structured, anisotropically conductive meanders encapsulated by prestrained stretchable films [28], [29].

When prestrain is released, adjacent traces establish electrical contact, effectively shorting the meander. Applying tensile strain causes contacting traces to separate, increasing measured resistance until saturation where contact points are minimized or eliminated [28]. This technology demonstrates exceptionally high gauge factors exceeding 85,000 with high linearity ($R^2 > 0.98$) and compatibility with high-strength conductors contributing to mechanical resilience [28].

3. Materials and Performance Characteristics

Conductive sensing films commonly incorporate low-dimensional carbons including carbon blacks (CBs), carbon nanotubes (CNTs), and graphene. Nanowires (NWs) such as silver nanowires (AgNWs) and gold nanowires (AuNWs), along with nanoparticles (NPs) like platinum (Pt) NPs and AgNPs, are also utilized. Various hybrid micro/nanostructures combining these elements provide enhanced performance characteristics [40].

Flexible substrates typically employ silicone-based elastomers including polydimethylsiloxane (PDMS), Ecoflex, and Dragon Skin as support materials [40]. Other rubber types including natural rubber and thermoplastic elastomers (TPEs) are frequently used [40]. SCARS sensors utilize laser-machined carbon fiber polymer composites (CFPC) as conductive elements with thermoplastic polyurethane (TPU) films serving as encapsulating layers and silicone pressure-sensitive adhesive (PSA) for component bonding [28], [29].

D. Capacitive Strain Sensors

1. Operating Principles

Capacitive strain sensors function through incorporation of highly compliant dielectric layers positioned between stretchable electrodes [40]. During tensile strain application, electrode separation changes and dielectric layer thickness reduces, resulting in capacitance variations [40]. The capacitance typically exhibits linear relationships with applied strain, though linearity may be constrained at very large strain levels [40]. The fundamental capacitance relationship for parallel plate capacitors is:

$$C = \epsilon_0 \epsilon_r A / d \quad (3)$$

where ϵ_0 is the permittivity of free space, ϵ_r is the relative permittivity of the dielectric material, A is the electrode area, and d is the electrode separation distance. Strain-induced changes in both area and separation distance contribute to overall capacitance variations.

Capacitive sensors demonstrate capability for detecting touch and pressure through capacitance variations [42]. However, electrical shielding is critically important due to inherent susceptibility to electromagnetic interference and proximity effects [27]. Shield implementation in soft systems introduces challenges through parasitic capacitance fluctuations between shields and sensing electrodes during sensor deformation, complicating stable signal readout [27].

2. Advanced Capacitive Technologies

Shielded capacitive sensor designs represent significant technological advancement, enabling reliable operation in electromagnetically noisy environments. These sensors incorporate conductive shielding layers that isolate sensing electrodes from external electromagnetic fields while maintaining mechanical flexibility [27]. The shielding effectiveness depends on material selection, layer thickness, and integration methods that preserve sensor deformability.

Differential capacitive measurement techniques enhance signal-to-noise ratios and reduce common-mode interference effects. These approaches utilize multiple electrode configurations to extract strain-related signals while rejecting environmental disturbances [43].

3. Materials and Performance

Dielectric layers typically comprise highly compliant polymers including silicone-based elastomers (Ecoflex, Dragon Skin) [40]. Dielectric properties can be substantially improved through incorporation of high-k dielectric fillers such as Barium Titanate (BTO) nanoparticles uniformly dispersed in elastomers, enhancing effective dielectric constant and overall capacitance [39].

Stretchable electrodes are often formed from percolation networks of one-dimensional nanomaterials including CNTs and AgNWs, maintaining stable electromechanical properties under high strains [40]. Carbon black (CB)/Ecoflex composite inks can be utilized for printing interdigital electrodes [39]. Liquid metals such as eutectic gallium indium (EGaIn alloy) integrated into microfluidic channels serve as highly conductive, stretchable electrodes [27].

E. Piezoelectric Strain Sensors

1. Operating Principles

Piezoelectric strain sensors generate electrical charge in response to applied mechanical stress, offering self-powered sensing capabilities without external power sources for signal generation. The piezoelectric effect involves asymmetric charge distribution within crystal structures when subjected to mechanical deformation, producing measurable voltage outputs proportional to applied strain rates. The fundamental piezoelectric relationship is expressed as:

$$D = dT \quad (4)$$

where D represents electric displacement, d is the piezoelectric coefficient, and T is applied mechanical stress. The generated voltage depends on sensor geometry, material properties, and mechanical coupling efficiency.

Piezoelectric sensors demonstrate particular sensitivity to dynamic strain variations, making them suitable for applications requiring high-frequency response characteristics. However, their inherent charge generation mechanism limits their effectiveness for static strain measurements due to charge leakage effects [44].

2. Limitations in Wearable Applications

Despite potential advantages, piezoelectric sensors face significant implementation challenges in skin-mountable and wearable applications. These challenges primarily stem from requirements for sophisticated measurement equipment, inherently low resolution, and often inadequate dynamic performance [40]. The complex signal conditioning requirements and sensitivity to environmental factors limit their practical deployment in flexible wearable systems.

Although piezoresistive strain sensors can achieve very high gauge factors, they frequently suffer from significant drawbacks, including non-linear responses, signal drift, hysteresis effects, and poor long-term durability [45], [46]. Additionally, the brittleness of many piezoelectric materials conflicts with flexibility requirements for wearable applications. Recent research has explored flexible piezoelectric materials including organic piezoelectric polymers and composite structures, though these typically exhibit lower piezoelectric coefficients compared to ceramic alternatives [47].

G. Comparison of Sensing Principle

A comprehensive comparison of strain gauge sensing modalities reveals distinct advantages and limitations for wearable applications. Table 1 provides a systematic comparison of key performance parameters across different sensor types.

Resistive sensors generally require relatively simple readout systems and exhibit high flexibility with potential for high sensitivity, particularly through microcrack and disconnection mechanisms [40]. However, they often present challenges including high hysteresis and nonlinearity, especially in nanocomposite designs [40]. SCARS technology addresses many of these limitations through innovative mechanical design approaches [28].

Capacitive sensors offer excellent linearity and superior hysteresis performance compared to resistive sensors, with faster response times and low power consumption [40]. However, they typically exhibit inherently low sensitivity due to theoretical constraints and require careful electromagnetic shielding for reliable operation [27].

Piezoelectric sensors can achieve high sensitivity for dynamic measurements but face limitations in static applications and require complex signal conditioning [40]. Their brittleness conflicts with wearable flexibility requirements [47].

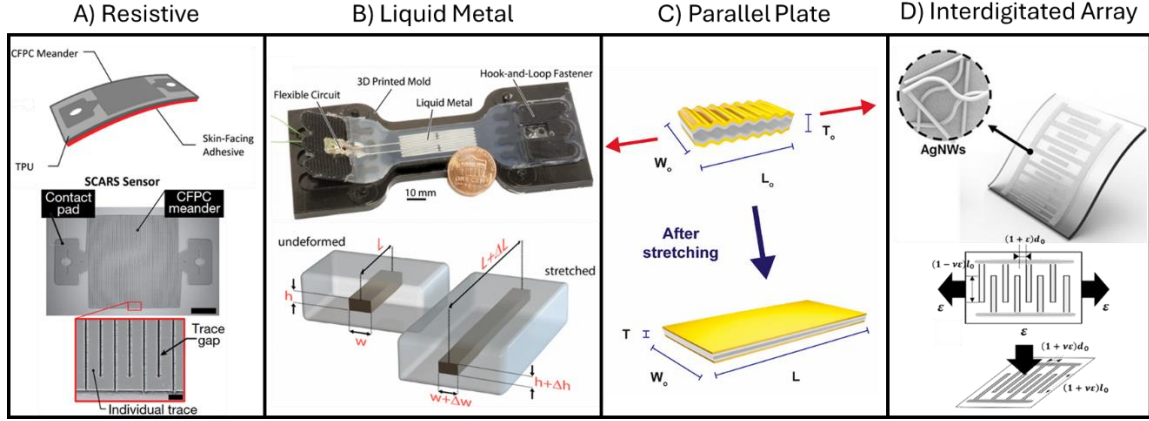


Figure 4. Different Stretchable Strain Gauge Architectures. A) Sensitive SCARS wearable strain gauge adapted from [33]. B) Liquid metal strain gauge and cross-section diagram adapted from [48]. C) Parallel Plate capacitive strain gauge, with wrinkled electrodes adapted from [49]. D) Interdigitated Array capacitive strain gauge adapted from [50].

H. Current Strain Gauge Technologies

1. Silicon-Based Rigid Strain Gauges

Traditional silicon-based strain gauges represent the established technology for precision strain measurement applications. These devices typically utilize piezoresistive silicon elements patterned on rigid substrates, offering excellent linearity, temperature stability, and long-term reliability. However, their rigid nature and limited strain range (typically $\leq 5\%$) severely restrict their applicability in highly stretchable wearable applications [40]. The fundamental limitation of silicon strain gauges lies in their incompatibility with the large deformations required for wearable applications, typically exceeding 50% strain [40]. The mechanical mismatch between rigid silicon elements and flexible substrates creates stress concentrations that can lead to device failure under repeated deformation cycles [41], [51].

2. Liquid Metal Strain Gauges

Liquid metal strain gauges represent an innovative approach to highly stretchable sensing, utilizing the unique properties of liquid metals such as eutectic gallium indium (EGaIn) alloy. These materials maintain high electrical conductivity while accommodating large mechanical deformations without structural degradation [27]. The implementation of liquid metal strain gauges typically involves microfluidic channel encapsulation, providing mechanical support while enabling shape changes during deformation. The primary advantages include excellent conductivity maintenance under strain, high stretchability, and potential for self-healing properties [52]. However, liquid metal systems face challenges including complex fabrication requirements, potential leakage issues, and temperature sensitivity affecting metal flow properties.

3. Conventional Resistive Strain Gauges

Traditional resistive strain gauges comprise thin metallic traces deposited on near-inextensible polymer substrates. Their utility in soft systems is limited by impedance mismatch, inherently low

strain sensitivity, and difficulty integrating rigid, inextensible devices into highly deformable soft machines [28]. The fundamental design limitations of conventional strain gauges include restricted strain range, poor mechanical compliance, and inadequate sensitivity for detecting subtle biological signals. These limitations have driven the development of advanced alternatives including SCARS technology and nanocomposite-based sensors [28].

I. Disadvantages of Traditional Strain Gauges for Wearable Applications

Traditional strain gauge technologies present several fundamental limitations when applied to wearable and highly stretchable applications. The primary disadvantages include:

Mechanical Incompatibility: The inherent rigidity of traditional strain gauges conflicts with the flexibility requirements of wearable systems. The mechanical mismatch between rigid sensing elements and flexible substrates creates stress concentrations that can lead to device failure or inaccurate measurements.

Limited Strain Range: Conventional metal or semiconductor-based strain gauges typically operate within strain ranges of 5% or less, far below the requirements for wearable applications that may exceed 50% strain [40]. This limitation severely restricts their applicability in dynamic human motion monitoring.

Poor Substrate Adhesion: Traditional strain gauges rely on rigid bonding to substrates, which can fail under repeated deformation cycles common in wearable applications. The adhesion failure leads to measurement drift and eventual device malfunction [41], [51].

Temperature Sensitivity: Many traditional strain gauge materials exhibit significant temperature coefficients, requiring complex compensation circuits for accurate measurements in varying environmental conditions typical of wearable applications [41].

Signal Conditioning Complexity: Traditional strain gauges often require sophisticated signal conditioning circuits including Wheatstone bridge configurations, amplification, and temperature compensation, increasing system complexity and power consumption.

Biocompatibility Concerns: Some traditional strain gauge materials may not be suitable for prolonged skin contact, requiring protective barriers that can interfere with mechanical coupling [53].

Based on the comprehensive sensor technology review, capacitive sensing mechanisms have been selected as the primary transduction approach for this limb volume monitoring application due to several critical performance advantages over resistive and piezoelectric alternatives. Capacitive strain sensors demonstrate superior thermal stability characteristics, exhibiting minimal thermal drift compared to resistive counterparts which suffer from temperature-sensitive material properties requiring complex compensation circuits. The fundamental capacitive transduction mechanism relies on geometric and dielectric property changes rather than intrinsic material resistance variations, providing inherent thermal

compensation essential for accurate long-term measurements in varying environmental conditions typical of wearable applications. Additionally, capacitive sensors demonstrate fast response capabilities with minimal settling time compared to piezoelectric systems, which are fundamentally unsuited for limb volume sensing due to charge leakage limitations in static measurements and requirements for sophisticated signal conditioning equipment conflicting with wearable system constraints.

Within the capacitive sensing framework, interdigitated electrode (IDE) arrays have been selected as the optimal sensing structure based on their superior fabrication characteristics and performance benefits for wearable applications. IDE configurations offer exceptional material simplicity through planar electrode arrangements, enabling single-layer fabrication processes that significantly reduce manufacturing complexity compared to parallel-plate capacitive structures requiring precise multi-layer alignment procedures. This simplified approach enhances process reliability while facilitating scalable manufacturing protocols essential for commercial development. The inherent high linearity of IDE arrays throughout large strain ranges provides consistent capacitance-strain relationships critical for accurate volumetric measurements, while their directional sensitivity properties offer inverse capacitive responses to orthogonal in-plane strain directions, effectively minimizing cross-talk interference. Although IDE configurations exhibit reduced sensitivity compared to parallel-plate alternatives due to fringing field effects, this trade-off is acceptable given the superior fabrication simplicity, enhanced linearity, and directional discrimination capabilities that provide more robust sensing performance for continuous limb volume monitoring applications.

2.3.4 Interdigitated Electrode Array Structures

Interdigitated electrode (IDE) arrays represent a highly advantageous capacitive sensing architecture for wearable strain measurement applications, offering distinct performance benefits over alternative geometries through their unique structural and functional characteristics. The fundamental structure of an IDE sensor consists of two coplanar, interpenetrating comb-like electrodes, where capacitance is generated by electric field lines that fringe between adjacent electrode fingers through the surrounding dielectric media [54], [55], [56]. This planar configuration is a defining characteristic that differentiates IDEs from traditional stacked-plate capacitors and provides significant advantages for flexible sensor applications. A relation describing the initial capacitance of an IDE capacitive sensor based on its geometry is shown below [56], [57], [58], [59]

$$C_0 = \epsilon_0 \epsilon_r \frac{(2l_0 - a + 2w_0)t_0}{d_0} (2n - 1) \quad (5)$$

Where ϵ_0 and ϵ_r represent the vacuum and relative permittivity of the dielectric layer and surrounding region respectively. The geometric parameters are denoted by w_0 , l_0 , t_0 , d_0 , and n , representing the element widths, lengths, trace thickness, dielectric thickness, and total number of

elements. Finally, a indicates the total width of the IDE, which integrates the gaps of the elements assuming that the spacing between the electrodes and connecting buses are equivalent.

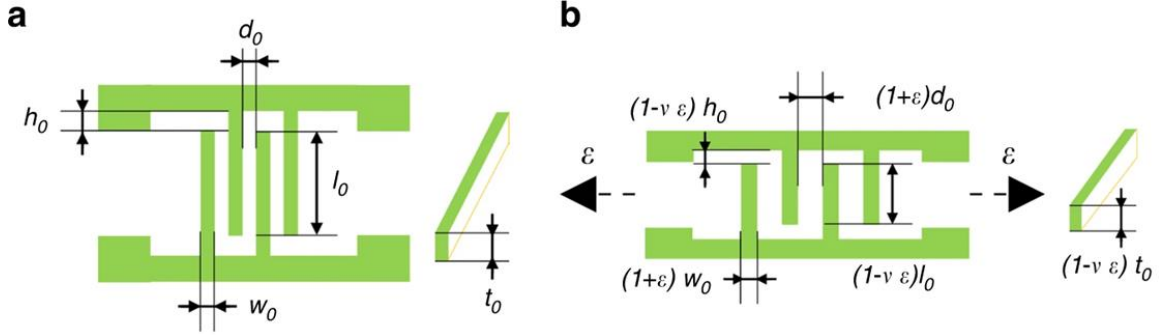


Figure 5. Interdigitated Electrode Array (IDE) Schematic diagram, showing different geometry parameters. A) Steady-state configuration dimensions. B) Applied horizontal strain and the simplified effects on geometry. Adapted from [60].

The primary sensing principle operates on the relative change in capacitance, expressed as $\Delta C/C_0$, that results from an applied mechanical strain, ϵ [55], [56]. In an IDE architecture, this applied strain deforms the sensor's geometry, directly modulating the capacitance by altering parameters such as the length, width, and spacing of the electrode fingers [56]. Under applied strain perpendicular to the electrode's length, the changes to the structure can be approximated by assessing the changes to the length according to the materials Poisson's contraction ratio ν . This predicts the length and thickness to decrease by $(1 - \nu\epsilon)$, and the spacing between the elements to increase by a factor of $(1 + \epsilon)$. Thus, the estimated capacitance under strain can be evaluated as:

$$C = \epsilon_0 \epsilon_r \frac{(1 - \nu\epsilon)(2l_0 - a + 2w_0)(1 - \nu\epsilon)t_0}{d_0(1 + \epsilon)} (2n - 1) \quad (6)$$

The sensor's sensitivity is quantitatively defined by its Gauge Factor (GF), which is the ratio of the relative capacitance change to the applied strain, given by the equation:

$$\frac{\Delta C}{C_0} \frac{(1 - \nu\epsilon)^2}{(1 + \epsilon)} - 1 \quad (7)$$

$$GF = (\Delta C/C_0)/\epsilon \quad (8)$$

The coplanar geometry of IDEs imparts an inherent sensitivity to the direction of applied stress, a feature not present in simple parallel-plate capacitors [55]. For instance, pressure applied perpendicular to the fingers (x-direction) can cause a decrease in capacitance, while pressure parallel to the fingers (y-direction) can cause an increase, a property that can be leveraged for advanced applications [55]. This directional sensitivity distinguishes IDE structures from parallel-tube capacitive sensors, which operate on a distinct mechanism where axial stretching increases the sensor's length, which, due to the Poisson effect, reduces the distance between the two parallel

conductive tubes [61]. The out-of-plane compression resulting from in-plane tension in parallel-tube sensors leads to a measurable increase in capacitance, but lacks the directional discrimination capabilities inherent to IDE architectures. The IDE architecture occupies a unique position by combining the manufacturing simplicity of a planar geometry with a complex, multi-parameter sensing mechanism sensitive to in-plane strain, contrasting with the three-dimensional assembly required for parallel-tube sensors and the simpler, one-dimensional sensing principle of inductive sensors[62], [62].

The essential geometric parameters that define an IDE array include the width of the individual electrode fingers (w), the spacing or gap between adjacent fingers (g), and the effective overlapping length of the fingers (L) [54], [63], [64]. The periodicity of the IDE structure is characterized by its spatial wavelength, defined as:

$$\lambda = 2(w + g) \quad (7)$$

From this, a critical dimensionless design parameter known as the metallization ratio, η , is derived, which describes the fraction of the unit cell area covered by the electrode and is given by:

$$\eta = \frac{w}{w + g} \quad (8)$$

The metallization ratio is a fundamental design parameter that exerts significant control over the performance of an IDE sensor [54], dictating the balance between the conductive electrode area and the insulating gap within each periodic unit of the array. This dimensionless metric provides a normalized measure of performance, allowing for direct comparison between different sensor designs and materials. The theoretical Gauge Factor for an ideal capacitive strain sensor, based purely on geometric deformation with a constant Poisson's ratio, is approximately 1 [55], derived from the expression:

$$GF = (1 + \varepsilon)^{-1} \approx 1 \quad (9)$$

Assuming Poisson's ratios of the electrode and dielectric are equal and cancel out. However, in practice, IDE strain gauges exhibit a wide range of GFs that deviate from the purely geometric ideal, with reported values including ~ 0.97 for a vertical graphene sensor and an exceptionally high GF of ~ 14 at 2% strain for a CNF/PANI/silicone rubber nanocomposite sensor [55], [56]. The achievement of high Gauge Factors ($GF \gg 1$) indicates that the sensing mechanism is not solely geometric but is a coupled electromechanical phenomenon, suggesting that applied strain also modulates the intrinsic electrical properties of the electrode or dielectric materials, such as the percolation network in a nanocomposite, which contributes significantly to the overall capacitance change[61].

IDE-based capacitive sensors demonstrate superior stability and performance characteristics compared to alternative sensing mechanisms [37], [63], [65], [66]. In contrast, the capacitive structure is an effective and relatively simple method for improving stability, as its

sensing mechanism is based on the highly recoverable elastic deformation of a dielectric layer. The inherent stability of capacitive IDEs arises from a functional separation within the device architecture, where the electrodes primarily create the electric field and the dielectric medium performs the sensing via elastic deformation [55]. This decoupling makes the device less susceptible to the irreversible micro-damage mechanisms, such as cracking in a conductive network, that often degrade the performance of percolation and piezoresistive sensors over time [63], [67], [68]. IDE-based capacitive sensors are capable of demonstrating excellent linearity and low hysteresis, which are critical for reliable and repeatable measurements. For example, a vertical graphene sensor showed that its loading and unloading capacitance curves were nearly identical, with a coefficient of determination (R^2) of 0.99992, confirming minimal hysteresis [4]. Capacitive sensor structures have been shown to possess excellent long-term durability and stability under cyclic loading, with a vertical graphene sensor demonstrating almost no performance decay over 1000 cycles at strains up to 80% [55].

As planar structures, IDEs are highly scalable and through their capability to be fabricated with cost-effective batch processes such as photolithography, screen-printing, and aerosol jet printing [54], [56], [62], [63]. This presents a significant advantage over stacked electrode geometries, which require more complex multi-step fabrication and are inherently less robust against mechanical bending and flexing [63]. The compatibility of IDE fabrication with flexible substrates and advanced functional materials facilitates the development of soft, lightweight, and highly conformable sensors. These characteristics are essential for applications in wearable technology, soft robotics, and direct skin-mountable health monitoring systems [9], [4], making the IDE architecture particularly well-suited for the demanding requirements of wearable strain sensing applications where mechanical robustness, manufacturing scalability, and sensing performance must be simultaneously optimized.

2.3.5 Material Review - Highly Stretchable Substrates and Conductive Materials for Capacitive sensors

A. Highly Stretchable Substrates

1. Silicone-Based Elastomers

Silicone-based elastomers represent the predominant substrate materials for wearable flexible sensors due to their exceptional mechanical properties and biocompatibility. Polydimethylsiloxane (PDMS), Ecoflex, and Dragon Skin are the most frequently utilized materials, each offering distinct advantages for specific applications [40].

Ecoflex™ 00-30 demonstrates particular promise as a substrate material, characterized by extensive elongation limits and low stiffness properties. While its intrinsic relative permittivity is modest ($\epsilon_r = 2.8$), this property can be significantly enhanced through incorporation of high-k dielectric fillers such as Barium Titanate (BTO) nanoparticles [39]. Substrates containing up to 40 wt% BTO in Ecoflex have demonstrated robust mechanical performance, successfully enduring 1000 stretch/relax cycles at 100% strain, confirming their stability and durability for extended

wearable applications [39]. PDMS (Sylgard 184) has been employed in various studies but may exhibit limitations at higher strain levels, potentially being restricted to 50% strain due to mechanical failure compared to more resilient elastomers like Ecoflex [39]. The selection between different silicone elastomers depends on specific application requirements including maximum strain levels, environmental conditions, and biocompatibility requirements.

Ultrasoft Silicone Foam (SF) represents an advanced substrate material featuring an exceptionally low elastic modulus of approximately 7 kPa, significantly softer than bulk silicone (1 MPa) [27]. This ultra-low modulus enables enhanced conformability to irregular surfaces and reduced mechanical interference with natural body movements.

2. Thermoplastic Polyurethane (TPU)

Thermoplastic Polyurethane (TPU) serves as an encapsulating layer for compliant strain gauges, particularly in SCARS technology implementations [28]. TPU films can be prestrained to specific levels (e.g., 4%) to enable sensing mechanisms while maintaining structural integrity over repeated deformation cycles. TPU demonstrates excellent compatibility with textile integration, enabling heat-bonding to knitted fabrics to form hybrid TPU-knit layers essential for creating integrated wearable sleeves [28]. This capability facilitates seamless integration of sensors into clothing articles without compromising comfort or aesthetics. The mechanical properties of TPU, including high tear strength, excellent elasticity, and resistance to environmental degradation, make it particularly suitable for demanding wearable applications.

4. Biocompatibility and Safety Considerations

A paramount requirement for wearable sensor substrates is biocompatibility for direct skin contact applications [30]. The inherent softness and mechanical compliance of elastomeric substrates, characterized by Young's moduli less than 1 MPa, are crucial for ensuring user comfort and minimizing skin irritation during extended wear periods [27].

Clothing-based sensor systems offer practical advantages over direct skin-mounted devices by eliminating requirements for special skin preparation and simplifying sensor alignment procedures [28]. This approach enhances user comfort and overall practicality for daily wear applications while maintaining measurement accuracy.

Materials maintaining structural integrity and performance over extended periods of repeated use demonstrate low hysteresis and minimal permanent deformation, essential characteristics for long-term wearability [27]. Durability prevents discomfort or irritation that could arise from degraded or deformed substrate materials during extended use.

B. Highly Stretchable Conductors

1. Carbon-Based Conductive Materials

Carbon-based conductive materials represent a fundamental category of conductors for flexible sensor applications, offering excellent electrical properties combined with mechanical flexibility.

Carbon Black (CB)/Ecoflex composite inks are specifically formulated for printing interdigital capacitor electrodes, prepared by mixing CB powder (50 nm particle size) with Ecoflex™ 00-30 and diluting with silicone oil for optimal printability [39].

The spherical morphology of carbon black renders it biocompatible, positioning it as a safer alternative to materials like Carbon Nanotubes (CNTs) for applications involving direct skin contact [39]. The carcinogenic nature of CNTs represents a significant safety concern, explicitly noted as a reason for their avoidance in healthcare-oriented sensor designs [39].

Carbon nanotubes and graphene, despite safety concerns, offer exceptional electrical and mechanical properties when properly encapsulated. These materials demonstrate high conductivity, mechanical strength, and flexibility, making them attractive for advanced sensor applications where direct exposure can be prevented.

2. Metallic Conductors

Silver-based conductive materials are extensively utilized in wearable sensor fabrication due to their excellent electrical conductivity and processability. Silver ink employed in roll-to-roll gravure printing forms underlying electrode layers and reference electrodes, exhibiting excellent electrical conductivity with resistivity of $1.8 \times 10^{-4} \Omega\text{-cm}$ when printed in thin layers (250 nm thickness) [30].

Silver nanowires (AgNWs) provide exceptional performance in stretchable conductor applications, maintaining stable electrical properties under large mechanical deformations. The high aspect ratio and percolation network formation enable conductivity preservation even under significant strain levels [69].

Silver-filled compositions are utilized for electrodes and electromagnetic shielding in advanced sensor designs, providing excellent conductivity while maintaining mechanical flexibility [27]. However, silver materials may face limitations in biological environments due to potential cytotoxicity and environmental degradation [62].

3. Liquid Metal Conductors

Liquid metal conductors, particularly Eutectic Gallium Indium (EGaIn) alloy, represent cutting-edge solutions for highly stretchable applications. EGaIn alloy fills microfluidic channels serving as electrodes in soft force sensors, maintaining high electrical conductivity while accommodating large deformations [27].

The unique properties of liquid metals include self-healing capabilities, excellent conductivity maintenance under strain, and potential for integration into complex three-dimensional structures. However, implementation challenges include complex fabrication requirements, encapsulation needs, and temperature sensitivity affecting flow properties.

4. Composite Conductors

Composite conductive materials combine multiple constituent materials to achieve optimized electrical and mechanical properties. Carbon black/elastomer composites, metal nanoparticle/polymer composites, and hybrid structures incorporating multiple conductive phases offer tailored properties for specific applications [38].

The design of composite conductors requires careful consideration of percolation thresholds, mechanical property matching, and environmental stability. Advanced characterization techniques enable optimization of composite formulations for specific sensor performance requirements [70].

C. Material Selection Criteria

The selection of materials for highly stretchable strain gauge applications requires consideration of multiple interdependent factors:

Mechanical Properties: Materials must accommodate required strain ranges while maintaining structural integrity over repeated deformation cycles. Mechanical property matching between substrates and conductors is crucial for preventing delamination and ensuring long-term reliability.

Electrical Properties: Conductors must maintain adequate electrical performance under mechanical deformation, including resistivity stability and minimal hysteresis effects. The electrical property preservation is essential for consistent sensor performance.

Biocompatibility: Materials intended for direct skin contact must demonstrate biocompatibility through appropriate testing protocols. The safety considerations are paramount for wearable applications involving prolonged skin contact.

Environmental Stability: Materials must withstand environmental conditions including temperature variations, humidity, and chemical exposure typical of wearable applications. Environmental stability ensures consistent performance across varying operational conditions.

Processing Compatibility: Materials must be compatible with selected fabrication methods, including printing, coating, and patterning processes. Processing compatibility affects manufacturability and cost-effectiveness.

Based on the material review presented, the following materials have been selected for this research investigation. Thermoplastic Polyurethane (TPU) has been chosen as the primary substrate material due to its exceptional wearability characteristics and integration potential within flexible electronics applications. TPU demonstrates superior durability and processability compared to alternative elastomeric substrates, while offering straightforward procurement and formulation capabilities essential for scalable fabrication protocols. A critical advantage of TPU lies in its thermal bonding compatibility with textile and fabric substrates, enabling seamless integration into comprehensive wearable sensor systems without compromising mechanical integrity or user comfort.

For conductive material implementation, two distinct approaches will be investigated. Silver nanoparticles (AgNPs) represent the primary conductive material due to their demonstrated safety profile, exceptional electrical stability, and high compatibility with the fabrication methodologies detailed in following Section 2.3.5. As a secondary investigation pathway, carbon-based conductive fillers will be evaluated specifically utilizing carbon black formulations. While carbon black exhibits reduced conductivity and stability compared to advanced carbon nanomaterials such as carbon nanotubes or graphene, this material selection prioritizes biocompatibility and safety considerations for direct skin contact applications. Carbon black provides reliable suspension characteristics and eliminates the carcinogenic risks associated with alternative carbon conductors, thereby ensuring safe integration within wearable sensor architectures intended for extended human contact.

2.3.6 Fabrication Methods Review

A. Photolithography

Photolithography represents the foundational fabrication technique for high-precision sensor patterning, offering exceptional resolution and reproducibility for rigid sensor applications. The process involves photoresist application, mask-based exposure, and selective material removal to create precise patterns with sub-micron resolution capabilities [71]. For flexible sensor applications, photolithography faces limitations due to substrate compatibility issues and thermal budget constraints. Many flexible substrates cannot withstand the processing temperatures and chemical exposures typical of conventional photolithographic processes [39]. Advanced photolithographic techniques including flexible substrate-compatible processes and low-temperature processing methods have been developed to address these limitations. These approaches enable high-resolution patterning on flexible substrates while maintaining material integrity.

B. Soft Lithography

Soft lithography encompasses a family of techniques utilizing elastomeric stamps and molds for pattern transfer, offering advantages for flexible sensor fabrication. The process typically involves master pattern creation, elastomeric stamp fabrication, and pattern transfer through contact printing or molding [72]. Microcontact printing (μ CP) represents a prominent soft lithography technique enabling high-resolution pattern transfer using elastomeric stamps. This approach offers advantages including room temperature processing, compatibility with diverse substrates, and potential for large-area patterning. Replica molding techniques enable creation of three-dimensional structures and complex geometries difficult to achieve through conventional lithography [73].

C. Screen Printing

Screen printing, also known as stencil printing, is a well-established and mature printing technology for sensor fabrication, offering significant advantages including high throughput, ease of mass production, low capital cost, and wide substrate compatibility [74]. The process involves

a simple setup comprising a screen, squeegee, press bed, substrate, and patterned stencil or mask. The screen printing process effectively prevents common clogging problems encountered in nozzle-based printing when handling particulate inks [74]. It facilitates rapid construction of multiple layers through repeated printing operations, enabling complex sensor architectures [74]. Conventional screen printing faces limitations in lateral resolution, typically above 100 μm , and challenges in producing thin films due to high ink viscosity requirements (500-5000 cP) [74]. However, advances in screen printing technology have achieved enhanced resolution with patterned stencils fabricated using photolithography, enabling line widths of 10-40 μm [74]. Flatbed screen printing is often preferred for flexible sensor applications due to lower capital costs and simpler processing compared to rotary screen printing, despite the latter's higher throughput capabilities [74].

D. Roll-to-Roll and Gravure Processing

Roll-to-Roll (R2R) processing represents a transformative manufacturing approach for high-volume, cost-effective sensor production. This technique adapts rotary printing methods for continuous processing, enabling economic mass production with higher throughput compared to batch processing methods [74]. This technique utilizes an engraved cylinder (gravure cylinder) containing recessed cells that hold ink, which is subsequently transferred to the substrate through direct contact under controlled pressure. The depth and geometry of these cells directly determine the ink transfer characteristics and final print quality. R2R gravure printing demonstrates particular promise for wearable sensor fabrication, offering additive manufacturing capabilities with high process speeds and superior resolution compared to other printing techniques [30]. The process is intrinsically robust and large-area compatible, making it suitable for industrial-scale production of disposable sensor components [30]. The R2R process involves continuous web movement under tension with adapted printing conditions to deposit patterns with high fidelity under demanding mechanical conditions [30]. Successful implementation requires careful optimization of ink rheology, printing pressure, and web tension to achieve consistent pattern quality [30]. Demonstrated applications include production of 150,000 electrodes on 150m PET web in approximately 30 minutes, illustrating the efficiency potential for large-scale disposable sensor manufacturing [30].

R2R gravure printing offers exceptional advantages for wearable sensor fabrication, including high-speed processing capabilities exceeding 300 meters per minute, excellent pattern resolution down to 20 micrometers, and superior layer-to-layer registration accuracy. The technique demonstrates remarkable consistency in ink deposition, with thickness variations typically less than 5% across the web width, which is crucial for ensuring uniform sensor performance [30]. The additive nature of gravure printing eliminates material waste associated with subtractive processes, making it economically viable for large-scale production of disposable sensing components. The implementation of R2R gravure printing for wearable sensors involves the sequential deposition of multiple functional layers. A typical electrochemical sensor architecture includes a silver base layer for conductivity, a carbon working electrode layer for

electrochemical activity, and an insulating layer for electrical isolation. Each layer requires specific ink formulations and printing parameters to achieve optimal adhesion and functionality [30].

G. Inkjet Printing

Inkjet printing has emerged as a versatile and precise fabrication technique for wearable flexible sensors, offering maskless patterning capabilities and exceptional design flexibility. This digital printing technology operates on the principle of on-demand droplet ejection, enabling the precise deposition of functional materials in predetermined patterns without the need for physical masks or templates. The fundamental mechanism of inkjet printing involves two primary approaches: Continuous Inkjet (CIJ) and Drop-on-Demand (DoD) systems. CIJ systems generate a continuous stream of charged droplets that are electrostatically deflected to achieve pattern formation, offering high-speed printing capabilities but with limited resolution and potential material waste. DoD systems, which have become predominant for wearable sensor applications, generate droplets only when required, providing superior material utilization and printing resolution [74]. DoD systems are further classified into thermal and piezoelectric actuation mechanisms, with piezoelectric systems preferred for printing temperature-sensitive functional materials commonly used in wearable sensors [74]. The inkjet printing process for wearable sensors requires careful optimization of ink formulations to achieve stable droplet formation and reliable pattern deposition. Critical ink properties include viscosity (typically 1-20 cP), surface tension (25-35 mN/m), and particle size ($< 1/10$ of nozzle diameter) to prevent clogging and ensure consistent droplet ejection. The formulation of conductive inks for sensor applications often involves the dispersion of metallic nanoparticles, such as silver or gold, in appropriate solvents with stabilizing agents to prevent aggregation [74]. The rheological properties must be carefully balanced to ensure proper jetting behavior while maintaining the functional characteristics required for sensor performance.

Pattern formation in inkjet printing involves the controlled deposition of droplets in predetermined locations, with droplet spacing and overlap determining the final pattern characteristics. The coffee ring effect, caused by differential evaporation rates across the droplet surface, can result in non-uniform material distribution and must be mitigated through ink formulation optimization or controlled drying conditions [74]. Post-printing processing, including thermal sintering or photonic sintering, is often required to achieve the desired electrical or mechanical properties of the printed patterns. For wearable sensor applications, inkjet printing offers several significant advantages. The maskless nature of the process enables rapid prototyping and customization of sensor designs without the need for expensive tooling. The ability to print on various substrate materials, including flexible polymers and textiles, makes it particularly suitable for wearable applications. Additionally, the precise control over droplet placement enables the creation of complex, multi-layer sensor architectures with minimal material waste [75].

The integration of inkjet printing with other fabrication techniques has expanded its capabilities for wearable sensor manufacturing. Hybrid approaches combining inkjet printing with

conventional lithography or screen printing enable the creation of devices with both high-resolution features and large-area coverage. The development of functional inks incorporating polymers, nanocomposites, and biomaterials has further broadened the application scope of inkjet printing in wearable sensor fabrication [74]. Recent advances in inkjet printing for wearable sensors include the development of multi-material printing systems capable of simultaneous deposition of different functional materials, enabling the creation of complex sensor architectures in single printing operations. The integration of real-time quality monitoring systems using machine vision and process control algorithms has improved printing consistency and reduced defect rates.

H. Direct Ink Writing (DIW)

Direct Ink Writing (DIW) represents an advanced extrusion-based additive manufacturing technique that has gained significant prominence in the fabrication of wearable flexible sensors due to its exceptional capability to create complex three-dimensional structures with multiple functional materials. This technique operates on the principle of continuous extrusion of viscoelastic inks through a controlled nozzle system, enabling the layer-by-layer construction of sophisticated sensor architectures. The fundamental mechanism of DIW involves the extrusion of specially formulated inks with shear-thinning properties that flow readily through the printing nozzle under applied pressure while maintaining structural integrity upon deposition. The rheological properties of DIW inks are critically important, requiring a delicate balance between flowability during extrusion and shape retention after deposition. Typical DIW inks exhibit apparent viscosities ranging from 10^3 to 10^6 Pa·s at low shear rates, with significant shear-thinning behavior that reduces viscosity by several orders of magnitude during extrusion [74]. The ink formulation for DIW wearable sensors involves the incorporation of functional materials within a polymer matrix that provides the necessary rheological properties. Common base materials include hydrogels, silicone elastomers, and thermoplastic polymers, which can be loaded with conductive fillers such as carbon nanotubes, graphene, or metallic nanoparticles to achieve desired electrical properties. The concentration of functional fillers must be optimized to achieve the required electrical conductivity while maintaining printability and mechanical properties suitable for wearable applications [74]. Process parameters in DIW significantly influence the final sensor characteristics.

The layer-by-layer construction approach of DIW enables the creation of complex sensor architectures not achievable through conventional planar processing techniques. This includes the fabrication of embedded sensing elements within elastomeric matrices, creation of strain-concentrating geometries for enhanced sensitivity, and integration of multiple sensing modalities within single device structures. The ability to vary material properties spatially within a single print job enables the creation of gradient structures that can optimize sensor performance for specific applications [74].

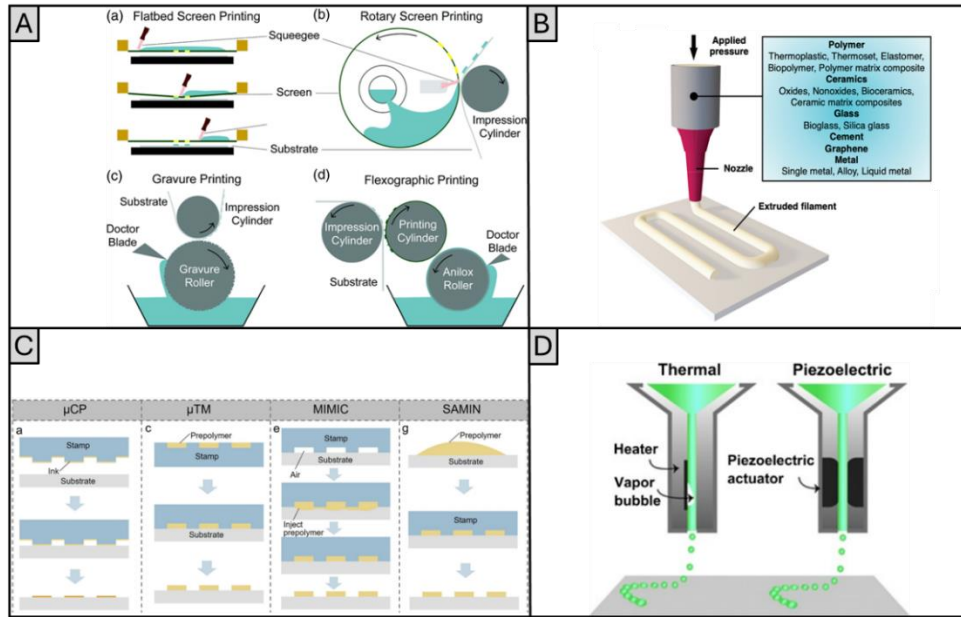


Figure 6. Modern Microscale fabrication techniques capable of producing wearable electronics. A) Masked transfer technologies, Flatbed Screen, Rotary Screen, Gravure, and Flexographic printing diagrams adapted from [76]. B) Direct Ink Writing process schematic adapted from [77]. C) Common soft lithography processes microcontact printing (μ CP), micro transfer molding (μ TM), capillary microforming (MIMIC), solvent assisted micromolding in capillaries (SAMIN), adapted from [78]. D) Ink jetting process overview showing operating principle of thermal and piezoelectric actuation modes adapted from [79].

For wearable sensor applications, DIW offers several unique advantages. The ability to print directly onto curved or irregular surfaces eliminates the need for secondary forming operations, enabling conformal sensor integration with human anatomy. The multi-material printing capabilities allow for the simultaneous deposition of sensing elements, interconnects, and encapsulation materials, reducing assembly complexity and improving reliability. Additionally, the room-temperature processing typical of DIW preserves the functionality of temperature-sensitive materials commonly used in biological sensing applications [80]. The integration of DIW with other fabrication techniques has expanded its capabilities for wearable sensor manufacturing. Hybrid approaches combining DIW with conventional lithography enable the creation of devices with both high-resolution planar features and three-dimensional structural elements. The development of conductive inks with improved stability and electrical properties has enhanced the performance of DIW-printed sensors.

Quality control in DIW involves real-time monitoring of extrusion parameters and post-printing characterization of dimensional accuracy and functional properties. The consistency of line width and layer thickness across complex geometries requires careful optimization of printing parameters and ink rheology. Post-printing processing, including thermal curing or UV crosslinking, is often required to achieve final mechanical and electrical properties. The development of in-situ monitoring systems using optical or electrical measurement techniques has improved process control and product quality [74].

The following comprehensive comparison summarizes the key characteristics, advantages, and limitations of the primary fabrication methods utilized in wearable flexible sensor manufacturing:

Table 3. Summary of flexible sensor fabrication methods: Characteristics, Advantages, Limitations and Applications.

<i>Method</i>	<i>Characteristics</i>	<i>Advantages</i>	<i>Limitations</i>	<i>Applications</i>
Screen Printing	Stencil-based ink transfer through mesh screens; ink viscosity 500-5000 cP; resolution >100 μm	High throughput; low capital cost; simple processing; wide substrate compatibility	Limited lateral resolution; challenging thin film formation	Large-area electrodes; thick conductive traces
Roll-to-Roll Gravure	Engraved cylinder ink transfer; high-speed processing >300 m/min; resolution ~20 μm ; multi-layer capability	Excellent consistency; superior resolution; high-speed production; minimal material waste; layer-to-layer registration	High setup costs; complex cylinder preparation; limited design flexibility; web tension requirements	Mass production; disposable sensors; multi-layer electrochemical devices
Inkjet Printing	Drop-on-demand droplet ejection; ink viscosity 1-20 cP; maskless patterning; digital control	Maskless direct printing; rapid prototyping; minimal material waste; complex pattern capability; substrate flexibility	Nozzle clogging; limited ink compatibility; slower speed; cost	Prototyping; custom designs; multi-material patterns; research applications
Direct Ink Writing	Continuous extrusion of viscoelastic inks; 3D printing capability; viscosity 10^3 - 10^6 Pa·s	multi-material printing; room temperature processing; Maskless	Complex rheology requirements; slower processing; limited resolution; post-processing needs	Complex architectures; 3D sensors; embedded systems; custom geometries

This comparative analysis demonstrates that each fabrication method offers distinct advantages for specific applications within wearable sensor manufacturing. Screen printing provides cost-effective, high-throughput processing for large-area applications but with limited resolution. Roll-to-roll gravure offers the highest throughput for mass production with excellent consistency but requires significant capital investment. Inkjet printing provides maximum design flexibility and rapid prototyping capabilities but with limited production speed and material selection.

Direct Ink Writing (DIW) has been selected as the primary fabrication methodology for this investigation based on its exceptional compatibility with the specific requirements of stretchable capacitive interdigitated electrode sensor development. The maskless fabrication capability of DIW eliminates the need for expensive photolithographic tooling and enables rapid iterative prototyping essential for systematic characterization of varying sensor geometries and material formulations within the research timeline constraints. The technique's inherent low capital

cost and simplified setup requirements facilitate comprehensive parametric studies involving multiple electrode configurations, spacing variations, and conductive ink formulations without significant investment in specialized manufacturing equipment. Furthermore, DIW demonstrates superior compatibility with stretchable electronics materials, particularly the carbon black and silver nanoparticle composite inks selected for this study, through its ability to accommodate the viscoelastic rheological properties and particle loading requirements necessary for achieving optimal electrical and mechanical performance. The spatial resolution capabilities of DIW, typically achieving feature sizes compatible with small-scale interdigitated electrode structures, provide adequate patterning precision for capacitive sensor applications while maintaining the flexibility to rapidly modify design parameters based on experimental feedback. This combination of design flexibility, material compatibility, cost-effectiveness, and prototyping efficiency positions DIW as the optimal fabrication approach for systematic investigation of stretchable capacitive sensor architectures and their integration within wearable monitoring systems.

3. Characterization and Optimization of Direct Ink Writing for Interdigitated Electrode Strain Gauges

3.1 Direct Ink Writing Process Overview

Direct Ink Writing (DIW) represents a material extrusion-based additive manufacturing technique that enables the fabrication of three-dimensional objects through the controlled deposition of a continuous filament of viscoelastic material, commonly referred to as "ink," in a sequential layer-by-layer fashion [77]. The manufacturing process initiates with a digital blueprint, typically derived from a Computer-Aided Design (CAD) model, which undergoes computational slicing into a series of horizontal cross-sections to generate the requisite toolpath for printhead navigation [77]. The fundamental component of the DIW apparatus consists of a dispensing system, which may be actuated through pneumatic pressure, piston mechanisms, or screw-driven configurations, that facilitates ink extrusion through a precision nozzle [80], [81]. This nozzle assembly is mounted on a computer-controlled gantry system capable of three-dimensional movement, enabling precise ink filament deposition onto either a substrate or the preceding layer.

The principal advantage of DIW over alternative additive manufacturing methodologies lies in its maskless processing, wherein minimal preprocessing steps are required to fabricate complex microstructures and patterns. Another advantage is the dependence on the rheological properties of the ink rather than phase change phenomena such as melting or photocuring processes. This characteristic enables operation at ambient temperature conditions [77], thereby unlocking access to an exceptionally comprehensive library of printable materials, including polymers, ceramics, hydrogels, metals, and complex composite systems, establishing DIW as one of the most versatile three-dimensional printing technologies available [82]. The processes' success depends almost entirely on the carefully engineered flow properties of the ink, which must demonstrate the ability to flow through the nozzle under applied pressure while subsequently solidifying sufficiently upon deposition to maintain structural integrity.

This chapter examines the Direct Ink Writing (DIW) process through systematic characterization of material properties, fabrication parameters, and design automation methodologies for stretchable conductive electronics applications. The investigation addresses three primary objectives: characterization of physical and electrical properties for two stretchable conductive ink formulations through rheological analysis, mechanical testing, and conductivity measurements; optimization of printing parameters including extrusion pressure, nozzle diameter, substrate temperature, and post-processing conditions to establish reproducible fabrication protocols for interdigitated electrode array structures; and implementation of a parametric design generation algorithm with quantitative assessment of resulting fabrication yield and dimensional precision. Experimental methodology incorporates materials property evaluation, process parameter mapping, and statistical analysis of manufacturing outcomes to establish correlations between ink formulation, printing conditions, and electrode performance characteristics. Results

provide fundamental understanding of ink-substrate interactions during DIW processing, validated fabrication protocols for complex electrode geometries, and empirical data regarding the effectiveness of automated design tools in reducing manufacturing variability and improving dimensional control.

3.1.1 Printing Considerations

The DIW printing process encompasses three primary stages: ink formulation, material extrusion, and post-processing operations.

3.1.2 Ink Formulation and Rheological Considerations

The most critical aspect of DIW implementation involves the development of an ink formulation with precisely tailored rheological properties that ensure both "printability" (the capacity for smooth extrusion) and "shape fidelity" (the ability to maintain form integrity after deposition) [77], [81]. To achieve these requirements, DIW inks must exhibit specific non-Newtonian behavioral characteristics. The ink must demonstrate shear-thinning behavior, wherein viscosity decreases significantly under the high shear forces experienced within the printing nozzle [77], [80]. This property enables fluid flow without requiring excessive pressure application. Upon nozzle exit, the removal of shear stress necessitates rapid transition from fluid-like to solid-like behavior. This transition is characterized by a "yield stress," representing the minimum stress required to initiate flow, and a storage modulus (G') that significantly exceeds the loss modulus (G'') under static conditions [77], [80], [81]. These rheological properties are typically engineered through the formulation of multi-component ink systems. A liquid polymer or solvent base provides the foundation, to which rheological modifiers such as fumed silica or nanoclay are incorporated to establish a percolated network that generates high viscosity under static conditions [77], [80]. Polymer binders are included to impart cohesion and mechanical integrity to the final component, while solvents facilitate binder dissolution and filler dispersion into a stable, homogeneous suspension [82].

3.1.3 Material Extrusion

During the extrusion phase, the prepared ink is loaded into a syringe and dispensed through a nozzle via a controlled pressure system. The nozzle, mounted on a three-axis gantry system, traverses according to the programmed toolpath.

3.1.4 Solidification and Post-Processing

Following deposition, the printed object requires solidification through post-processing methods dictated by ink composition, which can represent a significant workflow bottleneck [77]. Common solidification methods include solvent evaporation for solvent-based inks, thermal or UV curing for inks containing thermosetting or photocurable polymers, and sintering processes requiring high-temperature treatment for inks containing metallic or ceramic particles to achieve fusion and create dense, functional materials [77], [83]. The post-processing method selection must maintain

compatibility with substrate materials, representing a key consideration when printing on flexible or thermally sensitive substrates.

3.1.5 Challenges

Despite its versatility, the DIW process presents several significant challenges that must be addressed to achieve reliable and high-performance component production.

The primary challenge involves the inherent conflict between printability and final part performance. The rheological modifiers (e.g., rigid fillers) required to achieve necessary viscosity and yield stress for printing can be detrimental to the mechanical properties of the final object, acting as stress concentration points that lead to premature failure under applied strain [84]. Nozzle clogging represents a frequent and critical issue, particularly when utilizing inks with solid fillers or when printing with small-diameter nozzles to achieve high resolution. Agglomerated particles or misaligned fibers can easily obstruct the flow path, resulting in failed prints[77], [80].

Print resolution and defect formation present additional challenges, as DIW resolution is limited by nozzle diameter and ink properties. A direct trade-off exists between achieving finer features with smaller nozzles and the increased risk of clogging [77]. Furthermore, process-induced defects, including inconsistent trace width, edge roughness, or non-uniform thickness (an "edge taper" effect), can severely compromise the performance and reliability of printed components, particularly for narrow traces [84].

Achieving strong and durable adhesion between printed ink and substrate proves challenging, especially when printing on low-surface-energy materials such as elastomers. Poor adhesion can lead to delamination, representing a critical failure mode for functional devices such as sensors [80], [81]. Many post-processing steps, including high-temperature sintering, demonstrate incompatibility with common flexible substrates such as polymers, as these processes can cause melting or degradation, thereby limiting the palette of materials available for integrated device creation.

3.1.6 Process Parameters for Tuning and Optimization

The quality, fidelity, and performance of DIW-printed objects depend on the careful tuning and optimization of interdependent process parameters.

Ink rheology represents the most crucial parameter, requiring meticulous optimization to exhibit ideal shear-thinning properties for smooth extrusion and sufficient yield stress for shape retention upon deposition. This is typically controlled through composition adjustments, including the type and concentration of fillers, binders, and solvents [80], [82]. Nozzle geometry, specifically the inner diameter, directly controls minimum feature size and print resolution. However, nozzle diameter selection involves trade-offs, as smaller nozzles increase required extrusion pressure and elevate clogging risk.

The ratio between ink extrusion rate and printhead translational speed requires precise synchronization, as this ratio determines deposited filament diameter. Excessive speed relative to extrusion rate may cause filament stretching and breakage, while insufficient speed results in filament bulging and resolution degradation [77]. Post-processing parameters, including temperature, duration, and atmosphere for curing or sintering, require careful control. These parameters are specific to ink chemistry and must be optimized to achieve desired material properties without substrate damage.

The design of printed features themselves, such as conductive trace width, represents a critical parameter. Studies demonstrate that trace geometry significantly affects mechanical reliability and failure strain, with narrower traces exhibiting substantially greater vulnerability to strain-induced damage and process defects [84]. Therefore, design considerations must account for these geometric sensitivities.

3.2 Voltera Nova System

The Voltera Nova system represents a unified benchtop flexible circuit fabrication system that provides a compact and highly controllable platform for dispensing precise designs onto flexible substrates. The system utilizes a porous titanium vacuum plate that evenly mounts flexible substrate sheets to its flat surface, ensuring consistency, accurate alignment, and a level printing surface. A smooth and flat printing surface proves crucial, as certain configurations position the nozzle tip less than 40 microns from the substrate surface, and variations in printing height can lead to disrupted dispensing, broken nozzles, damaged substrates, or non-uniform depositions. To accommodate subtle variations in substrate thickness, the system incorporates a probing tool that measures the z-offset of the substrate at locations generated around the printing path. To ensure accurate alignment, scaling, and dispensing, the Voltera Nova system utilizes an XYZ positioner. See Figure 7 below, comprising three independent strain gauges that detect contact of mounting and dispensing tool heads to determine their coordinate offsets. An integrated camera module provides several advantages over other DIW systems, enabling users to align their substrates and designs when performing multilayered prints as well as inspecting depositions for calibration and characterization purposes. The Nova relies on this camera to calibrate design scale, allowing fine-tuning of designs quickly to ensure correct sizing. However, due to the fisheye lens used, different substrate thicknesses can impede the system's ability to accurately determine the correct pixel to micron calibration value.

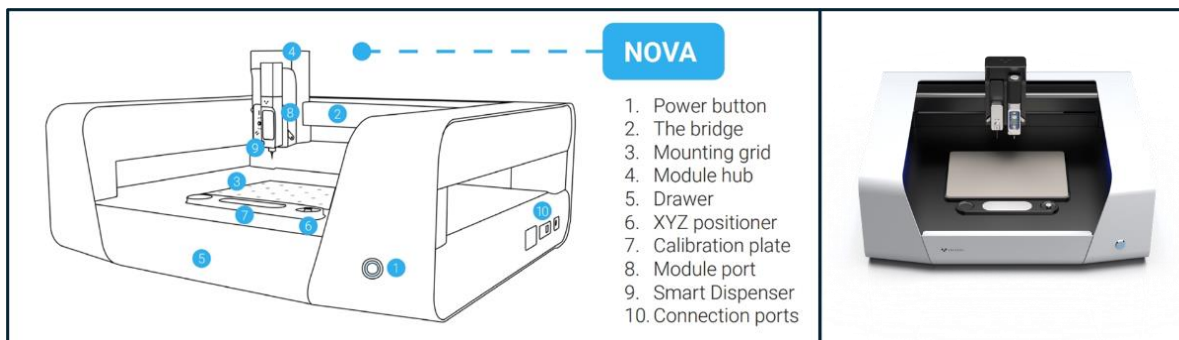


Figure 7. Voltera Nova Direct Ink Writing System schematic diagram.

The detachable dispenser head of the Nova enables quick changes to ink syringes contained within standard 5cc cartridges as well as nozzle changeout with a luer lock thread adapter. This configuration enables researchers to leverage a wide variety of nozzle geometries and types. Ink is dispensed through a driven plunger that actuates an internal piston sealed within the ink cartridge. The primary focus of the Voltera system involves the unique inclusion of a pressure feedback component in direct contact with the pressurized ink. This is achieved through a fluoropolymer elastomer membrane and a small load cell to measure the internal pressure of the ink above the attached nozzles.

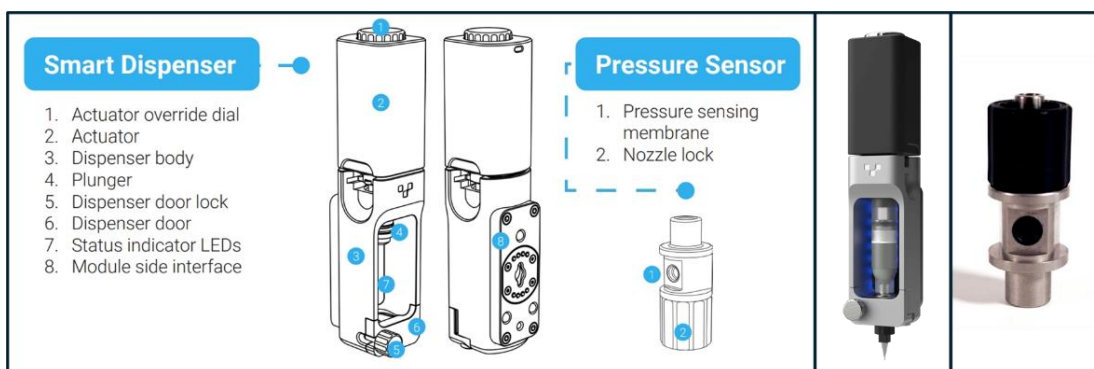


Figure 8. Nova Smart Dispenser assembly and pressure sensor.

This configuration enables a feedback loop that allows the system to dynamically adjust the actuator's displacement onto the piston to maintain consistent dispense pressure. This provides steady flow and improved retractions that prevent air from being pulled into the ink cartridge during print pauses or toolpath changes. Air within the cartridge can cause several print issues, primarily due to the compressibility of air pockets that reduce the accuracy of the pressure sensing membrane as well as the force exerted onto the ink by the plunger-piston pairing. To minimize the likelihood of air introduction during retraction events, the dispense parameters must be precisely tuned to reduce over-retraction of the plunger and piston.

3.3 Ink Characterization

The objective of the initial process optimization scoping involved the selection and characterization of suitable inks. For this initial proof of concept development toward stretchable strain gauges, existing ink formulations known to be compatible with the DIW system were leveraged. When selecting inks for testing, several selection criteria were established. Stretchability and durability requirements ensured that the conductive filler and polymer suspension were formulated for high strain environments, enabling stretching without degradation. Conductivity requirements, while considered less critical for capacitive-based sensors, remained important for overall sensor performance. Minimum trace width capabilities were essential to develop compact and dense sensors, ensuring accurate and consistent production of narrow trace widths.

When selecting conductive inks suitable for the DIW process, viscosity represents a major printability parameter, as ink viscosity dictates the pressure required for extrusion through small nozzle tips. A general guideline provided by Voltera specifies selecting conductive inks within the 1-200 Pa·s range [85]. This range allows the machine to effectively control and dispense inks with nozzle sizes of 100µm to 300µm. Inks outside this range will lead to either clogging or inability to dispense with small nozzle sizes, or if too thin, will result in poor retractions and uncontrollable oozing.

The final selection metric involved curing method considerations. Many inks require post-processing to ensure conductivity and permanent substrate bonding [85], [86]. The majority of inks are carried in a solvent vehicle that allows dispensing and storage while maintaining suspension. This solvent must be evaporated for inks to bind to their substrates and become conductive. Heat is utilized for this process, and the selected solvent dictates the required temperature. Solvents utilizing high temperatures limit substrate selection to those capable of withstanding equivalent temperatures without deformation or degradation, while solvents that evaporate at lower temperatures can be difficult to use and store, often having reduced shelf lives or requiring freezer temperature storage, making the printing process more variable. As thin stretchable substrates were intended for use, curing temperature was limited to under 135°C to prevent substrate damage during curing. Some conductive filler materials such as copper often require high-temperature sintering to become conductive and were ultimately not investigated due to process incompatibility with most stretchable substrates.

The inks meeting these criteria were ACI Materials SS1109 [87] and ACI Materials SC1502[88]. SS1109 is a highly stretchable silver-filled conductor designed for use on elastomeric substrates. After curing, the ink claims to have excellent conductivity and offers excellent elongation and flexibility. The second ink selected for testing was the SC1502, a carbon-filled conductor for use with elastomeric substrates. It can be cured at lower temperatures to accommodate sensitive substrates and devices. After curing, the ink has slightly lower conductivity than its SS1109 counterpart but offers higher elongation and flexibility.

Table 4. DIW Conductive Ink Properties

Name	Conductive Filler	Volume Resistivity	Maximum Elongation	Viscosity	Curing Temperature
SS1109	Silver	<0.017 Ω /square/mil	>200%	40 Pa·s	>135°C
SC1502	Carbon	<236 Ω /square/mil	>200%	60 Pa·s	>120°C

The characterization of these inks began with their initial printing process parameters. These were determined using the integrated material calibration tool within the Voltera Nova interface, which repeatedly prints test patterns to allow refinement of all print parameters. The primary parameters are print speed (the speed at which the dispenser tool head moves along the design while extruding), dispense pressure (the pressure target the system maintains during printing provided from the membrane pressure sensor), relief pressure (the pressure that the system targets during retractions and toolhead movements to new paths), and their respective threshold targets utilized to begin toolhead movement while printing and liftoff during retraction.

The substrate used for the ink calibration and characterization process was Intexar TE-11C [11], a stretchable bilayer thermoplastic polyurethane (TPU) film. TE-11C comprises high recovery and melt adhesive layers optimized for bonding onto textiles and other polymer surfaces. This film is composed of a high recovery TPU layer that is 50-75 μ m thick, which serves as the main surface for ink deposition, and an additional melt adhesive TPU layer (25-50 μ m) that enables bonding. A temperature-stable carrier film is used to protect the substrate during the curing process, minimizing deformation under heating.

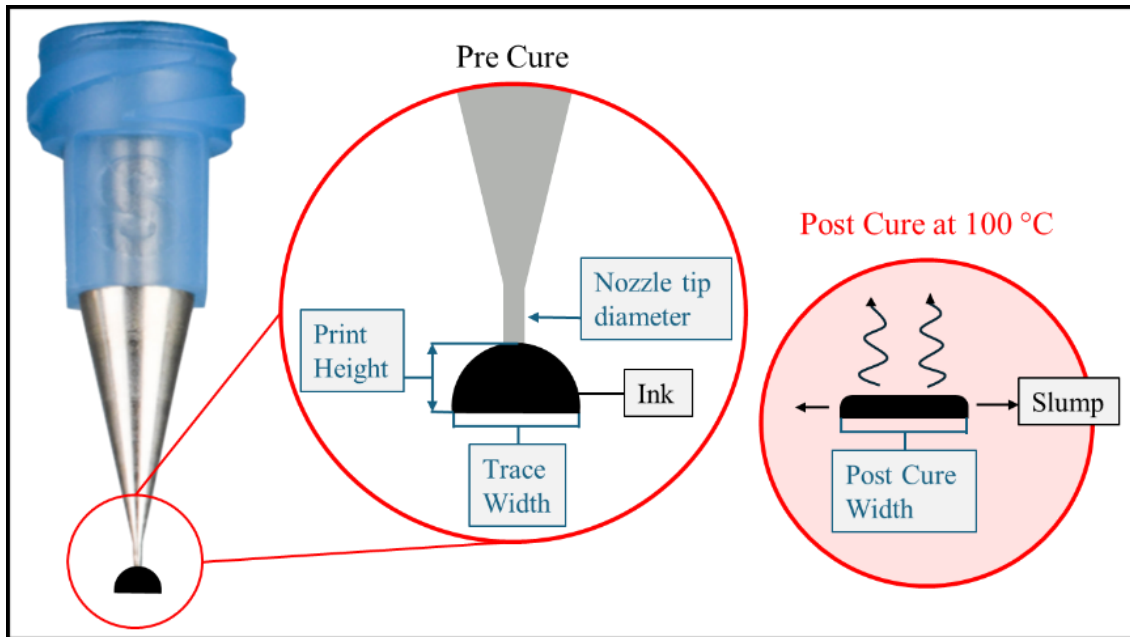


Figure 9. Diagram depicting DIW dispense properties and simplified process.

The nozzle size selected for initial calibration was the 150 μm Subrex Micro fluid dispensing nozzle [12]. This nozzle provides a tapered nozzle geometry and thin walls to provide high flow rates and uniformity with the selected range of conductive inks. After initial calibration was conducted, characterization of the printing ink designs was performed to understand post-cure trace width and trace height. These metrics were investigated to allow further refinement of initial print parameters and assess ink printability.

Analysis of the printing ink samples was performed using an OLS5100 Laser microscope, providing high-resolution surface maps of the prints. Through these light-scanned topologies, measurement of trace width, trace height, and uniformity along the printing lines was accomplished.

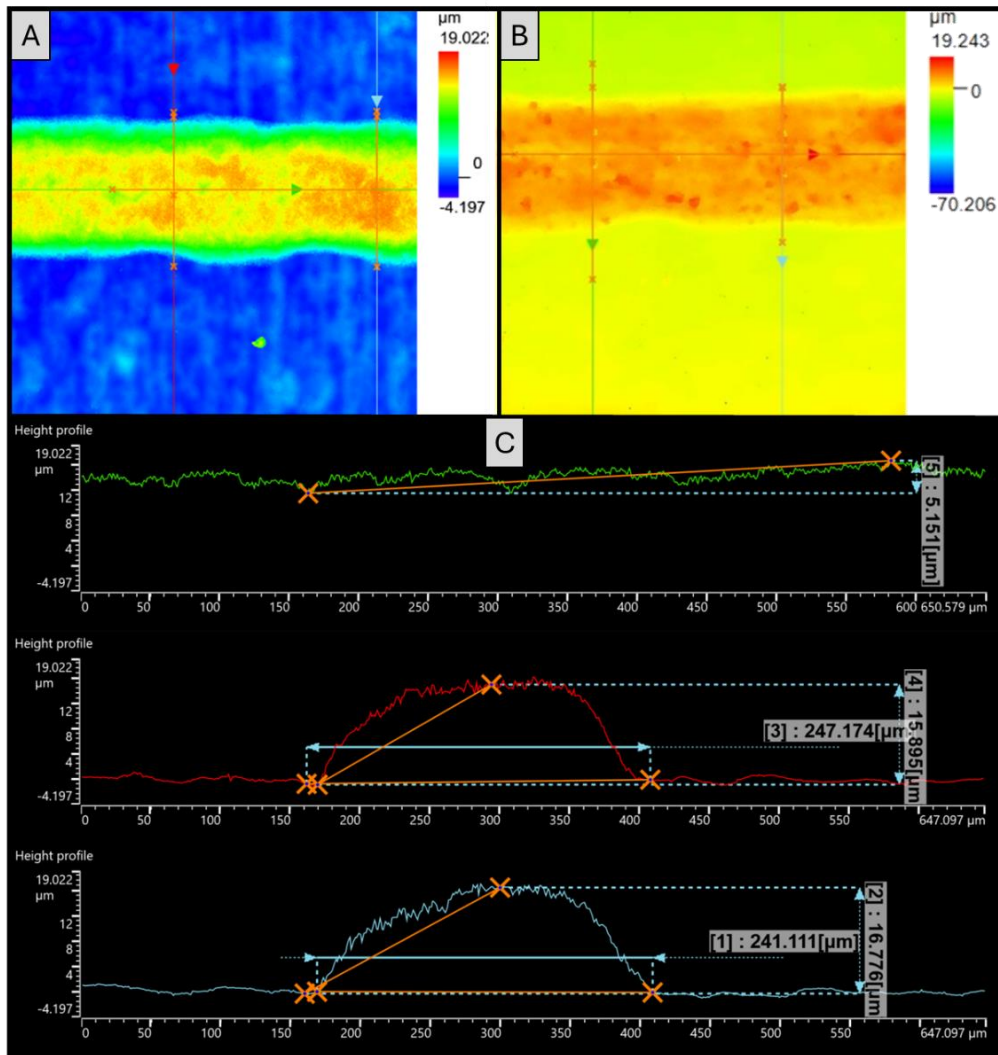


Figure 10. Light scanning results for initial DIW ink deposition. A) SS1109 Silver Ink profile. B) SC1502 Carbon Ink profile. C) Measurement Analysis example for SS1109 Ink profile.

Both the SS1109 and SC1502 inks were printed with a targeted trace width of $220\mu\text{m}$ and were printed with a print height of $50\mu\text{m}$, which was expected to produce a trace height of $25\mu\text{m}$. The SS1109 was found to produce an average trace width of $244.143\mu\text{m}$ with a standard deviation of $4.29\mu\text{m}$. The trace height was measured to be $16.386\mu\text{m}$ with a standard deviation of $0.55\mu\text{m}$. A measurement along the length of the trace line was performed to measure the maximum variation of the trace height to be $5.15\mu\text{m}$.

The SC1502 ink was found to have an average trace width of $215.059\mu\text{m}$ with a standard deviation of $4.942\mu\text{m}$. The average trace height was measured to be $16.569\mu\text{m}$ with a standard deviation of $0.9327\mu\text{m}$. The maximum trace height variation was found to be $11.164\mu\text{m}$. From these characterizations, the silver ink dispense pressure was decreased to bring it closer to the intended target of $220\mu\text{m}$. The carbon ink calibration profile was not altered further.

Subsequently, characterization of these printed inks under uniaxial tensile strain was performed. Five patterns were printed with both inks to test their resistance change under uniaxial strain. These patterns, shown in the figure below, comprised five geometries tested to observe their effect on resistance change. The geometries were straight line, narrow curved, wide curved, narrow square, and wide square. These patterns were designed with three width variations of $200\mu\text{m}$, $250\mu\text{m}$, and $300\mu\text{m}$.

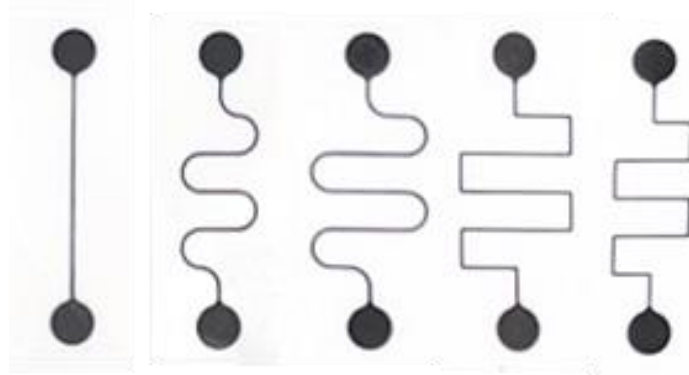


Figure 11. Scan of printed Ink Characterization Structures. Showing single trace width version for Straight line, Narrow Curved, Wide Curved, Wide Square, and Narrow Square patterns.

All test samples were printed three times on a single A4 sheet of Intexar TE-11C with the calibrated printing parameters and $150\mu\text{m}$ Subrex nozzles. The integrated path generation function within the Nova system was used to create the toolpaths with the trace widths measured through light scanning. The test setup comprised the Mark 10 F305 tensile test system, which holds and pulls the test samples, a Keysight 34461A Digital Multimeter (DMM) that measures sample resistances through test leads connected via conductive copper tape to the sample pads connected to the Multi-Threaded Python Application (MTPA), which controls and collects data synchronously for both systems.

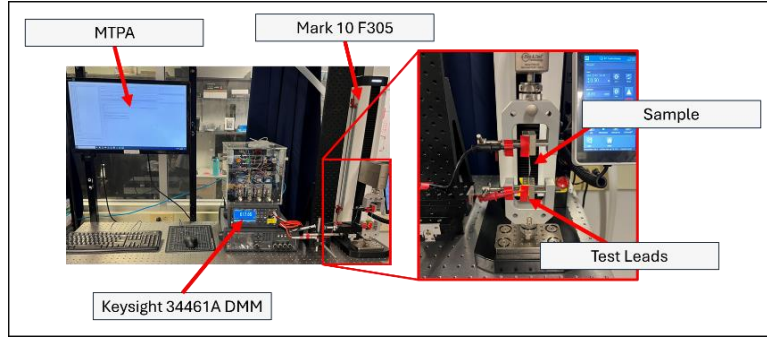


Figure 12. Overview of Ink Characterization Mechanical Testing. (left) MTPA computer system, DMM and Mark 10 F305 Test Machine. (right) Sample mounting and connection.

The samples were each measured for their initial length and resistance and then pulled until no conductivity was detected. The box plot of the initial resistance values shows the expected difference between the silver and carbon inks, with the carbon ink patterns having their initial unstressed resistance in the 100k Ω range and the silver ink patterns having conductivity in the 10 Ω range. In the pattern pull test plot, the silver ink exhibited a greater change in resistance for a given strain. It can also be observed that the silver samples became non-conductive at much lower strains when compared to the carbon ink counterparts. Investigation of the patterns' effects on the relationship between change in resistance and strain demonstrated that the straight-line samples performed worst with the highest change in resistance for a given strain, while the wide curved samples shown in red performed best.

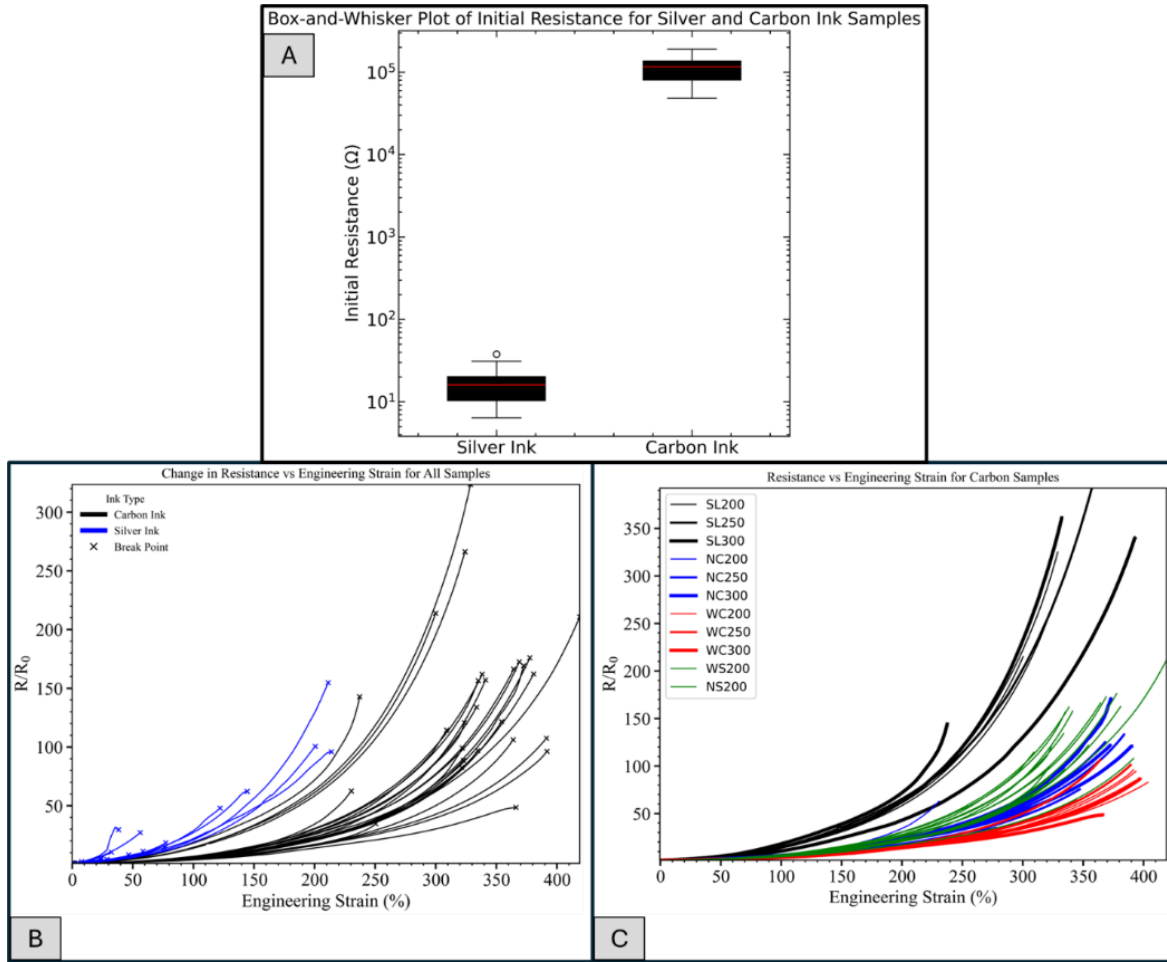


Figure 13. Ink Characterization Results comparing SS1109 Silver Ink and SC1502 Carbon Ink. A) Initial Capacitance results for both inks. B) Pull-test strain versus change in resistance for both inks. C) Change in resistance versus strain for Carbon Ink test structures.

ACI SS1109 was chosen due to its printability, consistency, and initial conductivity. While the carbon ink provided reduced strain conductivity correlation and greater maximum elongation before loss of connection, this trade-off was not considered critical as the desired operating strain range for the proposed wearable sensors would be less than 30%. The reduced printing consistency and nozzle clogging was believed to be connected with the carbon black conductive filler used in the carbon-based ink. These factors led to continuation of the process optimization with the SS1109 silver ink.

3.4 Interdigitated Electrode Array Printing

After characterizing and optimizing the printing parameters for the SS1109 silver conductive ink, investigation of the printing process for compact and stretchable interdigitated electrode arrays was undertaken. While the general structure of IDEs is simple, printing them via the DIW process was found to be a low-yield and manually intensive process, both in file generation and dispense optimization, as well as toolpath generation.

Due to the use of Gerber file standards, which are used extensively in the printed circuit board industry, there is a lack of design and parametric tools available that researchers can use to develop and quickly iterate on sensor geometries and architectures. As full DIW capabilities were desired to be leveraged with easy design changes, this lack of advanced sensor design software poses a significant challenge.

Another issue found when printing IDE structures via DIW is the optimization of the dispense system and reliably printing the small repetitive components. For the Nova system to correctly dispense ink accurately with the user's desired geometry, it relies on a large number of retractions to ensure that the nozzle tip does not overwrite previously deposited ink or over extrude, which can lead to parallel digits short-circuiting to the opposing pair, rendering the sensor non-functional. Another disadvantage of the high number of retractions is the time component, as retractions attempt to slowly relieve pressure to minimize the chance of air introduction into the ink, adding increasingly more time that can make large IDE prints difficult to iterate with. Each retraction and print start requires precise process optimization, with even small errors in the optimal dispense pressure or relief pressure leading to poor starts or over-extrusions after repeated toolpath changes.

Attempts were made to minimize the impact of these problems through manual toolpath generation and optimization within the Nova software shown in Figure 14 A) below. This allows users to change print directions and merge certain paths together but represents a tedious and labor-intensive process. Through this approach, it was found that aligning all print starts onto the IDE digit bus bar would allow over-extrusion events to be non-defect causing, which greatly reduced the occurrence of short digit short-circuit defects. However, this did not address the air pocket defects, which can be seen in Figure 14 B) where no ink is present in the nozzle during printing. The only way to mitigate these errors is to reduce the total number of retractions and continuously correct relief pressure threshold as the print progresses.

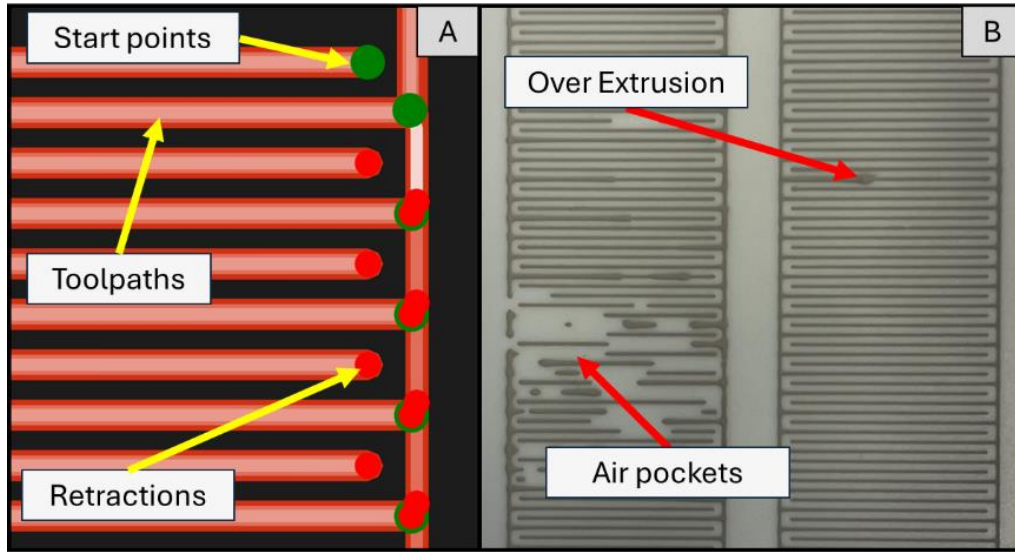


Figure 14. DIW process challenges. A) DIW toolpath generation software. B) Failures observed using unoptimized toolpaths for IDE structures.

These challenges and lack of an adequate tool to support the development of IDE structures led to the development of an in-house Python toolset with the goal of creating a rapid parametric Gerber file creator for sensor generation.

The Python application fundamentals leverage KiCAD 8.0, an open-source software suite for Electronic Design Automation (EDA). User inputs generate polygon placement calls within KiCAD through the Python binding modules pcbnew translation library. This quickly enables large parametric geometry generation and dimensionally accurate designing to be carried out in seconds rather than manual design within traditional ECAD software. Subsequently, optimization of the standard IDE geometry design traditionally used in MEMS devices and lithography-based fabrication was undertaken for DIW.

Three functional design geometries were created to assess the impacts of these new geometries. The first being the traditional straight perpendicular digit geometry, with an additional offset between the digit ends and the opposing bus bars. A curved geometry that includes fillets on the digit attachment points to the bus bars was developed. Finally, a new form of geometry was developed, one that is formed from a single continuous trace segment. The motivation for this design was to remove the need to perform any retractions during the printing process, which was believed to have caused the previously observed print defects.

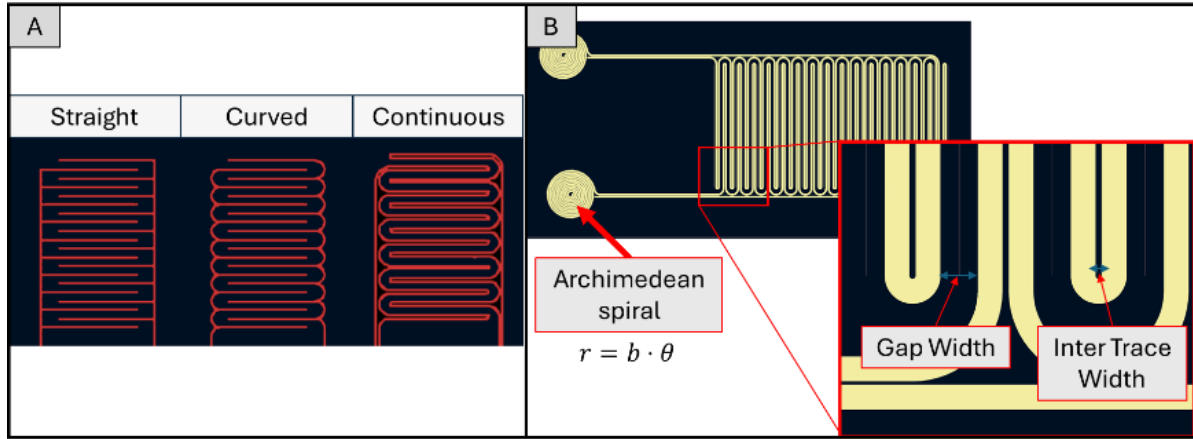


Figure 15. Depiction of python IDE optimization tool. A) Three generated IDE structures, straight being the standard IDE configuration, curved including rounded fillets connecting the digits, and continuous pathing with dual paths to improve DIW toolpathing. B) Components of a continuous pathed IDE structure, including connection point spiral pad, and additional parameters used in the generation routine.

All three structures have parametric inputs for the number of digits, length of digits, inter-digit gap, trace width, as well as bus bar padding, which is used for the straight and curved structures to provide extra clearance for print starts. The continuous structure generation also requires an extra parameter, the inter-trace width parameter that controls the space left between the two trace paths, which can be seen in Figure 15 B) above. Additionally, to improve the initial electrical contact pad for each IDE terminal, an Archimedean spiral geometry was generated to create a constant gap between each subsequent layer and produce these larger pads without any retractions and at constant velocity.

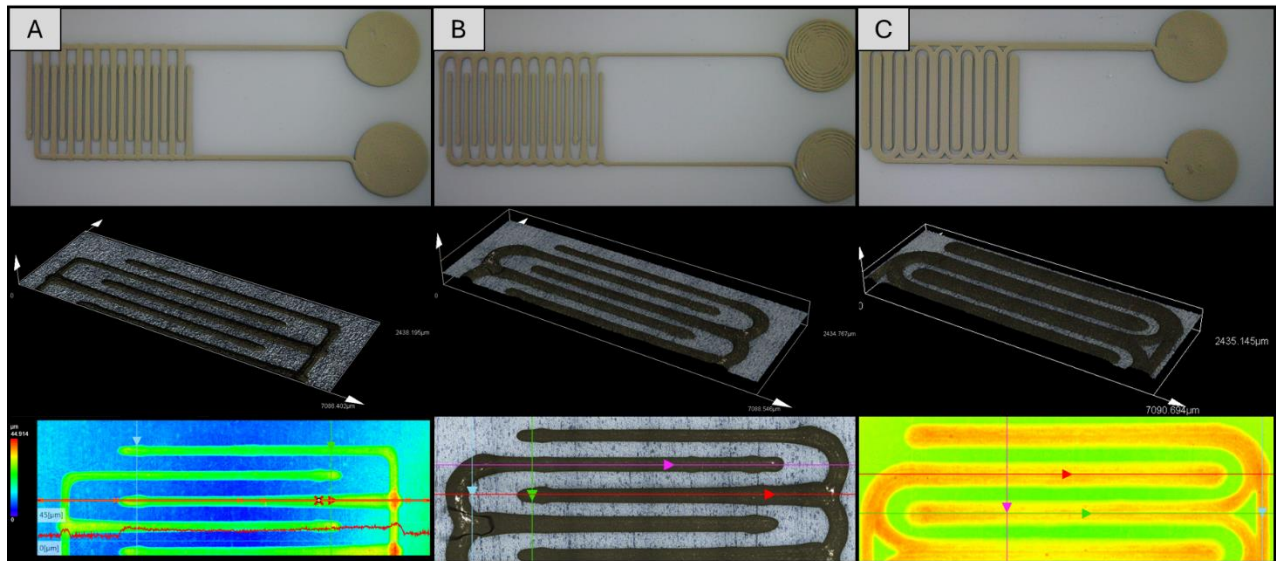


Figure 16. Comparison of three IDE structures printed with SS1109 Silver Ink. Showing lightscanning images and measurement locations. A) Straight conformation. B) Curved conformation. C) Continuous conformation.

Each new geometry structure was printed, with toolpaths optimized and inter-trace width for the continuous path geometries determined. During the printing process, a noticeable difference in both print yield and print speed for the continuous pathed structures was observed. Each sample printed was successful, and no nozzles clogged during the printing process. While the optimization to the tool pathing and increased spacing near the trace start locations for the straight and curved structures did improve their printability, both had several samples that failed during printing. The samples were imaged and scanned as shown in the bottom row of Figure 16 above. Analysis of trace width variability, trace height variability, as well as the maximum variation along a digit trace for each of the samples was performed.

Table 5. Light scanning topology measurement results for three IDE structures.

<i>Structure</i>	<i>Trace Width Mean</i>	<i>Trace Width SD</i>	<i>Trace Height Mean</i>	<i>Trace Height SD</i>	<i>Max Trace Height Variation</i>
<i>Straight</i>	214.084 μm	36.242 μm	15.988 μm	2.730 μm	23.949 μm
<i>Curved</i>	225.396 μm	32.673 μm	18.298 μm	1.701 μm	14.721 μm
<i>Continuous</i>	449.303 μm	14.514 μm	18.370 μm	1.131 μm	11.502 μm

Analysis of the IDE structures light scanning results reveals a significant improvement to the uniformity of both trace width and trace height. Standard deviation of trace widths in both straight and curved configurations was reduced by close to half when compared to the continuous pathed results. Similarly, a notable decrease in the variation in trace height was observed, with both the standard deviation and maximum variation being notably reduced compared to the other structures.

In summary, a robust method for generating compact IDE structures that is parametric, automated, highly consistent and uniform while being faster than traditional IDE design approaches has been developed. Through leveraging the continuous pathing configuration, 100% yields of IDE structures with precise tolerances and minimal variation can be achieved. The automated Python tool minimizes both manual design and manual toolpath generation, providing greater flexibility and rapid iteration to researchers leveraging the DIW process.

4. Multiphysical modelling of stretchable DIW IDE capacitance strain gauges

The computational modeling framework employed in this investigation utilized COMSOL Multiphysics 6.3, leveraging its comprehensive coupled simulation capabilities to address the complex multiphysical phenomena inherent in HSCSGs. The software suite provides finite element analysis tools capable of simultaneously solving coupled electrostatic and solid mechanics problems, enabling the accurate representation of the electromechanical behavior exhibited by these sensor structures under various deformation states. The implementation of numerical simulation techniques served multiple critical objectives within the research methodology. The computational approach enables rapid exploration of geometric configurations, material properties, and operational conditions that would prove prohibitively expensive and time-consuming to investigate through purely experimental means. Furthermore, the simulation-driven design methodology significantly enhances workflow efficiency by providing predictive capabilities that inform fabrication decisions prior to material commitment. This approach substantially reduces material waste associated with unsuccessful prototype iterations while simultaneously accelerating the overall development process. The ability to virtually prototype and optimize sensor geometries before physical fabrication represents a critical advancement in the systematic development of stretchable electronic devices.

The computational investigation commenced with a comprehensive evaluation of numerical solution methodologies, specifically examining the relative merits of finite element methods (FEM) versus boundary element methods (BEM). While BEM has experienced increasing adoption within the multiphysical modeling community due to its computational efficiency for certain problem classes, the complex geometry and material heterogeneity present in stretchable interdigitated electrode arrays necessitated the superior geometric flexibility provided by FEM approaches. Primarily, the required incorporation of both structural mechanics as well as electrostatics for the coupled simulation would significantly contribute to the complication of both BEM and FEM approaches, as the solid mechanics solver can only be implemented with FEM approaches. Due to these factors, a completely FEM based model was used.

4.1 Study setup

Initial modeling attempts employed two-dimensional approximations to capture the fundamental electrostatic behavior of interdigitated electrode arrays. These preliminary models aimed to reproduce the primary capacitive effects through simplified geometric representations that assumed dominance of electric field components perpendicular to individual finger elements. However, extensive experimental validation through direct-ink-write (DIW) fabrication processes revealed significant limitations in the achievable aspect ratios of printed electrode structures.

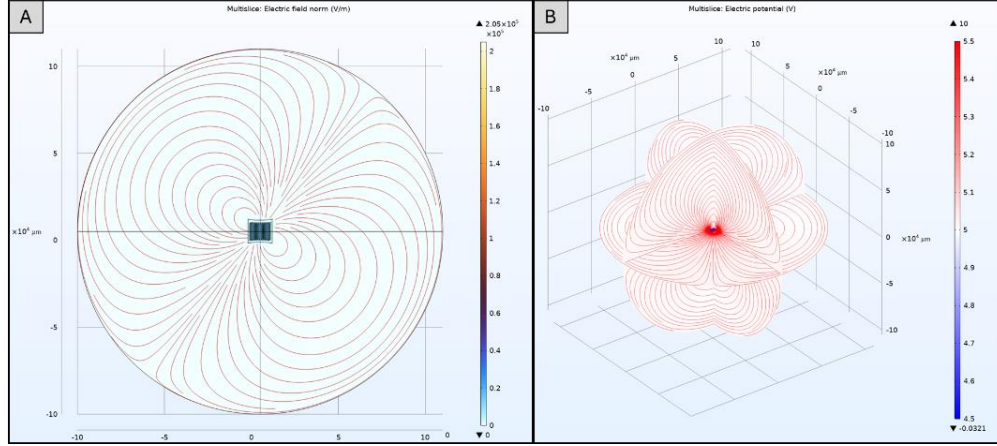


Figure 17. Comparison of 2D and 3D electric field distributions within COMSOL 6.3 for stationary electrostatics simulation of IDE structure.

The experimental observations demonstrated that DIW processes could not achieve sufficiently high aspect ratios to justify the assumption that capacitive coupling occurs primarily through perpendicular field components between adjacent finger elements. Instead, substantial capacitive contributions arose from coupling between electrode bus bars and opposing finger elements, necessitating more comprehensive three-dimensional field analysis to accurately capture the complete electrostatic phenomena.

Alternative two-dimensional modeling approaches investigating in-plane field effects were considered but ultimately rejected due to their inability to account for fringe field (that propagate above the sensor through the air domain) contributions that significantly impact the total capacitance of interdigitated electrode arrays. These fringe effects, particularly prominent at electrode terminations and geometric discontinuities, represent non-negligible contributors to overall sensor performance that cannot be adequately captured through the 2D planar approximations.

Consequently, a comprehensive three-dimensional simulation framework was adopted to ensure accurate representation of both substrate mechanical deformation and electrostatic field distributions. This approach enables precise modeling of sensor capacitance variations during dynamic deformation states while maintaining accuracy in steady-state capacitance predictions across the operational parameter space.

4.1.1 Fundamental Meshing Considerations

Mesh generation represents a critical component for accurate and efficient finite element modeling, requiring careful balance between element quality, symmetry, and computational efficiency. The mesh construction process must ensure high element quality while maintaining uniformity throughout the computational domain, simultaneously balancing computational cost against solution accuracy requirements. While generally higher resolution meshes yield more stable and accurate solutions, they impose considerable computational overhead that can impede the rapid

iteration and investigation cycles essential for parametric design optimization. Furthermore, each physics solver type possesses distinct optimal mesh generation characteristics, necessitating careful consideration of multiphysical coupling requirements during mesh design.

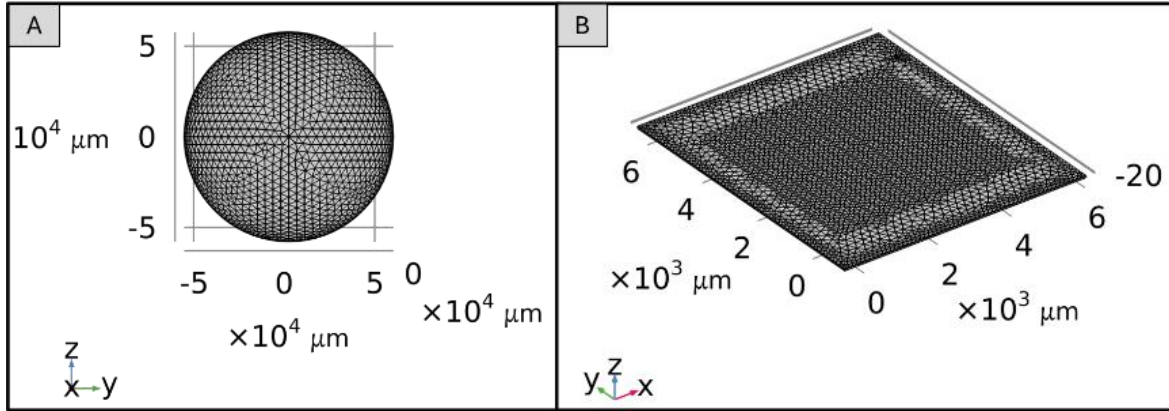


Figure 18. COMSOL Meshing domains and regions. Showing the two primary domains. A) Air domain. B) Sensor structure and substrate domain.

The multiphysical model was strategically partitioned into three discrete computational regions: the air domain, substrate domain, and sensor domain. This domain decomposition approach enables independent optimization of mesh characteristics for each physics module while maintaining appropriate interface continuity between regions.

4.1.2 Air Domain Mesh Development

The air domain mesh generation process was prioritized to establish a stable reference framework for subsequent mesh independence studies. This domain was implemented as a spherical region surrounding the sensor and substrate geometries, positioned at the computational origin to ensure geometric symmetry. Free tetrahedral mesh generation was employed to guarantee accurate connectivity with substrate and sensor domain surfaces, enabling precise representation of electric field distributions across material interfaces.

Initial mesh generation utilized relatively coarse discretization parameters, with minimum element sizes of $100 \mu\text{m}$ and maximum sizes of $4200 \mu\text{m}$, to establish baseline computational performance benchmarks. A critical investigation was conducted to determine the minimum air domain size required to capture complete fringe field effects emanating from the sensor geometry. The spherical domain was initially sized to match substrate dimensions and subsequently scaled using a dimensionless parameter designated as airScale.

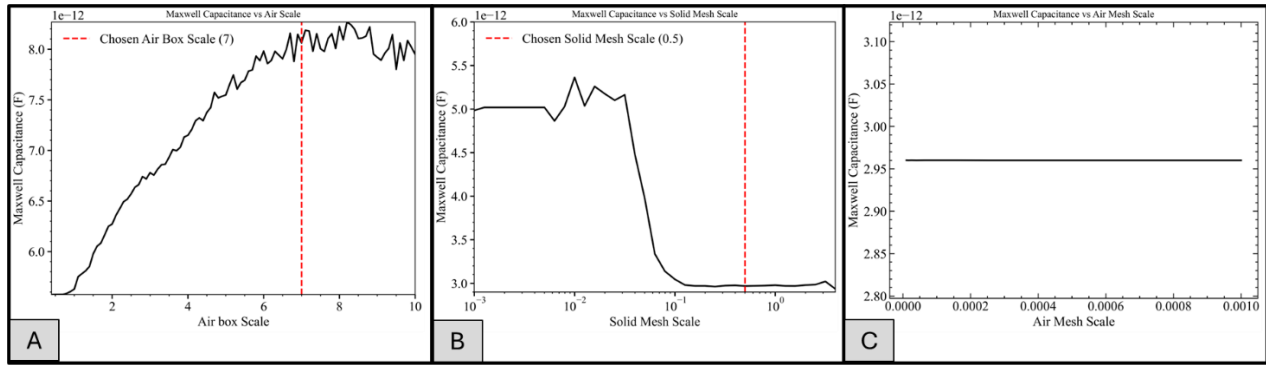


Figure 19. Mesh independence study results. A) Air domain scaling study and the chosen scale value. B) Solid mesh scale and selected scaling value. C) Air mesh study results showing no mesh dependence.

Parametric analysis revealed continuous increases in computed Maxwell capacitance with increasing air domain size until reaching a plateau at an airScale factor of 6. A final airScale factor of 7 was selected to ensure operation within the stable convergence region across all geometric configurations under investigation. Following air domain size optimization, a comprehensive study was performed to analyze the influence of air domain mesh density on solution accuracy.

The mesh scaling parametric study examined scaling factors ranging from 1×10^{-5} to 1×10^{-3} , revealing minimal variation in computed capacitance values across this range. These scaling factors represent the maximum allowable mesh feature sizes before COMSOL automatic mesh quality algorithms generate warnings regarding poor mesh quality regions. A final mesh scaling factor of 0.5 was selected to ensure accuracy maintenance for smaller geometric configurations while preventing mesh quality degradation.

4.1.3 Substrate Domain Mesh Optimization

The substrate domain presents unique meshing challenges due to its dual role in both solid mechanics and electrostatics physics modules. This domain requires definition as a hyperelastic material for solid mechanics calculations while simultaneously serving as a charge conservation domain within the electrostatics solver. These dual physics requirements necessitate specialized mesh generation strategies to ensure both accuracy and computational efficiency.

Electrostatics solvers typically benefit from increased mesh density near charge sources and terminals to accurately capture near-field charge distributions that propagate through solid substrate materials. Conventional single-physics electrostatics models frequently employ boundary layer meshes to provide enhanced mesh density near regions of strongest field components, which decay rapidly with distance from charge sources. While this approach stabilizes electrostatics solvers and improves accuracy for confined air domains and narrow gaps, it significantly compromises mesh uniformity required for solid mechanics applications.

Solid mechanics solvers traditionally utilize uniform, coarser mesh distributions to minimize localized stress concentrations that can lead to material failure predictions and model divergence. Reduction of concentrated mesh pockets around stress concentration regions, particularly corners and edges, represents a critical factor in maintaining solution stability. The

thin and geometrically complex nature of interdigitated electrode sensor structures precludes utilization of many conventional solid mechanics mesh strategies, particularly swept meshing techniques.

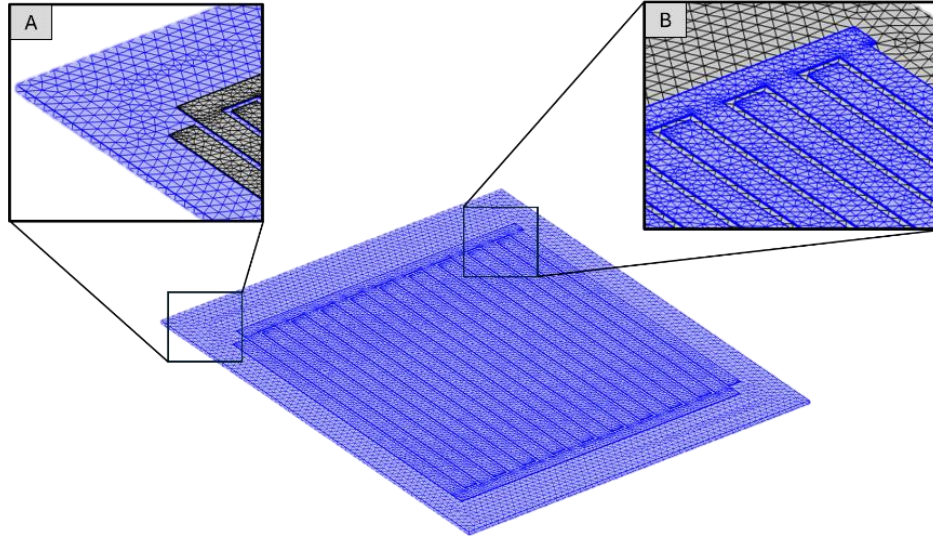


Figure 20. Solid mesh domains. A) Zoomed image of substrate mesh geometry and scaling. B) Zoomed image highlighting sensor structure meshing.

Swept meshing generates structured or semi-structured meshes composed of prismatic or hexahedral elements, characterized by structured arrangement in the sweep direction with either structured or unstructured orthogonal distribution [89]. While this meshing approach would provide ideal symmetry, uniform distribution, and efficient generation, it proved incompatible with electrostatics requirements due to difficulties maintaining uniformity while achieving high mesh density near electrode boundaries.

Given the requirement for accurate substrate domain modeling to support hyperelastic material behavior prediction, free tetrahedral mesh generation was selected with a reduced growth rate factor of 1.2 to enhance mesh uniformity. Maximum mesh size was established at 2500 μm divided by a solid scaling factor, while minimum element size was set to 12 μm , subsequently divided by the same solid scaling factor during parametric optimization. Curvature factor and narrow region resolution parameters were maintained at default values due to the absence of curved boundary domains and the desire to prevent mesh density variations between sensor and substrate regions.

The Maxwell capacitance was selected as the primary metric for determining mesh quality adequacy, given that electrostatics physics exhibits the greatest sensitivity to mesh element size and would demonstrate the most significant impact from mesh refinement. Parametric sweeping from 1×10^{-3} to 5 for the scaling factor, with 10 points per decade resolution, initially revealed mesh instability followed by a sudden decrease in Maxwell capacitance. Subsequently, the computed capacitance exhibited minimal variation and achieved stability, indicating the mesh

independence regime. A final mesh scaling value of 0.5 was selected within the plateau region to ensure accuracy and stability maintenance across geometric variations.

4.1.3 Sensor Domain Mesh Configuration

The sensor structure domain presents the most complex meshing requirements due to its contribution to both electrostatics and solid mechanics calculations. To ensure continuity with the substrate mesh, sensor domain discretization was derived from the previously established solid mesh configuration while incorporating refinements to improve electrostatics accuracy. Initial mesh scaling utilized minimum feature sizes set to half the minimum gap width between interdigitated electrode elements, ensuring adequate resolution of critical geometric features that govern capacitive coupling behavior. Minimum element sizing was reduced to 10 μm , with maximum size decreased to 2000 μm compared to substrate domain parameters.

Principal modifications included increased growth rate and curvature factor parameters to enhance mesh density near edge domains that dominate electrostatics contributions. Narrow region resolution was specified at 0.5 to improve corner element resolution. Additionally, corner refinement nodes were incorporated to enforce minimum edge angles between boundaries of 250 degrees with a scaling factor of 0.35. The reduction in mesh element size and inclusion of additional refinement factors enables the electrostatics solver to better conform to sensor deformations and accurately resolve resultant electric field distributions. While this approach compromises mesh uniformity for solid mechanics contributions, this compromise was deemed acceptable given that the thin 20 μm sensor domain would not significantly contribute to total substrate stress distributions.

4.1.4 Conductive Trace modelling analysis

A critical investigation was conducted to evaluate whether thin electrode structures could be neglected in favor of surface-based representations without significant accuracy degradation. Experimental measurements indicated electrode thicknesses of 10-20 μm , representing extremely small dimensions compared to electrode widths of approximately 400 μm and lengths extending to 5 mm, with substrate thicknesses of approximately 100 μm . The comparative analysis utilized mesh control boundaries applied to interdigitated electrode structures with minimum mesh sizes of 24 μm to ensure complete feature resolution while maintaining computational tractability. For three-dimensional electrode representations incorporating 20 μm thickness, minimum mesh sizes of 10 μm were employed at electrode boundaries to adequately resolve interface conditions.

Computational performance evaluation revealed significant differences between modeling approaches. The three-dimensional electrode representation with thickness generated meshes containing 1,989,738 degrees of freedom, requiring 1 minute and 1 second computation time, yielding a Maxwell capacitance of 1.9349 pF. In contrast, the two-dimensional surface representation produced 1,598,591 degrees of freedom with 52 seconds computation time,

generating a Maxwell capacitance of 1.8254 pF, representing a 5.824% difference between approaches.

This comparison was performed on a relatively modest geometry consisting of 1 mm electrode element length with 10 finger elements. Scaling analysis to the largest proposed sensor geometry incorporating 50 elements with 10 mm element lengths revealed more pronounced computational demands. The thick electrode model generated 98,587,740 degrees of freedom requiring 32 minutes and 39 seconds solution time, producing a capacitance of 19.435 pF. The corresponding surface model utilized 95,313,386 degrees of freedom with 27 minutes and 39 seconds solution time, yielding 18.297 pF and a 6.032% difference.

Given the modest increase in computational time, enhanced simplicity in parametric domain selection, and superior representation of actual fabricated geometry, the three-dimensional thick electrode model was selected for all subsequent analyses.

Table 6. Final Meshing parameters and refinements.

<i>Domain</i>	<i>Min Mesh Size</i>	<i>Max Mesh Size</i>	<i>Growth Rate</i>	<i>Refinements</i>
<i>Air</i>	4200 μm	100 μm	1.3	None
<i>Substrate</i>	24 μm	4000 μm	1.2	None
<i>IDE</i>	15 μm	4000 μm	1.4	Corner Refinement

4.2 Geometric Modeling and Parametric Analysis

The interdigitated electrode parametric model employed rectangular geometric primitives rather than the curved continuous profiles observed in fabricated sensors. This geometric simplification was deemed acceptable given the substantial reduction in geometry generation complexity and mesh generation overhead while maintaining adequate representation of fundamental electrostatic behavior.

The implementation of a parametric modeling framework enables rapid and accurate geometric modifications while facilitating parallel simulation execution across multiple design configurations. This computational approach provides comprehensive understanding of the design space available for fabricating stretchable interdigitated electrode arrays while maintaining high throughput analysis capabilities essential for optimization studies.

The parametric model incorporates five primary geometric control parameters that directly influence sensor electromechanical performance:

1. **Number of Elements** - The total count of interdigitated fingers generated for both terminal and ground electrode arrays
2. **Element Length** - The longitudinal dimension of individual finger elements within the array
3. **Element Width** - The transverse dimension of individual finger elements

4. **Spacing/Gap** - The separation distance between adjacent interdigitated elements
5. **Element Thickness/Height** - The vertical dimension of electrode structures

Based on previous characterization studies, the element thickness was fixed at 20 μm to reflect experimental fabrication capabilities achieved through direct-ink-write processes. Similarly, the element width was standardized at 400 μm to maintain consistency with light scanning characterization performed on continuous direct-ink-write sensors, ensuring direct comparability between simulation predictions and experimental validation measurements.

4.2.1 Steady-State Capacitance Analysis

The initial parametric investigation focused on steady-state capacitance characterization, representing a critical performance metric for determining the operational window of capacitive strain gauges when integrated with electrical measurement instrumentation. Pure electrostatic analysis was performed across the full parameter space to establish fundamental sensor characteristics prior to coupled multiphysical modeling.

The parameter ranges investigated were constrained by both manufacturing feasibility and size optimization requirements. Initial ink characterization studies established that minimum spacing between interdigitated electrode elements of 100 μm could be consistently achieved through available fabrication processes. The total number of elements was similarly limited to balance computational mesh size requirements with manufacturing yield considerations, as larger sensor designs with increased element counts demonstrated reduced fabrication success rates in DIW processes.

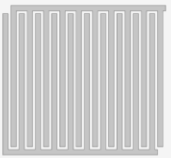
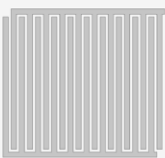
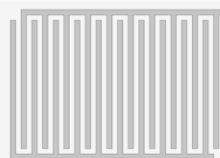
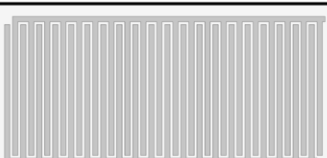
A	Trace length	B	Spacing/ Gap	C	Number of electrodes
1mm		100 μm		8	
3mm		300 μm		10	
5mm		400 μm		20	

Figure 21. Parametric sensor structure generation. A) IDE trace length parameters investigated. B) Inter-digit spacing values investigated. C) Condensed example of number of electrode generated geometries studied.

The primary parametric study revealed the fundamental relationship between element count, trace length, and steady-state capacitance. Increased trace length enhanced the rate of capacitance increase with element count, consistent with theoretical expectations that each element contributes a larger capacitive domain as geometric dimensions increase. This behavior aligns with fundamental electrostatic principles where capacitance scales proportionally with electrode area and inversely with separation distance.

The optimal capacitance range for integration with both high-accuracy desktop instrumentation (Keysight E4980AL Precision LCR Meter) and portable capacitance-to-digital converters was established to be within the 5-10 pF range. This specification simultaneously minimizes sensor footprint while maximizing full-scale output capabilities of portable capacitive sensing solutions. The initial parametric sweep was conducted using minimum achievable element spacing to establish upper bounds on capacitance performance.

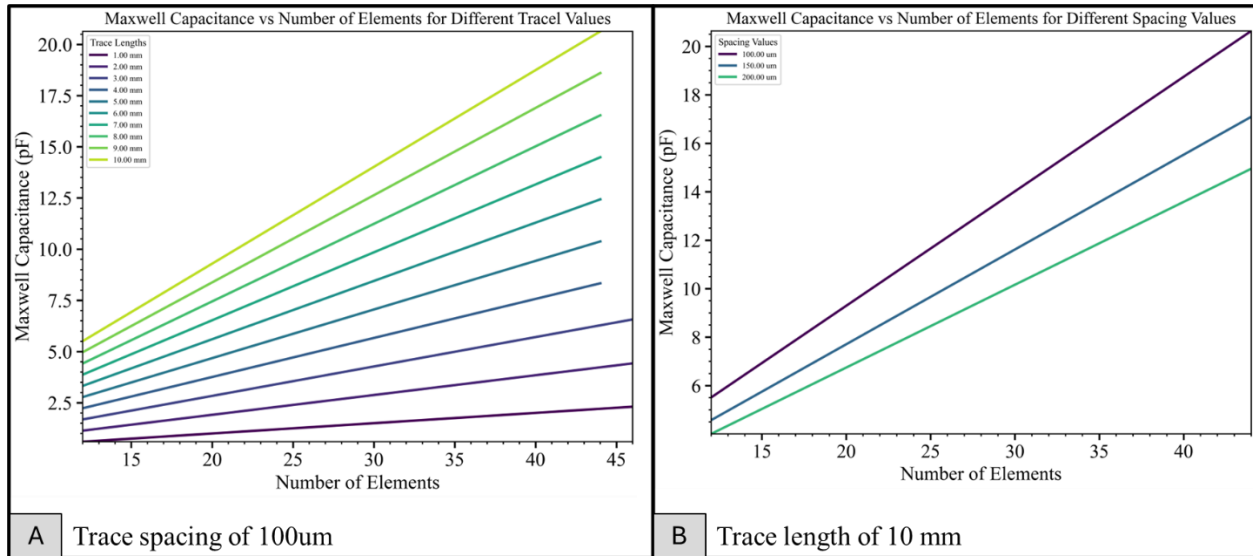


Figure 22. FEM steady-state results from electrostatics solver. A) Capacitance values associated with increasing number of elements at varying trace lengths with a constant spacing of 100μm. B) Parametric sweep results of differing trace spacing values compared to number of electrodes with a constant trace length of 10 mm.

4.2.2 Element Spacing Analysis

The investigation of inter-element spacing effects on steady-state capacitance revealed significant sensitivity to geometric optimization. Decreased spacing between terminal and ground electrode elements increases the total charge storage capacity, resulting in enhanced capacitance per element. This relationship demonstrates the fundamental trade-off between sensor sensitivity and manufacturing constraints, where reduced spacing improves electrical performance but increases fabrication complexity.

The spacing parametric study established the relationship between geometric parameters and achievable capacitance ranges, enabling selection of specific configurations for subsequent

coupled solid mechanics analysis. The results demonstrate that element spacing represents the most sensitive design parameter for capacitance optimization, with small reductions in gap distance yielding substantial improvements in sensor performance.

Parameter Selection for Coupled Analysis

Based on the comprehensive steady-state electrostatic analysis, specific geometric configurations were selected for advanced coupled solid mechanics simulations. The selection criteria prioritized configurations that:

1. Achieved target capacitance ranges (5-10 pF) for optimal measurement system integration
2. Remained within manufacturing feasibility constraints established through fabrication trials
3. Demonstrated sufficient sensitivity to mechanical deformation for strain sensing applications
4. Maintained computational tractability for iterative design optimization

The selected parameter combinations represent optimal balance points between electrical performance, manufacturing feasibility, and computational efficiency requirements. These configurations provide the foundation for subsequent multiphysical coupling analysis that incorporates mechanical deformation effects on sensor capacitance behavior.

The parametric investigation identified sensor geometries exhibiting steady-state (no-load) capacitances of approximately 10 pF as optimal for subsequent detailed analysis. This capacitance range provides suitable sensitivity for strain measurement applications while maintaining adequate signal-to-noise ratios for practical implementation across diverse sensing scenarios.

Three-Dimensional Model Architecture and Physics Configuration

The three-dimensional computational model architecture comprises three fundamental geometric components that collectively represent the complete sensor system within the simulation environment. The solid substrate material forms the foundational element, constructed from thermoplastic polyurethane (TPU) to replicate the flexible substrate employed in experimental fabrication. The sensor interdigitated electrode elements are positioned atop the substrate surface, providing the capacitive sensing functionality central to strain measurement capabilities. Finally, the air domain encompasses the entire sensor-substrate assembly, enabling accurate electrostatic field propagation analysis essential for capacitance calculations.

All geometric elements within the model are parametrically generated through automated construction algorithms, enabling precise control and systematic evaluation of design parameters across the full operational parameter space. This parametric approach facilitates comprehensive design space exploration while maintaining geometric consistency and computational efficiency throughout the analysis process.

The sensor geometry construction process initiates within a designated work plane where individual electrode elements are generated as rectangular primitives according to user-defined input parameters. These rectangular elements are systematically arranged, mirrored, and positioned to create the two distinct electrode bodies that comprise the interdigitated array structure. The electrode geometry is subsequently extruded vertically with a prescribed thickness value of 20 μm , reflecting the dimensional characteristics achieved through DIW fabrication processes.

The substrate geometry is implemented as a simple rectangular body with constant thickness of 100 μm , representing the TPU film substrate upon which sensor elements are deposited during fabrication. The substrate dimensions are configured to center the interdigitated electrode bodies within the substrate area while maintaining a small clearance gap surrounding the sensor region to prevent boundary effects from influencing electrostatic field distributions.

A spherical air domain volume completes the geometric model, providing the necessary computational space for the electrostatics solver to accurately simulate charge distribution and electric field propagation emanating from the interdigitated electrode structure. The spherical geometry ensures uniform boundary conditions while minimizing computational overhead associated with rectangular air domain configurations.

4.3 Physics Model Configuration

The multiphysical simulation framework employs three distinct physics modules within the COMSOL Multiphysics environment: solid mechanics, deformed geometry, and electrostatics. Each physics module addresses specific aspects of the sensor electromechanical behavior while maintaining appropriate coupling interfaces to capture the complete system response.

The solid mechanics physics module determines stress and strain distributions within the substrate material under prescribed displacement boundary conditions. Prescribed displacement boundary conditions were selected based on the fundamental interest in strain-versus-capacitance relationships for these sensor systems. This approach significantly simplifies the modeling requirements by eliminating the need to accurately characterize the complete spectrum of material properties associated with hyperelastic materials such as thin TPU films, focusing instead on the fundamental Poisson ratio behavior.

The prescribed displacement approach enables stretching of the sensor film to predetermined increments while neglecting the stresses exerted by the film onto the boundaries and within the bulk material. This represents a key modeling assumption that substantially reduces computational complexity, as accurate stress-strain characterization of hyperelastic materials within simulation environments can be extremely computationally expensive and requires careful selection of appropriate material models to reflect real-world behavior across specific strain ranges. Multiple material models are often required to accurately capture deformation properties across different strain regimes [90], [91].

For the TPU substrate material, a five-parameter Mooney-Rivlin hyperelastic model was selected to represent the system behavior, with coefficients derived from experimental [92]. This model was validated across strain ranges from 0-60%, providing adequate coverage for the proposed simulation parameter space.

Table 7. Five-parameter Mooney-Rivlin Hyperelastic model parameters for TPU films [92]

<i>Parameter</i>	<i>Value</i>	<i>Unit</i>
C_{10}	-3.281×10^6	<i>Pa</i>
C_{01}	8.399×10^6	<i>Pa</i>
C_{11}	3.538×10^5	<i>Pa</i>
C_{20}	1.140×10^{-4}	<i>Pa</i>
C_{02}	-4.086×10^{-13}	<i>Pa</i>
κ	5.085×10^8	<i>Pa</i>
ν	0.490	—

The hyperelastic material model implementation was configured to better reflect real-world deformation characteristics while assuming perfectly incompressible material behavior to avoid additional computational intensity. The substrate boundary conditions constrain displacement in the z-axis to maintain substrate and sensor planarity while enabling stretching in either the x or y directions according to the specific loading scenario under investigation.

4.3.1 Deformed Geometry Physics

The deformed geometry physics module updates model boundaries and mesh locations following mechanical deformation of the substrate and sensor elements. COMSOL Multiphysics provides two distinct approaches for mesh deformation implementation: deformed geometry functionality and moving mesh functionality. The fundamental difference lies in the reference frame treatment, where deformed geometry functionality deforms the material frame mesh relative to the geometry frame mesh, while moving mesh functionality deforms the spatial frame mesh relative to the material frame mesh. Both deformation types can be implemented simultaneously for complex multiphysical applications [91].

With the modern COMSOL version 6.3 implementation, the practical differences between these two approaches are minimal for the multiphysical coupling under investigation, as mass conservation is maintained throughout the simulation process. The deformed geometry node is configured with hyperelastic material properties, solving partial differential equations derived from continuum mechanics principles established by the solid mechanics module with boundary conditions specified by the movement of geometric boundaries. The hyperelastic smoothing

method employed seeks to minimize mesh deformation energy inspired by neo-Hookean material behavior[93]:

$$W = \int_{\Omega} \frac{\mu}{2} (I_1 - 3) + \frac{\kappa}{2} (J - 1)^2 dV \quad (10)$$

Where μ and κ represent artificial shear and bulk moduli, respectively, and the invariants J and I_1 are defined as:

$$J = \det(\nabla_X x) \quad (11)$$

$$I_1 = J^{-\frac{2}{3}} \text{tr}((\nabla_X x)^T \nabla_X x) \quad (12)$$

4.3.2 Electrostatics Physics Module

The electrostatics physics module computes electric field distributions, electric displacement fields, and potential distributions within dielectric materials under conditions where electric charge distributions are explicitly prescribed. This module provides the fundamental capacitance calculation capabilities essential for sensor performance characterization.

The electrostatics boundary conditions are implemented through three distinct boundary types. A terminal boundary condition applies 10 V to the first electrode set of the interdigitated array, generating the initial charge distribution that creates the charged capacitor plate. A ground boundary condition is applied to the second electrode set, establishing a zero potential domain that represents the uncharged capacitor plate. A zero charge boundary condition is applied to the air domain surfaces, enabling free electric field propagation throughout the surrounding medium.

Charge conservation boundary conditions are applied to the substrate domain, allowing electric field propagation through the TPU substrate material while maintaining appropriate charge continuity across material interfaces. This boundary condition treatment ensures accurate representation of the electrostatic coupling between electrode elements through both air and substrate media.

4.3.3 Solver Configuration and Solution Strategy

The computational solution strategy employs a stationary solver configured to execute physics modules in a prescribed sequence to ensure accurate multiphysical coupling. The solution process initiates with solid mechanics deformation analysis based on applied prescribed displacement boundary conditions, utilizing a segregated solution method with direct PARDISO solver implementation to determine internal stress distributions and mesh displacements.

The solid mechanics solution generates material mesh displacement partial differential equations that are subsequently transferred to the deformed geometry physics module. This module solves for new mesh positions and boundary configurations through direct solver implementation,

completing the displacement field variable set required for electrostatics boundary condition updates and relative position calculations.

The electrostatics solver executes following the completion of geometric deformation analysis, utilizing an iterative solution approach to calculate electric field distributions and charge distributions across the deformed computational domains. The Maxwell capacitance is computed globally upon completion of the electrostatics solution to determine the capacitance of the interdigitated electrode structure under the specified deformation conditions.

This sequential solution approach ensures that mechanical deformations are accurately reflected in the electrostatic analysis while maintaining computational efficiency through appropriate physics module coupling and solution strategy implementation.

4.4 Strain-Capacitance Response Analysis

4.4.1 Parametric Strain Testing Methodology

The comprehensive strain-capacitance response characterization was conducted through systematic application of prescribed displacement boundary conditions to evaluate sensor performance across the operational strain range. The model was subjected to displacement sweeps calculated as percentages of total substrate length to accurately model the strain conditions imposed on sensor elements during practical applications.

The displacement boundary conditions were applied symmetrically to opposing substrate edges, with each boundary receiving displacement equal to half the total prescribed strain. This symmetric loading approach ensured that sensor elements remained centered within the spherical air domain throughout the deformation process, preventing artificial shifts in fringe field distributions that could introduce spurious effects in capacitance calculations.

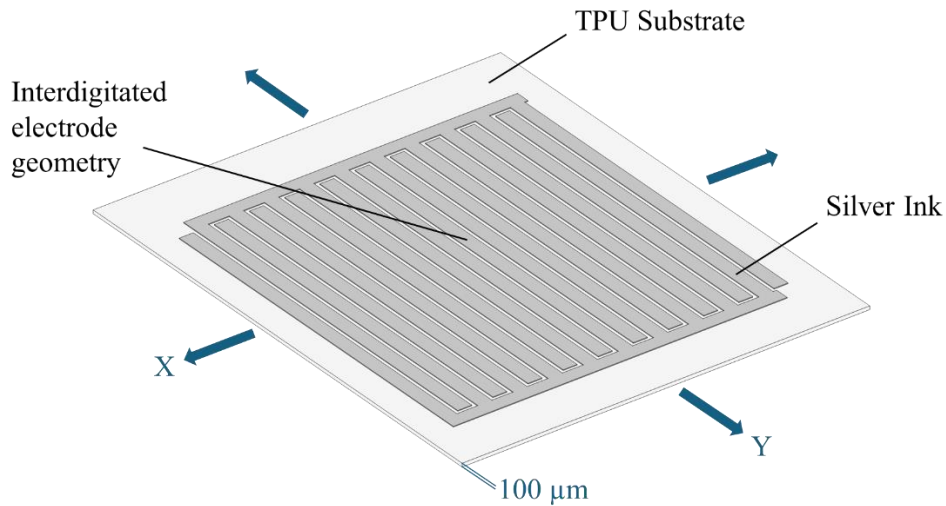


Figure 23. Parametric Strain Model setup.

The strain parametric sweep ranged from 0% to 30% strain with incremental steps of 5% strain, providing comprehensive coverage of the operational parameter space. The geometric parameters evaluated included element counts of 10 and 20 elements, trace lengths of 5 mm, 7 mm, and 10 mm, and inter-element spacing values of 100 μm , 150 μm , and 200 μm . Strain levels exceeding 30% resulted in hyperelastic material model instability, leading to localized high stress concentrations near the prescribed displacement boundaries that compromised solution accuracy.

4.4.2 Element Count Performance Analysis

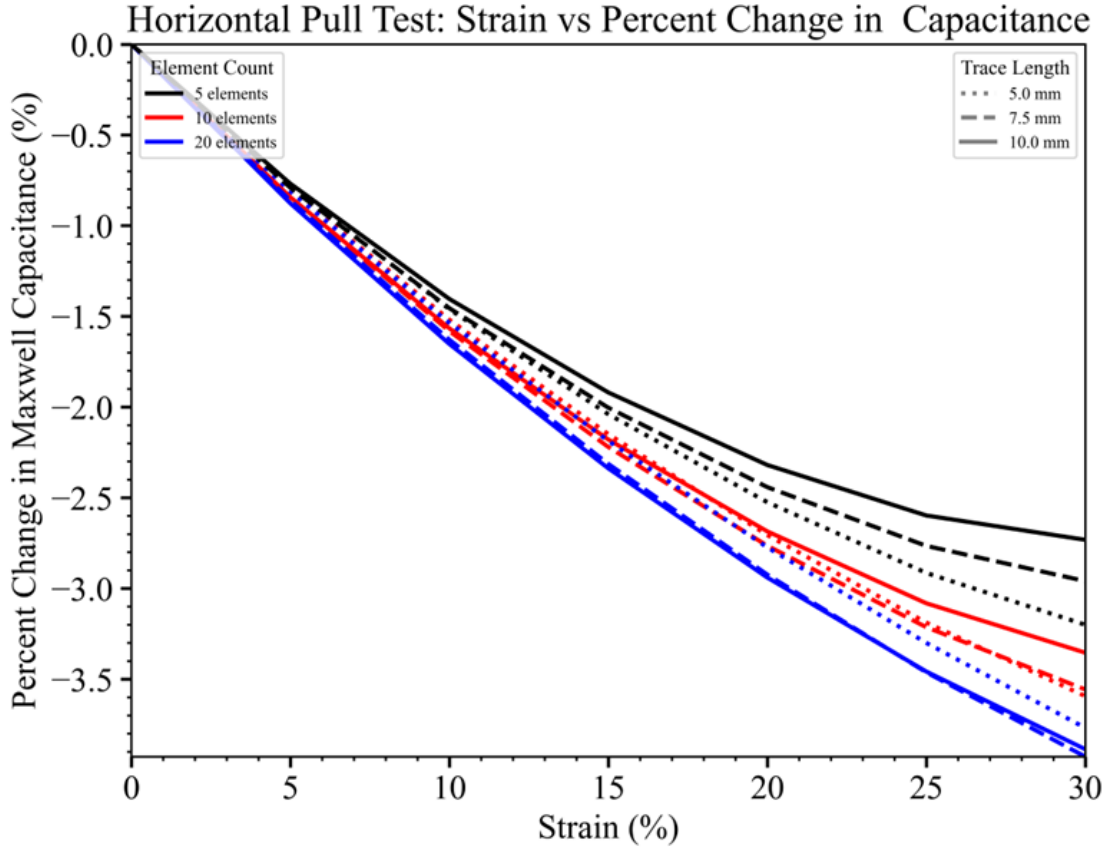


Figure 24. Percent Capacitance change versus strain for different number of elements and trace length groupings.

The initial analysis focused on the influence of element count on sensor capacitance-strain response characteristics. The optimization objectives prioritized linearity maintenance throughout the operational strain range, ensuring that sensor response remains linear to facilitate accurate strain measurement and calibration procedures. Additionally, sensitivity optimization was pursued, defined as the slope of the capacitance-strain response curve, representing the sensor's ability to detect small strain variations.

While highly stretchable capacitive strain sensors are not primarily optimized for maximum sensitivity but rather for linearity maintenance across their operational range, achieving the highest possible sensitivity within linearity constraints remains desirable for improved

measurement resolution. The relative percent change analysis revealed distinct performance characteristics across different element count configurations.

The experimental results demonstrated that lower element counts exhibited degraded performance, characterized by slope reduction in the capacitance-strain response around the 15% strain range. Both 10-element and 20-element configurations maintained acceptable performance throughout the complete 30% strain range, with 20-element configurations demonstrating superior linearity and sensitivity characteristics compared to their 10-element counterparts.

4.4.3 Trace Length Optimization

Following identification of optimal element counts, the investigation focused on trace length effects for 20-element sensor configurations. The analysis isolated these high-performing geometries to conduct detailed evaluation of trace length influence on sensor performance characteristics.

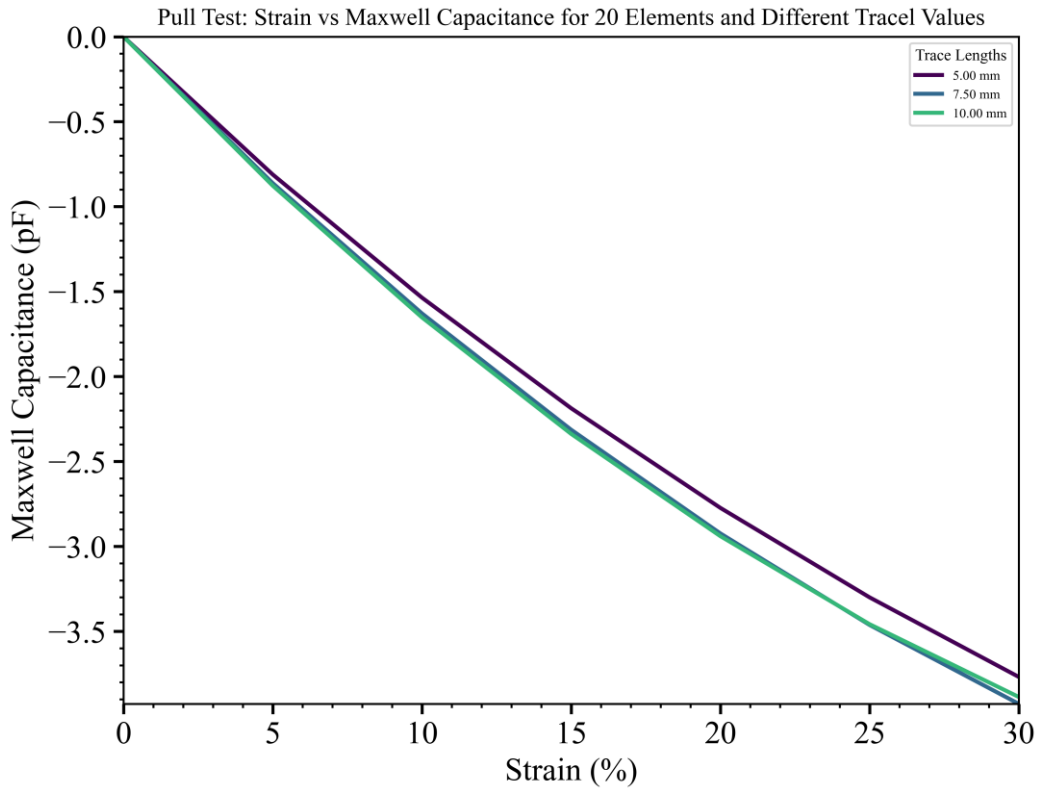


Figure 25. Percent Change in Capacitance versus applied strain for 20-element sensors structures with varying trace lengths.

The trace length parametric study revealed minimal performance differences between 7.5 mm and 10.0 mm trace lengths, with both configurations exhibiting linear response characteristics throughout the operational strain range. These longer trace lengths demonstrated slightly improved sensitivity compared to the 5 mm trace length geometry, indicating that increased electrode area enhances sensor response without compromising linearity.

The marginal performance differences between 7.5 mm and 10.0 mm trace lengths suggest that sensor performance approaches saturation at longer trace lengths, with diminishing returns for further increases in electrode dimensions. This finding provides important guidance for sensor design optimization, indicating that moderate trace lengths provide optimal balance between performance and sensor footprint.

4.4.4 Inter-Element Spacing Analysis

The final geometric parameter investigation examined the influence of inter-element spacing on sensor performance for 20-element configurations. This analysis represents a critical design consideration, as spacing directly affects both manufacturing feasibility and electrostatic coupling strength between electrode elements.

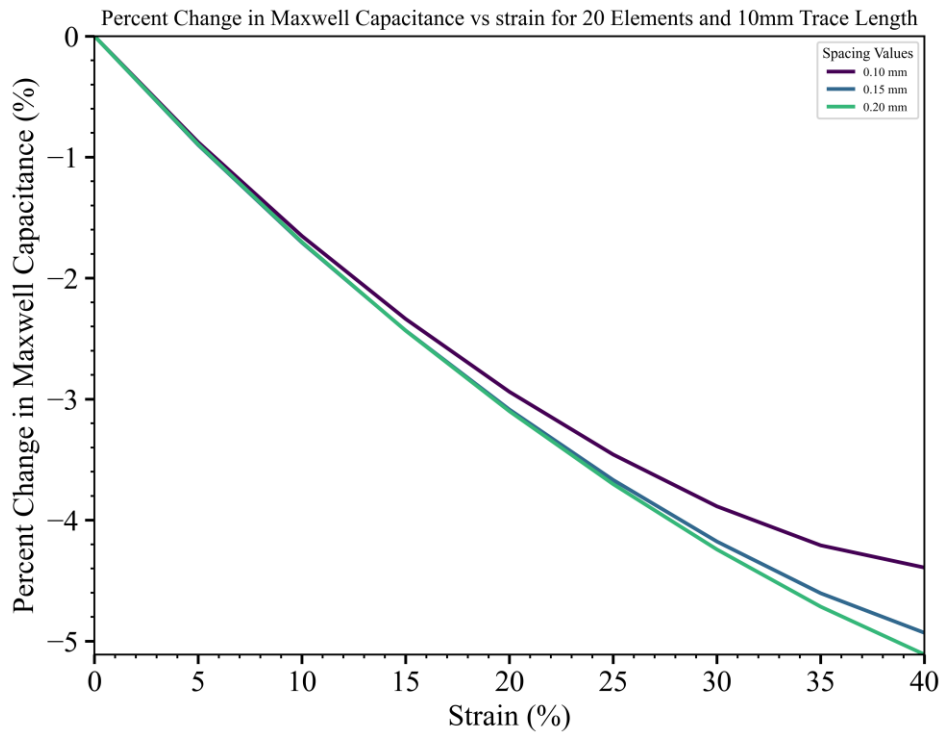


Figure 26. Percent change in Capacitance versus applied strain for 20-element ide structures with varying inter-digit spacing values.

Extended strain range testing to 40% strain was successfully achieved for all three spacing configurations under investigation. The results demonstrated that the largest spacing value of 200 μm provided optimal performance, maintaining linearity throughout nearly the complete strain range while achieving the highest sensitivity compared to 100 μm and 150 μm spacing configurations.

This counterintuitive result, where increased spacing enhances rather than degrades sensor performance, likely results from improved mechanical coupling between substrate deformation and electrode displacement, combined with reduced manufacturing-induced variations in narrow

spacing configurations. The 200 μm spacing configuration provides sufficient separation to minimize fabrication tolerances while maintaining adequate electrostatic coupling for sensitive capacitance measurements.

Optimized Geometry Selection

Based on the comprehensive parametric analysis, the final optimized sensor geometry was established as 20-elements with 10 mm trace length and 200 μm inter-element spacing. This configuration provides optimal balance between linearity, sensitivity, and manufacturing feasibility while maintaining computational tractability for design optimization studies.

4.4.5 Directional Sensitivity Analysis

The final simulation study investigated the directional sensitivity characteristics of the optimized sensor geometry through independent strain application in both x and y directions. This analysis provides critical insights into sensor anisotropic response behavior essential for practical strain measurement applications.

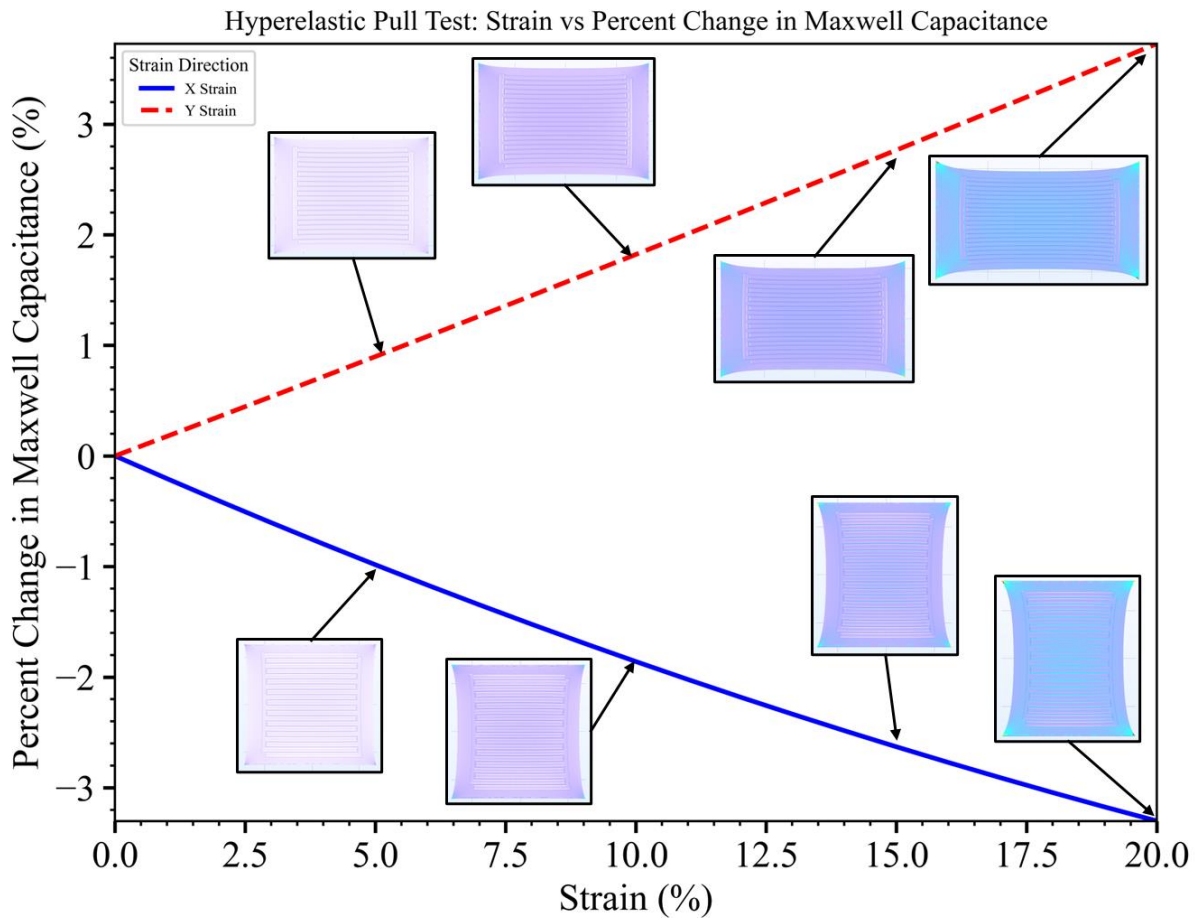


Figure 27. Comparison of percent change in capacitance versus applied strain in both horizontal and vertical planar directions.

The directional sensitivity analysis was conducted with strain ranges limited to 20% due to solver instability encountered when computing higher strains in the y-direction. The computational limitations likely result from increased mesh distortion and convergence difficulties associated with transverse loading of the interdigitated electrode structure.

The experimental results revealed extremely linear response characteristics from both loading directions with opposing magnitude responses. This directional sensitivity behavior demonstrates the sensor's capability for directional strain measurement, providing valuable information for applications requiring discrimination between different strain components in complex loading scenarios.

The opposing magnitude responses in perpendicular directions indicate that the sensor exhibits positive capacitance change for longitudinal strain (parallel to electrode fingers) and negative capacitance change for transverse strain (perpendicular to electrode fingers). This anisotropic behavior results from the geometric asymmetry of the interdigitated electrode structure and provides inherent directional sensitivity that can be exploited for multidirectional strain sensing applications.

Performance Metrics Summary

The comprehensive parametric analysis established optimal sensor design parameters that achieved:

1. **Linearity:** Maintained throughout the operational strain range up to 30% for longitudinal loading and 20% for transverse loading
2. **Sensitivity:** Maximized within linearity constraints through optimal geometric parameter selection
3. **Directional Sensitivity:** Demonstrated anisotropic response enabling directional strain discrimination
4. **Manufacturing Feasibility:** Balanced performance requirements with practical fabrication constraints

The simulation results provide comprehensive design guidelines for stretchable interdigitated electrode strain sensors, enabling informed design decisions for specific application requirements while maintaining predictable performance characteristics throughout the operational parameter space. Utilizing the steady-state capacitance results and the relations between parameters and sensor performance we focused the fabrication and design efforts in the following section.

5. Design of Highly Stretchable and Durable Wearable Strain Gauges for Limb Volume Measurement

5.1 Design and Optimization Goals

The development of highly stretchable capacitive strain gauges (HSCSGs) for wearable limb volume monitoring applications necessitates a comprehensive design approach targeting multiple performance criteria. The primary objective centers on minimizing sensor dimensions while maintaining functional integrity, thereby enabling the incorporation of increased sensor densities within sleeve-based measurement systems. This miniaturization approach directly contributes to enhanced volume estimation accuracy through improved spatial resolution, while simultaneously reducing material consumption and accelerating the fabrication process for individual sensor units.

Manufacturing reliability constitutes a critical design parameter, with optimization efforts focused on achieving high-yield production processes that maximize repeatability while minimizing fabrication defects. The optimized sensor geometries must demonstrate consistent performance characteristics, including reliable minimum trace widths that enable compact designs without compromising fabrication reliability or inducing nozzle clogging during the DIW process. This balance between miniaturization and manufacturability represents a fundamental trade-off that directly impacts the scalability of the sensor production methodology.

Linearity performance across the operational sensing range of 25% strain emerges as a paramount design consideration, enabling simplified calibration procedures and ensuring consistency across multiple sensor units despite inevitable geometric variations arising from fabrication tolerances and differential preload tensions experienced during actual wear conditions. This emphasis on linearity over absolute sensitivity reflects the practical requirements for long-term deployment across diverse body physiologies, where the ability to produce accurate measurements over varying circumferences and initial states proves more valuable than achieving maximum resolution within constrained operational ranges. The prioritization of linearity fundamentally reduces the calibration complexity and data processing requirements necessary for reliable measurement capture.

Mechanical compliance represents another essential optimization target, where the combined sensor and substrate system must exhibit low stiffness characteristics to ensure comfortable wear while minimizing measurement errors associated with regional constriction of the monitored anatomy. The substrate material properties and sensor geometry must collectively contribute to a compliant system that deforms readily under physiological loading conditions without introducing significant mechanical artifacts into the measurement process.

The operational sensing range specification of 25% strain deformation demands highly stretchable sensors capable of repeatable performance throughout their intended working range. This requirement encompasses minimal plastic deformation, reduced hysteresis effects, and

enhanced resistance to damage during extended deformation cycles and repeated loading. The durability characteristics directly impact the long-term viability of the sensing system for continuous monitoring applications where sensor replacement would be impractical.

5.2 Fabrication and Testing Methodology

5.2.1 Fabrication Procedure

The development of a streamlined fabrication procedure required addressing the fundamental challenge of aligning the DIW system with subsequent laser cutting operations for substrate preparation and sensor release. The Nova DIW system employs optical alignment protocols compatible with smooth vacuum table surfaces lacking mechanical alignment capabilities, while the Universal Laser Systems VLS3.60DT compact 50W laser processing system operates exclusively through mechanical registration to a fixed origin using precision guides positioned along the work surface perimeter.

To establish reliable processing capabilities for HSCSG fabrication, a specialized alignment system was developed utilizing 10mm thick acrylic sheets configured with a flat bottom surface and top frame component, compressed using threaded inserts and bolts. This configuration applies uniform pressure across the substrate surface while maintaining exposure for laser processing operations. The alignment system incorporates four precision-manufactured 3D printed bushings that interface with corresponding substrate holes, ensuring repeatable positioning accuracy throughout the fabrication sequence.

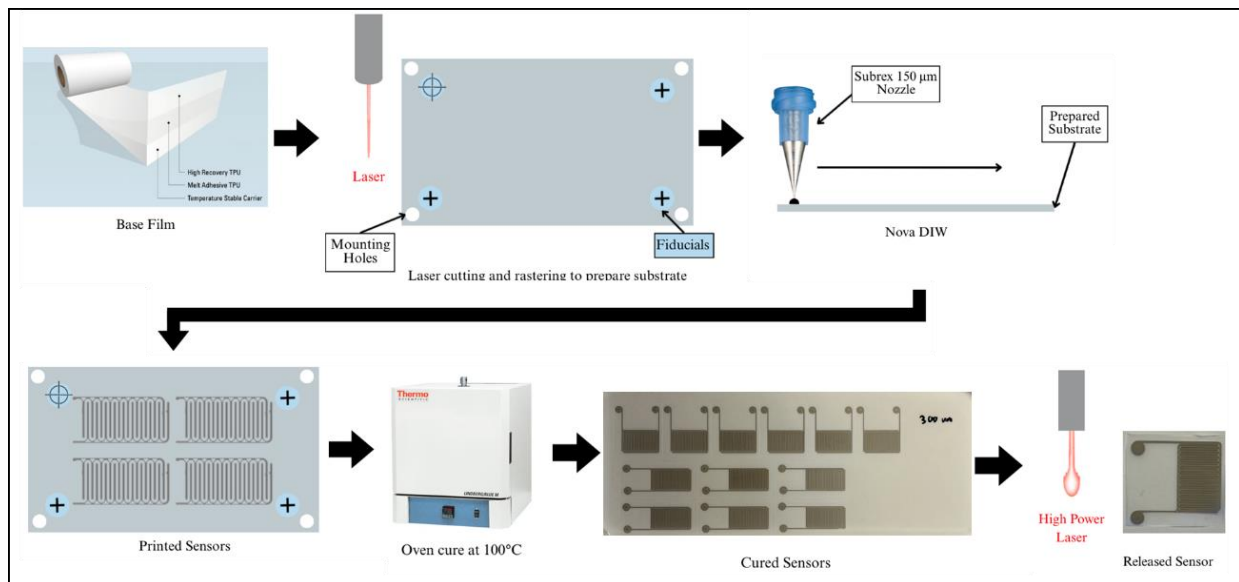


Figure 28. HSCSG Fabrication process outline. Showing base film preparation using laser cutting to create alignment markers. DIW dispense process. Thermal cure processing. and final laser cut release sensors.

The fabrication process initiates with substrate preparation, where materials supplied in either large roll format or precut A4 pages are sectioned into standardized coupons measuring 20

cm wide by 8 cm tall to accommodate the alignment fixture dimensions. Four bushing interface holes are precision-cut with a 0.1 mm undersize tolerance to achieve tight mechanical registration with the fixture components. Following substrate loading and securing within the alignment system, the laser cutter performs light engraving operations to create four alignment crosshairs and an additional reference circle positioned on the top left marker. The substrate preparation sequence continues with removal from the alignment system and placement on the Nova vacuum platform using an additional outer film to ensure uniform vacuum pressure distribution across the entire substrate surface. The DIW process commences with scaling and alignment procedures where the design artwork is precisely registered with the previously engraved laser cutter fiducial markers. Following successful alignment verification, the printing process deposits the conductive sensor traces according to the optimized geometric parameters. Post-deposition thermal curing occurs in a benchtop oven maintained at 100°C for a 10-minute duration to ensure complete ink solidification and adhesion. The cured substrate assembly is subsequently reinserted into the alignment fixture where individual sensor units are precision-cut from the substrate using the laser cutting system, producing finished sensors ready for characterization testing.

5.2.2 Sensor Testing Methodology

Comprehensive electrical and mechanical characterization of the printed HSCSGs was conducted using a synchronized multi-instrument approach coordinated through the MTPA system for experimental routine execution and data acquisition. Released sensor units undergo initial preparation involving copper tape application to enable accurate four-probe measurements using the Keysight E4980AL Precision LCR meter. The prepared sensors are positioned within custom 3D printed clamp fixtures specifically designed to minimize weight and maximize the operational measurement range of the 10N load cell integrated within the Mark 10 F305 tensile test system. Standard metal clamps were determined to significantly compromise load cell operational range, necessitating the development of specialized fixtures.

The custom fixturing components were fabricated using a Form 4 Masked Stereolithography (MSLA) system utilizing Clear V5 resin, selected for its combination of high stiffness and optical transparency properties. Sensors undergo alignment and clamping procedures using an additional positioning system to ensure consistent placement relative to the clamp components and maintain flat substrate orientation. Initial length measurements are recorded using digital calipers prior to assembly insertion onto the tensile test machine.

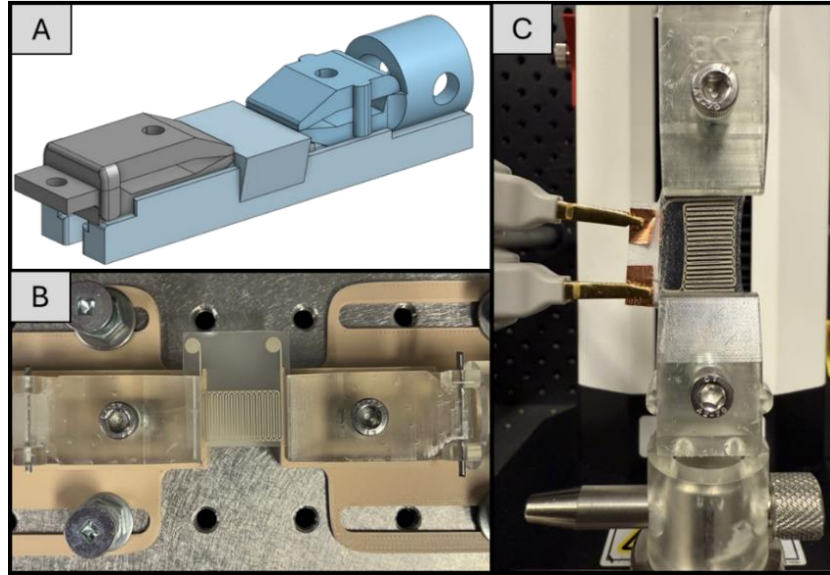


Figure 29. 3D printed sensor film clamp fixtures. A) 3D CAD representation of clamp pairs and alignment platform. B) Sensor shown inserted and fixed within clamps. C) Clamped sensors stationed within Mark 10 F305 test machine and electrical leads connected.

Following mechanical setup, electrical connections are established between the LCR meter test leads and the copper tape contacts. LCR measurement parameters underwent optimization through systematic frequency response characterization across the complete operational range from 1Hz to 300kHz using a 1V excitation voltage. The frequency sweep results demonstrate increasing measurement speed and accuracy with higher frequencies, with the mean capacitance measurements and standard deviations calculated from 25 measurements at each frequency point showing optimal performance characteristics at 100kHz, which was subsequently selected as the standard test frequency for all sensor characterization procedures. The results of the sweep are shown in the Figure 30 below, which plots the mean measurement of capacitance, and the standard deviation of the 25 measurements made at each frequency.

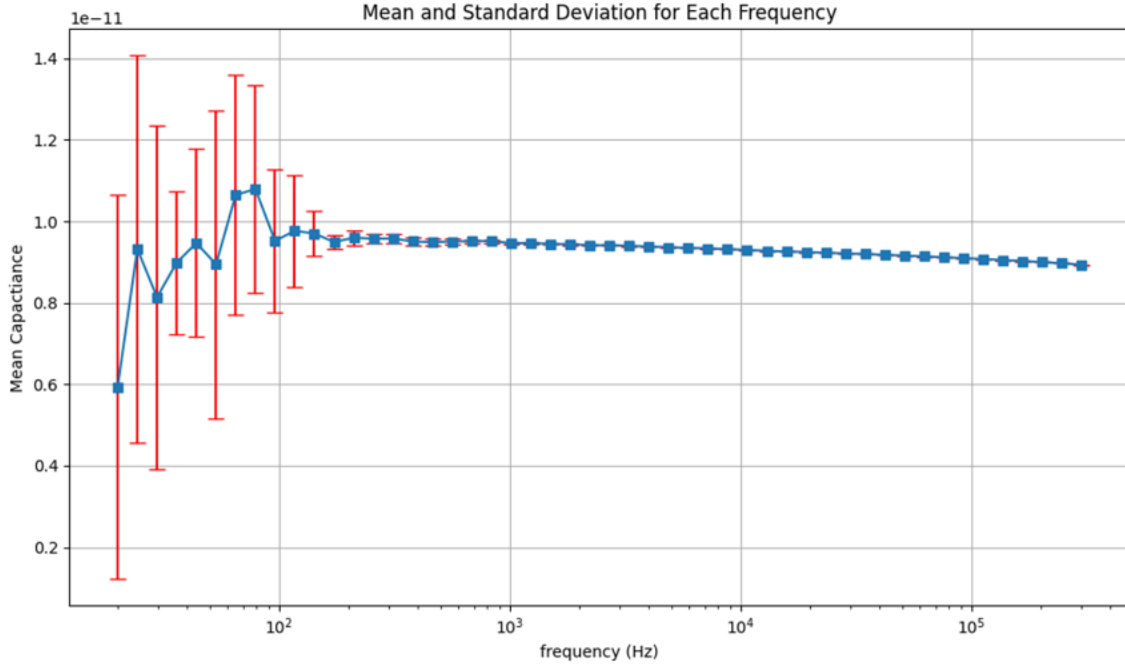


Figure 30. LCR Frequency sweep analysis results.

The selection of appropriate pull speed parameters for uni-axial strain testing required consideration of viscoelastic substrate material responses and their impact on observed hysteresis characteristics. Given the intended application of HSCSGs for limb volume sensing, which does not necessitate high extension rates, testing was conducted at 5.00 mm/min, consistent with established research protocols [33], [94] and compliant with ASTM D882 standards for thin film mechanical testing [95]. Each sensor design underwent evaluation in both vertical configuration (digits parallel to pull direction) and horizontal configuration (digits perpendicular to pull direction), with connection traces and contact pads oriented orthogonally to the pull direction to eliminate displacement-induced connection effects during LCR measurements.

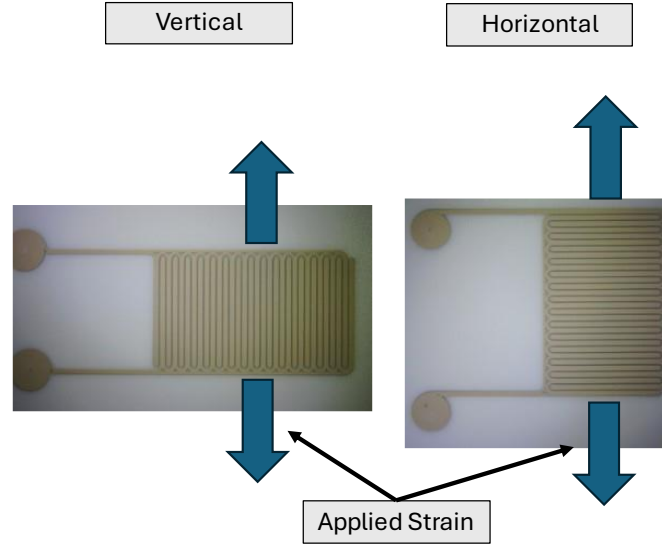


Figure 31. Pull test applied strain direction diagram.

5.3 Sensor Geometry Characterization

The initial geometric parameter investigation focused on inter-digit spacing effects, which determines the edge-to-edge separation between adjacent IDE digits relative to the programmed digit width. Increasing spacing values enhance process yield and fabrication reliability, though simulation results indicate corresponding reductions in initial steady-state capacitance values. Based on preliminary experiments establishing achievable spacing constraints while maintaining compact sensor dimensions, evaluation parameters were selected at 225 μm , 250 μm , 275 μm , and 300 μm for performance assessment under both horizontal and vertical strain orientations.

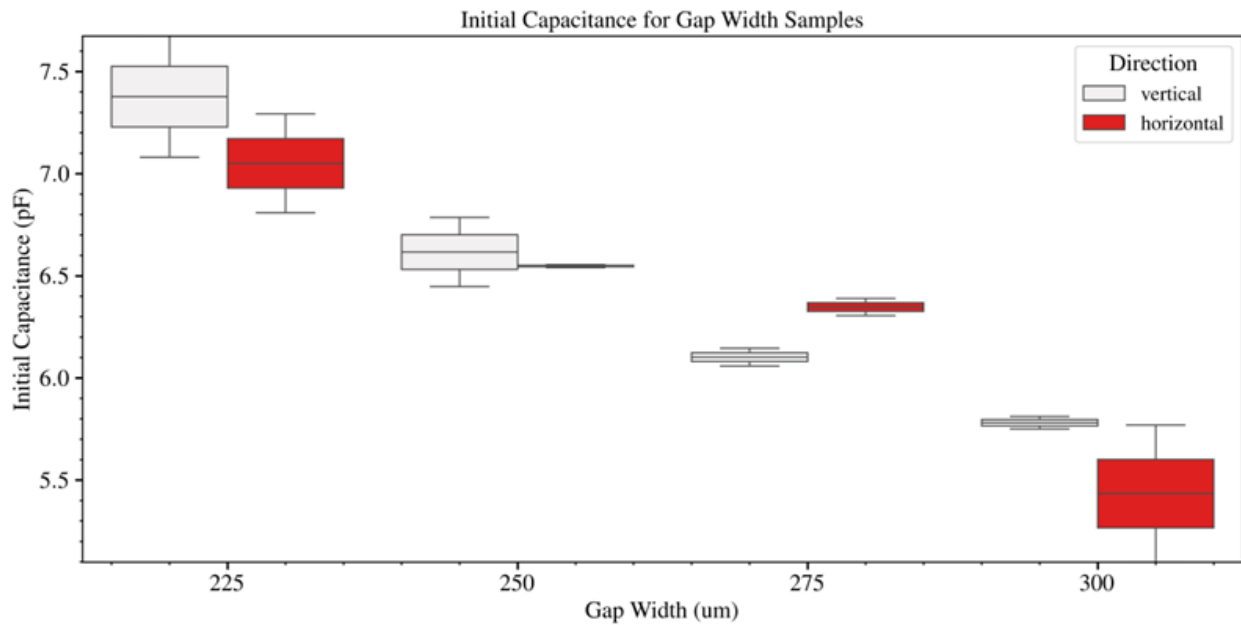


Figure 32. Initial Capacitance measurements for varying gap widths in both horizontal and vertical structure orientations.

Inter-digit spacing samples underwent cyclic testing to 20% strain over 5 repetition cycles, with results demonstrating the expected relationship between reduced spacing and increased initial capacitance, accompanied by corresponding increases in manufacturing variability. The results shown in Figure 32 are an analysis on the average initial capacitance of 3 sensors for each configuration and their respective inter-quartile ranges. As expected, the reduced inter-digit spacing results in higher initial capacitances but was found to increase the manufacturing variability with the same trend except for the horizontal sample set, which had low sample-to-sample variation for the 225 μ m spacing samples but elevated variation for 250 μ m samples, contrasting with the consistent trend observed in vertical orientation testing.

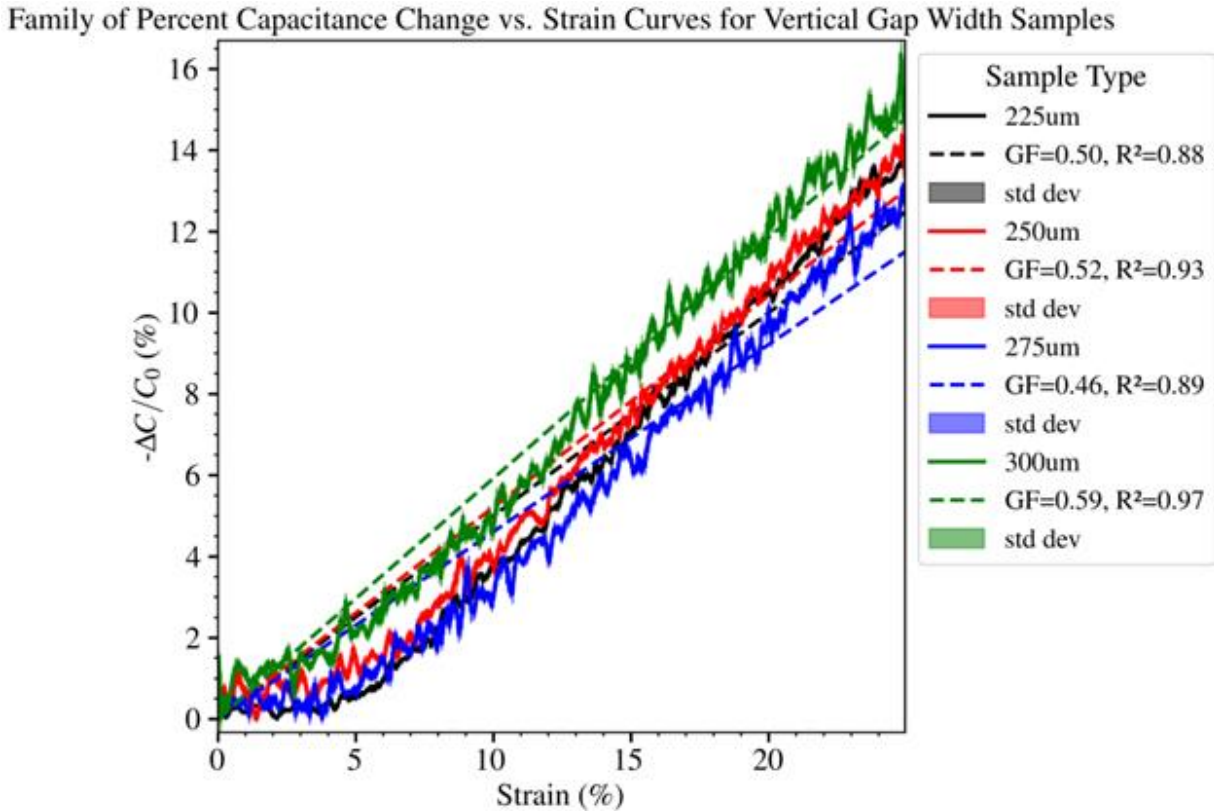


Figure 33. Percent change in capacitance versus applied vertical strain for IDE Gap width geometries.

Comparative analysis of percent capacitance change for vertically oriented samples across the inter-digit spacing range revealed minimal sensitivity differences between spacing configurations, with all samples following similar response trends throughout the test procedure when analyzed using rolling mean calculations with a window size of 10 across the 3 samples per configuration. In Figure 33 we compared the percent capacitance change for the vertically oriented samples over the range of inter-digit spacings, with each curve representing the rolling mean with a window size of 10 for the 3 samples. From this we see that there is little to no difference in the sensitivity between the different spacing values with all following similar trends throughout the test procedure. Based on these findings, a standard inter-digit spacing of 300 μ m was selected to

optimize process reliability while maintaining initial capacitance values within the target range of 5-10pF.

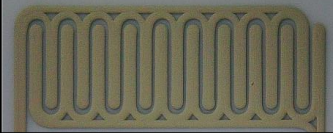
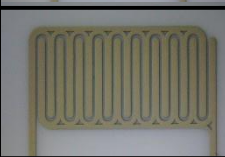
A	Trace length	B	Digit Count
3mm		3	
5mm		4	
		6	
10mm		8	
		10	

Figure 34. Microscope imaging of printed IDE structures with varying trace length and number of digits.

The investigation of digit quantity and length effects on sensor performance characteristics involved fabricating sensors with digit counts of 3, 4, 6, 8, and 10 using a fixed 5mm length, while digit length evaluation examined 3mm, 5mm, and 10mm configurations with a fixed 10-digit count. These parameter ranges were constrained by fabrication limitations and dimensional requirements for compact sensor geometries not exceeding 1cm height and 2cm width. The fabricated sensors can be seen in the figure above.

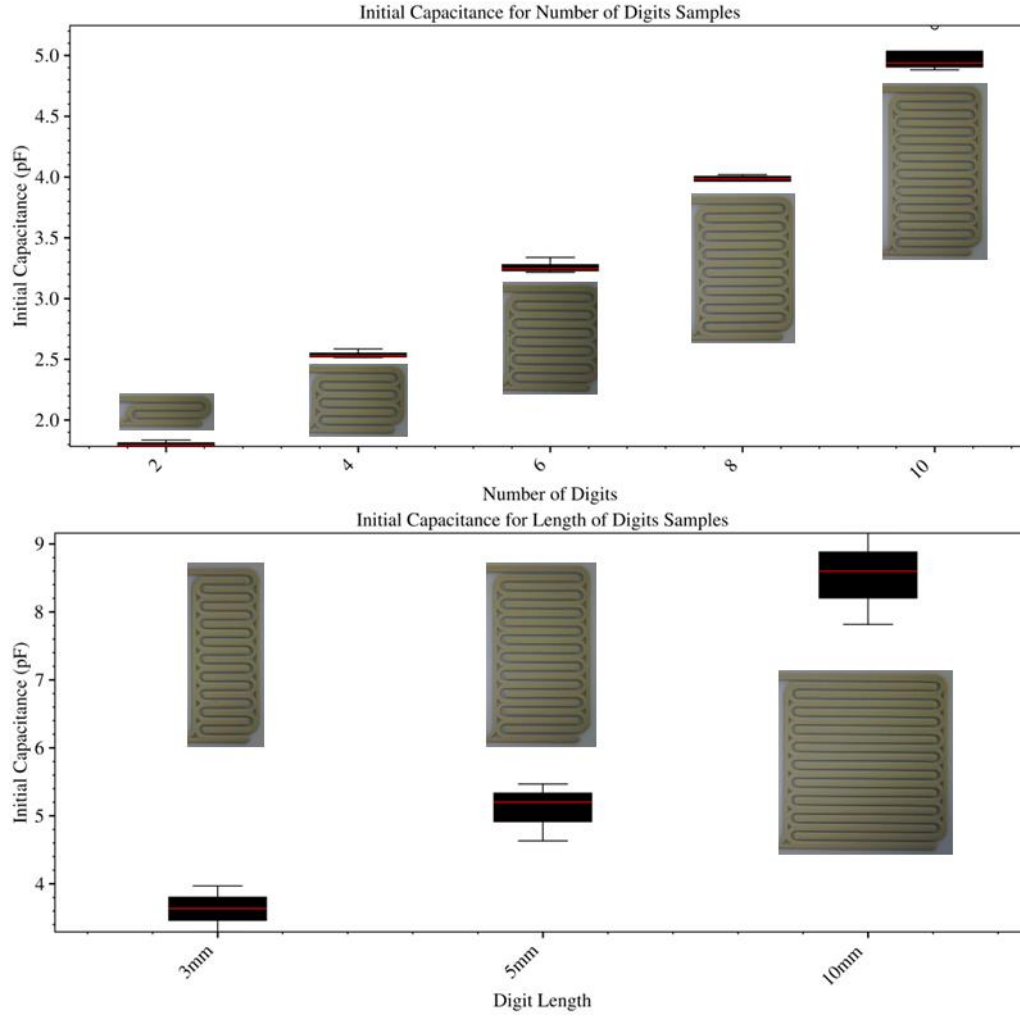


Figure 35. Initial capacitance measurements for fabricated sensor samples with varying number of digits and digit lengths.

Fabricated sensors underwent identical testing protocols with maximum strain limited to 10% to validate steady-state capacitance characteristics and sensitivity measurements. Results confirmed the anticipated increase in steady-state capacitance with increasing digit length, accompanied by corresponding increases in measurement variation. From these experiments we validated the steady state capacitance of the fabricated sensors as well as the sensitivity of each sample. In Figure 35 above we can see the expected increase in steady state capacitance as the length of digits increases as well as an increase in the variation. Similarly, digit count increases produced elevated initial capacitance values approaching the target 5pF specification. In Figure 35 we again see an increase as the number of digits increases bringing the initial capacitance close to our 5pF goal.

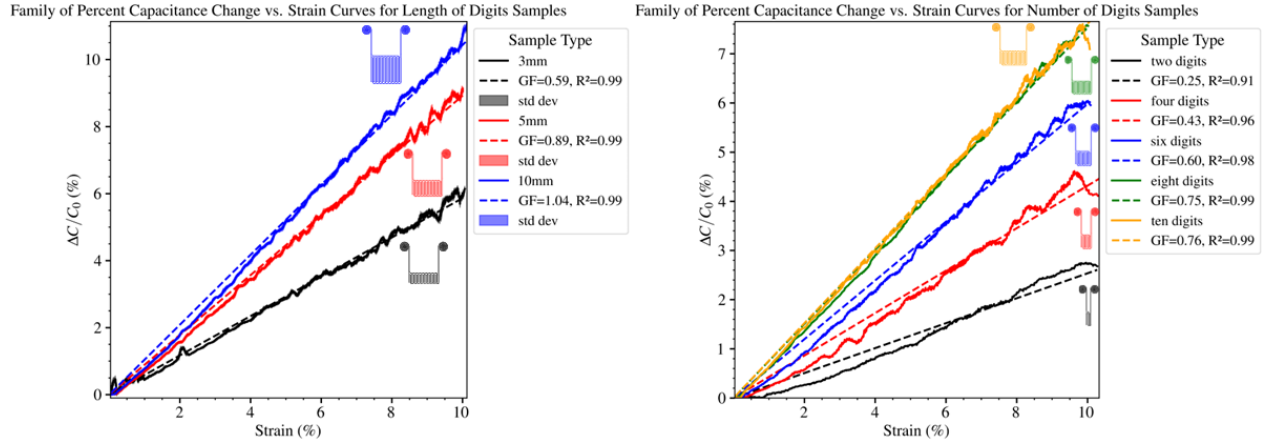


Figure 36. Sensor Geometry pull test results, showing percent change in capacitance versus applied strain for varying trace length(left), and number of digits(right).

Sensitivity analysis across geometric variations demonstrated minimal performance differences, with all configurations exhibiting similar response characteristics throughout the evaluation range. In Figure 36 the sensitivity of the geometry changes is shown to have little difference between the different geometries with all generally performing similar. The final optimized IDE geometry parameters were established with trace lengths between 5-10mm and digit counts of 8-10, providing ideal initial capacitance values for HSCSG applications while maintaining manufacturing feasibility and compact form factors.

5.4 Substrate Material Evaluation

The investigation of substrate material effects on sensor manufacturability and performance characteristics encompassed three candidate materials: Panasonic Beyolex [96], BEMIS 3914 [97] and Intexar TE-11C [98] which was previously used in Chapter 3. Panasonic Beyolex represents a thermosetting stretchable film specifically engineered for printed electronics applications, featuring a single-layer 100 μ m thick design with additional protective cover and carrier films for handling and curing operations. The material exhibits exceptional high-temperature resistance, withstanding temperatures up to 300°C before degradation, though this thermal stability necessitates additional adhesive systems for textile bonding applications due to its thermosetting chemistry.

BEMIS 3914 material consists of a three-layer stretchable film architecture incorporating polyurethane top and bottom layers with an elastic inner layer, totaling 100 μ m thickness. This material system is specifically designed for textile applications, enabling direct fabric bonding through heat-pressing processes. The material properties can be seen in the Table below. All evaluated substrate materials demonstrate minimal hysteresis characteristics with recovery properties exceeding 95%, with BEMIS achieving the highest recovery performance at 99% recovery following 100% strain application.

Table 8. Table of substrate material property comparison for Intexar TE-11C, BEMIS 3914, and Beyolex materials.

Name	Type	Material	Modulus	Thickness	Recovery
Intexar TE-11C	Wearable Film	TPU	2.15 - 3.1 MPa	100 μ m	97% at 40% strain
BEMIS 3914	High Recovery Adhesive	TPU	2.2 MPa	100 μ m	> 99% at 100% strain
Beyolex	Thermosetting Stretchable Film	Polyurethane	<2.5 MPa	100 μ m	99% at 50% strain

Sensor fabrication employed optimized geometric parameters including 10mm digit length, 300 μ m inter-digit spacing, and 10-digit configuration. DIW dispense parameters required individual calibration for each substrate material prior to sensor fabrication. The BEMIS substrate presented significant processing challenges, requiring reduced dispense heights and elevated pressures to achieve adequate conductive ink adhesion to the substrate surface. Beyolex substrate processing required minimal parameter modifications from the established Intexar calibration profile. The printed sensors are shown in the figure below.

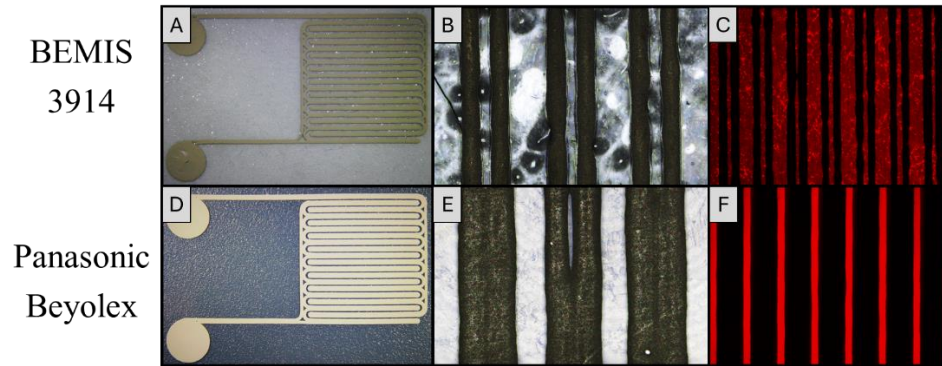


Figure 37. Comparison of additional substrate materials investigated. A) and D) Microscope imaging of printed continuous IDE structures. B) and E) Light scanning imaging of printed electrodes. C) and F) Transmission optical microscope image of substrate with printed conductive ink.

Fabrication quality analysis revealed substantial deposition quality differences between substrate materials, with BEMIS exhibiting noticeable surface roughness and poor ink adhesion characteristics. From the fabrication analysis we can observe the noticeable roughness and poor deposition quality that was achieved with the BEMIS substrate. As this substrate has not been developed for wearable sensing applications we can attribute the lesser deposition quality to both the surface roughness and surface chemistry. The inferior deposition quality can be attributed to both surface roughness and surface chemistry incompatibilities, as evidenced by significantly reduced ink trace widths compared to Beyolex and Intexar substrates in the light scanning results where the amount of ink trace width is significantly smaller than that of the Beyolex and Intexar substrates.

Post-curing microscope examination revealed visible cracking in BEMIS samples, potentially resulting from poor substrate wetting characteristics and material shrinkage under curing temperature conditions. We also observe cracking visible in the post cured microscope images, which could be due to the poor wetting characteristics of the BEMIS surface chemistry as well as potential material shrinkage under the curing temperatures. Both Beyolex and Intexar substrates demonstrated ideal printing characteristics with perfect fabrication yields and comparable print accuracy, exhibiting fully filled digit structures without post-curing defects. Both the Beyolex and Intexar substrates are shown to have ideal printing characteristics both having perfect yields during fabrication and having similar print accuracies with the digits being fully filled and defect free after curing.

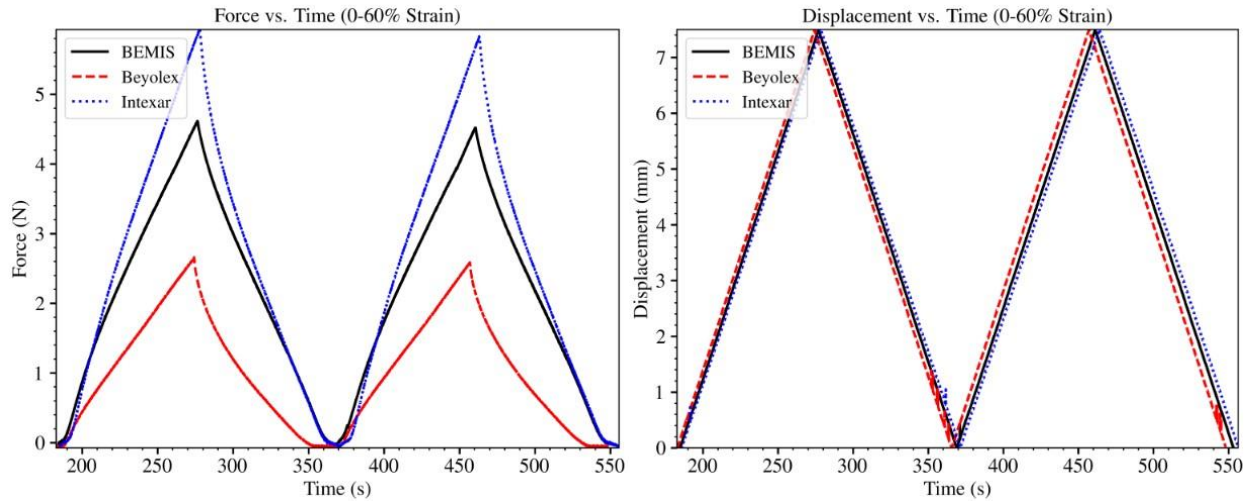


Figure 38. Pull test of results of different substrate films. (left) Force versus time plot for each substrate under 5mm/min of uniaxial strain. (right) Strain displacement profile followed by Mark 10 F305 system.

Mechanical characterization involved testing three samples per substrate material in both horizontal and vertical configurations through three cycles to 20% strain. Force-displacement analysis highlighted significant material property differences, with Beyolex demonstrating the lowest stiffness characteristics, requiring less than 3N force to achieve 60% strain. The force required versus time plot highlights some key material differences between the three substrates. Firstly, we can observe the lowest stiffness material to be the Beyolex, with it requiring less than 3N of force to pull the sample to 60% strain. BEMIS required approximately 5N tensile force for 60% strain during initial cycles. Intexar exhibited the highest stiffness with over 6N force requirements during first cycle extensions. All materials demonstrated slight force reductions in subsequent cycles, with BEMIS and Intexar substrates exhibiting excellent recovery responses at 5mm/min extension rates through extremely linear response characteristics in second and third extension cycles. All the materials saw a slight decrease in the required force after the first cycle. The BEMIS and Intexar substrates were found to exhibit excellent recovery responses at the 5 mm/min extension rate, with an extremely linear response shown in the second and third extension cycles. Beyolex displayed observable hysteretic behavior with force tapering prior to reaching 0% elongation, indicating extended relaxation time requirements.

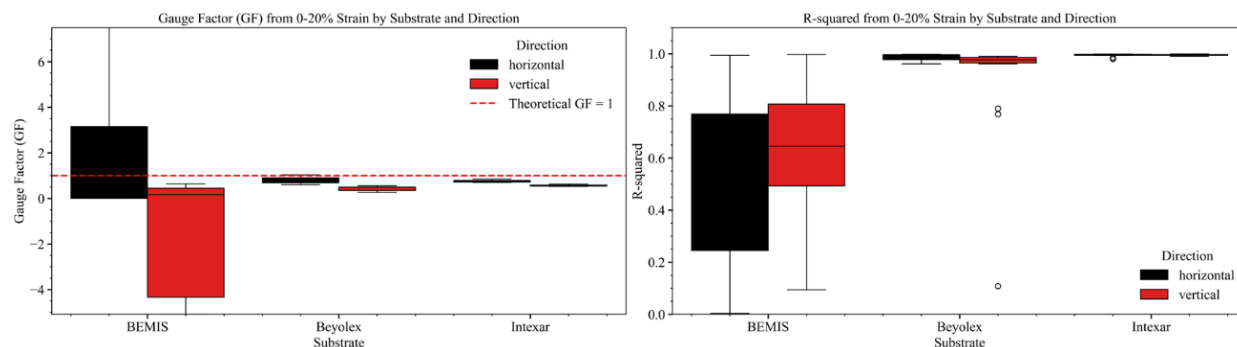


Figure 39. Substrate performance analysis. (left) Sensitivity GF plot for horizontal and vertical sensors. (right) Linearity analysis for both vertical and horizontal sensors.

Electrical performance analysis compared sensor sensitivities across substrate materials in both horizontal and vertical configurations through gauge factor calculations over the 0-20% strain range, necessitated by BEMIS sample failure at strains exceeding 20%. Next, we analyzed the sensors electrical performance by comparing the sensitivities of each substrate in both horizontal and vertical configurations. The gauge factor was calculated over a range from 0-20% strain as the BEMIS samples were found to fail at strains higher than 20%. In Figure 39 we compare the gauge factor (GF) of each substrate to the theoretically achievable IDE strain gauge of 1. The BEMIS material was shown to have the greatest variation which can be attributed to the poor adhesion of the conductive inks and cracks becoming visible in the conductive ink under strain.

Both Beyolex and Intexar materials demonstrated similar performance characteristics approaching unity GF values, with Intexar exhibiting the lowest variation due to reduced material hysteresis compared to Beyolex. The Beyolex material and Intexar have similar performances approaching a GF of 1. The Intexar material had the lowest variation which is believed to be due to the low hysteresis of the material when compared to the Beyolex. R-squared statistical analysis comparing percent capacitance change to ideal linear response revealed similar BEMIS deviation from optimal sensing performance, while both Intexar and Beyolex substrates achieved R-squared values exceeding 95%. In Figure 39 the R-squared statistics are calculated through comparing the percent change capacitance of each sensor to an ideal GF line of a perfectly linear line. In this we see a similar deviation in the BEMIS material, being far from the ideal sensing performance. Both the Intexar and Beyolex materials approached an R-squared of over 95%. Horizontal orientation testing demonstrated higher sensitivity and reduced variation compared to vertical orientation for both Beyolex and Intexar substrates. When comparing the horizontal and vertical configurations for the Beyolex and Intexar substrates we can see that the horizontal orientation has a higher sensitivity and slightly lower variation for both.

5.5 Sensor Orientation and Laser Cutting

Further optimization of HSCSG sensitivity and linearity characteristics led to the development of post-processing laser cutting procedures targeting material removal within inter-digit spaces. In an effort to further optimize the sensitivity and linearity of the HSCSGs we developed a post

processing laser cutting that removes material within the inter-digit spaces. We hypothesized that by removing material in these regions, the digit traces would be able to deform more freely and minimize the stress and strain exerted upon the print elements, which would both increase the gauge factor and durability of the sensors.

The processing sequence involved laser cutting single lines between adjacent elements prior to outer edge cutting for sensor release. . Light scanning analysis confirmed successful laser cutting implementation with precise positioning between IDE digits. The samples were then light scanned to analyze the results of laser cutting. The laser cut pathing is shown below in Figure A.

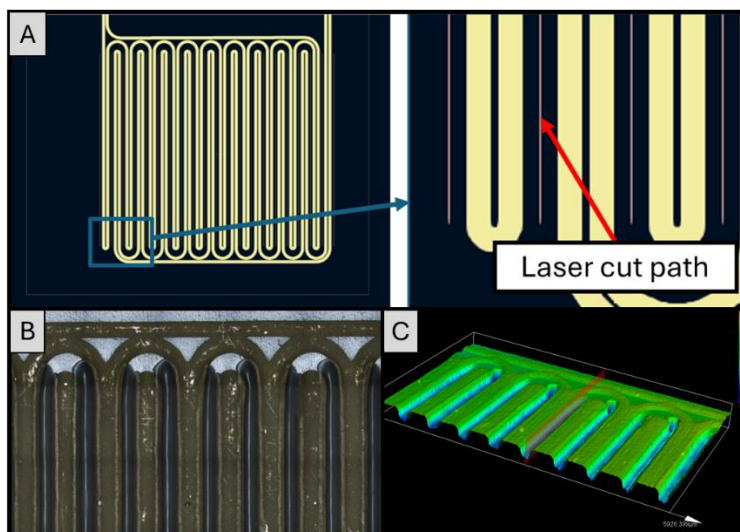


Figure 40. Laser cutting of Sensor Structures. A) Programmed laser cutting path. B) Light scanned surface of laser cut sensor structures. C) Light scanning analysis of laser cut sensor.

Depth measurements indicated average cutting depths of approximately $49.57\ \mu\text{m}$, representing approximately half the $100\ \mu\text{m}$ substrate thickness. The light scanning images shown in Figure C and D show that the laser cutting efforts were successful being centered in between the IDE digits. The laser cut depth was assessed to be approximately $49.57\ \mu\text{m}$ on average which is close to half of the $100\ \mu\text{m}$ film thickness. Attempts to achieve complete substrate penetration using higher laser powers resulted in damage to adjacent conductive ink paths, establishing the processing window limitations for this optimization approach. Higher laser powers were subsequently attempted in an effort to cut through the Intexar substrate completely but were found to damage the nearby conductive ink paths in the process.

Laser-cut samples underwent identical pull testing protocols with comparative analysis against Beyolex substrate and uncut Intexar samples. The laser cut samples were then tested following the same pull test process as the substrate comparison. In the figure below we compare the results to the Beyolex substrate and uncut Intexar following the same analysis procedure. Horizontally oriented laser-cut samples demonstrated gauge factor values exceeding unity with increased variation relative to uncut Intexar samples. The horizontally oriented laser cut samples

were found to produce a gauge factor higher than 1 with some larger variation than the uncut Intexar samples.

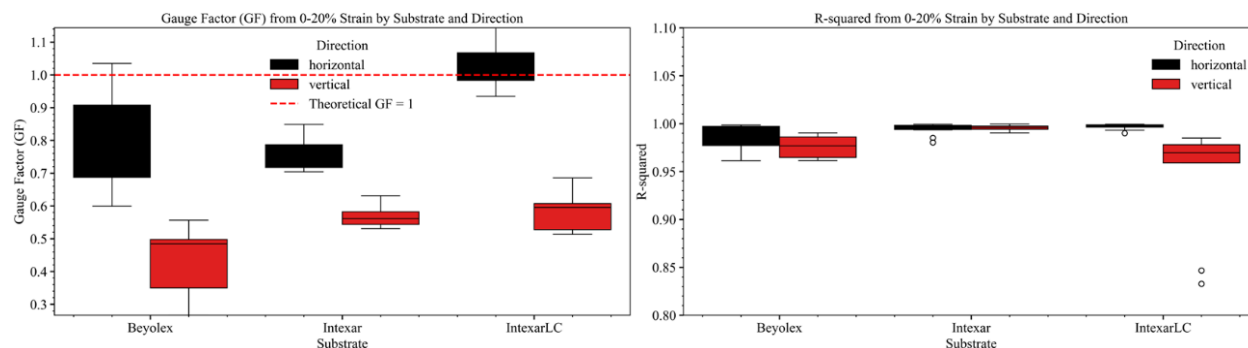


Figure 41. Sensitivity and Linearity analysis of Laser cut Intexar sensors compared to Beyolex and uncut Intexar. (left) Sensitivity GF for vertical and horizontal sensor configurations compared to theoretical GF of 1. (right) Linearity analysis of sensors.

In Figure 41 we see that the horizontal sample was also highly linear in the 0-20% range showing a tighter distribution compared to the uncut Intexar substrate. Vertically oriented laser-cut samples displayed reduced performance in both gauge factor and linearity metrics, attributed to minimal laser cut impact on this testing orientation where strain application occurs perpendicular to the cut line directions.

5.6 Durability Characterization

The durability and stability investigation of optimized Laser Cut Highly Stretchable Capacitive Strain Gauges (LSHSCSGs) examined long-term performance characteristics and maximum operational capabilities through systematic testing protocols. Finally, we set out to investigate the durability and stability of the optimized LSHSCSGs to understand their performance over their expected long-term use, as well as see their maximum performance range and capabilities. Cycle testing involved 30% strain amplitude repeated over 100 cycles at 5mm/min extension rate, representing a compromise between desired testing duration exceeding 1,000 cycles and data capture system limitations that prevented reliable operation beyond this threshold. This was performed through cycle testing the sensor with a strain of 30% which was repeated for 100 cycles, with a speed of 5mm/min. While this is lower than our goal of over 1,000 cycles, we experienced an unreliable data capture and control of the Mark 10 system when we exceeded this value and could only successfully retrieve data up to [this threshold].

The max elongation test was performed with the same speed and a maximum strain of 150% which was the highest strain that could be achieved before the 10 N load cell would exceed its maximum allowable force.

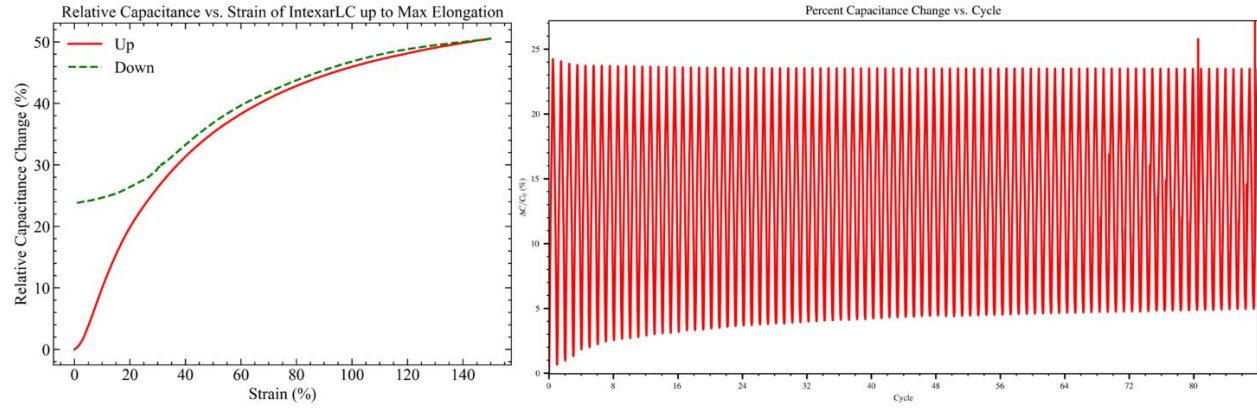


Figure 42. Life cycle performance analysis of LSHSCSGs. (left) Maximum elongation test results. (right) Cyclical testing results.

Durability validation demonstrated continued sensor functionality following cyclical testing, with minor zero-level shifts observed that can be attributed to extension rates exceeding the Intexar substrate relaxation time constants. The sensors durability was validated with it remaining functional after cyclical testing with a small zero level shift being observed which could be attributed to the pull-speed exceeding the relaxation time of the Intexar substrate. The maximum elongation test highlighted conductive inks ability to continue conducting under extremely high strains, we do however observe a noticeable plastic deformation with the relaxation cycle leaving the sensor with a higher initial capacitance than the unstretched state.

5.7 Summary of Sensor Optimization

The comprehensive optimization study established horizontally oriented sensors as the preferred configuration due to reduced strain concentration on individual elements, minimizing crack formation and discontinuity development that compromise linearity and capacitance performance consistency. The final optimized sensor design incorporates 300 μ m inter-digit spacing, 8-10 digit count, 5-10mm digit length, and Intexar substrate material with optional laser cutting post-processing for enhanced sensitivity applications. These parameters provide optimal balance between manufacturing reliability, electrical performance, mechanical compliance, and durability characteristics for wearable limb volume monitoring applications.

6. Development and Control of a Pneumatic McKibben Muscle-Based Limb Volume Phantom Model for Wearable Sensor Calibration

6.1 Background and Motivation

The development of accurate sensor calibration methodologies represents a critical challenge in wearable biomedical sensing applications. Current approaches to sensor validation for wearable strain gauges frequently rely on rigid approximations that fail to capture the complex biomechanical properties of human tissue. This limitation significantly impacts the accuracy and reliability of wearable sensors designed for clinical monitoring applications, particularly in lymphedema detection and management. Complete sensor structure development for real-world applications in their final form yields substantially more accurate and representative calibration data compared to purely uniaxial testing of small sub-sensor assemblies. Furthermore, implementing a calibration model that exhibits compliance characteristics similar to human tissue enables a comprehensive understanding of sensor optimization and packaging strategies for their intended applications.

Current Limitations in Sensor Calibration Methods

Existing methods for sensor validation of wearable strain gauges predominantly employ rigid approximations across various applications. For liquid metal strain gauges commonly utilized in biomechanics studies and muscle deformation monitoring, these sensors comprise elastomeric rubber containing either mercury-based (toxic) or non-toxic lower-performance liquid metal alloys [25]. The calibration of these strain gauges typically involves uniaxial tensile testing or stretching over known solid circular cross-sections to establish calibration models for the sensors.

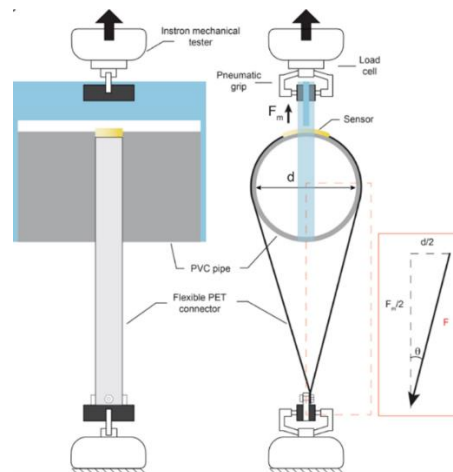


Figure 43. Rigid Circumferential Strain Gauge Testing Apparatus used for calibrating human monitoring sensors. Adapted from [33]

These methodologies present significant limitations as they fail to translate effectively to human subjects and their unique physiological characteristics. Primary concerns include:

1. Soft, non-uniform cross-sections: Human limbs exhibit complex geometry that deforms under applied strain gauge loads
2. Sensor-induced discomfort: Rigid sensors can cause discomfort and measurement inaccuracies when applied to compliant biological tissue
3. Incomplete sensor state testing: Applying loads and monitoring sensor output in incomplete states can lead to measurement misalignments during operational deployment

Rigid approximation methods enable researchers and engineers to understand expected values at different circumferences or curvatures but fail to provide insights into intermediate positions or transitions. This limitation restricts the ability to monitor slow, gradual changes over extended time periods, which is essential for the wearable sensor applications developed in this research.

6.1.1 Objectives and Requirements

This research aims to address the identified limitations through the development of a dynamic bio-phantom model with the following specific objectives:

Primary Objectives:

- Create a dynamic bio-phantom model capable of expanding its circumference by 25% to calibrate sensors for limb swelling monitoring applications
- Develop a compliant, soft system that prevents damage to sensitive sensors while providing representative characteristics of the compressible environment for which the sensors are being optimized
- Design a system large enough to accommodate multiple sensors for synchronous calibration and provide capabilities for calibrating integrated sensing sleeves for upper arm monitoring

Technical Requirements:

- Minimum diameter within normal range of an average person's arm, approximately 30 cm in circumference
- Pneumatic operation to provide inherent compliance, control, and safety characteristics
- Integration capability with available Mark 10 F305 universal tensile compression test machine

6.1.2 Design Constraints and Limitations

The development of the limb volume phantom model must address several critical constraints:

Operational Constraints:

- Non-contact measurement capabilities for accurate sensor calibration

- Low profile design to allow fully developed sensors and sleeves to be properly donned
- Pneumatic control and sealing requirements ensuring air-tight operation with puncture resistance

Geometric Requirements:

- Linearity for at least 24 cm length to accommodate upper arm sleeve calibration and development
- Cylindrical geometry to maintain consistent curvature throughout the calibration range
- Safety and Performance Constraints:
 - Pneumatic system safety under high-stress and deformation conditions
 - Repeatability and accuracy requirements for scientific measurement applications

6.2 Model Concept

The limb volume phantom model concept derives from anatomically inspired design considerations aimed at matching the profile of a standard upper arm region from elbow to shoulder. This approach ensures that the phantom model accurately represents the biomechanical environment encountered by wearable sensors in clinical applications. The selection of pneumatic actuation and control systems addresses the fundamental requirement for compliance while maintaining precise control over limb volume variations. Multiple potential solutions were evaluated to form a bio-phantom limb volume model addressing both objectives and constraints. Mechanical and hydraulic systems were deliberately excluded due to their rigid operation characteristics and potential safety concerns when operating under high stresses and deformations.

6.2.1 McKibben Muscle Technology

To achieve the desired long, linear, and cylindrical expansion characteristics required for sensor development, this research investigated the implementation of McKibben artificial muscles as the primary actuation mechanism.



Figure 44. Example of McKibben Artificial muscles and different material constructions. Adapted from [99], [100]

McKibben artificial muscles, also known as Pneumatic Artificial Muscles (PAMs), represent a well-established actuation technology with unique characteristics suitable for bio-phantom applications. A PAM operates by incorporating a thin-walled rubber bladder inside an axially stiff but radially compliant sheath. When compressed air is supplied to the PAM, the internal bladder expands against the braided sheath, which does not stretch axially, causing the actuator to shorten and increase its radius while generating pulling forces if connected to a load. The force exerted occurs in the axial direction, allowing the muscle to perform external work. This operational principle provides the fundamental mechanism for controlled radial expansion required for the limb volume phantom model [101], [102].

The McKibben muscle technology offers several advantages for limb volume phantom applications:

1. Inherent Compliance: The pneumatic operation provides natural compliance characteristics similar to biological tissue
2. Precise Control: Pneumatic pressure regulation enables accurate control of expansion characteristics
3. Safety: Air-based actuation eliminates safety concerns associated with high-pressure hydraulic systems
4. Scalability: The technology can be readily scaled to accommodate various limb sizes and expansion ranges
5. Repeatability: Pneumatic control systems provide excellent repeatability for scientific measurement applications

The integration of McKibben muscle technology into the limb volume phantom model represents a novel approach to addressing the limitations of existing sensor calibration methodologies while providing the compliance and control characteristics essential for accurate wearable sensor validation.

6.2.2 Technological Significance

PAMs represent critical actuator technologies distinguished by inherent compliance, exceptional power-to-weight ratios, and biomimetic functionality [103]. These characteristics enable unique capabilities including intrinsically safe human-robot interaction, robust locomotion in unstructured environments, and dexterous manipulation of fragile objects [103],[99]. The McKibben actuator, developed in the 1950s, serves as the archetypal PAM configuration, consisting of a pneumatically inflatable elastomeric bladder constrained by an outer braided sheath[99].

6.2.3. Fundamental Operating Principles

Classical linear control theory proved inadequate for managing the highly non-linear behavior and significant mechanical hysteresis inherent in PAMs [104], [105]. The resurgence began with Bridgestone's commercialization of "Rubbertuators" and MacDonald Dettwiler's ROMAC system [99], [106], coinciding with advances in computational tools and non-linear control strategies.

The McKibben actuator comprises three primary components:

- Inner Bladder: Airtight elastomeric tube (natural rubber, latex, or silicone) containing pressurized fluid [99], [104], [107], [108].
- Braided Sheath: Inextensible fiber mesh (nylon, polyester, or Kevlar) with helical weave pattern [99], [106], [107]
- End Fittings: Mechanical interfaces providing pneumatic sealing and load attachment [106]

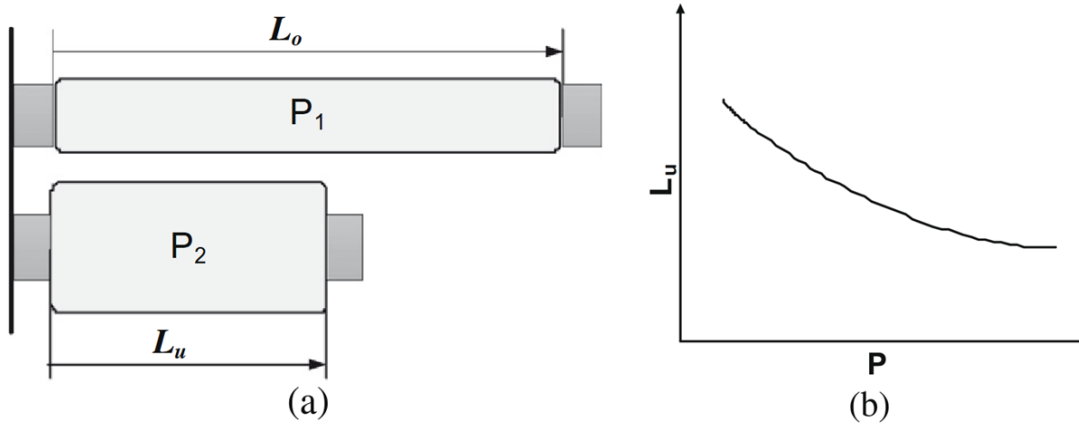


Figure 45. Fundamental operating principles of PAMs. (left) Contraction mechanism. (right) General contraction trend for an applied internal pressure. Adapted from [105]

The actuation mechanism converts pneumatic pressure to mechanical work through geometric reconfiguration. Internal pressure causes radial bladder expansion, forcing angular changes in the braided sheath fibers, resulting in axial contraction and tensile force generation [99], [104], [106]. Performance metrics include contraction ratios of 25-50% and power-to-weight ratios exceeding 1 kW/kg [99].

6.2.4 Material Systems and Fabrication Technologies

Traditional Silicone-Based Systems

Silicone remains the conventional bladder material, fabricated through casting or molding processes [101], [103], [109]. While providing excellent elasticity and compliance, silicone contributes significantly to non-linear and hysteretic behavior through friction at the bladder-sheath interface [102], [107], [108]. Performance characteristics of silicone-based systems serve as baseline comparisons for advanced materials [110].

Thermoplastic Polyurethane (TPU) Integration

TPU offers compatibility with additive manufacturing processes, including Fused Deposition Modeling (FDM) and Selective Laser Sintering (SLS) [111], [112], [113]. Direct 3D printing enables monolithic designs with complex internal geometries, integrated fluidic channels, and

variable wall thicknesses [111], [113]. TPU demonstrates superior durability, higher stiffness, and enhanced abrasion resistance compared to silicone [112].

Hybrid Bladderless Fabric Architecture

Naclerio and Hawkes developed a transformative bladderless design utilizing airtight, bias-cut technical fabric (silicone- and urethane-impregnated ripstop nylon) [114]. This architecture eliminates the bladder-sheath interface, directly addressing the primary source of friction and hysteresis.

Performance Improvements:

- Hysteresis reduction to <1% (compared to 10-20% in traditional designs) [114]
- Enhanced dynamic response through unobstructed airflow [114], [115]
- Exceptional fatigue life exceeding 100,000 cycles [114]
- Foldability when depressurized for deployable applications [114], [116], [117]

6.2 Design and Development

6.2.1 Design Rationale and Technology Selection

The development of the LVPM necessitated a comprehensive evaluation of alternative actuation mechanisms to achieve the stringent requirements for wearable sensor calibration applications. The selected pneumatic air-based McKibben muscle configuration emerged from systematic analysis of fundamental limitations inherent in alternative approaches. Liquid-based actuation systems were eliminated due to gravitational effects that would inevitably cause non-uniform circumference distribution along the longitudinal axis, compromising the geometric consistency required for accurate sensor calibration. The inherent density variations in liquid systems under gravitational influence would introduce systematic errors in the phantom's dimensional stability, particularly during extended calibration procedures where consistent geometry is paramount.

Mechanical expansion systems, while offering potentially high force capabilities, were rejected due to their tendency to create discrete gaps and inflection points in the curvature profile of the expanding surface. These discontinuities would fundamentally compromise the smooth cylindrical geometry essential for accurate strain gauge response characterization. The McKibben muscle architecture provides continuous, uniform radial expansion characteristics while maintaining the axial compliance necessary for comprehensive sensor testing protocols across the full operational envelope.

6.2.2 Iterative Development Process and Design Evolution

The development process encompassed four distinct design iterations, each systematically addressing specific fabrication challenges and performance limitations identified through rigorous testing protocols and failure analysis. This iterative approach enabled progressive refinement of

both design parameters and manufacturing processes, ultimately achieving the performance specifications required for precision sensor calibration applications.

Version 1—Design Analysis and Failure Mechanisms: The initial prototype encountered significant fabrication challenges, particularly in the execution of ripstop fabric seaming operations where the material's inherent characteristics posed substantial manufacturing difficulties. The miniaturized silicone components implemented in this iteration resulted in insufficient adhesive surface area, fundamentally compromising the bond strength at the critical ripstop-to-silicone interface. Post-failure analysis revealed that the reduced contact area created stress concentration factors that exceeded the ultimate strength of the sil-poxy adhesive system under operational pressures. This configuration exhibited premature failure through progressive bond rupture propagation, initiating at the highest stress concentration points and propagating along the adhesive interface under cyclic loading conditions.

Version 2—Scaling Optimization and Mechanical Analysis: Version 2 addressed the component sizing deficiencies identified in the initial prototype but inadvertently introduced new failure modes related to geometric scaling effects. The reduced diameter configuration created unfavorable stress concentrations during pressurization cycles, where the differential expansion characteristics between the compliant ripstop fabric and rigid silicone cap elements generated complex stress states. The rigid silicone cap elements remained geometrically stationary while the ripstop fabric underwent significant radial expansion, creating high mechanical advantage conditions that systematically exceeded the ultimate bond strength of the sil-poxy adhesive system. This failure mode manifested as catastrophic delamination at the interface, with crack propagation rates accelerated by the cyclic loading inherent in operational use.

Version 3—Dimensional Optimization and Performance Enhancement: Version 3 incorporated a strategically larger 5 cm radius design, specifically optimized for compatibility with anthropometric dimensions representative of the target application domain. The enhanced dimensional characteristics provided several critical improvements including an integrated base mounting mechanism designed for improved structural integrity under operational loads, and a specialized silicone-printed sealing port engineered for reliable pneumatic supply connection with minimal leakage potential. The improved dimensional compatibility with sensor sleeve integration systems significantly enhanced the practical utility of the phantom for comprehensive sensor validation protocols. Despite these improvements, Version 3 revealed limitations in manufacturing complexity, particularly in the base silicone fabrication processes which proved excessively complex for reliable production. Additionally, the overall assembly exhibited unacceptable bulk characteristics that compromised the practical implementation for sensor testing applications where compact form factors are essential for laboratory integration.

Version 4 - Manufacturing Process Optimization: Version 4 implemented a comprehensive design refinement strategy focusing on manufacturing optimization while maintaining performance specifications. The design incorporated minimized overall diameter characteristics

for enhanced portability and laboratory integration, while simultaneously implementing enhanced base expansion characteristics through systematic geometric optimization. The increased utilization of resin-printed components provided improved dimensional accuracy and manufacturing repeatability compared to previous silicone-based approaches. The integration of through-hole resin components enabled streamlined assembly processes that reduced manufacturing complexity while maintaining structural integrity requirements.

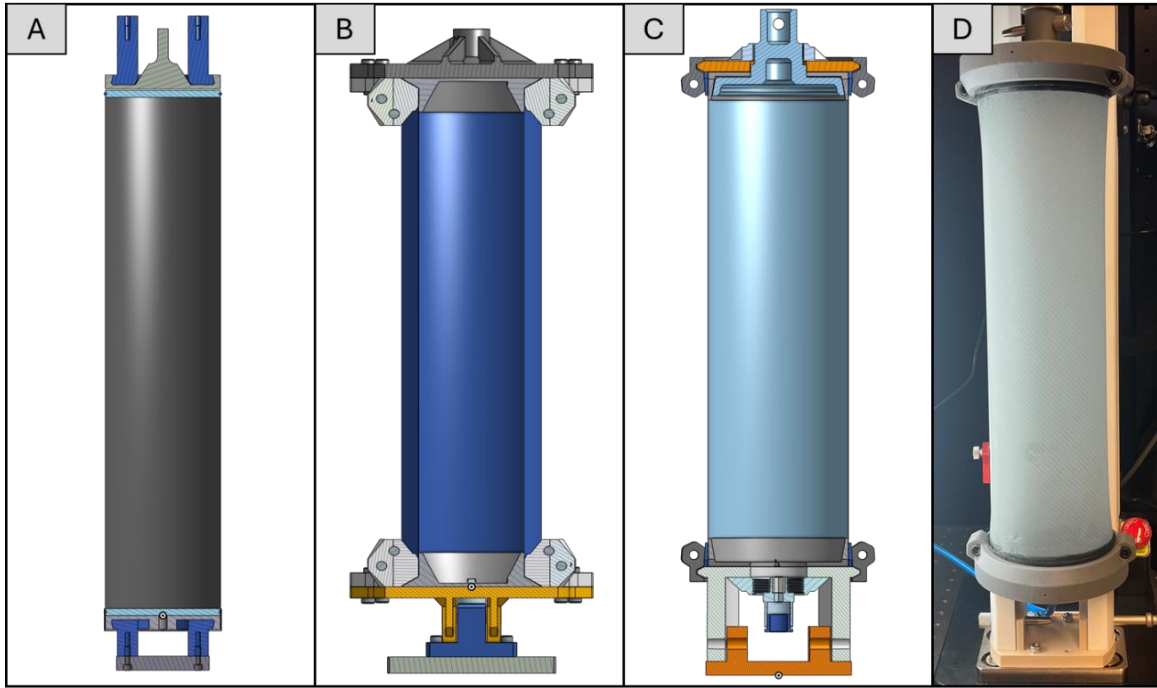


Figure 46. LVPM iterations showcasing the different fabrication techniques and strategies investigated to develop a working and optimized model. A) Version 1-2, low profile and simple proof of concept. B) Version 3-4, rigid but too bulky. C) Version 5, low profile, airtight, and simplified fabrication. D) Fabricated prototype of the Version 5 design.

6.2.3 Advanced Fabrication Process Development

The development of standardized fabrication protocols represents a critical contribution to the reproducible manufacturing of precision pneumatic actuators for sensor calibration applications. The established protocol encompasses sequential operations optimized for consistent quality and dimensional accuracy across production batches.

Surface Preparation and Activation Protocols: The material preparation sequence initiates with comprehensive component cleaning utilizing isopropyl alcohol (IPA) degreasing procedures designed to remove manufacturing residues and surface contaminants that could compromise adhesive bond strength. Subsequent oxygen plasma cleaning provides surface activation through the generation of reactive functional groups that enhance adhesive wetting characteristics and ultimate bond strength. Critical inspection procedures ensure the identification and removal of

sharp edges or surface irregularities on internal forming components that could initiate stress concentrations or cause premature failure during operational cycling.

Precision Fabric Assembly Methodology: The fabric assembly process requires precise ripstop fabric cutting at 45-degree bias orientation relative to the material's woven structure, with carefully controlled 1-inch seam allowances to ensure adequate bonding area. The bias orientation maximizes the fabric's compliance characteristics while maintaining structural integrity under pressurization. Internal ripstop form installation with controlled fabric wrapping ensures proper pre-tensioning and geometric accuracy, while external ripstop form positioning provides essential dimensional control during the critical adhesive bonding phase.

Adhesive Application and Curing Optimization: The adhesive application protocol utilizes silicone with controlled application via squeegee technique, ensuring uniform distribution through systematic dollop placement at predetermined intervals along the bonding surface. The top ripstop layer folding and compression sequence, executed with a secondary squeegee, enables controlled excess adhesive removal while maintaining optimal bond line thickness. The strategic maintenance of 1-inch uncured gaps on both assembly ends accommodates subsequent silicone cap installation without compromising the primary seam integrity.

Quality Control and Assembly Validation: The curing and assembly sequence includes internal form removal post-curing to verify proper release characteristics and dimensional accuracy. Subsequent internal form reinstallation provides dimensional support during final assembly operations, while silicone cap preparation utilizing IPA and plasma cleaning protocols ensures optimal adhesive conditions for the final sealing operations.

6.2.4 Fabrication Process Validation and Optimization Study

The systematic fabrication validation study provided comprehensive process optimization data essential for establishing manufacturing protocols capable of producing consistent, high-quality phantoms suitable for precision sensor calibration applications.

Material Processing Protocol Validation: The material processing sequence utilized a 60 × 40 cm ripstop fabric sheet prepared through precision cutting protocols designed to maintain fabric integrity while achieving the geometric accuracy required for consistent assembly. Grain alignment verification procedures utilizing cutting mat reference lines ensured proper fabric orientation relative to the stress patterns experienced during operational use. The implementation of 45-degree bias marking using precision geometric templates, combined with rotary cutting techniques, produced clean edge preparations essential for optimal adhesive bonding characteristics.

Critical Process Parameter Identification: Systematic observation during the validation study revealed that squeegee pressure application caused significant fabric orientation distortion during longitudinal movement, indicating the need for modified application techniques to maintain fabric alignment accuracy. Surface preparation via controlled sandpaper scuffing demonstrated

measurable enhancement of adhesive bond strength through increased surface area and mechanical interlocking mechanisms. The implementation of comprehensive IPA cleaning protocols proved essential for achieving consistent bond quality across multiple fabrication cycles.

Next-Generation Design Considerations: The analysis of Version 3 performance characteristics identified specific areas for continued optimization in Version 4, including reduced fixturing requirements to enable streamlined sensor integration procedures, enhanced silicone cap geometry designed for improved base expansion characteristics, and optimized radial expansion control through advanced geometric constraint mechanisms.

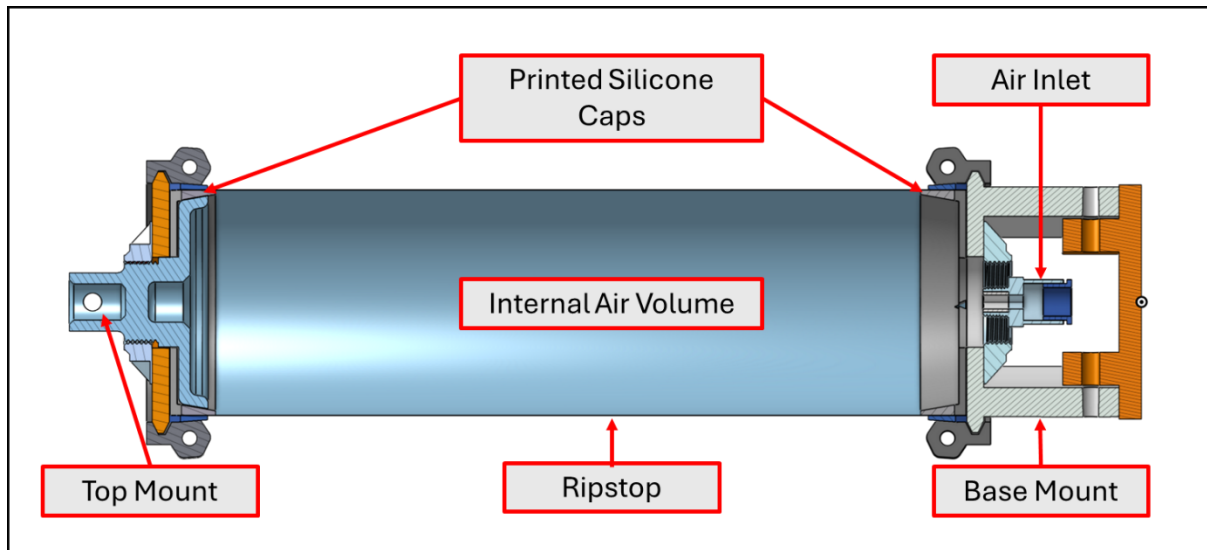


Figure 47. Cross-Section Schematic of final LVPM version, showcasing the complete assembly with its internal sealed volume forming the McKibben Muscle PAM, and rigid connectors that precisely interface with the Mark 10 F305 Test machine.

6.3 Operational Framework and Advanced Measurement Techniques

6.3.1 Integrated System Architecture and Control Implementation

The LVPM operational framework represents a sophisticated integration of multiple electro-mechanical subsystems designed to provide comprehensive diameter control and real-time monitoring capabilities essential for precision sensor calibration applications. The system architecture enables independent and combined control of internal pneumatic pressure and external mechanical forces, providing unprecedented flexibility in replicating physiological limb volume variations.

The internal air pressure regulation system utilizes the μ Pump desktop air pressure control system [118], providing precision pneumatic actuation through PC-based serial communication protocols. The system's capability for precise pressure control across the operational range of 0-500 mbar enables fine-resolution diameter adjustments essential for comprehensive sensor

response characterization. The integration of real-time pressure feedback ensures system stability and enables closed-loop control implementation for enhanced accuracy and repeatability.

The universal testing machine provides supplementary tension or compression forces through controlled displacement, enabling bidirectional control of McKibben muscle geometry through external mechanical constraint or assistance of the pneumatic expansion process. This dual-actuation approach significantly expands the operational envelope of the phantom while providing independent control variables for comprehensive sensor testing protocols. The coordination of pneumatic and mechanical actuation enables exploration of complex loading scenarios that more accurately represent physiological conditions encountered in lymphedema monitoring applications.

The integrated safety system provides multiple layers of protection against equipment damage and operational hazards through continuous monitoring of critical system parameters. Real-time internal air pressure monitoring ensures adherence to safe operational parameters, while integrated force measurement and logging through calibrated load cell instrumentation provides comprehensive documentation of system state throughout testing procedures. The maximum operating pressure limitation of 500 mbar, representing 50% of the empirically determined failure threshold, provides a conservative safety factor of 2.0 to account for potential software failures or unexpected system behavior. This safety limit implementation within the Pump 2.0 microcontroller firmware ensures failsafe operation independent of higher-level control software functionality.

The Mark-10 F305 automatic stop feature configuration for 100 N force threshold with persistent exception handling prevents system damage through automatic motion termination when force limits are exceeded. This safety interlock system prevents continued operation following communication failures, ensuring system protection even in scenarios where the controlling software loses communication with the hardware after motion commands have been transmitted.

6.3.2 Advanced Camera-Based Measurement System Development

The development of non-contact measurement techniques became essential due to the fundamental limitations of traditional contact measurement methods when applied to the highly compliant LVPM surface. Digital calipers and mechanical contact probes induced significant surface deformation in the compliant phantom structure, introducing measurement errors that exceeded the precision requirements for sensor calibration applications. The surface compliance characteristics, while essential for realistic sensor interaction, created challenges for accurate dimensional measurement that required innovative solutions. The systematic evaluation of available measurement technologies revealed fundamental limitations in several approaches commonly used for precision dimensional measurement. Laser-based detection systems were eliminated due to their inherent complexity and critical alignment requirements that would be difficult to maintain in the dynamic testing environment. The requirement for precise beam

alignment and potential interference from surface characteristics made these systems impractical for routine calibration procedures. Ultrasonic and laser ranging technologies were similarly rejected due to their reliance on precise alignment and potential sensitivity to surface properties that could vary during testing procedures.

Camera-based silhouette imaging emerged as the optimal solution due to its rapid acquisition capabilities and software-configurable focus optimization that enables adaptation to varying test conditions. The implementation of silhouette imaging techniques effectively mitigated the effects of not having telecentric lenses, which would otherwise introduce perspective distortion errors in diameter measurements. The silhouette approach provides robust edge detection capabilities that are less sensitive to surface variations and lighting conditions compared to alternative optical measurement techniques. The imaging system utilizes a Pixelink PL-D795CU-T camera featuring 2/3" sensor format with 5.0MP resolution and C-Mount USB 3.0 interface for high-speed data acquisition. The camera is equipped with a Navitar HR F2.8/5mm lens configured at f/16 aperture to maximize depth of field characteristics, thereby minimizing focus sensitivity and improving measurement consistency across the operational range. The custom 3D-printed mounting adapter provides vibration isolation capabilities while enabling dual-axis translation stage integration for precise positioning and alignment procedures.

The strategic 25 cm standoff distance represents an optimized balance between edge resolution capabilities and fisheye distortion minimization. This distance provides sufficient resolution for sub-millimeter measurements while reducing the angular deviation from the lens center to the LVPM edge, thereby minimizing the geometric distortion that could compromise measurement accuracy. The standoff distance optimization considered both the lens characteristics and the operational envelope of the phantom system to ensure consistent measurement performance across all test conditions.

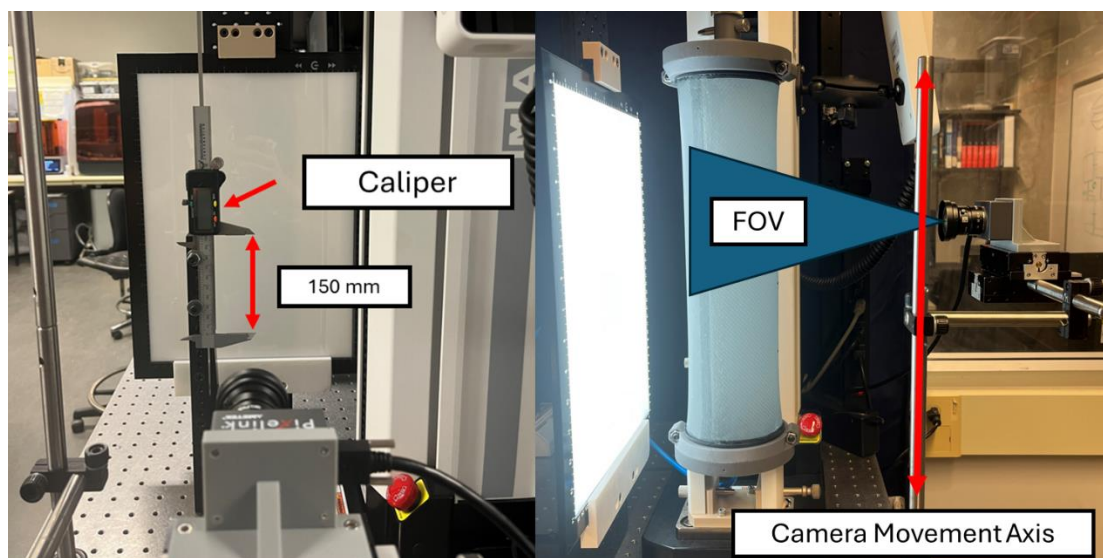


Figure 48. LVPM Image Measurement calibration and validation setup.

Pixel-to-micrometer calibration procedure utilizes precision digital calipers set to 150.00 mm positioned at the LVPM center plane to minimize lens distortion effects and establish the fundamental measurement reference. The calibration is performed specifically at the phantom's center plane where the optical axis intersects the measurement region, ensuring optimal accuracy in the primary measurement zone. Focus optimization procedures utilize a fine-pitch measurement rule positioned at the system centerline to achieve optimal sharpness across the measurement region. The geometric alignment validation includes bubble level verification for optical axis alignment and squareness validation using precision square references against both the camera body and the Mark-10 F305 test machine. The LVPM maintains squareness with the test machine through its bolted mounting bracket configuration, ensuring consistent geometric relationships throughout the measurement range. Fine adjustment procedures utilizing precision linear motion stages enable centering of the silhouette image within the camera's field of view, a critical requirement for measurement accuracy and consistency.

6.3.3 Edge Detection Algorithm Development and Validation

The development of sophisticated edge detection algorithms represents a critical advancement in precision measurement techniques for compliant surface characterization. The transition from binary image data to accurate diameter measurements requires robust algorithms capable of handling surface variations, sensor attachments, and alignment imperfections that are inherent in practical calibration applications.

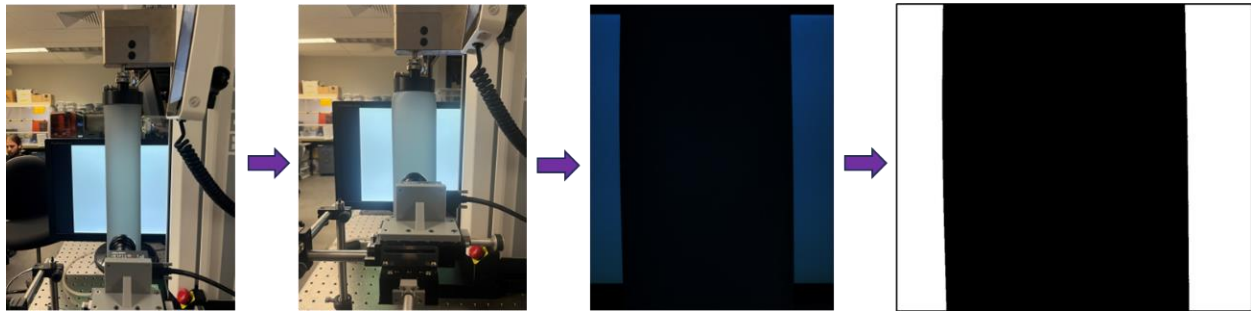


Figure 49. LVPM Image measurement process outline.

The preprocessing pipeline implements strategic image cropping to eliminate regions of high optical distortion while maintaining measurement accuracy. Vertical cropping to a 7.5 cm span centered on the lens optical axis eliminates high-distortion regions at the image periphery where lens characteristics introduce measurement errors. Horizontal cropping to 5 cm margins reduces computational requirements while minimizing noise influence from regions outside the measurement zone. This region of interest optimization significantly improves processing efficiency while maintaining measurement accuracy across the operational range.

The initial algorithmic approach utilized direct black pixel counting per horizontal image row, operating under the assumption of perfect camera-to-LVPM alignment. This simplified approach provided computational efficiency and could achieve acceptable accuracy under ideal

alignment conditions. However, systematic testing revealed significant susceptibility to surface-mounted sensors and alignment variations that are unavoidable in practical calibration scenarios. The algorithm's fundamental assumption of perfect horizontal alignment proved limiting when sensors or other surface features disrupted the ideal cylindrical silhouette.

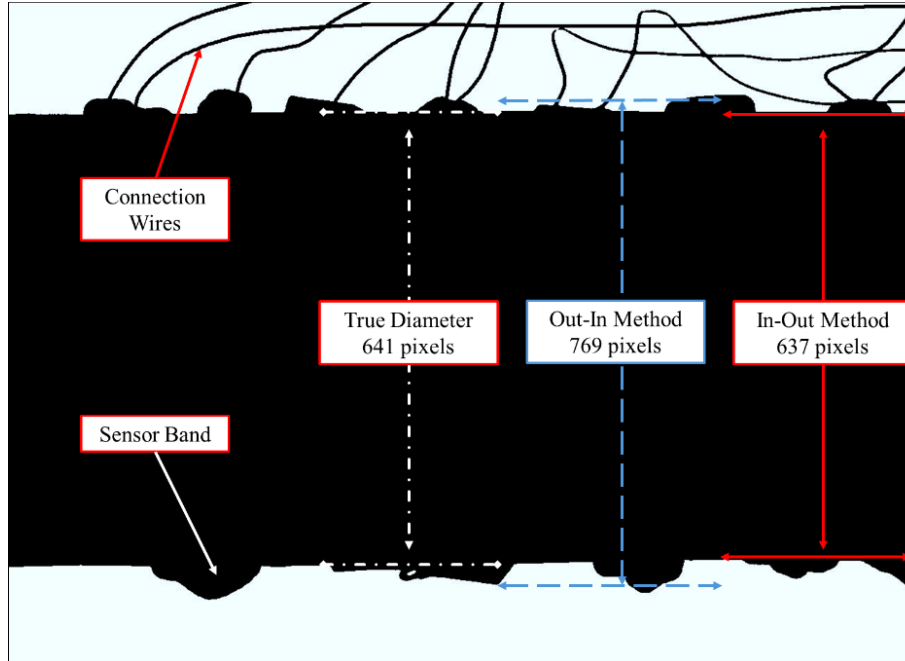


Figure 50. LVPM Image measurement edge case. Showing difficulties in estimating true diameter with the inclusion of sensors on the LVPM. Ground truth diameter shown in white. Initial outside-in technique shown in blue. Refined Inside-out method shown in red.

Enhanced Statistical Edge Detection Implementation: The second-generation algorithm incorporated statistical analysis techniques for outlier rejection and median-based edge determination to improve robustness against surface variations. This approach attempted to minimize the influence of sensor attachments and surface irregularities through statistical filtering of edge detection results. However, testing revealed persistent accuracy limitations with 780 pixels predicted versus 648 pixels actual diameter, indicating continued sensitivity to surface artifacts that could compromise calibration accuracy.

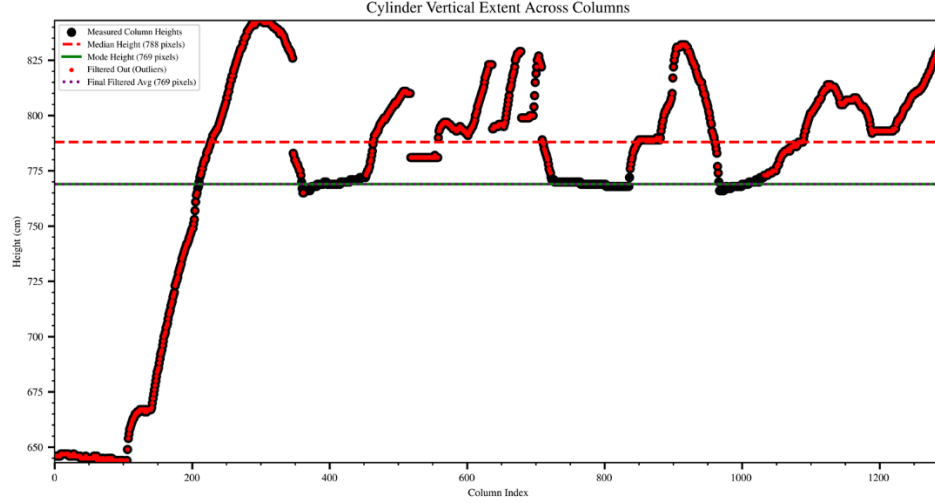


Figure 51. Initial edge detection and measurement technique resultant diameter estimation.

Mode-Based Boundary Detection with Outlier Rejection: The third algorithmic iteration implemented mode-based edge detection incorporating outlier rejection using two-standard-deviation bounds to improve measurement consistency. This approach demonstrated improved accuracy with 644 pixel prediction compared to previous methods but maintained overestimation tendencies that required validated bounds across the operational diameter range. The algorithm's performance remained dependent on proper characterization of the outlier rejection bounds, limiting its robustness across varying test conditions.

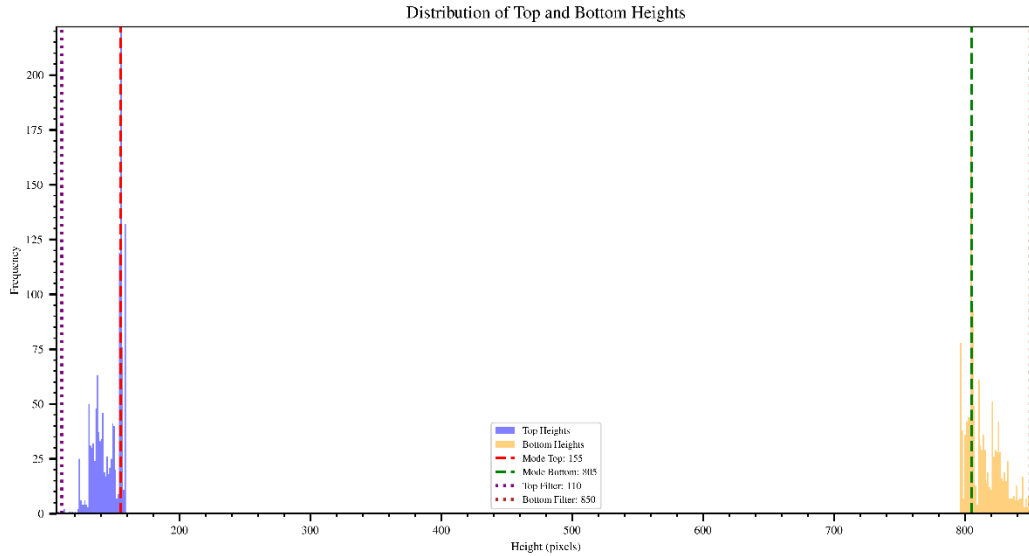


Figure 52. Mode-Based boundary detection with outlier rejection analysis results for estimated diameter.

The final algorithmic implementation utilizes minimum upper and lower edge values for diameter calculation, representing a paradigm shift toward conservative measurement approaches that prioritize consistency over absolute accuracy. This method demonstrates exceptional computational efficiency and repeatability characteristics that are essential for real-time control applications. The algorithm exhibits robust performance against surface artifact interference,

achieving 637 pixel diameter prediction with -1.698% error relative to the 644 pixel ground truth measurement. The consistent underestimation characteristics of the inside-out method enable implementation of linear correction factors that can be validated across the operational range. This systematic bias, while requiring correction, provides predictable behavior that enhances the algorithm's suitability for control applications where consistency is more critical than absolute accuracy.

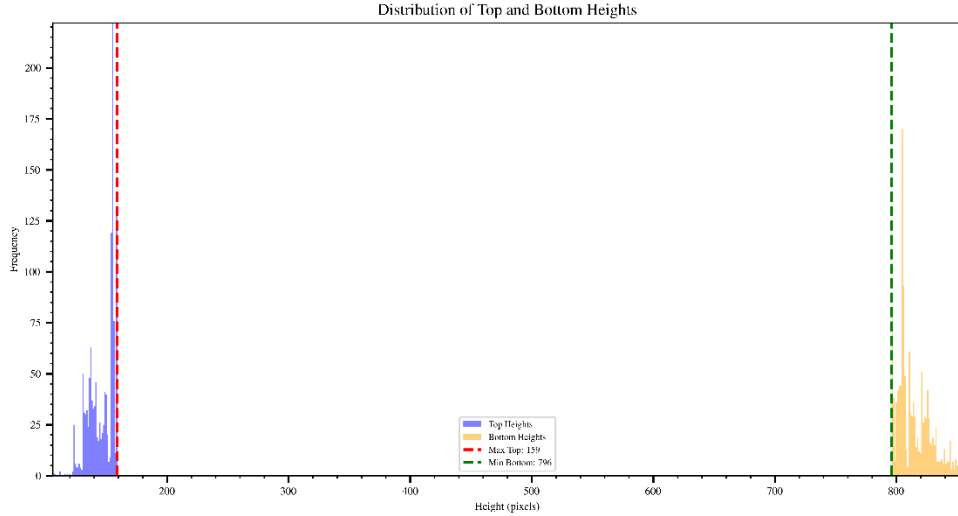


Figure 53. Final Inside-out edge detection algorithm.

The inside-out method requires operation within the linear LVPM region where straight edge profiles are maintained throughout the measurement zone. Non-compliance with these geometric constraints results in significant diameter underestimation that cannot be corrected through simple linear scaling. The algorithm's performance depends critically on maintaining the phantom within its linear operational region, emphasizing the importance of proper system characterization and operational envelope definition.

6.4 Comprehensive System Characterization and Performance Validation

6.4.1 Research Objectives and Characterization Framework

The comprehensive characterization of the LVPM system addresses four critical performance parameters that directly influence the system's suitability for precision sensor calibration applications. These parameters form the foundation for understanding the system's capabilities and limitations, enabling proper implementation of sensor validation protocols. The primary objective involves verification of the system's capability to achieve a minimum 25% circumference increase within the established safe operating parameters. This requirement derives from the physiological variations observed in lymphedema patients, where circumference changes of this magnitude are clinically significant. The characterization must demonstrate that the achieved range exceeds design requirements while maintaining operational safety margins. Additionally, the determination of achievable circumference control resolution with a target accuracy of 0.5% ensures that the

system can provide the precision necessary for accurate sensor calibration across the full operational range.

The linearity characterization addresses the critical requirement for uniform diameter characteristics across the usable LVPM length, ensuring that sensor calibration results obtained from localized measurements can be extrapolated to the complete sensor array. The identification of non-linear regions near end cap constraints directly impacts sensor mounting strategies and calibration protocol development. Understanding these geometric limitations enables optimization of sensor placement and calibration procedures to maximize accuracy while avoiding regions of compromised measurement reliability.

Repeatability and Hysteresis Evaluation Framework: The repeatability evaluation encompasses comprehensive hysteresis characterization across operational cycles to understand the system's behavior under repeated loading conditions. This analysis is essential for understanding the long-term stability characteristics required for extended calibration protocols where consistent performance over multiple cycles is critical. The evaluation must demonstrate that the system maintains calibration accuracy over the operational lifetime expected in research and clinical applications.

6.4.2 Operational Range and Resolution Performance Analysis

The range and resolution characterization utilized sophisticated automated pressure and displacement sweeps conducted across the complete operational envelope to ensure comprehensive coverage of all achievable system states. Each test sequence implemented incremental pressure increases until either maximum force threshold (within 10% tolerance) or maximum operating pressure (500 mbar) was achieved. This systematic approach ensures that the characterized performance envelope represents the actual operational capabilities under realistic constraints. The automated sweep methodology provides unprecedented insight into the system's behavior across the operational space, revealing performance characteristics that would be difficult to identify through manual testing procedures. The systematic data collection enables statistical analysis of system performance and identification of optimal operating regions for specific calibration requirements.

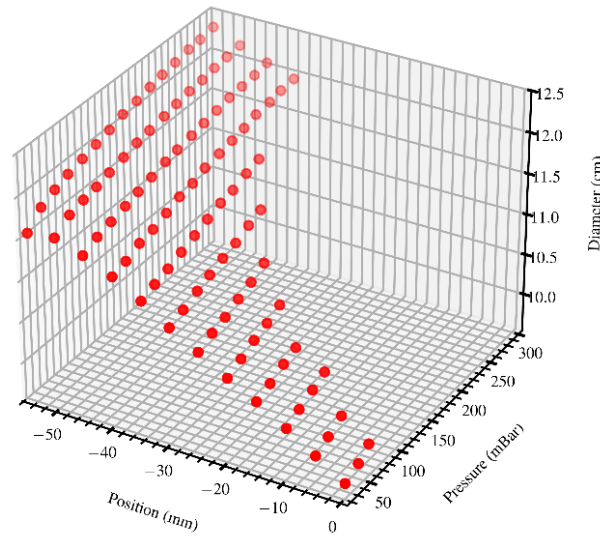


Figure 54. LVPM mapped performance space with 3D visualization of the resultant diameter versus input position and pressure.

The comprehensive characterization revealed system performance that exceeds all design requirements for sensor calibration applications. The achieved minimum diameter of 9.7 cm and maximum diameter of 12.5 cm provide a total diameter range representing a 28.87% increase that significantly exceeds the 25% design requirement. This performance margin ensures that the system can accommodate sensor calibration requirements across the full range of physiological variations encountered in lymphedema monitoring applications. The resolution characterization demonstrated that sub-0.5% diameter changes are consistently achievable through 20 mbar pressure increments across the entire operational range. This resolution performance ensures that the system can provide the precision necessary for accurate sensor calibration while maintaining the fine control required for comprehensive response characterization. The consistent resolution across the operational range eliminates the need for variable calibration procedures at different diameter settings.

6.4.3 Advanced Linearity and Repeatability Analysis

The linearity characterization employed a sophisticated experimental approach utilizing systematic camera positioning along the LVPM longitudinal axis at precisely controlled 7 cm increments. This positioning strategy ensures comprehensive coverage of the phantom's length while providing overlapping measurement regions that enable validation of measurement consistency. Each positioning location underwent complete pressure sweep cycles with comprehensive silhouette capture and edge detection processing to generate detailed spatial characterization data.

The experimental design incorporates four discrete camera positions with carefully controlled overlapping fields of view to ensure continuous coverage of the phantom's operational length. This overlapping approach enables identification of measurement discontinuities and provides validation of the edge detection algorithm's performance across varying geometric conditions. The characterization encompassed two critical operational extremes to bound the system's performance envelope. The minimum expansion configuration utilized 50 mbar pressure with 37 cm total phantom length, representing the system's most extended operational state. The maximum expansion configuration employed 475 mbar pressure with 30 cm total length achieved through 7 cm mechanical compression, representing the system's most compressed operational state. This comprehensive approach ensures that the linearity characterization encompasses the full operational envelope.

The captured silhouette images underwent comprehensive processing using the validated edge detection protocol with systematic manual alignment of overlapping regions to compensate for camera field-of-view distortions at higher expansion parameters. The manual alignment process, while labor-intensive, ensures accuracy in the final dataset by eliminating systematic errors introduced by automatic alignment algorithms that might not properly account for the complex geometric relationships present in the overlapping regions. The data processing methodology addresses the challenges introduced by camera field-of-view distortions that become more pronounced at higher expansion parameters due to the reduced phantom length. The systematic approach to alignment ensures that the final dataset provides accurate representation of the phantom's geometric characteristics across the operational range.

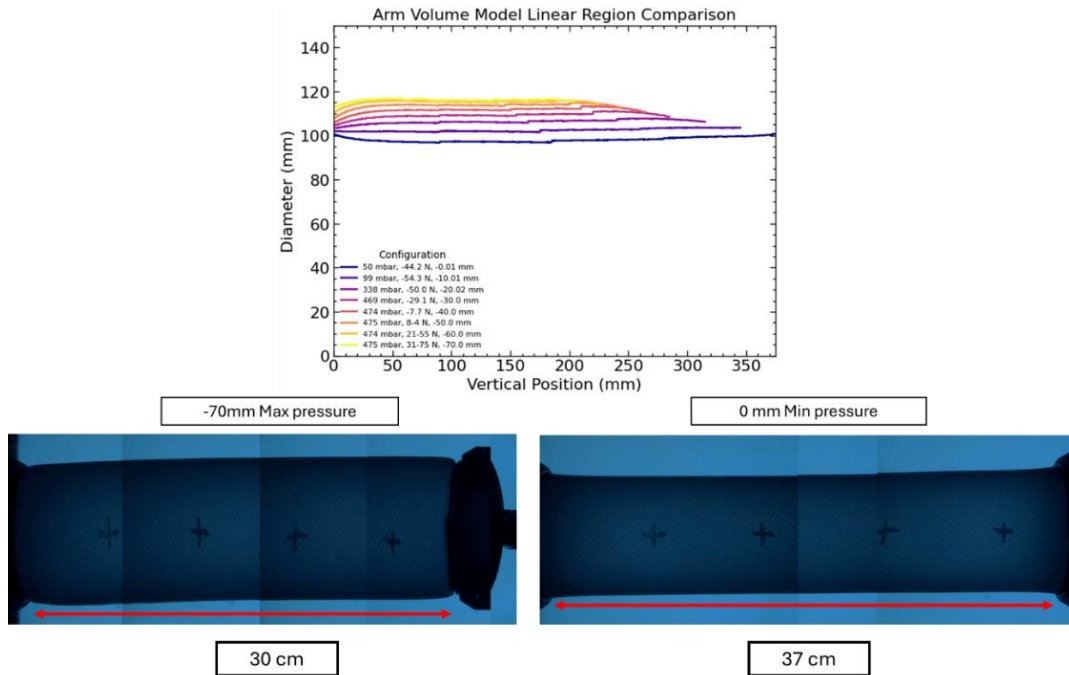


Figure 55. LVPM surface linearity analysis. (Above) Stitched resultant diameter estimate from aggregated captures at varying LVPM configurations. (Below) Stitched raw images at max expansion and minimum expansion configurations.

The analysis revealed distinct uniform regions across all LVPM configurations with minor discontinuities at data boundary interfaces that represent artifacts of the measurement and alignment processes rather than fundamental system limitations. These discontinuities, more pronounced in extended configurations, result from well-understood sources including camera field-of-view distortion effects at image periphery, setup misalignment introducing systematic measurement shifts, and manual alignment errors during data processing. The presence of these discontinuities does not compromise the fundamental linearity of the phantom within individual measurement regions but rather represents challenges in the measurement methodology that can be addressed through improved alignment procedures and enhanced data processing algorithms. The identification of these effects enables the development of improved characterization procedures for future system iterations.

The determination of the usable linear operating region employed rigorous statistical analysis to identify the longest continuous segment within 1% of the mode diameter value for each operational configuration. This analytical approach prevents the measurement discontinuities from manual alignment processes from incorrectly influencing the classification of the true linear region. The 1% tolerance criterion ensures that the identified linear region meets the accuracy requirements for sensor calibration applications. The quantitative analysis revealed that the maximum diameter configuration provides a 24 cm linear region, while the minimum diameter configuration offers a 30 cm linear region. The variation in linear region length with operational configuration reflects the complex geometric relationships present in the McKibben muscle system, where the relative influence of end cap constraints varies with the overall system geometry. This analysis establishes the validated sensor mounting regions for accurate calibration procedures and enables optimization of sensor placement strategies.

6.5 Advanced Controls Implementation and Comprehensive System Validation

6.5.1 Integrated Control System Architecture and Implementation

The Multi-Threaded Python Application (MTPA) provides a synchronized operation backbone for all system components including the Pump 2.0 air pressure controller, Mark-10 F305 universal testing machine, and Pixelink camera system. This integrated approach enables precise coordination of multiple actuators while maintaining real-time feedback through the advanced camera-based measurement system. The control architecture addresses the complex challenges associated with coordinating multiple actuators with different dynamic characteristics while maintaining system stability and measurement accuracy. The MTPA implementation enables independent control of each actuator while providing coordination mechanisms for combined operation modes that maximize the system's operational envelope.

The control system must achieve diameter accuracy within 0.5% of setpoint values across the complete operational range while maintaining integrated safety systems that prevent equipment

damage under all operational conditions. The real-time feedback through camera-based measurement enables closed-loop control implementation with measurement latency sufficiently low to enable stable control operation. The system must demonstrate robust performance under varying operating conditions and maintain accuracy over extended operational periods.

6.5.2 Advanced Plant Identification and Mathematical Modeling

The initial plant identification studies revealed fundamental system characteristics that directly inform the control design process. The system exhibits linear, independent responses to pressure changes at fixed position and position changes at fixed pressure, indicating that the complex interactions between actuators can be managed through proper control design. The step response analysis demonstrated approximately first-order, time-invariant behavior that establishes suitability for classical control approaches including P control implementation. The independent response characteristics simplify the control design process by enabling decomposition of the multi-input system into manageable single-input components. This characteristic enables development of control strategies that can be implemented and tuned independently before integration into the complete system architecture.

The control design objectives reflect the stringent requirements for sensor calibration applications where accuracy, stability, and safety are paramount. The accuracy requirement of within 0.5% of setpoint diameter across the operational range ensures that the calibration system maintains sufficient precision for research-grade sensor validation. The overshoot limitation of less than 20% prevents system damage while maintaining acceptable transient response characteristics for practical calibration procedures. The settling time objective of under 60 seconds balances the need for reasonable calibration throughput with the practical constraints of the pneumatic actuation system. This specification enables efficient calibration procedures while accommodating the inherent time constants of the pneumatic system that cannot be eliminated through control design alone. The system limitation analysis established critical boundaries that ensure safe operation while maximizing the available performance envelope. The position range limitation of 0 to -55 mm prevents the system from reaching force inflection points that would compromise the monotonic relationship between actuator inputs and system response. The pressure range reduction from the maximum capability of 500 mbar to 300 mbar for control applications improves system responsiveness while maintaining an adequate performance range.

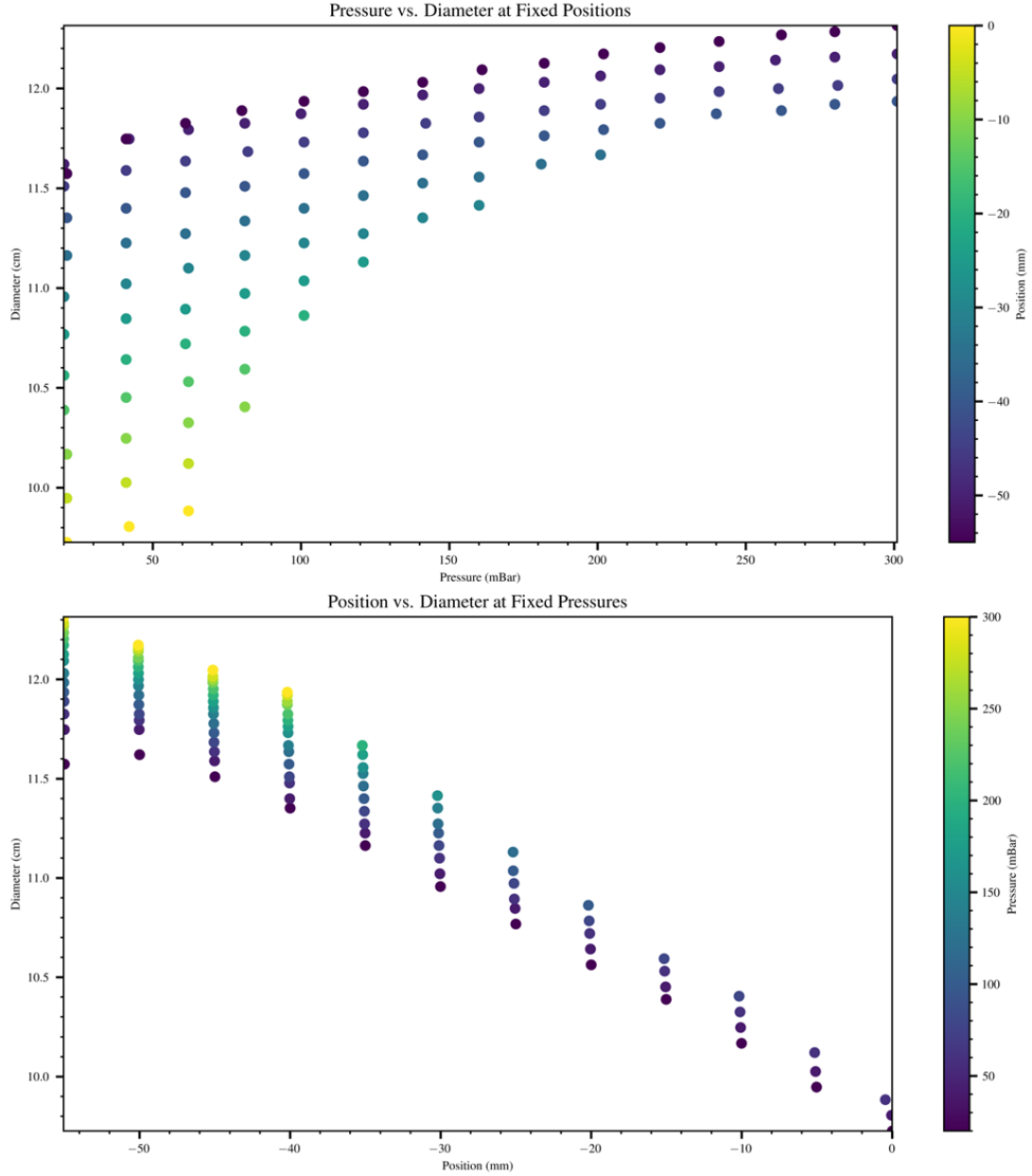


Figure 56. Mapping of LVPM performance over reduced operating window. (above) Diameter versus position with varying pressure. (below) Diameter versus pressure for varying Positions.

The diameter range of 9.7 to 12.3 cm reflects the practical operational envelope constrained by the intersection of safe operating limits and performance requirements. The force constraint limiting operation to tension conditions (negative force) maintains the monotonic system response characteristics essential for predictable control behavior.

6.5.3 Multi-Input Single-Output System Conversion and Control Mapping

The conversion of the dual-input pressure and position system to single-input control through operational space mapping represents a critical innovation that enables implementation of classical

control techniques while maintaining the system's full operational capabilities. This approach simplifies the control problem while preserving the ability to access the complete operational envelope through systematic mapping of desired outputs to appropriate actuator combinations.

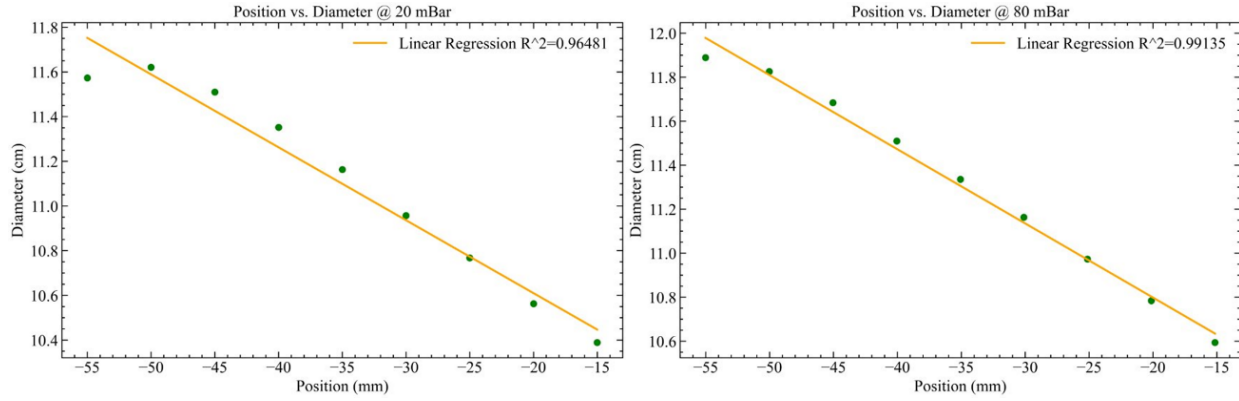


Figure 57. Central diameter mapping region and generated regressions.

The central region mapping analysis identified optimal linearity at 80 mbar constant pressure across the primary diameter range, achieving a linear correlation coefficient of $R^2 \approx 0.993$. This exceptional linearity enables precise control in the most commonly used operational region while minimizing the complexity of the control implementation. The high correlation coefficient indicates that simple proportional control can achieve excellent performance in this region.

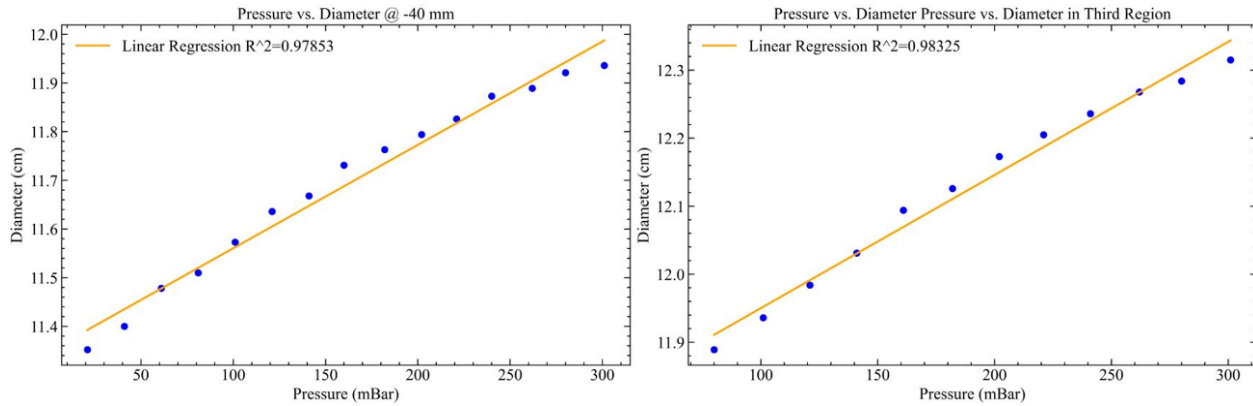


Figure 58. Maximum diameter mapping region and generated regressions.

The maximum diameter region analysis demonstrated that constant position control at -55 mm displacement provides optimal performance for accessing the upper portion of the operational envelope. Pressure range optimization focusing on pressures ≥ 80 mbar yielded $R^2 \approx 0.983$, indicating excellent linearity in this operational region. This mapping enables access to the maximum system performance while maintaining predictable control characteristics.

The minimum diameter region analysis revealed that combined pressure and position control is required to access the lower portion of the operational envelope. The exceptional

linearity achieved with $R^2 \approx 0.9998$ demonstrates that even complex multi-actuator control can achieve excellent performance when properly implemented. This region's characteristics require more sophisticated control implementation but provide access to the complete operational range.

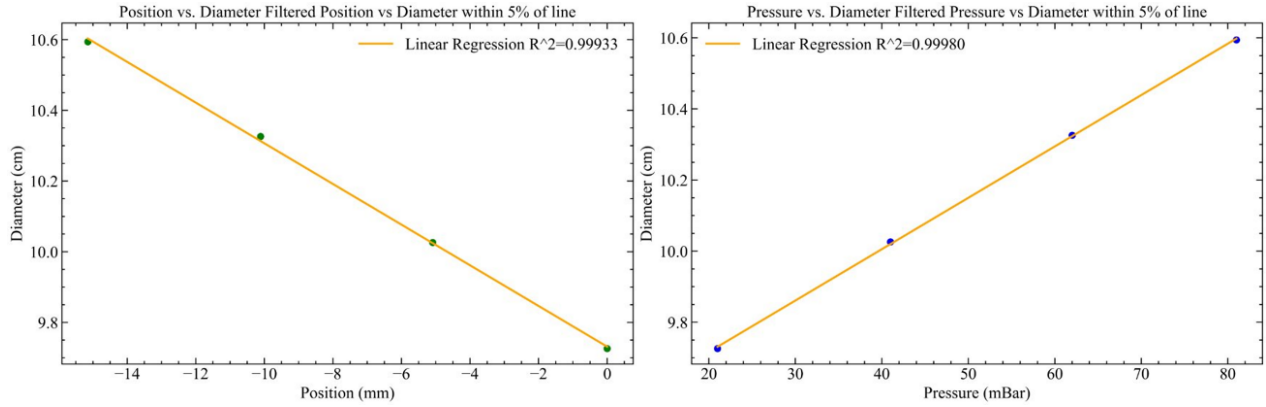


Figure 59. Minimum diameter mapping region and generated regressions.

Final Control Mapping Implementation: The final control mapping creates a three-dimensional monotonically increasing control surface that provides comprehensive diameter-to-actuator mapping across the entire operational envelope. The mapping incorporates real-time disturbance compensation through minimum condition baseline measurements that account for daily setup variations and environmental factors that could affect system performance.

Predicted Position and Pressure from Regression Model vs. Diameter

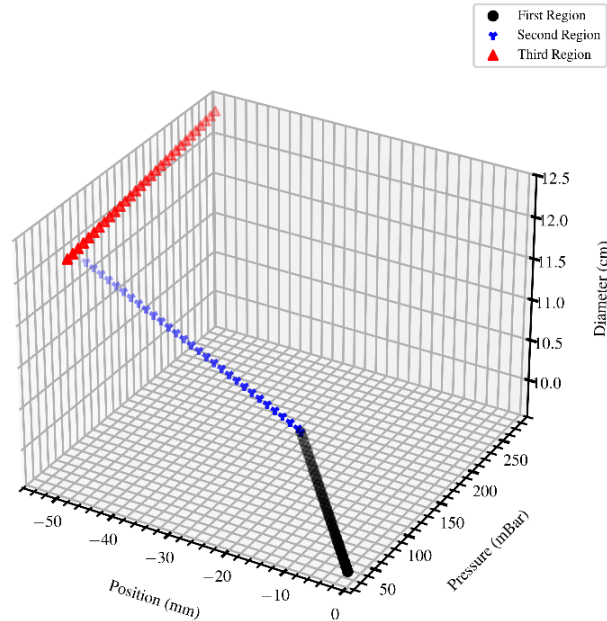


Figure 60. Final control discretization for three regions of LVPM.

The disturbance compensation approach measures the system's baseline diameter at minimum conditions ($x=0$ mm, $P=20$ mbar) and adjusts the control mapping accordingly. This

adaptive approach ensures consistent performance across multiple operational sessions while compensating for factors such as temperature variations, material aging, and setup variations that could otherwise compromise calibration accuracy.

6.5.4 Proportional Controller Implementation and Performance Analysis

The proportional feedback control implementation utilizes a sliding setpoint approach along the characterized control mapping surface, enabling continuous operation across the complete operational envelope. The control input calculation applies proportional gain to the diameter error with systematic updates at discrete time intervals optimized for system response characteristics. This approach maintains simplicity while providing the performance necessary for precision calibration applications. The sliding setpoint methodology enables seamless operation across the different operational regions identified in the mapping process. The controller automatically selects the appropriate actuator combination based on the desired diameter while maintaining consistent control characteristics across transitions between operational regions.

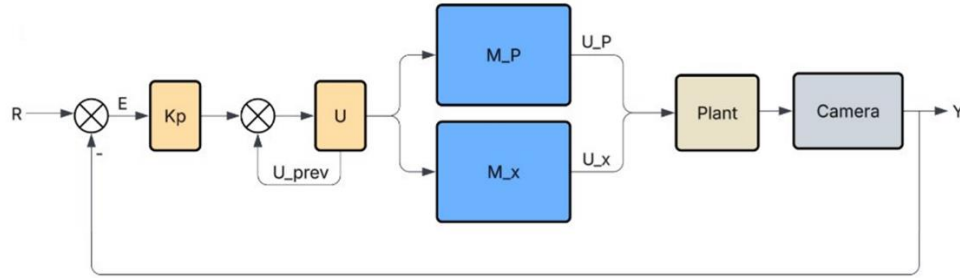


Figure 61. Final LVPM controller diagram.

$$U[n] = \begin{cases} Y & n = 0 \\ U[n - 1] + K_p * E & n > 0 \end{cases} \quad (11)$$

$$E = R - Y \quad (12)$$

The disturbance compensation system addresses fixed disturbances, including daily setup variations, through systematic baseline measurements and dynamic mapping adjustment. The baseline measurement at minimum conditions (x=0 mm, P=20 mbar) provides a reference point that enables compensation for systematic shifts in system behavior. This approach ensures consistent performance across multiple operational sessions while maintaining the accuracy required for sensor calibration applications. The dynamic mapping adjustment capability enables the control system to adapt to gradual changes in system characteristics while maintaining calibration accuracy. This adaptive capability is essential for maintaining long-term system performance in research applications where consistent results over extended periods are critical.

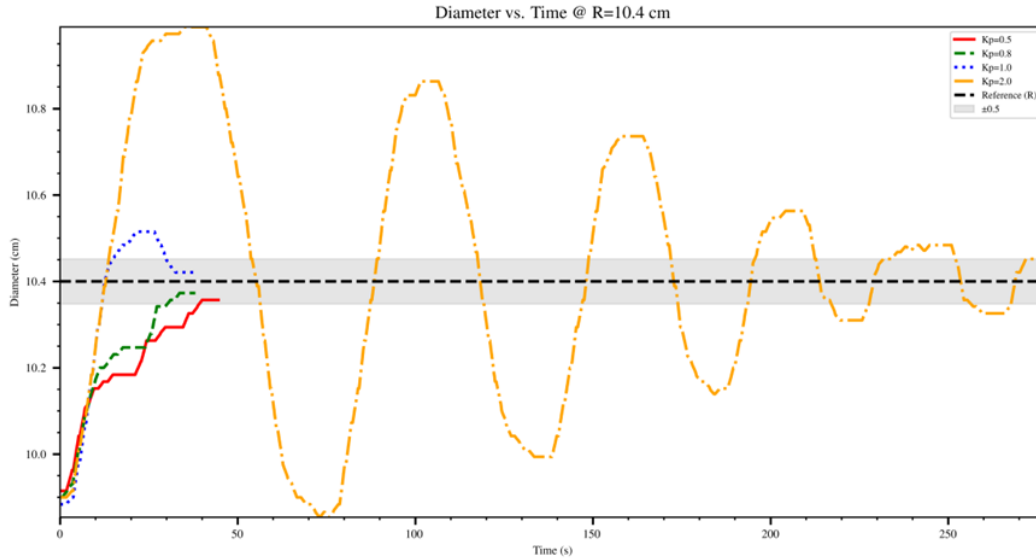


Figure 62. LVPM controller performance for varying K_p values to achieve a set diameter of 10.4 cm from minimum diameter state versus time.

The comprehensive performance testing evaluated proportional gain values of $K_p = 0.5$, 1.0, and 2.0 across step response protocols covering minimum to maximum diameter transitions within each operational region. This systematic approach ensures that the selected gain values provide optimal performance across the complete operational envelope while maintaining stability under all operating conditions. The testing protocol encompassed both individual regional testing and cross-regional transition testing to ensure that the controller maintains performance when operating across the boundaries between different operational regions. This comprehensive approach ensures robust performance under all practical operating conditions.

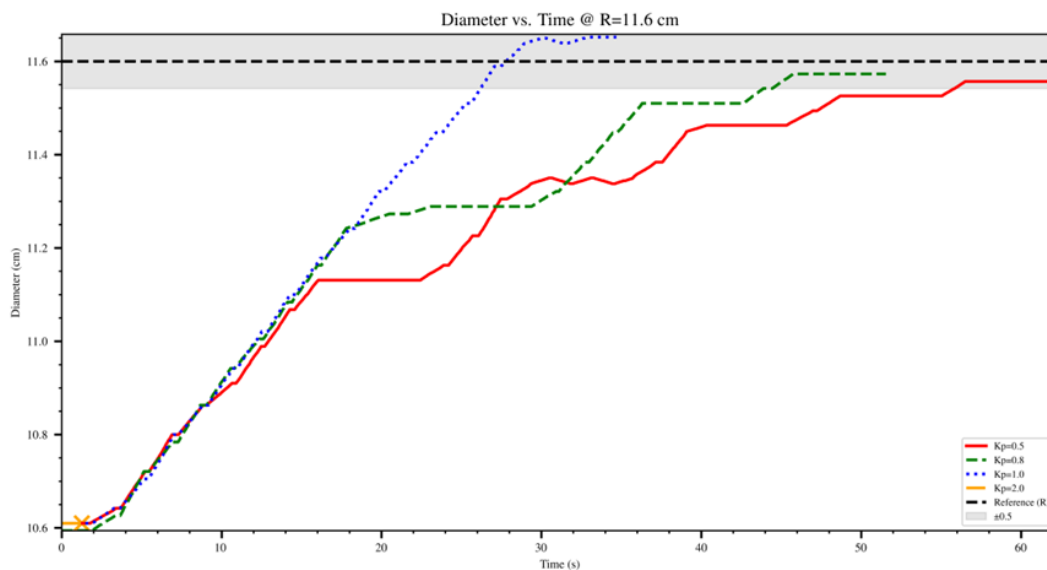


Figure 63. LVPM controller performance for varying K_p values, showing diameter versus time to reach a set diameter of 11.6 cm.

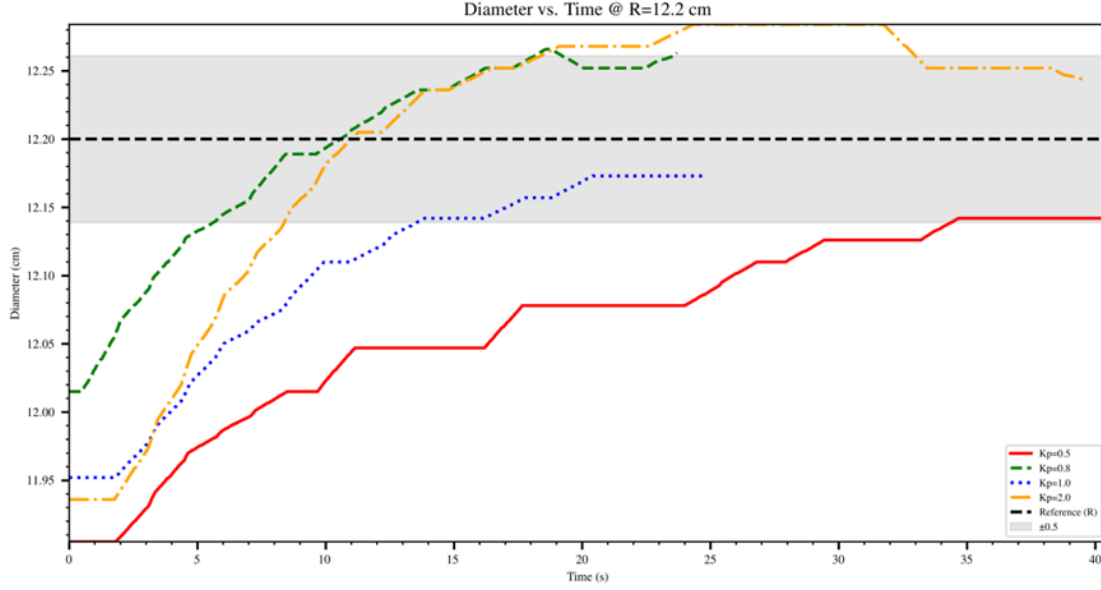


Figure 64. LPVM controller performance for varying K_p values, showing diameter versus time to reach maximum diameter of 12.2cm.

The systematic performance analysis identified an optimal gain range of $0.5 \leq K_p \leq 1.0$ that provides excellent performance across all specified metrics. The achieved accuracy of $\leq 0.5\%$ steady-state error meets the stringent specification requirements for sensor calibration applications while maintaining consistency across the operational range. The overshoot limitation of $\leq 20\%$ ensures safe operation while maintaining acceptable transient response characteristics. The settling time performance of < 40 seconds provides acceptable response for practical calibration procedures while reflecting the inherent time constants of the pneumatic actuation system. The optimal gain value of $K_p \approx 0.8$ provides balanced performance across all operating conditions while maintaining stability margins sufficient for robust operation. The evaluation of alternative PID configurations including PD control for overshoot reduction and PI control for steady-state error improvement revealed that these approaches offered marginal benefits with increased complexity. The proportional controller with integrated mapping provides the optimal balance of performance, simplicity, and robustness for the sensor calibration application.

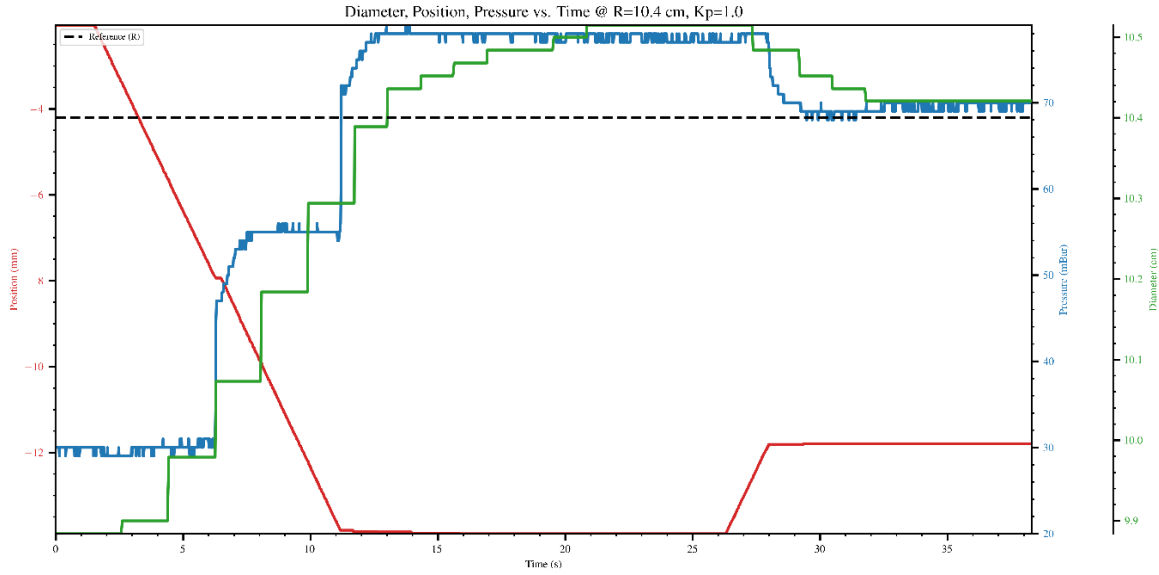


Figure 65. Optimized LPVM controller performance with a $K_p=1.0$, showing set point diameter of 10.4 cm in black, Mark 10 position in red. Applied pressure in blue. Measured diameter in green.

6.5.5 System Performance Limitations and Future Enhancement Opportunities

Precision Limitation Analysis and Mitigation Strategies: The camera pixel resolution constraint limits the minimum discernible change to approximately 50 micrometers, representing a fundamental limitation of the current measurement system. This limitation, while acceptable for current sensor calibration requirements, may constrain future applications requiring higher precision. The fisheye distortion effects and calibration accuracy limitations result in overall system accuracy of ± 0.5 mm, which meets current requirements but represents an area for potential improvement.

6.6 HSCSG Sensor Validation on LVPM

The validation of the optimized single sensor developed in Chapter 5 was conducted through comprehensive testing on the Limb Volume Phantom Model (LVPM) test platform. While uni-axial pull testing demonstrated that the laser cut sensor achieved reliable and highly linear performance characteristics throughout the desired 25% strain range, the translation of these performance metrics to a more representative operational environment necessitated systematic investigation of sensor characteristics and performance behavior when deployed on the LVPM system. The LVPM provides a controlled testing environment that more closely approximates the complex mechanical loading conditions encountered in practical applications, where sensors experience multi-directional strain patterns and surface curvature effects that cannot be fully characterized through simple uni-axial testing protocols.

The sensor integration process onto the LVPM platform required careful consideration of mounting methodologies and electrical connectivity to ensure reliable data acquisition while maintaining the mechanical integrity of the sensor-substrate interface. The sensor was initially

bonded onto a strip of stretchable fabric using a heat press configured to operate at 120°C for a duration of 30 seconds. This thermal bonding process facilitates the activation and adhesion of the melt adhesive layer integrated within the Intexar substrate, creating a mechanically robust bond with the fabric that can withstand the repeated deformation cycles anticipated during testing. The fabric strip was precisely cut to a length of 31 cm to match the minimum circumference specifications of the LVPM, ensuring proper sensor placement and consistent mechanical coupling between the sensor and the phantom model surface. Two magnetic clasps were subsequently attached to the terminal ends of the fabric strip, providing a secure connection mechanism that maintains a compact profile and minimizes the overall height of the sensor packaging when mounted on the LVPM surface, thereby reducing potential interference with the measurement system.

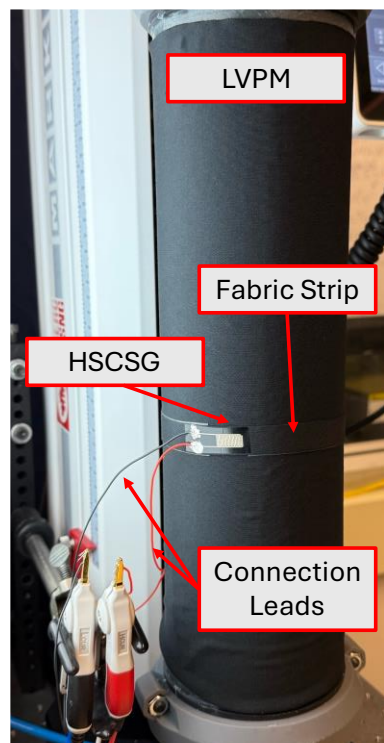


Figure 66. Sensor Validation setup on LVPM.

Electrical connectivity was established through the implementation of lightweight 24 AWG silicone-insulated wires that were connected to the sensor contact pads using silver conductive epoxy. This connection method provides low-resistance electrical pathways while maintaining flexibility during mechanical deformation cycles. The completed sensor band assembly was positioned on the LVPM at a location approximately 15 cm from the base, situated just below the center point of the phantom model to ensure optimal measurement conditions and minimize edge effects that could influence sensor response characteristics. The experimental setup configuration is illustrated in Figure 13, which demonstrates the sensor positioning and overall test arrangement.

The initial validation phase implemented a progressive expansion test protocol designed to characterize sensor response across the full operational range. The LVPM was systematically configured to increasing diameters in precise 1mm increments, spanning from an initial diameter of 9.8 cm to a maximum diameter of 12.25 cm. This diameter range corresponds to a 25% increase in overall circumference, which aligns with the maximum operational range previously established through uni-axial testing protocols. Throughout the expansion sequence, capacitance measurements and corresponding diameter values were continuously monitored and recorded using the Multi-channel Test Platform Architecture (MTPA) system, providing synchronized data acquisition with high temporal resolution. The progressive nature of this testing protocol allows for detailed characterization of sensor linearity, sensitivity variations, and identification of any non-linear response regions that may exist within the operational range.

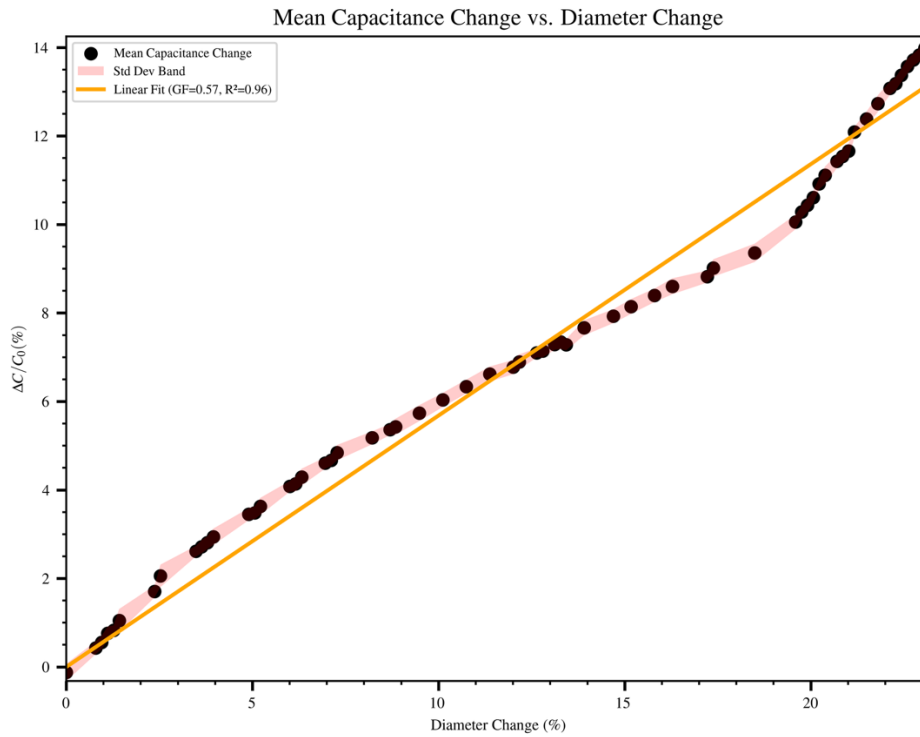


Figure 67. Single HSCSG sensor band tested on LVPM in progressive expansion test up to 25% increase in diameter.

The experimental results from the progressive expansion testing, as presented in Figure 14, demonstrate a strong correlation between the raw percent capacitance change and the relative diameter change of the LVPM throughout the tested range. However, detailed analysis reveals that this relationship does not exhibit the ideal one-to-one mapping that would be expected from a perfectly linear strain sensor. Linear regression analysis of the experimental data yields a gauge factor of 0.57 for the sensor output, indicating that the sensor response magnitude is approximately 57% of the applied mechanical strain. This deviation from unity gauge factor suggests that the complex mechanical interactions between the sensor, substrate, and mounting configuration result

in strain transfer coefficients that differ from those observed in simple uni-axial testing conditions. The implications of this finding indicate that reliable calibration protocols for estimating circumference changes from uni-axial calibration data require the development of additional modeling approaches that account for the multi-axial stress states and mechanical coupling effects present in the mounted configuration.

A particularly notable observation from the progressive expansion testing is the presence of an inflection point within the 15-20% diameter change range, where the sensor sensitivity exhibits a localized decrease followed by increased sensitivity beyond the 20% threshold. This non-linear behavior suggests complex mechanical interactions occurring at the sensor-substrate interface or within the bulk sensor material that may be related to stress redistribution, substrate compliance variations, or changes in the mechanical coupling between the sensor and the LVPM surface. The identification of this sensitivity transition region is significant for applications requiring precise measurements across the full operational range, as it indicates the need for piecewise calibration approaches or more sophisticated modeling techniques to accurately interpret sensor output throughout the entire measurement range.

To comprehensively evaluate the sensor performance characteristics under repeated loading conditions, life cycle testing was conducted to assess hysteresis behavior, long-term durability, and measurement accuracy over multiple deformation cycles. The cyclical testing protocol was implemented over a reduced range of 0-10% diameter change to focus on the most linear response region while enabling detailed characterization of repeatability and stability. The original experimental plan called for 10 complete cycles; however, system stability limitations associated with the simultaneous control of the LVPM equipment ensemble and capacitance data collection system prevented reliable data acquisition beyond 6 complete cycles. These stability challenges were primarily attributed to the complexity of coordinating multiple measurement systems and maintaining precise environmental control throughout extended testing periods.

The cyclical performance results, presented in Figure 15, provide detailed insight into the sensor's behavior under repeated loading conditions within the 0-10% diameter change range. The left panel of Figure 15 displays the relationship between percent capacitance change and relative diameter change, with mean values plotted in black and standard deviation bands indicating the measurement variability across cycles. The right panel presents the raw percent capacitance change and percent diameter change data plotted as functions of cycle number, allowing for direct observation of any temporal trends or degradation effects. Linear regression analysis of the cyclical data yields an R^2 value of 0.97, demonstrating excellent correlation between sensor output and mechanical deformation and confirming the high linearity of the sensor response within this operational range.

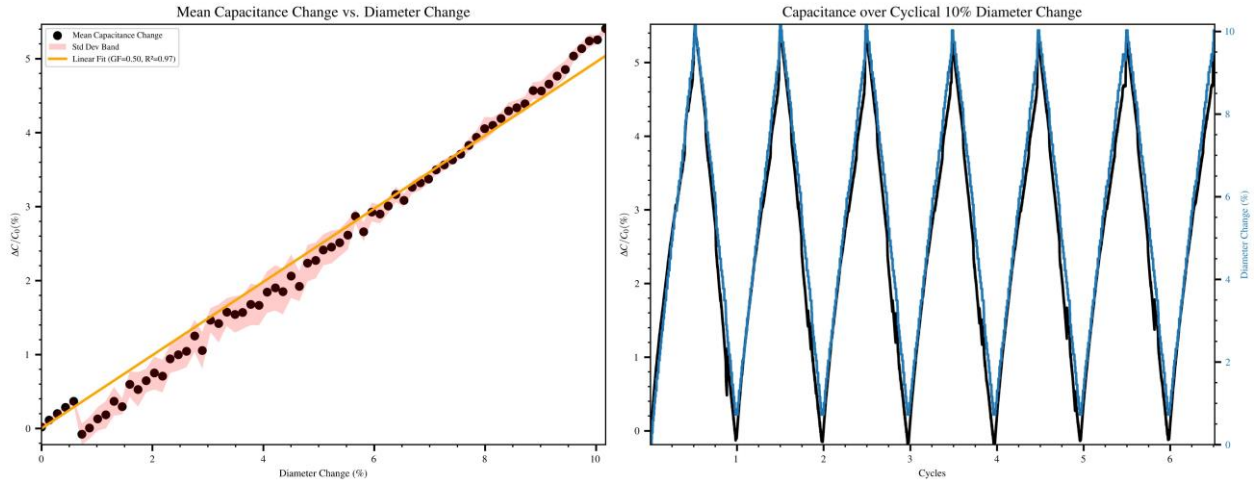


Figure 68. Cyclical test performance of single HSGSG band on LVPM over 6 cycles of 0-10% diameter change. (left) Percent Capacitance change versus relative diameter change with mean values plotted in black and standard deviation bands shown. (right) Raw percent capacitance change, and percent diameter change plotted over cycles.

The cyclical testing results reveal minimal variation in sensor response characteristics with negligible hysteresis effects or performance degradation over the duration of the testing period. The analysis demonstrates low deviation between individual cycles, indicating consistent sensor behavior and minimal drift in baseline response. The most significant variation observed occurs during the relaxation phase of each cycle, where the minimal or initial capacitance values do not return precisely to zero when the LVPM returns to zero percent diameter change. This deviation from perfect baseline recovery suggests either physical displacement of the sensor band following the initial deformation cycle or continued relaxation processes occurring within the bulk polymer properties of the HSCSG material system.

The latter explanation involving continued polymer relaxation is considered less likely given that the cyclical testing was conducted at relatively slow loading rates that were constrained by the camera imaging feedback system used for diameter measurement and control. The slow loading rates should provide sufficient time for viscoelastic relaxation processes to reach equilibrium, suggesting that the observed baseline shift is more likely attributable to mechanical factors such as sensor band repositioning or changes in the mechanical coupling between the sensor and the LVPM surface. This finding has important implications for long-term monitoring applications, where baseline stability is critical for accurate measurement interpretation and may indicate the need for periodic recalibration or improved mounting techniques to minimize mechanical drift effects.

6.7 Conclusion of LVPM

The development of the pneumatic McKibben muscle-based Limb Volume Phantom Model (LVPM) represents a systematic engineering approach to addressing fundamental limitations in wearable sensor calibration methodologies. Through four iterative design cycles, the research

established optimized fabrication protocols utilizing bias-cut ripstop fabric assembly with 3D printed Silicone and rigid components forming a robust platform. This comprehensive investigation of the pneumatic McKibben muscle-based Limb Volume Phantom Model (LVPM) demonstrates the successful development of a sophisticated calibration platform that addresses critical limitations in existing wearable sensor validation methodologies. The systematic design evolution through four iterative versions, culminating in an optimized fabrication protocol utilizing bias-cut ripstop fabric and precision adhesive bonding techniques, resulted in a phantom model capable of achieving 28.87% diameter expansion with sub-0.5% control resolution across a 24-30 cm linear operational region. The integration of advanced camera-based measurement systems with multi-threaded control architecture enabled precise diameter control through coordinated pneumatic and mechanical actuation, while comprehensive characterization studies validated the system's linearity, repeatability, and safety performance under operational conditions.

The successful validation of the optimized HSCSG sensor on the LVPM platform confirms the phantom model's effectiveness as a calibration tool for wearable strain gauge applications, achieving strong correlation ($R^2 = 0.97$) between sensor output and mechanical deformation with minimal hysteresis effects over cyclical testing. The identified gauge factor of 0.57 and the observed sensitivity transition within the 15-20% diameter change range provide critical insights into complex mechanical interactions between sensors, substrates, and mounting configurations that cannot be characterized through conventional uni-axial testing protocols. While minor baseline drift effects were observed during extended cyclical testing, potentially attributable to mechanical repositioning rather than material degradation, the overall system performance demonstrates exceptional suitability for precision sensor calibration applications. The developed LVPM platform represents a transformative advancement in wearable sensor technology development methodologies, establishing validated protocols for tissue-representative calibration environments while providing a foundation for future phantom model development and sensor characterization applications in lymphedema monitoring and related biomedical sensing domains.

7. Conclusions and Recommendations

7.1 Thesis Conclusions

The main goal of this thesis was to investigate and develop a complete wearable sensing system to monitor limb volume for patients with lymphedema through the design, fabrication, and characterization of advanced capacitive strain gauge sensors. The presented thesis work guided through the entire journey of ideation, conceptualization, investigation, and sharing of a multi-staged development of highly stretchable capacitive strain gauge (HSCSG) technology for lymphedema monitoring applications. Upon an extensive literature review examining current lymphedema monitoring methods and wearable sensing technologies, the justification was provided for the selection of capacitive sensing as the optimal modality for this application. Keeping in mind the objective of developing an innovative sensing system capable of providing accurate, long-term monitoring of limb volume changes, further investigation of capacitive sensing technologies narrowed down to interdigitated electrode (IDE) arrays as the most promising approach.

As the first stage of the development progress, the details of the investigation into lymphedema patient needs and existing monitoring solutions were thoroughly examined. By first exploring current clinical methods and their limitations, the working principle and fundamental requirements for wearable lymphedema monitoring were established. After a careful investigation of available sensing modalities and their suitability for long-term wearable applications, capacitive sensing was identified as an ideal candidate due to its low drift, high linearity response, and compatibility with textile integration requirements. Upon introduction of interdigitated electrode arrays as a potential solution, the resultant sensing approach provided a promising foundation to address the long-term wearable, high deformation, and accuracy requirements for the proposed objectives while offering excellent linearity and directional sensitivity characteristics.

For the purpose of advancing the fabrication capabilities and enabling rapid prototyping of IDE sensors, an extensive investigation of manufacturing techniques was conducted. With the provision of reasonable justification for material and process selection, direct ink writing (DIW) was chosen as the optimal fabrication approach due to its high resolution capabilities, rapid-prototyping advantages provided from the maskless approach, and room temperature processing that allows stretchable materials to be leveraged effectively. Additional investigations were carried out to identify suitable substrate materials, with thermoplastic polyurethane (TPU) selected as the ideal candidate due to its material properties specifically tuned for wearable electronics applications and the simplicity it provides while maintaining ideal mechanical characteristics for the intended application.

The fabrication process development resulted in successful characterization and optimization of the direct ink writing process for interdigitated electrode capacitive strain gauges specifically designed for wearable sensing applications. Through systematic analysis of DIW

materials and parameters, an ideal conductive ink was selected for IDE printing applications. A novel sensor generation software was developed to improve sensor fabrication precision and repeatability, which significantly enhanced the speed, reliability, and accuracy of DIW fabrication for IDE geometries. This comprehensive fabrication study established reliable and repeatable manufacturing protocols that enabled consistent sensor production throughout the research program.

To further advance the understanding of IDE sensor behavior and reduce experimental trial-and-error requirements, multiphysical simulation of stretchable IDE capacitive sensors was performed to develop a comprehensive design space that guides sensor fabrication and optimization. Leveraging COMSOL Multiphysics 6.3 for steady-state capacitance analysis and sensor performance evaluation over parametric sweeps of geometries and imposed mechanical deformations, valuable insights were gained into IDE parameters and their impacts on sensor performance. The numerical simulation models, which were based on validated material properties and geometric configurations, accurately predicted the sensing performance of the IDE sensors and provided guidance for optimal design parameter selection.

Through extensive design and optimization efforts, highly stretchable and durable wearable strain gauges were successfully developed for limb volume measurement applications. The development process established highly repeatable fabrication processes and characterized sensor performance over a range of geometries and test environments using different substrate materials. Implementation of optimization techniques utilizing laser cut post-processing led to the formation of an optimized highly stretchable capacitive strain gauge (HSCSG) sensor which met the objective criterion of providing linear response up to 25% strain while approaching the theoretical gauge factor sensitivity of IDE capacitive sensors. The sensors demonstrated excellent durability under high elongations and successful cyclical life cycle testing, confirming their suitability for long-term wearable applications.

For the purpose of validating sensor performance in realistic testing conditions, a novel limb volume phantom model (LVPM) was successfully developed to aid in the calibration and assessment of the wearable sensors and systems for accurate limb swelling monitoring. The model utilizes pneumatic artificial muscles (PAMs) to create a safe and soft test platform that provides highly accurate expansion across a large linear region. Through iterative development of several versions, the model was refined until it met the calibration objectives. An optimized control system was created to enable precise feedback control allowing accurate diameter setting using silhouette imaging techniques. With the LVPM, successful validation of the optimized sensors' performance at monitoring circumference changes was achieved while requiring minimal calibration procedures.

Through this comprehensive study, the HSCSG sensors emerged as promising wearable sensing devices with significant potential for practical lymphedema monitoring applications. The developed sensors demonstrated the required sensitivity, durability, and integration capabilities necessary for real-world deployment in wearable sensing systems. The established fabrication

methods, design optimization procedures, and validation protocols provide a solid foundation for advancing the technology toward clinical applications and commercial implementation.

7.2 Challenges and Limitations

This research presents several limitations that affect the interpretation of results and future implementation considerations for wearable limb volume monitoring systems. These limitations span technological, methodological, and practical domains.

The capacitive sensing approach demonstrated linearity and minimal drift under controlled conditions, however several factors may impact performance in practical applications. Capacitive sensors exhibit sensitivity to electromagnetic interference, which could affect measurement consistency in environments with multiple electronic devices. Environmental conditions, particularly humidity variations and moisture from perspiration or liquid ingress, may cause baseline drift in the fringe field detection used by capacitive-to-digital conversion systems. The implementation of portable capacitive-to-digital conversion requires more complex electronics compared to resistive alternatives, presenting engineering challenges for compact wearable systems. All capacitive measurements in this work were conducted using desktop LCR systems, which provide superior noise rejection and stability compared to portable integrated circuits that would be required for wearable implementation. The testing system demonstrated reliability limitations, failing after approximately 50 cycles due to communication conflicts between equipment components, preventing comprehensive long-term stability assessment.

The limb volume phantom model presented operational constraints due to the speed limitations of the Mark 10 system and air pressure supply. These constraints prevented high-speed testing and precluded derivative control implementation, resulting in slower cycling and circumference changes. While this may not significantly impact applications targeting long-term volume monitoring, it limits applicability to scenarios requiring rapid response characteristics.

Several considerations emerged regarding wearability implementation. User compliance factors for continuous daily wear remain undefined. The effects of repeated device removal and replacement on measurement accuracy and calibration stability require investigation. User alignment procedures necessary to maintain baseline measurement validity need development. Initial baseline establishment may still require conventional limb volume measurement techniques. Inter-individual physiological variations, particularly in patients with lymphedema-related anatomical changes, may affect system performance across different populations. Limb curvature may influence sensor accuracy in circumference estimation. The balance between measurement sensitivity requirements and user comfort presents design considerations. Normal daily activities and physical movements may contribute to sensor baseline drift.

The measurement approach itself presents considerations for wearable monitoring applications. Limb volume changes are characteristically small in magnitude and require extended measurement periods for clinical significance. Substantial inter-individual physiological

variability exists across patient populations. These factors indicate that the suitability of limb volume as a parameter for continuous wearable monitoring may benefit from further evaluation. Alternative physiological parameters or complementary measurement approaches may warrant investigation to optimize continuous monitoring capabilities. Additional research and development will be necessary to address these considerations in developing clinically viable wearable limb volume monitoring systems.

7.3 Recommendations

The methods presented in this thesis provided successful precedents for HSCSG sensor development, DIW fabrication optimization, and LVPM validation systems, each with promising results demonstrating the potential for lymphedema monitoring applications. While the proposed technology can be applied to various wearable sensing applications, the investigations conducted represent preliminary but substantial progress toward clinical implementation. Several important hurdles need to be overcome for this promising technology to be adopted in real-world clinical applications. The following recommendations are based on the limitations and opportunities identified during the development period and represent critical next steps for advancing the technology toward practical deployment.

First and foremost, fabrication and experimentation into electromagnetic interference shielding should be prioritized to enhance sensor robustness in clinical environments. Preliminary work was conducted investigating the potential of creating multilayered processes to encapsulate the printed sensors within stretchable conductor and surrounding insulator materials. This approach would minimize electrical interference and other environmental impacts on sensor performance while creating robust and durable sensors that can be effectively incorporated into wearable sleeves. Further investigation of shielding materials, fabrication techniques, and integration methods should be conducted to develop sensors capable of reliable operation in the electromagnetic environments typically encountered in clinical settings.

Development of portable data acquisition systems and sensor telemetry represents another critical advancement required for practical implementation. An important design consideration maintained throughout the sensor development efforts was optimizing for compact, linear, and durable sensors, which required accepting trade-offs in sensitivity compared to laboratory-grade sensors. While this design philosophy did not significantly impact the analysis and characterization conducted with benchtop LCR meters, the reduced sensitivity could potentially affect the efficacy of these sensors in portable sensing systems with limited signal processing capabilities. Through careful parameter selection and design optimization, sensor capacitances were maintained above the 5pF lower threshold typically required by small capacitance-to-digital integrated circuits, but validation and optimization of complete wearable systems must be conducted with small, low-power, and portable electronics platforms to ensure reliable operation in clinical environments.

The development of an integrated wearable sensing sleeve and garment represents the final critical step in bringing the HSCSG sensors outlined in this thesis to the envisioned complete monitoring system. This advancement would require the integration of sensors in a dense array configuration across a textile substrate that provides comfort, durability, and valuable clinical insights to both patients and healthcare providers. Through sensor fusion techniques and advanced data processing of the aggregated information produced by such sensor arrays, comprehensive limb volume monitoring could be achieved. This integrated approach would enable clinical trials and real-world testing to be conducted, providing the validation data necessary for regulatory approval and clinical adoption.

As specific application directions for the proposed HSCSG technology, several promising avenues should be pursued to maximize the clinical impact and commercial potential of the developed sensing systems. The first recommendation involves leveraging the modular design capabilities of the sensor technology to create comprehensive monitoring solutions for different stages of lymphedema progression. The HSCSG sensors can be configured to provide varying levels of monitoring complexity, from simple single-point measurements for early-stage detection to comprehensive multi-sensor arrays for advanced lymphedema management and treatment monitoring.

The second application direction focuses on integration with existing lymphedema treatment protocols and equipment. The proposed technology can be incorporated into compression garment systems to provide real-time feedback on treatment effectiveness and patient compliance. This integration would allow healthcare providers to optimize treatment parameters and adjust therapy protocols based on objective measurements rather than subjective patient reports or infrequent clinical assessments.

The third prospective direction involves the development of predictive analytics and machine learning capabilities utilizing the continuous monitoring data provided by the HSCSG sensor arrays. Through classification methods and pattern recognition algorithms, early warning systems could be developed to detect the onset of lymphedema episodes before they become clinically apparent. This predictive capability would enable proactive interventions and potentially prevent the progression of lymphedema to more severe stages.

The final recommended application direction centers on telemedicine integration and remote patient monitoring capabilities. Using wireless communication protocols and cloud-based data management systems, the HSCSG sensor data can be transmitted to healthcare providers for remote monitoring and assessment. This approach would allow continuous patient care while reducing the frequency of clinical visits and enabling more responsive treatment adjustments based on real-time physiological data. The integration of such remote monitoring capabilities would be particularly valuable for patients in rural or underserved areas where specialized lymphedema care may not be readily available.

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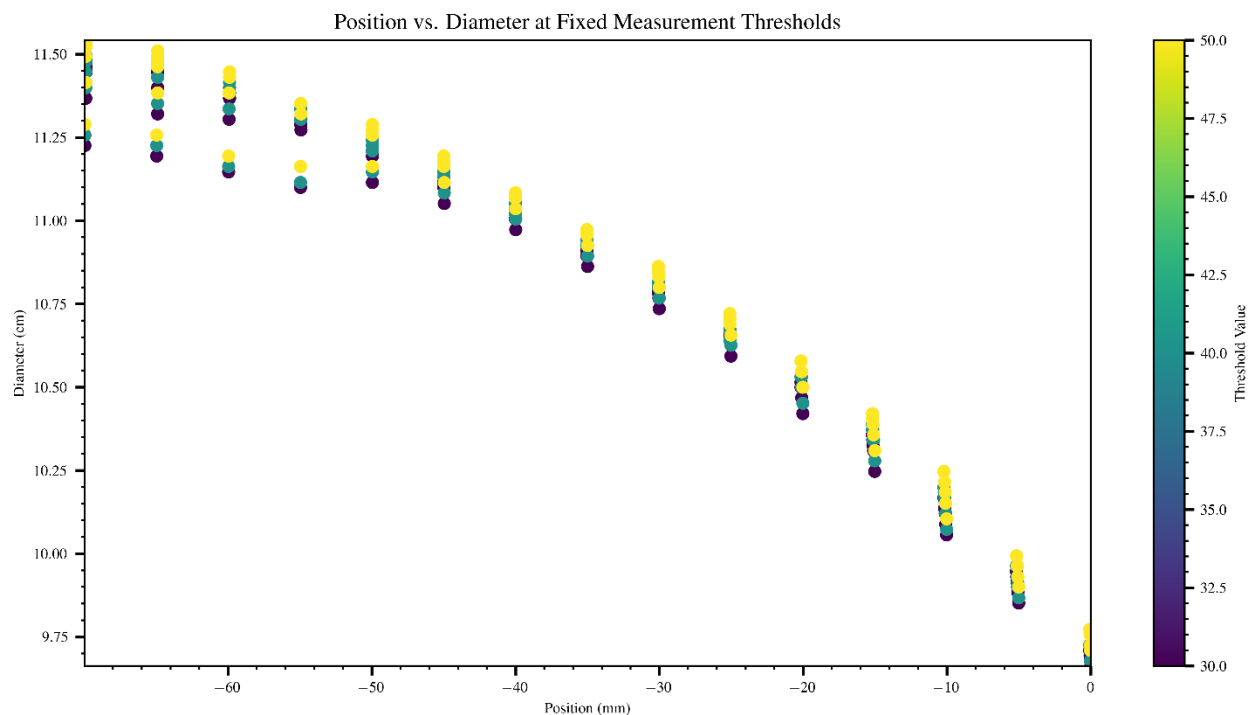
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APPENDICES

LVPM Test Apparatus

Computer Vision processing

The image processing pipeline represents a sophisticated approach to extracting precise dimensional information from silhouette images while maintaining computational efficiency suitable for real-time control applications. The process initiates with RGB colour image acquisition through the Python camera control interface, providing full-resolution capture for subsequent processing. Grayscale conversion utilizing the OpenCV `cv2.cvtColor` function maintains image quality while reducing computational requirements for subsequent processing steps. The binary threshold conversion process employs the OpenCV `cv2.threshold` function with carefully optimized threshold values determined through systematic analysis of image characteristics across the operational range. The threshold optimization methodology involves systematic sweep analysis across potential threshold values to identify regions of consistent measurement performance. This analysis reveals clusters of threshold values that provide valid measurements, enabling selection of median threshold values that maximize measurement reliability while minimizing sensitivity to lighting variations and surface characteristics.



The threshold optimization study revealed critical insights into the relationship between image processing parameters and measurement accuracy that directly impact the precision of sensor calibration procedures. The analysis demonstrated that threshold values that are too high result in no measurable distance due to insufficient white pixel identification, while threshold

values that are too low classify all pixels as white, similarly preventing distance measurement. The identification of optimal threshold clusters enables selection of processing parameters that maintain measurement accuracy across varying test conditions and surface characteristics.