ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

DEVELOPMENT OF CAPACITIVE-BASED SOFT PRESSURE SENSOR ARRAYS FOR E-TEXTILES APPLICATIONS

M.Sc. THESIS

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

E-TEKSTİL UYGULAMALARI İÇİN KAPASİTİF TABANLI YUMUŞAK BASINÇ SENSÖRÜ DİZİLERİNİN GELİŞTİRİLMESİ

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Çağatay GÜMÜŞ, a M.Sc. student of ITU Graduate School 503201818 successfully defended the thesis entitled "DEVELOPMENT OF CAPACITIVE-BASED SOFT PRESSURE SENSOR ARRAYS FOR E-TEXTILES APPLICATIONS", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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FOREWORD

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ABBREVIATIONS

TPU	: Thermoplastic Polyurethane
AgNPs	: Silver Nanoparticles
IoT	: Internet of Things
4IR	: Fourth Industrial Revolution
VR	: Virtual Reality
AR	: Augmented Reality
CAGR	: Compound Annual Growth Rate
MeNPs	: Metal Nanoparticles
IL	: Ionic Liquid
PPy	: Polypyrrole
PANI	: Polyaniline
PEDOT	: Poly(3,4-ethylenedioxythiophene)
PSS	: Polystyrene Sulfonate
ICPs	: Inherently Conductive Polymers
CAD	: Computer-Aided Design
GF	: Gauge Factor
EDL	: Electric Double Layer
TENG	: Triboelectric Nanogenerator
PDMS	: Polydimethylsiloxane
PVDF	: Polyvinylidene Fluoride
SWCNT	: Single-Walled Carbon Nanotubes
PET	: Polyethylene Terephthalate
EA	: Elastane
PI	: Polyimide
TBAF	: Tetrabutylammonium Fluoride
ITO	: Indium Tin Oxide
PMMA	: Polymethyl Methacrylate

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SUMMARY

The development of textiles dates back thousands of years as one of the humanity's first material inventions. Textiles have been used to convey messages in artistic or materialistic ways, as well as to protect people from the surroundings. However, today's society has undergone drastic changes recently with the intention of establishing a more intelligent and comfortable world. Soft pressure sensors have attracted a lot of attention in the recent decade owing to their wide range of applications, including human motion recognition, object detection, and human–computer interaction. In this situation, textile-based sensors are a cutting-edge technology that offers sensing capabilities along with flexibility, light weight, and breathability, making them the perfect option for smart gadgets.

Due to the difficult and time-consuming methods involved, their large-scale production and availability to end users are limited. Another important drawback is the sensors' lack of scalability in terms of working range, sensitivity and durability making them challenging to utilize in a variety of applications. Therefore, a laborless, rapid, and scalable manufacturing technique for capacitive-based soft pressure sensors with high sensitivity and working range that meet market demands and end-user expectations is proposed in this thesis.

The developed manufacturing method enables manipulation of sensor properties by varying production parameters based on specific application needs. The proposed sensor's electrode is made of conductive knit fabric that containing silver nanoparticles (AgNPs), and the dielectric layers are made of thermoplastic polyurethane (TPU) sheets. As a result of the novel approach, it is possible to generate scalable air gaps between electrodes and dielectric layers to capture low pressures of less than 1 kPa. The usage of multi-layer TPU sheets also increases the working range of sensors up to 1000 kPa. The proposed technology is used to create several sensor mats for various purposes, including improved gesture and shape recognition, as well as interactive gaming mats for children.

E-TEKSTİL UYGULAMALARI İÇİN KAPASİTİF TABANLI YUMUŞAK BASINÇ SENSÖRÜ DİZİLERİNİN GELİŞTİRİLMESİ

ÖZET

Tekstil, insanlığın geliştirdiği tarihi binlerce yıl öncesine dayanan ilk malzemelerden biridir. Tekstil materyalleri, verilmek istenen sanatsal veya maddiyat içerikli mesajları iletmek ve insanları çevresel doğa şartlarından korumak için kullanılmıştır. Ancak günümüz toplumu, akıllı sistemlerle donatılmış bütünleşik bir dünya kurmak amacıyla son zamanlarda tekstil biliminde büyük buluşlara imza atmıştır. Yumuşak basınç sensörleri, insan hareketi tanıma, nesne algılama ve insan-bilgisayar etkileşimi dahil olmak üzere geniş uygulama yelpazesi nedeniyle son on yılda birçok bilimsel araştırmaya konu olmuştur.

Bu araştırmalar ve ortaya çıkarılan ürünler içerisinde, tekstil tabanlı sensörler, esneklik, hafiflik ve nefes alabilirlik yetenekleri sunan ve bu sayede akıllı cihazlar için mükemmel bir seçenek haline gelmiş son teknoloji ürünlerdir. Giyilebilir sensörlerin dünya pazarındaki payı, 2020 yılı için 660 milyon dolar seviyesinde olmakla beraber 2028 yılına kadar bu pazarın yıllık bileşik %29 büyüme oranı ile birlikte 5 milyar dolar seviyesini geçmesi beklenmektedir.

Akademik ve sektörel alanlarda yapılan çalışmalar sonucu bir takım basınç ve hareket algılayıcı sensörler piyasada kendilerine yer bulabilmişlerdir, lakin bu sensörlerin üretimleri esnasında oluşan zorluklar ve zaman kaybı nedeniyle seri üretimleri ve son kullanıcıya ulaşmaları oldukça kısıtlıdır, bu husus ürün fiyatlandırılmasında da olumsuz etki yaratmaktadır.

Sorun teşkil eden diğer bir konu ise, piyasada bulunan ve akademik araştırmalara konu olan sensörlerin üretimleri esnasında çalışma aralıklarının ve hassasiyetlerinin kullanım alanlarına göre farklılık gösterecek şekilde ölçeklendirilememesidir. Bu doğrultudan yola çıkarak, geniş çalışma aralıklı ve yüksek hassasiyete sahip kapasitif basınç sensörlerinin zahmetsiz, seri ve ölçeklendirilebilir şekilde üretilmesi için yapılan çalışmalar bu teze konu olmuş, geliştirilen üretim tekniği sayesinde sensör özelliklerinin manipüle edilerek farklı kullanım alanlarına uyumluluğunu sağlamak amaçlanmıştır.

Temel olarak çalışma mekanizmasına göre piezoresistif, piezoelektrik, kapasitif ve diğer hibrit cihazlar olmak üzere basınç sensörlerinin sınıflandırılması mümkündür. Bunlar içerisinde kapasitif sensörlerin çalışma mekanizması kapasitans esasına dayanmaktadır. Kapasitif tabanlı sensörlerin, yüksek basınç hassasiyeti, düşük enerji tüketimi ve sensör tasarımı anlamında üreticiye esneklik sunması gibi öne çıkan özellikleri kullanım alanları

ve araştırma sahasını genişletmiştir. Kapasitans bir devrenin elektrik yükleri biçiminde enerjiyi depolama ve toplama yeteneğidir. Uygulanan basınç neticesinde ortaya çıkan kuvvetin, sensör devresinde toplanan enerjiye etkisi kapasitans değişimi olarak nitelendirilir.

Üretim kolaylığı ve sürdürülebilirliği açısından paralel plaka düzenli kapasitif sensörler en yaygın olarak kullanılan ve üzerine geliştirmeler yapılan sensör sistemleridir. Kapasitif basınç sensörleri, alt ve üst kısımda olmak üzere elektrot olarak adlandırılan paralel yerleştirilmiş iletken materyaller ve bu iletken katmanların dielektrik olarak tanımlanmış izolasyon malzemesi ile birbirleriden ayrılması ile oluşmaktadır. Kapasitif sensöre bir doğru akım voltajı verildiğinde, yalıtkan dielektrik tabaka akımın iletken katmanların arasından akmasını engellediğinden, iki elektrot üzerinde zıt kutuplar oluşmaktadır. Uygulanan kuvvet sonucu dielektrik materyalin elektrik geçirgenliği artmakta ve elektrotlar arası mesafe azalmaktadır, bu sayede gerçekleşen kapasitans değişimi ölçülebilmekte ve sensör üzerine gelen basıncın miktari tespit edilebilmektedir.

Bu tez çalışması dahilinde üretilen tekstil tabanlı kapasitif basınç sensörlerin elektrotları gümüş nanopartiküller (AgNPs) ve %78 poliamid %22 elastan içeriğinden oluşan -30 ile +90 derece çalışma aralığına sahip iletken örme kumaşlardan, dielektrik katmanları ise termoplastik poliüretan (TPU) malzemeden oluşmaktadır. Sensörlerde kullanılan termoplastik poliüretanın elektrik yalıtkanlığının yanısıra diğer önemli bir özelliği ise başlangıç boyutunun yaklaşık %500 kadarına kadar çıkabilen esneklik özelliğidir. Çalışmalar kapsamında üretilen kapasitif sensör katmanlarının birbirleriyle olan ara bağlantısı ise ısıtıldığında eriyip materyalleri birbirine yapıştırabilen çift taraflı film ile sağlanmıştır.

Kapasitif tabanlı basınç sensörleri üzerine yapılan çalışmalar bize göstermektedir ki, dielektrik katmanlarda oluşturulmaya çalışılan boşluklar uygulanan kuvvet ile birlikte kolayca deforme olabilmekte böylelikle sensör hassasiyeti ve sensörlerin tepki verme süreleri üzerinde olumlu bir takım etkilere sahip olmaktadırlar. Bu doğrultudan yola çıkarak sensör dizilerinin içerisinde hava boşlukları oluşturmak amacıyla çift taraflı eriyebilir filmler modifiye edilmiş ve akrilik pleksiglas levhalardan baskı plakaları tasarlanmıştır.

Üretim aşamasında iletken kumaşlar lazer kesim cihazında sensör dizileri halinde farklı boyutlarda kesilmiş, eriyebilir katman ise elektrotların ve dielektrik malzemenin arasında olacak şekilde konumlandırılmıştır. Sonrasında ise katmanların tamamı baskı plakası üzerine titizlikle yerleştirilmiştir. Tasarlanan baskı plakası üzerine yerleştirilmiş olan katmanlara, sıcak basınç makinesi yardımı ile ısı ve baskı uygulanmış böylelikle çift taraflı film eritilmiş, dielektrik materyal ve elektrotlar arasında hava boşluğu oluşacak şekilde sensörlerin üretilmesi gerçekleştirilmiştir.

Basınç sensörlerinin özelliklerinin kullanım alanlarına göre modifiye edilebilmesi için, dielektrik katmanların ve sensör dizisi hücre boyutlarının hassasiyet ve çalışma aralığı üzerindeki etkisini anlamak önemlidir. Bu amaçla, basınç sensörlerinin çalışma aralığına olan etkisi farklı miktardaki TPU katmanlarının (1, 2 ve 3 katman) eklenmesi ile incelenmiş olup aynı zamanda hücre içerisinde oluşturulan hava boşluklarının sensör özelliklerine olan etkisini gözlemlemek için iki farklı hücre boyutuna (10 ve 15 mm kenar uzunluğu) sahip sensörler üretilmiştir.

Üretim tekniğinin sensör tasarımları üzerine olan ölçeklendirilebilirliğinin gözlemlenebilmesi açısından 18 adet farklı boyutlarda elektrot yüzey alanlarına, dielektrik (TPU) katmana ve hava boşluğu miktarına sahip tekil sensör hücreleri üretilmiştir. Bu üretilen sensör hücreleri enine kesilerek mikroskop altında incelenmiş, istenilen düzeyde hava boşluğunun oluşup oluşmadığına bakılmıştır. Kapasitif sensör hassasiyeti üzerinde büyük öneme sahip olan bu hava boşluklarının, üretim tekniğinin ölçeklendirilebilirliği sayesinde istenilen konumda istenilen miktarda oluşumunun mümkün olduğu sonucuna varılmıştır. Bu gözlem sonucunda geliştirilen üretim metodunun sensör hücrelerinin çeşitlendirilebilmesi açısından kritik öneme sahip olduğu ve farklı uygulama alanlarına özel olarak tasarımları mümkün kıldığı sonucuna varılmıştır.

Sensör hassasiyeti, çalışma aralığı, tepki süresi ve sensör dayanıklılığı kullanım alanlarının genişliği açısından üzerinde durulması gereken önemli sensör parametreleridir. Yapılan karakterizasyon çalışmaları sonucunda, ekstra TPU katmanları eklemenin sensörlerin çalışma aralığını arttırdığı ve daha yüksek hava boşluğu (AG) / hücre boyutu (CS) oranına sahip sensör dizilerinin daha yüksek hassasiyet özelliğine sahip olduğu gözlemlenmiştir. Üretilen sensörlerin 140 milisaniye gibi çok hızlı tepkime sürelerine sahip olduğu belirlenmiştir. Dahası sensörlerin elektriksel performansının 1000 kez kullanm sonrasında %6 değişim gösterdiğini saptanmış ve üretilen basınç sensörünün performansının uzun süreli kullanım için uygun olduğu tespit edilmiştir. Bütün bu sonuçlar açıkça bize göstermektedir ki gerek rehabilitasyon gerekse eğlence uygulamaları alanlarında kullanılmak üzere üretilen bu sensörler piyasada rekabet edebilecek hassasiyete ve dayanıklılığa sahiptir.

Geliştirilen bu teknik sayesinde, üretilen sensörlerin elektrot ve dielektrik katmanları arasında hava boşlukları başarıyla oluşturulmuş ve böylece 1 kPa’dan küçük basınçların sensör tarafından algılanabilmesi sağlanmıştır. Dielektrik katmanların sayısı artırılarak sensörlerin çalışma aralığı 1000 kPa basınca kadar genişletilebilmiştir. Son olarak, geliştirilen üretim tekniği ile çeşitli uygulamalara yönelik parmak hareketlerinin takip edilmesine olanak sağlayan dokunmatik yüzeyler, üzerine yerleştirilen cisimlerin konumlarını, şekillerini ve ağırlıklarını algılayabilen basınç matı ve çocukların eğlenirken matematik becerilerini geliştirebileceği oyun platformları tasarlanmıştır.

1. INTRODUCTION

Textile innovation 27,000 years ago could be regarded one of humanity's first material inventions. Textiles have been used for millennia to protect people from the environment as well as to send outward messages in artistic, or wealth-related aspects [1]. However, modern society has made a paradigm shift in recent years, aiming to make the world smarter and more comfortable. To achieve these goals, various electronic products have been innovated. In these well-developed products, flexible and wearable smart gadgets that modify our life styles are on the top. Therefore, countless researchers are currently developing compact and lighter instruments that measure and quantify electronic signals generated by human activities [2, 3].

Traditional sensors, which are typically made of rigid materials like metals or semiconductors, can only resist small strains and these sensors are bulky, inflexible, and difficult to wear. Textile-based sensors represent a new generation of instruments that integrate sensing functionality with flexibility, low weight, and breathability, making them an ideal choice for use close to the skin [4]. The method of embedding sensing components into textiles enables for long-term monitoring without irritation, as well as design flexibility relying on the application [5].

Electronic textiles (E-textiles) provide electronical functionality to textiles while preserving their inherent qualities. The innovation of smart materials and the scalability of production processes are highly required for the expansion of E-textiles [6]. The Internet of Things (IoT) is the most important aspect of the Fourth Industrial Revolution (4IR), and textile-based wearable sensor technology is a vital part of it [7]. Since textiles are porous, anisotropic three-dimensional (3D) materials with inherent softness and flexibility, applying functional substances to traditional textiles and developing scalable manufacturing techniques is critical [8, 9].

Based on the sensing mechanism, classifications can be made between piezoresistive [10], capacitive [11, 12], piezoelectric [13], and also hybrid devices [14, 15], demonstrating the relevance and diversity of the sensor researches These sensing mechanisms will be explained in detail in the following sections. Stress/strain sensors should have sensing capabilities similar to human skin in order to be employed in a variety of applications, such as, virtual reality (VR) and augmented reality (AR) applications [16, 17], rehabilitation/personal healthcare [18, 19], pressure mapping [20, 21], electronic skin [22, 23], and motion detection such as breathing, speaking, and joint movements [24-26]. The textile sensors, which have been placed primarily on the trunk, upper arm, forearm, wrist, and finger to monitor kinematics, have a significant impact in many areas including health, sports, and entertainment [27].

Wearable technology has rapidly evolved in recent years and is now considered a serious competitor in the consumer electronics market. In 2020, the global market for wearable sensors was worth 660.89 million dollars, and by 2028, it is predicted to be worth 5208.05 million dollars, with a compound annual growth rate (CAGR) of 29.3% from 2021 to 2028. (See Figure 1.1) [28].

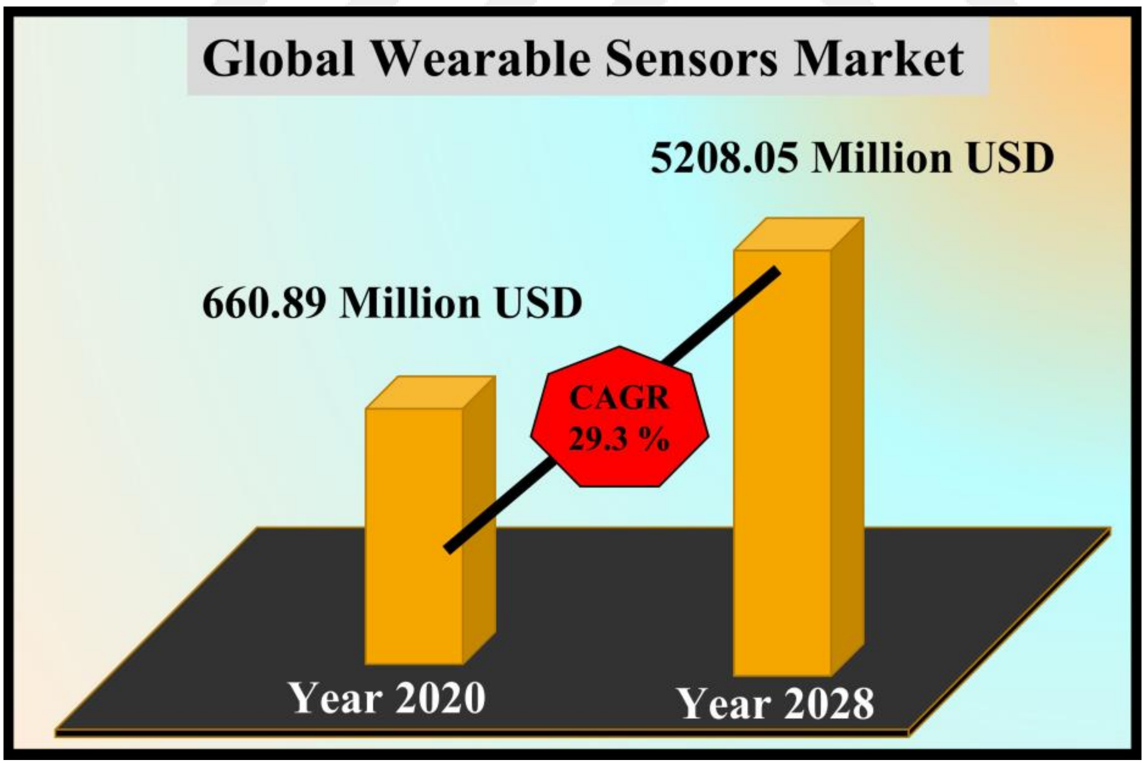

Figure 1.1 : Wearable sensors market size and forecast [28].

This thesis is divided into six sections. The first chapter provides an overview of the general research area as well as a summary of the e-textile field, including benefits, application areas, and market share. Chapter 2 summarizes the materials used in flexible sensors, distinguishing between matrix/substrate and conductive materials. The material types, sensor types, structural designs, and fabrication methods are discussed. Finally, recent pressure sensor researches in the literature is presented. In Chapter 3, the materials and methodology used in this project are explained. The macrostructures of manufactured specimens, as well as electromechanical measurements of pressure sensors in terms of sensitivity, response time, durability, and working range, are discussed in Chapter 4. Chapter 5 presents an object recognition system based on pressure mapping, a touch pad system with finger gesture detection, and interactive educational gaming platforms for children. Chapter 6 evaluates the research and finally summarizes the progress that has been made thus far, followed by a discussion.

2. MATERIAL DEVELOPMENTS IN E-TEXTILES

2.1 Conductive Materials

Smart textiles can be developed by integrating new functionalities into traditional textiles through a variety of methods such as spinning, weaving, knitting, embroidery, printing, and coating [4]. Graphene, metal nanowires, nanoparticles, and nanosheets, as well as conductive polymers and liquid metals, are commonly found in conductive materials. Notably, Metal nanoparticles (MeNPs) exhibit outstanding optoelectrical characteristics, fast kinetics, and easy absorption, related to their large surface area to volume ratio [29]. Geometric engineering of conductive materials with special structures such as wrinkled, coiled, double helical, accordion and buckled improves the flexibility of sensors derived from these materials [30]. On the textile side, conductive materials are separated into innately conductive and specially treated conductive yarns and textiles. Metal yarns or filaments are used to make inherently conductive yarns, particularly stainless steel, nickel, copper, and aluminum being the most popular metals employed. Similarly, conductive yarns or fabrics that have been specially treated obtain their conductivity as a result of additional processing processes including printing, coating, and so on [7]. Figure 2.1 below depicts the evolution of fibers as well as their functionalities.

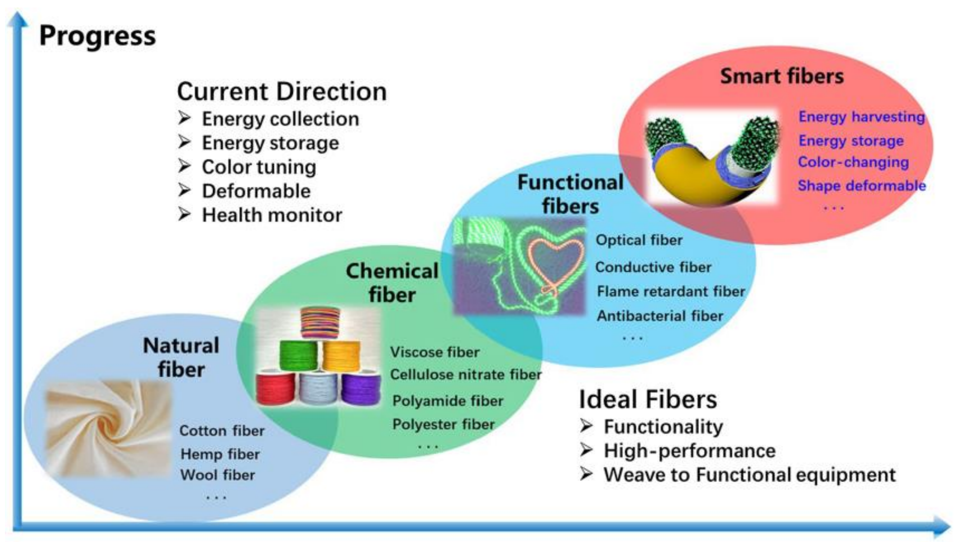

Figure 2.1 : A chronology of fiber developments for various purposes [4].

2.1.1 Inherently conductive fibres

Ionic liquid (IL), polypyrrole (PPy), polyaniline (PANI), and poly(3,4-ethylenedioxythiophene): poly(styrene sulfonate) (PEDOT:PSS) are examples of inherently conductive polymers (ICPs) that have significant potential for making cost-effective, lightweight, and flexible sensors. Biocompatibility, ease of surface modification, and a large surface area are among the benefits of conducting polymers. Conducting polymers have leveraged new synthesis and characterization techniques as a result of their behavior. Due to their high sensitivity to the physiochemical conditions, using inherently conducting polymers is an effective way for altering fabric surfaces and producing fabric sensors [4].

2.1.2 Surface modifications

The purpose of surface modification is to create a pattern with an unique design that is limited to the active layer's surface. These shapes have a large aspect ratio and are made with a photolithographic or soft-lithographic mold. To improve the surface area and deformability of the active layer surfaces, pyramid or rod patterns are commonly used [3]. Screen printing, ink-jet printing, and gravure printing have been used to construct the flexible and stretchable devices. The printing process has attracted interest for future applications due to low material waste, large-area manufacturing capacity, and low cost [31].

Inkjet printing is a process for applying ink to a wide surface area of textiles that is controlled and automated. The fundamental benefit of printing methods is that they can be done at room temperature and pressure, which makes them simple to manufacture [6]. Furthermore, many different types of 3D printing technologies have been used in the fabrication of different types of sensors, such as piezoresistive, capacitive, and piezoelectric sensors. 3D printing is a collection of technologies that build three-dimensional items layer by layer using computer-aided design (CAD) models. Almost any sophisticated structure can be fabricated in a simple and low-cost manner with 3D printing [32].

Coating fibers, yarns, or fabrics with conductive compounds is used to create textile-based sensors. This application can be carried out using in situ chemical polymerization, vapor phase polymerization, spray coating, dip-coating, roller coating, and rod coating. Coating techniques can result in high sensitivity and a wide sensing range. High linearity and cycling stability, on the other hand, can be difficult to achieve through coating [5]. Textiles are commonly coated with conducting inks such as copper (Cu), silver (Ag), and gold (Au) to produce diverse characteristics and surface appearances. Hand-applied thicker coatings, such as carbon loaded pastes or other organically doped polymers, can be applied through masking techniques, screening, dip-coating, soft lithography, embossing, or imprinting [33].

2.2 Sensors Types In E-textiles

Over the last few years, pressure sensors have gained a lot of research attention, specifically for skin-based electronics. Sensing functions can be added to textiles at many phases of production, such as during fiber spinning, yarn/fabric manufacturing, or finishing. From a structural standpoint, textile strain sensors can be classed as fiber, yarn, or fabric sensors [5]. Flexible sensors can be closely bonded to the human skin and can offer improved signal quality due to their specific characteristics of flexibility, durability, biocompatibility, and lightweight [34]. The two categories of sensors are active and passive sensors. The former can convert input energy into output signals without requiring an external power supply, whereas the latter does [7]. Fabric sensing approaches have been investigated for a wide range of applications. However, none of them has been considered the most promising in the area [33].

Strain sensors and pressure sensors both sense mechanical forces, but the key difference is in the sensing orientation: the former works in a planar or longitudinal direction, whilst the latter works in a transverse direction [35]. Stress/strain sensors can either transform or modify the stimulus into an electrical signal. Piezoresistive, capacitive, and piezoelectric transduction processes are used to classify flexile pressure sensing systems. Because of their ease of manufacture and embedding, piezoelectric and capacitive sensors are more widely used in textile applications. These sensors can be used in wearables to detect a variety of human movements and muscle activities, such as breathing, pulse, and respiration [36]. Several studies have been conducted in order to improve the properties of the flexile pressure sensing devices based on the three conversion principles stated previously. The advantages and disadvantages of the three distinct types of pressure sensing systems are compared in Table 2.1

Table 2.1 : Advantages and disadvantages of the three types of sensing systems [28].

Transduction Principles	Pros	Cons
Capacitance	Extraordinary sensitivity, simple structure, big dynamic span, good temperature constancy, fast response, approriate for small force test.	Poor linearity, vulnerable to EM interference, prone to parasitic capacitance.
Piezoresistivity	Simple fabrication process, cost-effective, large deformation, strong anti-interference ability, easy to attain small size.	Poor stability, low sensitivity, poor temperature stability.
Piezoelectricity	High sensitivity, fast response, low power utilization.	Poor stretchability, low spatial resolution, only applicable to dynamic testing.

2.2.1 Piezoresistive

When it comes to piezoresistive sensing, a sensing layer consisting of piezoresistive materials converts mechanical impulses into resistive/conductance changes, which are then analyzed by an external circuit [37]. The electrical characteristics of conductive materials alter as they are mechanically deformed. The piezoresistive effect, as seen in Fig. 2.2(a) is an electromechanical reaction. Elongated materials shrink in the transverse direction due to the Poisson ratio (v). As a result, the resistance R of a conductive material changes, as demonstrated by the equation:

$$R = \rho L/\mathrm{A}, \tag{2.1}$$

where ρ is the resistivity, L is the length, and A is the conductor's cross-sectional area. Due to its simple readout, high sensitivities, and simple device designs, the piezoresistive effect has been broadly utilized in wearable electronics for the sensing of human movements [38]. In piezoresistive systems, the gauge factor (GF) is commonly used to describe strain sensitivity:

$$GF = \frac{\Delta R}{R} / \varepsilon, \quad (2.2)$$

where ΔR is the change in resistance, R is the unstrained resistance, and ε is strain [39]. These commercial strain sensors, despite their high sensitivity and inexpensive cost, are fixed directional sensors that can only sense modest strains. As a result, they are unsuitable for multifunctional, multidirectional wearable tactile sensors that demand great sensitivity over a broad pressure range. Novel sensing elements based on different nanomaterials are required to satisfy the needs of flexible sensors for wearable electronics [32].

2.2.2 Piezoelectric

Due to their flexibility, ease of electrical signal acquisition, and simple and low-cost manufacture, piezoelectric sensors have received much interest in recent years. The mechanism of operation of a piezoelectric type pressure sensor is that dipole moments in the active material produce electrical potential (Figure 2.2(b)). When mechanical force, pressure, or strain is applied to piezoelectric sensitive materials, electrical charges are generated. When a material is deformed by external pressure, the positive and negative charges separate, forming a potential difference that defines the magnitude of the applied pressure. These materials are employed for energy harvesting as well as pressure sensors in wearable applications [40]. Furthermore, the electrospinning technology is frequently employed for piezoelectric pressure sensor production. Additionally, because piezoelectric pressure sensors create current and voltage by moving electrons when placed under pressure, they can readily be used as self-powered sensors. In the wearable electronics industry, self-powered pressure sensors are appealing since they do not require an external power source or energy storage device, such as a battery. However, due to the low stretchability of the materials employed in piezoelectric pressure sensors, their usage in wearable electronics has been limited [3].

2.2.3 Capacitive

Capacitive sensors are a promising sensing mechanism for mechanical stimuli in consumer electronics due to its high device sensitivity, low power consumption, and customizable sensing designs. Because it is simple to construct, the parallel-plate layout is the most common structure used in capacitive sensor systems [41]. In textile-based capacitive sensors, an insulating layer called dielectric separates two textile electrode layers. When a direct current (DC) voltage is given to the sensor, opposing charges build up on the two electrodes since the insulating dielectric layer prevents current from flowing between them [35]. The capacitance change is defined by the classic equation:

$$C = \frac{\varepsilon A}{d}, \tag{2.3}$$

where A and d describe the overlap area and distance between two plates, respectively, and ε is the permittivity of the cavity between two plates. External loads change the distance, area, or permittivity, resulting in changes in capacitive readouts that could be monitored [42].

Capacitive fabric sensors are available in various of dimensions, from micro to large sensing surfaces. A capacitive sensor is commonly placed on a frame that can be sewed, snapped, or glued to a fabric substrate before being attached to other devices. Fabric capacitors can also be made using flexible conductive materials that perform as electrode plates and are separated by dielectrics and spacers. Synthetic foams, soft polymers and fabric spacers are commonly utilized as dielectrics [33]. There are upsides and downsides to various arrangements. The capacitive arrangement, on the other hand, has the advantage. These have faster drift response, stability, lower power consumption, and are less prone to misalignment errors. The capacitive type is very cost-effective, has less dependency on the environment, and has a very consistent performance. These properties offer large-area scalable textile sensor production, which can then be implemented into clothing for real-time measurement of human movements [43].

2.2.4 Iontronic

In recent years, iontronic capacitive pressure sensors with an ionic gel layer between two flexible electrodes have been invented. When a little voltage is applied, an electric double layer (EDL) that behaves like a capacitor forms at the electrode-ionic gel interface. Electrical changes in an electrolyte-containing substance caused by charge distribution and ion transport are detected by iontronic physical sensors [44]. Due to the microstructure used in existing iontronic sensors, nonlinear responses still exist. As a result, developing a highly sensitive sensor with linear response over a wide pressure range continues to be challenging [45].

2.2.5 Other types

Alternative transduction techniques have also been used to detect external pressure. Transistors are mostly investigated for organic field-effect transistors, and similar to capacitive-type pressure sensors, their sensitivity is characterized by the deformability of the gate dielectric layer with pressure [46]. Similarly, different strategies have been proposed to increase the deformability of the dielectric layer. Another significant self-powered pressure sensor is the triboelectric sensor. In 2012, Wang's group developed the triboelectric nanogenerator (TENG), which combines triboelectrification and electrostatic induction. TENGs are mostly utilized in the contact/separation mode, having two dielectric layers. To maximize the triboelectric effect, dielectric materials replaced at the reverse ends of the triboelectric series are required [47].

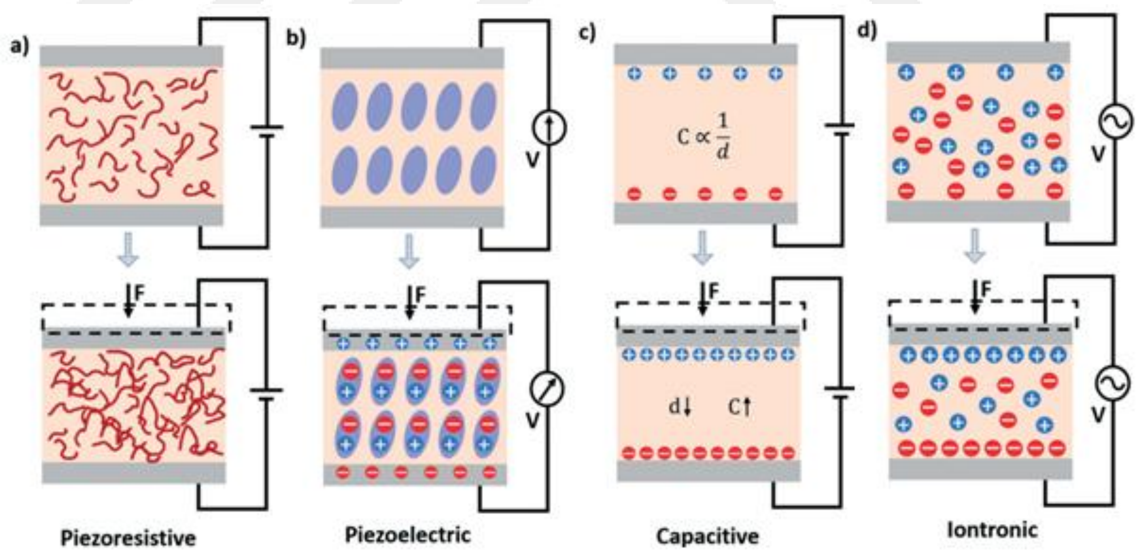

Figure 2.2 : Schematics depicting the various types of mechanical sensors. A) Piezoresistive, B) Piezoelectric, C) Capacitive, D) Iontronic [2].

2.3 Manufacturing Techniques

Textiles have a great level of programmability due to the intrinsic character, allowing researchers to change and adjust characteristics at many interdependent material levels.

As a consequence, flexile pressure sensing devices are suitable for arbitrarily curved surfaces and have important implications in the fields of human-machine interface, wearable electronics, and electronic skin [28]. Since the initial demonstration of an incorporated flexible pressure sensor matrix, various groups have been dedicated to building high-performance macroscale flexible systems to accomplish the spatial and temporal profile mapping of objects using pressure sensor arrays [48]. In this part, we will go through the appropriate materials and fabrication procedures for wearable sensor devices, such as flexible supporting materials, porous structures, and composite sensor structures as well as their challenges.

2.3.1 Structural designs

Dielectric materials comprising microstructures such as fabrics, pores, microcylinders, pyramids, beads, microspheres, and needles have noticeably increased sensitivity, sensing range, reaction time, and mechanical compatibility in capacitive sensors-based e-skin. More contact region, reversible elastic deformation, and stress direction-sensitive structural deformation can be provided by the micro or nanostructure of the sensor matrix. Microstructures cause a rapid response time and excellent sensitivity. The air gap between the electrodes is widened by microstructures, and deformation has a significant impact on the dielectric layer [49].

2.3.1.1 Flexible supportive materials

Various manufacturing technologies have been developed in recent years to increase the electrical performance, flexibility, and stretchability of the pressure sensors. Many capacitive sensors employ elastomers as the dielectric material since they are intrinsically insulators. They may be employed as the base layer of all sensing components in both capacitive and resistive modes since they are compatible with most conductive fillers [50]. Rubbers/elastomers, including silicone-based rubber e.g. polydimethylsiloxane (PDMS), thermoplastic polyurethane (TPU) elastomer, Ecoflex (SMOOTH-ON), and many others, have also been classified as flexible support materials [30]. For thousands of loading/unloading cycles, elastomers can withstand high dynamic strain (typically greater than 100%). Reportedly, the majority of substrate materials are silicone or polyurethane based, because of their elasticity, thermal stability, transparency, chemical inertness, curability, non-toxicity, and biocompatibility [51].

2.3.1.2 Porous structures

Pressure sensors have been implemented using elastomers, as discussed in earlier sections. A morphological variable technique, in which the elastomer is rendered porous and employed as the dielectric in capacitive sensors, has been in focus since the late 1990s but has recently been extended towards generating porous elastomers [50]. The pores in between designs are filled with air, and their volumes are decreased by external pressure as the patterns deform. Because the permittivity "ε_r" is greater than that of air, the effective dielectric constant rises as the amount of air decreases, and the capacitance rises as a result. The sensor's sensitivity can be considerably increased thanks to the synergetic impact of increased dielectric layer deformability and variable effective dielectric constant. One of the simplest methods for creating porous structures is to use a particle template. Because it may extend the surface area and increase deformability by reducing the density and Young's modulus of the layer, a porous structure is employed in practically all types of pressure sensors [3]. Flexible pressure sensors with porous microstructures can also be made using a porogen, such as NaCl or sugar particles, as a sacrificial template and a matrix component, most often silicone rubber. To complete all fabrication procedures, the particles are dissolved and removed after the matrix material has been hardened [52].

2.3.1.3 Laser usage in structural designs

Laser cutting to produce flexible sensors has recently become an important technique due to advantages such as low production costs, easy sample preparation, the ability to process a variety of raw materials, reduced human intervention in sample preparation, and its usability for various functionalities. Previously, laser cutting was restricted to glass, metals, and ceramics, but it has lately been upgraded to operate with polymeric substrates and nanoparticle-based electrodes. Various types of laser cutters are now available that use laser parameters to operate on specimens very precisely. As a consequence, laser-cutting processes bring up a wide range of options for prototyping in a variety of sizes and shapes [53].

2.3.1.4 Thread-type processes

Thread-type processes including such knitting, weaving, and embroidering are constantly being developed for minimization of wearable textile-based sensors. Moreover, the electrical and mechanical properties of threads attached to insulating fibers or fabrics can be controlled based on their topology or structure. As a result, they are simple to combine with a variety of electronic systems [54]. Knits are textile structures made up of interlaced loops of yarn that provide for the largest variety of mechanical characteristics. Very stiff and very flexible regions of material can be manufactured homogeneously on one piece of equipment by altering the way threads interlock. Knit sensors comprise the majority of the textile structured sensor market. This textile construction approach has been highly successful in producing sensors from conducting materials, either through knitting conductive yarns or coating knit surfaces with conductors, since the looped knit structure allows stiff yarns to generate flexible fabrics. Distributed regions of knit sensors can be generated in clothing using multi-material 3D knitting mixed with intarsia knitting. The conductive parts in these knit sensors are made of stainless steel, carbon fibers, silver-plated nylons, and conducting polymers. Yarns with conductive compounds have been optimized for the knitting processes and sensor performance in the past. [50, 55].

2.3.1.5 Composite sensor structures

Composite textile sensors are made by stacking and attaching existing textiles into sensors, as well as adding nontextile elements such as elastomers, adhesives, and films, which are highly needed for operation. This design is highly suitable to capacitive sensors; electrodes and dielectric materials can be stacked and bonded to construct textile-based pressure and strain sensors, resulting in applications that are optimized for low-cost materials and fabrication simplicity. The necessity for bonding and adhering textiles together is a disadvantage of this approach: delamination remains an issue in terms of durability, especially over long periods of time, and yarn motion can be negatively impacted by the adhesive material, making the textile less "textile-like" but more like a film [55].

2.4 Applications of Pressure Sensors in Literature

Many researches have been conducted to manufacture pressure sensors and develop the properties of sensors in terms of high sensitivity, broad working range and cyclic durability for long term use. For example, in order to overcome the sensitivity and sensing range limitations of pressure sensors, Yang et al. created a solution based on polyvinylidene fluoride (PVDF) powder and carbon nanotubes that is used in the electrospinning process to create a nanofiber dielectric layer. Indium tin oxide polyethylene terephthalate films are preplaced to the surfaces of the nanofiber dielectric layer as electrodes [56]. Vu et al. used single-walled carbon nanotubes (SWCNT) ink and stretchable silver paste to create electrode patterns on polyethylene terephthalate/ elastane (PET/EA) fabrics in another study. Screen printing was used to print SWCNTs on the top and bottom sides of the spacer fabric. Following that, the sensors are shaped by a laser cutting, and the encapsulation pastes are injected into the spacer layer. At the end of this step, capacitive pressure sensors with Ag/SWCNT electrode layers were formed [57].

Lee et al. proposed a method to fabricate capacitive air gap touch sensors via printing and coating. The bottom electrode was first printed on a PET substrate with silver ink using roll-to-roll gravure printing. Then, using a polyimide (PI) pattern mask, PDMS was mixed with a curing agent and spin-coated to form a sacrificial layer. The top electrode was created by spin coating a stretchable silver ink onto the sacrificial layer. The sensor samples were then immersed in a tetrabutylammonium (TBAF) bath to remove the sacrificial layer and create an air gap [58].

Another advancement was reported by Atalay et al. who proposed a way to increase the sensor sensitivity by generating micropores in the dielectric layer. Towards this aim, silicone elastomer and sugar granules were mixed and cured, then the granules were dissolved in an ultrasonic washing tank, leaving micropores in the silicone elastomers. The electric layer is sandwiched between two conductive fabrics at the end [59].

A capacitive sensor enhanced by a tilted micropillar array-structured dielectric layer is developed by Luo et al. in this work, photoresist was spin coated on a silicon wafer and exposed to UV light to create the template. Following that, PDMS was poured and cured to create a dielectric layer structure with tilted micropillar arrays, which was then bonded to Au-coated PET electrodes [60].

Pyo et al. present a capacitive tactile sensor comprised of graphene electrodes that are separated by spacers which form air gaps. Chemical vapor deposition was used to create monolayer graphene, which was then transferred to PET substrates. Electrodes patterned by photolithography and etched by O_2 plasma. For spacer fabrication, photolithography was used to pattern SU-8 on the PET film. In the meantime, PDMS was spin-coated on the other graphene and exposed to N_2 plasma to form amino groups capable of reacting and bonding with epoxy groups on the SU-8 surface. Finally, the top and bottom layers were aligned and bonded together [61]. Furthermore, a multimaterial 3D printing technology was utilized to produce a tactile sensing mechanism that have a specific geometry to fit the curved surfaces by Guo et al. Using Ag/silicone ink, the bottom electrode layer was printed on the silicon base layer. The silicone and pluronic inks were used to print the isolating and supporting layers, respectively, and the top electrode was printed on the supporting layer to create the sensor [62].

Takamatsu et al. discovered a method for producing pressure sensors that uses a continuous functional film coating approach. Wefts and warps of coated fibers with PEDOT:PSS and Cytop were woven as wefts and warps, and also the rest was filled with pristine nylon fibers, resulting in a pressure sensitive handkerchief. Die-coating systems with thicknesses ranging from hundreds of nanometers to several millimeters are used for coating. The resulting fibers are looms into a sensor fabric with a 16 cm x 16 cm surface area [63].

Lastly, Mannsfeld et al. developed a manufacturing technique to increase pressure sensitivity while decreasing response time. By combining various microstructured and porous dielectric elastomeric layers with stretchable electrodes made of conductive flexible PET sheet coated with indium tin oxide (ITO). Dropcasting a dilute solution of the PDMS base and cross-linker combination in hexane onto a Si wafer mould comprising arrays of the reverse of the characteristics to be replicated. The PDMS coating has been vacuum-degassed and partially cured. An ITO-coated PET electrode is bonded to the mould, and the PDMS film is cured under pressure for around three hours at a temperature of 70 °C [64].

2.5 Research Gap and Motivation

A variety of techniques have been used to create flexible and stretchable sensors. These methodologies have been extensively pursued in order to increase electrical performances such as sensitivity, detection limit, cycle stability, and so on. Studies of electrode and dielectric materials, structural designs, and manufacturing processes have also been investigated. Lab scale methods are typically used for exploratory studies involving new materials or new applications for existing materials, as well as performance optimization. Despite advances in soft pressure sensor technologies, there is still significant manufacturing difficulty that limits the scalability of sensors for real world applications in terms of high sensitivity, high resolution, quick response, long-term stability, and durability across a wide range of applications [54].

Furthermore, there are several difficulties in terms of commercialization, such as high costs, multistep manufacturing procedures, prototyping and scaling challenges. Cost effective manufacturing processes are critical for achieving large-scale adaptable systems with high-throughput capabilities in order to enable the penetration of human-interactive gadgets into global markets and households [48]. Here, a novel pressure sensor arrays fabrication technique will be described in order to meet the demand for a scalable, laborless, rapid, and repeatable fabrication strategy for mass production and commercialization.

3. MANUFACTURING OF TEXTILE-BASED CAPACITIVE PRESSURE SENSOR ARRAYS

3.1 Material Specifics

In this thesis work, above mentioned difficulties are solved by proposing an effective and simple novel manufacturing method for textile-based capacitive pressure sensors fabricated with conductive knit fabric electrodes (Shieldex® Med-Tex P130) and dielectric TPU (Fibre Glast Developments Corp - Stretchlon 200 Bagging Film) layers. 99% pure Silver plated conductive knitted fabrics that is made of 78% Polyamide + 22% Elastomer have chosen due to their high conductivity and broad temperature range -30℃ to 90°C. On the other hand, TPU film that stretches up to 500% its original length is used as dielectric layer in order to provide the sensor integrity and flexibility. For layer bonding and cell formation double-sided fusible sheet are used.

3.2 Preparation of Sensors Step by Step

Here, an effective and simple novel manufacturing method for textile-based capacitive pressure sensors is proposed. In order to achieve high sensitivity, we used a novel technique to generate air gaps within the sensor itself, and we also alternated sensor properties (sensitivity, working range, and response/recovery time) by modifying manufacturing parameters, resulting in versatility for various application areas. While the presence of air gaps significantly enhances sensitivity, the dielectric layers maintain the integrity of the produced sensor arrays and determine their operating range. This strategy is essential for real-world applications that require highly sensitive and robust pressure sensors.

In order to adjust the capabilities of pressure sensors, it is important to understand the effect of dielectric layers and sensor array cell sizes on sensitivity and working range. For this aim, we also investigated the contribution of number of different TPU layers (1, 2, and 3 layers) on the working range of the pressure sensors and formed two different cell sizes (10 and 15 mm side length) to observe air gaps formation within the sensor cells to better understand how air gaps affect sensor sensitivity.

We found that adding extra TPU layers increases the working range of sensors whereas the sensor arrays that have bigger air gap (AG) / cell size (CS) ratio yielded higher sensitivity, which can be explained by the amount of air gap and lower stiffness. On the other hand, the sensor density of pressure mats is dependent on cell size and proximity of each cell, therefore utilizing smaller cell sizes provided the best object resolution, as expected.

Our novel manufacturing technique can be divided into four main steps: (1) laser cutting of the conductive knitted fabric as upper and lower electrode layers, (2) the formation of square cells in a double-sided fusible sheet using laser cutting, (3) generating cavities in the pressure plate (Polymethyl methacrylate) (PMMA)) that are consistent with the cell dimensions from the previous stage, and (4) replacing dielectric (TPU) layers between electrodes and applying heat at 90 °C for 5 seconds to all sensor layers that are stacked over the designed pressure plate. The unique production approach for textile based capacitive pressure sensors is shown in Figure 3.1.

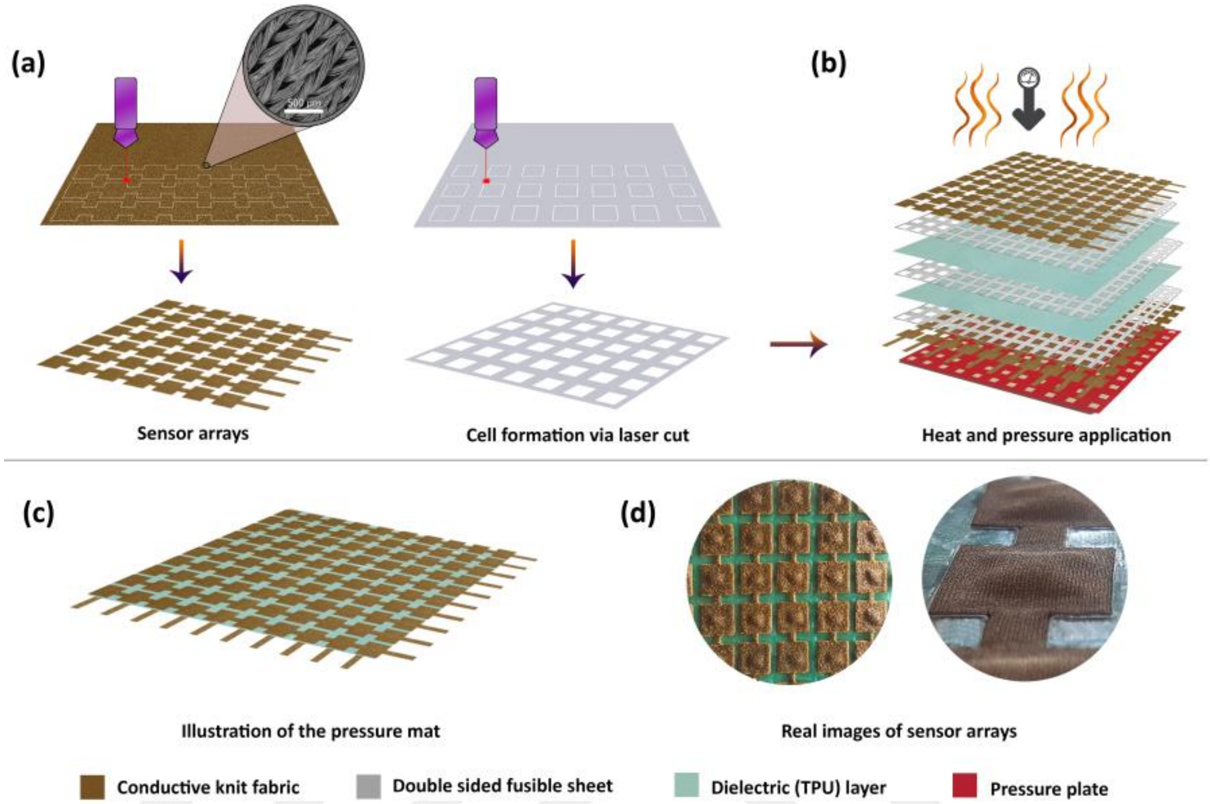

Figure 3.1 : Schematic diagram of the fabrication process of the textile-based capacitive pressure sensor. (a) Laser cutting of conductive knitted fabric into sensor arrays and the creation of square cells in a double-sided fusible sheet. (b) Replacement of dielectric (TPU) layers between electrodes and application of heat to all sensor layers stacked over the designed pressure plate. (c) Illustration of fabricated the textile-based pressure mat. (d) Actual images of pressure sensor arrays having air gaps in each cell.

Figure 3.1(a) demonstrates the shaping of conductive knitted fabric into sensor arrays with desired dimensions for end-use applications, as well as an optical microscopy image of the loops in the knitted fabric. Following that, creating square spaces via laser cutting in the double-sided fusible sheets which is responsible for keeping electrode and dielectric layers together. It should be noted here that creating cells in the fusible sheet has a direct impact on the amount of air gap formation in the manufactured pressure sensors therefore it ought to be carefully adjusted in terms of dimensions.

The stacking sequence of all the sensor layers is shown in Figure 3.1(b), with upper and lower conductive knitted fabrics acting as electrodes, TPU layers between them acting as dielectric layers, and double-sided fusible sheets bonding all together. The image also illustrates the application of heat and pressure to the layers that are replaced one by one over the pressure plate by the heat press (Serfo - Automatic Transfer Printing Press). The importance of the pressure plate here is that it is positioned beneath the layers during the manufacturing process, and when heat is applied from the top to melt the fusible layers, the edge points of the arrays are determined by the cavities of the plate, so that the pressure is only applied to the edges of the arrays, and the knit fabric begins to widen through these holes, generating air gaps.

After all, as shown in Figure 3.1(c), the textile-based pressure mat has been obtained in the desired shape and size, following the application of heat and pressure. The real images of pressure sensor arrays along with air gaps in each cell can be seen in Figure 3.1(d). The elimination of complex fabrication steps to enable mass production, as well as the controllability of sensor characteristics in terms of working range and sensitivity by adding extra dielectric layers and altering air gap formation are inherent advantages of this manufacturing approach.

4. CHARACTERISATION OF SENSOR SAMPLES

4.1 Introduction

The sensitivity, sensing range, limit of detection, response time and recovery time, and stability are critical factors to consider when evaluating the performance of sensors [49]. The lowest pressure that may generate a steady and discernible output signal from the pressure sensor is referred to as the limit of detection, showing the possibility of detecting an ultralow pressure. A pressure sensor's valid functioning range is known as the pressure detection range. To detect multi-range pressure induced by human activities, a vast detection range is required. The time required to get a stable signal change after applying pressure to the sensor is referred to as response time. A rapid response time (less than 100 milliseconds) is essential for real-time monitoring of human health. Furthermore, for the practical application of all types of pressure sensors, excellent stability and dependability are essential. In general, human body pressures range from 1 to 100 kPa (low and medium pressure regimes), including mild touch and intraocular pressure (10 kPa), blood, pulse, and jugular venous pressure (100 kPa). Furthermore, the ultralow pressure regime (less than 1 Pa) created by sound and the high-pressure regime (greater than 100 kPa) induced by body weight should be considered [36]. Figure 4.1 illustrates the variation of pressure ranges.

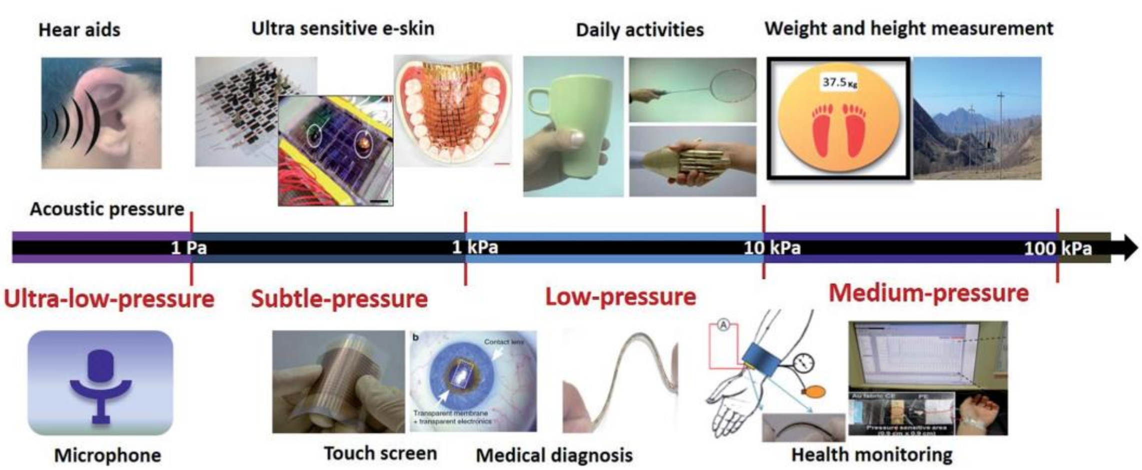

Figure 4.1 : The pressure range illustration and the associated applications [65].

4.2 Manufactured Specimens and Macrostructure

In order to scrutinize the efficiency of sensor cells as well as demonstrate the scalability of the manufacturing approach, 9 pieces of 10 x 10 mm^2, and 9 pieces of 15 x 15 mm^2 pressure sensor cells were produced utilizing the introduced manufacturing process. The electrode dimensions, number of dielectric sheets, and air gaps within the sensor cells were modified during the study to alternate the sensitivity, durability, working range, and stability performance for identification of optimum sensors in various fields of application. During the study, three experimental setups were designed to examine the sensitivity, durability, working range, and stability performance of samples. The photographs and microscopic images are illustrated in Figure 4.2 to demonstrate the prepared 15 x 15 mm^2 sensors that are designed with increasing numbers of dielectric layers for the further characterization stages. Figure 4.2(a) represents the pressure sensor cells that are devoid of air gaps to truly comprehend how air gaps influence the sensor performance, while Figure 4.2(b) and (c) show the sensor cells with varying amounts of air gaps as an outcome of modifying pressure plate cavities and changing fusible layer dimensions, demonstrating the scalability of the developed technique. Also, the cross-sectional microscopic images of 10 x 10 mm^2 sensor cells are shown in Figure 4.3.

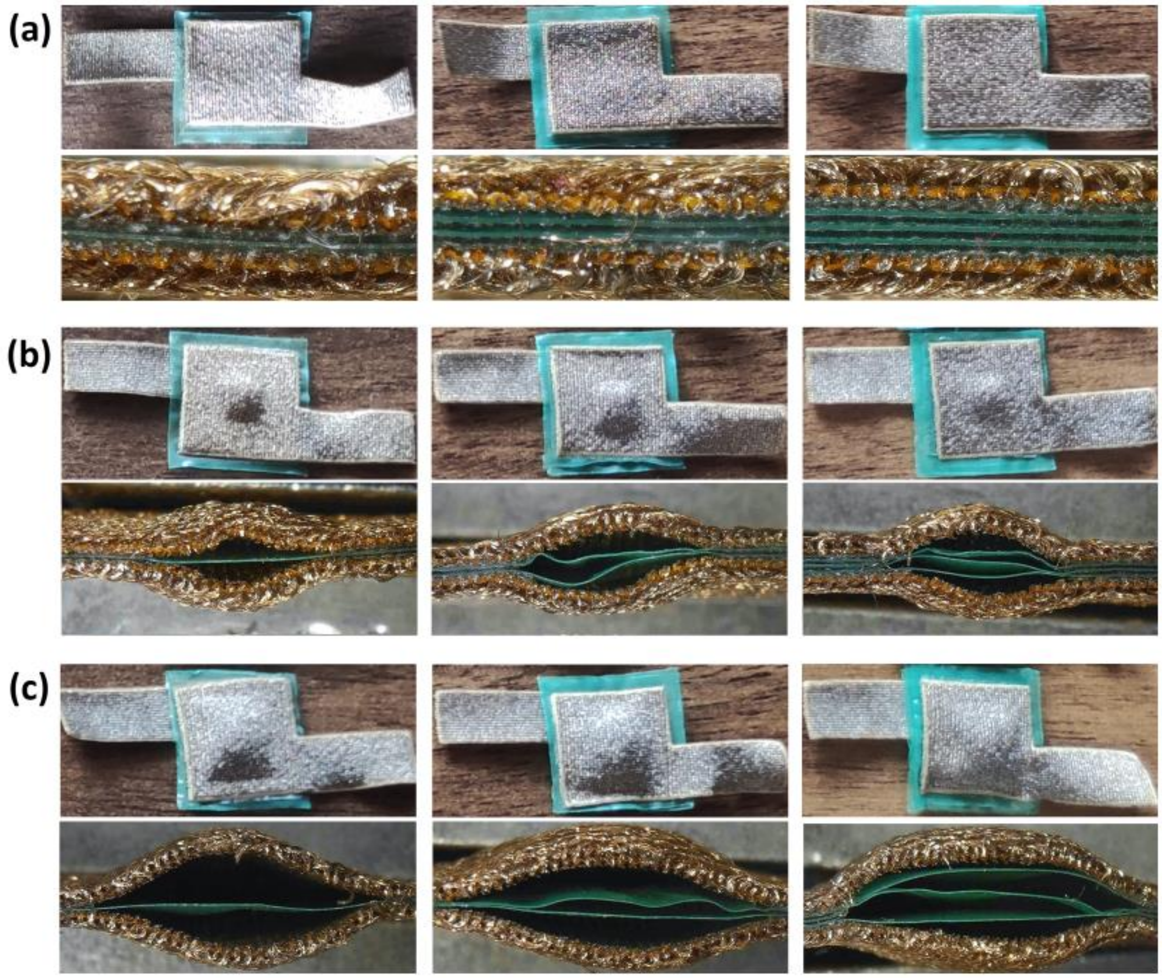

Figure 4.2 : Optical and cross-sectional microscopic images of 15 x 15 mm^2 textile-based capacitive sensor specimens with one, two, and three dielectric TPU layers from left to right. (a) Sensor cells with no air gaps. (b-c) Air-gapped sensor cells manufactured by utilizing pressure plates with a cavity of 5 x 5 mm^2 and 10 x 10 mm^2, respectively. These two airgapped sensors are named as "11%" and "44%" due to their air gap/cell size (AG/CS) ratio.

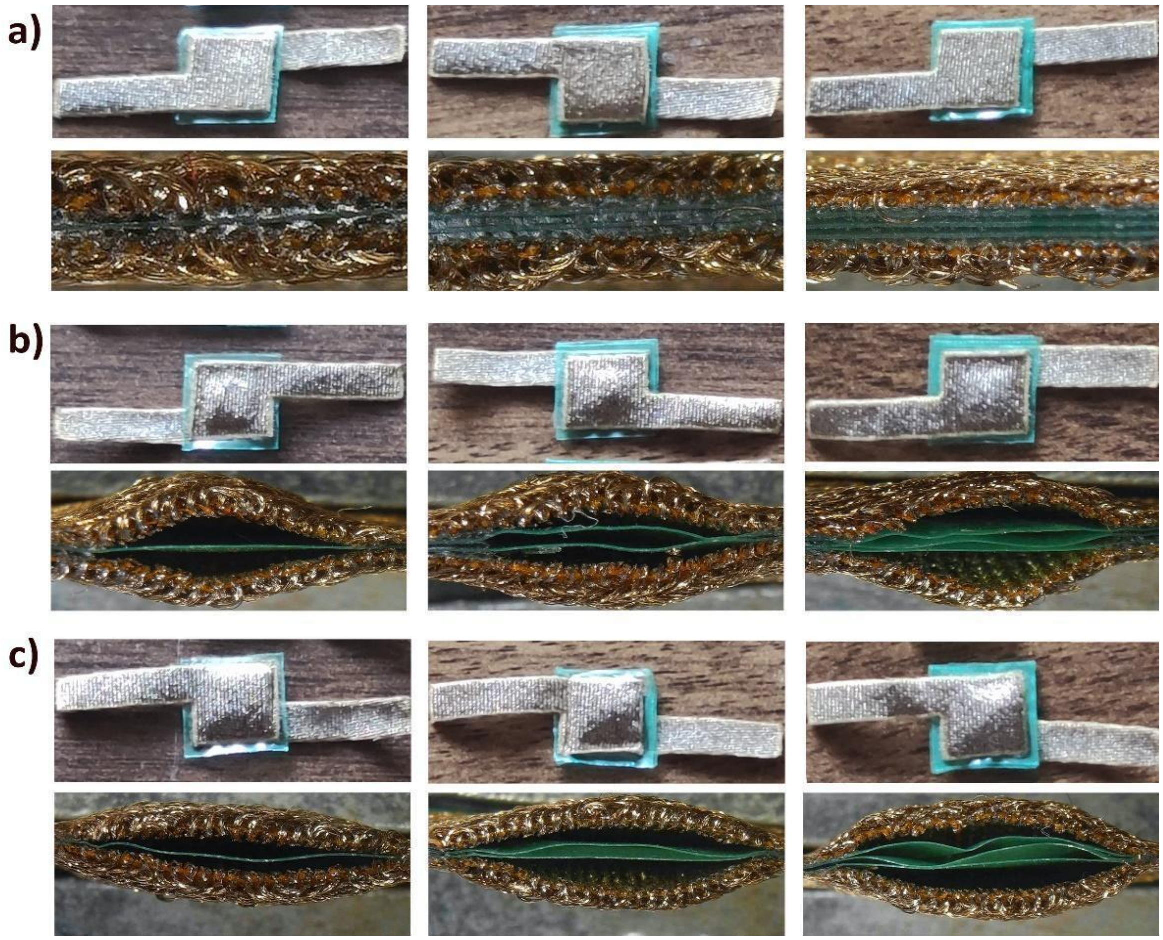

Figure 4.3 : Optical and cross-sectional microscopic images of 10 x 10 mm textile-based capacitive sensor specimens with one, two, and three dielectric TPU layers from left to right. a) Sensor cells with no air gaps. b-c) Air-gapped sensor cells manufactured by utilizing pressure plates with a cavity of 5 x 5 mm and 7.5 x 7.5 mm respectively.

4.3 Sensitivity Characterisation

The sensing capabilities of the capacitive pressure sensors are assessed as shown in Figure 4.4. To determine the scalability of manufacturing procedure, the above mentioned 15 x 15 mm^2 and 10 x 10 mm^2 sensor cells with varying air gaps and TPU layers were tested and compared to sensors with no air gap by using the experimental setup which is developed for the sensitivity characterization. Figure 4.4(a-c) represent the sensing behavior of 15 x 15 mm^2 sensor cells with increasing numbers of dielectric TPU layer. The pressure sensitivity of the fabricated sensor cells increases as the air gap amount increases from 0 to 44%, according to the results of the sensitivity characterization. The sensor with the highest amount of air gap and the thinnest dielectric layer as in see Figure

4.4(a) had best sensitivity with 306.69 x 10^{-2} kPa^{-1} (below 1 kPa) and 9.44 x 10^{-2} kPa^{-1} (between 1 kPa and 30 kPa). This is then followed by the sensor of 11% in terms of AG/CS ratio which has lower amount of air gap, with the sensitivities of 110.79 x 10^{-2} kPa^{-1} and 2.76 x 10^{-2} kPa^{-1}, respectively. Moreover, the sensor that has no air gap showed the least sensitivity performance while proving the efficiency of our approach (see Table 4.1)

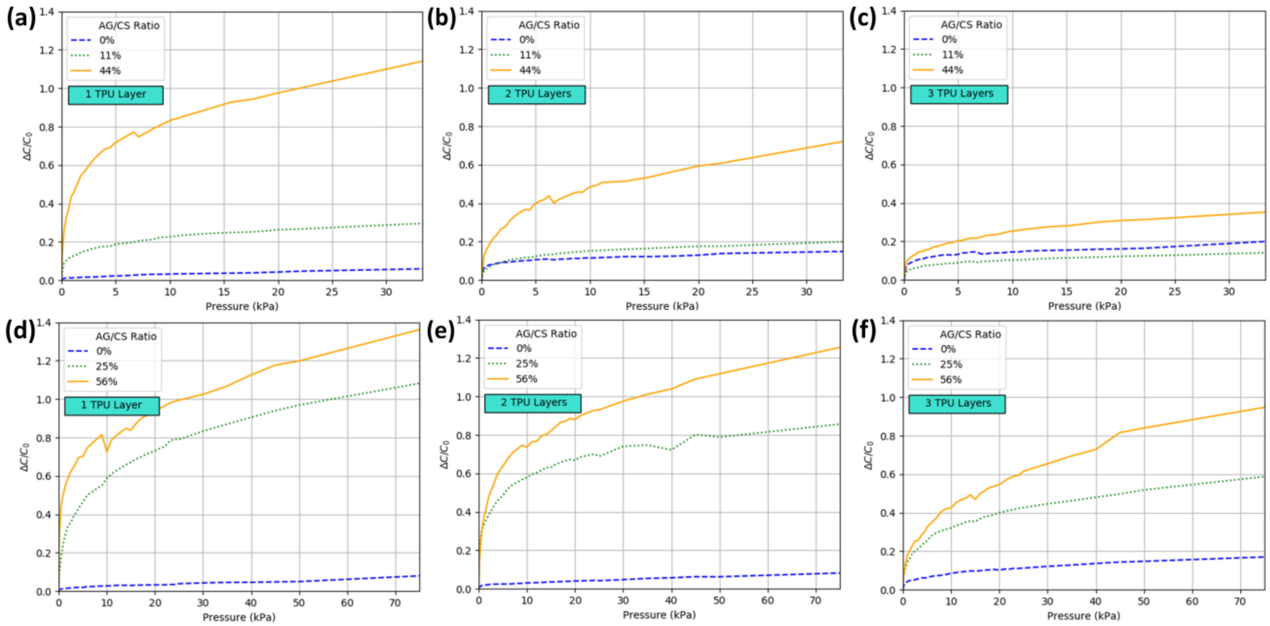

Figure 4.4 : Sensitivity results of the square sensor cell specimens with one, two, and three dielectric TPU layers from left to right. (a-c) The sensitivity values of 15 x 15 mm^2 pressure censor cells. (d-f) The sensitivity values of 10 x 10 mm^2 sensor cells. Different colors represent the different AG/CS ratios within sensor cells that are generated by the pressure plate cell cavities and fusible layer cells depending on the dimensions.

Table 4.1 : Sensitivity values (10^{-2} x kPa^{-1}) for each sample.

Cell Size (mm)	AG/CS ratio	1 TPU Layer		2 TPU Layers		3 TPU Layers	
		0-1 kPa	1-30 kPa	0-1 kPa	1-30 kPa	0-1 kPa	1-30 kPa
15 x 15	0	11.75	0.27	64.97	0.94	38.56	1.75
	11	110.79	2.76	33.44	1.53	33.78	1.27
	44	306.69	9.44	84.84	5.52	67.91	3.95
10 x 10	0	7.40	0.31	7.93	0.24	15.55	0.78
	25	86.09	7.55	177.12	4.11	58.74	3.85
	56	268.82	6.36	129.11	7.84	58.12	3.90

On the other hand, 10 x 10 mm^2 sensor cells performed higher sensitivity compared to 15 x 15 mm^2 cells, due to the higher air gap/cell size ratio of 10 x 10 mm^2 sensors. Similar to the previous sensitivity tests, Figure 4.4(d-f) show the sensitivity characteristics of 10 x 10 mm^2 sensors, with a similar increase depending on the amount of air gap. Among these sensors, the sensor 56% which has a single layer of TPU and highest amount of air gap exhibited the best sensitivity 268.82 x 10^{-2} kPa^{-1} (below 1 kPa) and 6.36 x 10^{-2} kPa^{-1} (between 1 kPa and 30 kPa). This followed by the sensor 25% which has relatively low amount of air gap, with the sensitivities of 86.09 x 10^{-2} kPa^{-1} and 7.55 x 10^{-2} kPa^{-1}. In terms of TPU layer comparison, due to dielectric thickness, sensors with single layers performed highest sensitivity, and followed by sensors that has 2 and 3 TPU layers, respectively. This demonstrates that, dielectric thickness has a negative impact on sensor sensitivities as expected.

Our sensors stand out among the prior sensors produced in the literature in terms of sensitivity and working range. There are a few sensors that can sense up to 1 MPa in comparison to ours, but their sensitivity values are insufficient and can not detect low pressures, whereas sensitive sensors can only detect a few kPa pressure and have a limited range. Table 4.2 shows a comparison of our sensors to other sensors in terms of sensitivity.

Table 4.2 : Comparison of our most sensitive sensord with other sensors found in the literature.

References	Measurement technology	Electrodes	Dielectric layer	Maximum pressure level	Sensitivity
56	Capacitive	ITO-PET	CNT-PVDF	15 kPa	0.99 kPa^{-1}, < 1.2 kPa 0.63 kPa^{-1}, 2 – 15.0 kPa
57	Capacitive	SWCNT/Ag paste	Spacer Fabric	1 MPa	4.2×10^{-2} kPa^{-1} < 100 kPa
58	Capacitive	PET/Silver ink	Air Gap	2.5 N	Not given
59	Capacitive	Conductive knit fabric	Microporous silicone	1 MPa	121 x10^{-4}, < 100 kPa 25 x 10^{-4}, up to 1 MPa
60	Capacitive	Au-coated PET	Tilted PDMS micropillar array	25 kPa	0.42 kPa^{-1}, < 1.5 kPa 0.04 kPa^{-1}, > 5 kPa
61	Capacitive	Graphene/PET	Spacer Fabric	30 kPa	6.55 kPa^{-1}, 0 - 16 kPa 1.15 kPa^{-1}, 16 - 30 kPa
62	Piezoresistive	Ag/silicone	Silicone	500 kPa	Current changes (ΔI/I0) 2500%, 60 kPa 8500%, 120 kPa 17 000%, 250 kPa
66	Capacitive	AgNW/PDMS	Micro Cilia Array	200 kPa	0.28 kPa^{-1}, < 10 kPa 0.02 kPa^{-1}, 50 - 200 kPa
67	Capacitive	Copper tape	PDMS	6 kPa	0.1851 kPa^{-1}, 0.5 - 3 kPa 0.7298 kPa^{-1}, up to 6 kPa
Our work (15 x 15 mm^2)	Capacitive	Conductive knit fabric	TPU	444 kPa	306.69 x 10^{-2}, < 1 kPa 9.44 x 10^{-2}, 1 - 30 kPa 0.535 x 10^{-2}, 30 - 100 kPa 0.264 x 10^{-2}, > 444 kPa
Our work (10 x 10 mm^2)	Capacitive	Conductive knit fabric	TPU	1 MPa	268.82 x 10^{-2}, < 1 kPa 6.36 x 10^{-2}, 1 - 30 kPa 0.416 x 10^{-2}, 30 - 100 kPa 0.344x 10^{-2}, > 1 MPa

4.4 Analysis of Response and Recovery Time

Response and recovery durations of pressure sensors are also important parameters to consider when minimizing the delays in applications, therefore response and recovery time of the sensor cells with different sizes and air gaps were analyzed. We first tested 15 x 15 mm^2 sensors with one layer of dielectric TPU to determine the effect of air gap on response time of the proposed sensors. The tests for the electrical response were carried out by putting 100 g weight (corresponding to 4.35 kPa) on the sensors and the sensor without air gap shows a response time of 140 ms and a recovery time of 360 ms (Figure 4.5(a)). On the contrary, the response time was measured to be only 160 ms and a recovery time of 7.32 seconds for the sensor with 44% air gap (Figure 4.5(b)).

The results of 10 x 10 mm^2 sensors tested with 50 g weight (4.9 kPa) are shown in Figure 4.5(c) and Figure 4.5(d). The sensor without air gaps has a response/recovery time of 140 ms and 240 ms, whereas the sensor with air gaps, similar to the previous sensors, has a response time of 220 ms and a long recovery time of 7 seconds, respectively. The results reveal that the recovery time of an air-gapped sensor is longer than that of a non-air gapped sensor. The difference in recovery times can be ascribed to the fact that the relaxation time of conductive knit fabric takes a long time after unloading the weight.

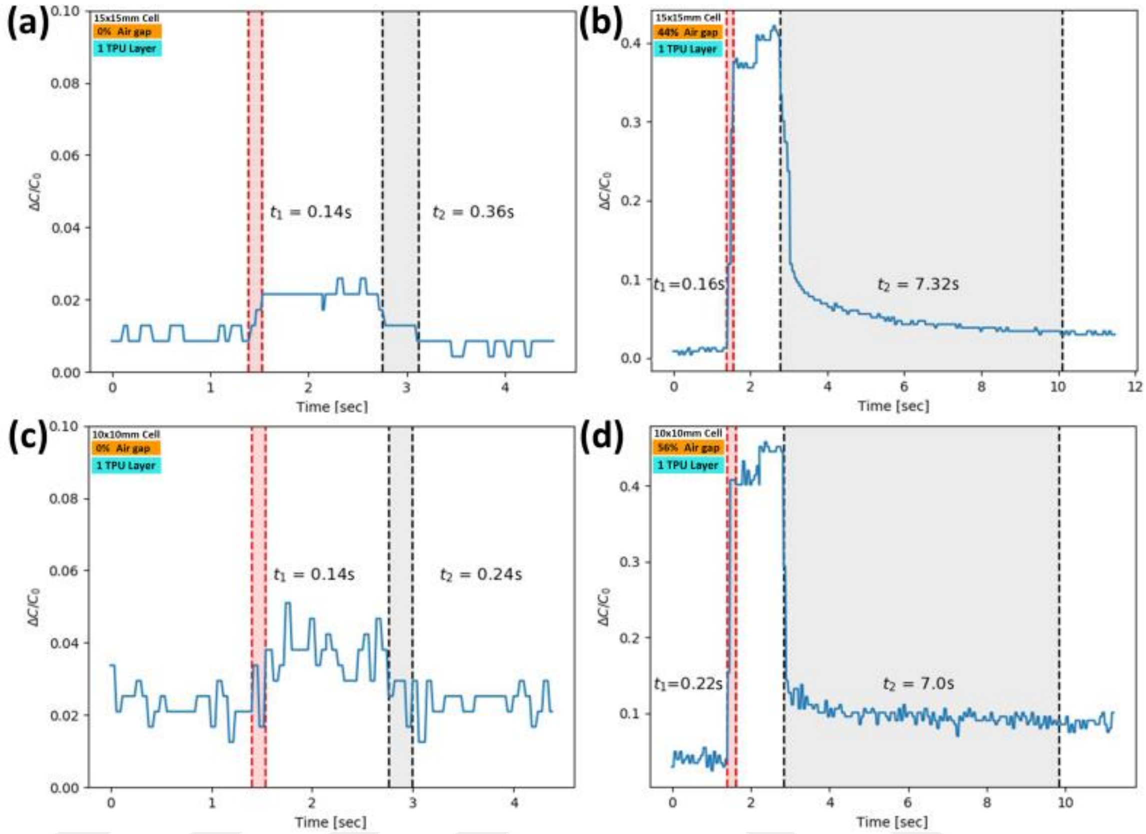

Figure 4.5 : Response and recovery times of the proposed pressure sensors. (a,b) Performance of the 15 x 15 mm^2 non-airgapped and air-gapped pressure sensors with loading-unloading of 100 g (4.35 kPa) weight. (c,d) Performance of the 10 x 10 mm^2 non-airgapped and air-gapped pressure sensors using 50 g (4.9 kPa) weight.

4.5 Characterizations of Durability and Working Range

The mechanical durability of the capacitive pressure sensors in terms of pressure sensitivity is tested by subjecting the 10 x 10 mm^2 cells and 15 x 15 mm^2 cells to 1000 cycles of loading/unloading pressure of 50 and 22.2 kPa, respectively at a speed of 20 mm/s. Following the sensitivity results, the best performing air-gapped sensors and air gap-free sensors are chosen for comparison in the cycle test. By comparing the initial and last cycles of air-gapped 15 x 15 mm^2 sensors (Figure 4.6(a)) and air-gapped 10 x 10 mm^2 sensors (Figure 4.6(b)), we observed that electrical performance of 15 x 15 mm^2 sensors show less than 6.32% and 10 x 10 mm^2 sensor show less than 4.47% variation over the 1000 cycles, demonstrating that the performance of manufactured pressure sensor is consistent for long-term use. However, the sensors that are devoid of air gaps exhibit relatively lower degradation less than 1.83%, due to the robustness of sensors without air gaps.

Figure 4.6(c) and (d) illustrate the sensitivity change of the sensors under a constant load 100, 250, and 500 g of weight (approx. 4.35, 10.9 and 21.8 kPa for 15 x 15 mm^2 sensor and 9.8, 24.5 and 49 kPa for 10 x 10 mm^2 sensor cell) for 1 hour. As shown, when a constant pressure was applied to the sensor cells, the capacitance abruptly increased within milliseconds, then reached a plateau and no other significant capacitance chance has been observed during the period of 1 hour. This property has demonstrated that the proposed sensors are durable for constant pressure and are suitable for applications that require long-term stability, such as shoe insoles, wheelchairs, or smart beds. Furthermore, in order to meet the practical engineering application, it was necessary to investigate the effect of dielectric thickness on the developed sensors' sensing range and sensitivity. The detection limit of the sensors was demonstrated by applying pressure to the sensor over a wide range of pressures ranging from 1 to 1000 kPa. Figure 4.6(e) depicts the responses of a 15 x 15 mm^2 air-gapped sensor with varying numbers of dielectric TPU when pressure is applied (measured up to 435 kPa), and Figure 4.6(f) depicts the capacitance change of a 10 x 10 mm^2 sensor when pressure is applied (measured up to 1 MPa). The result reveals a detection limit of less than 1 kPa, indicating that the sensor's performance is only valid within a relatively narrow pressure range; in our case, the sensor remains sensitive at pressures up to 1 MPa. It is expected that the sensitivity and detection range can be customized by adjusting structural parameters such as electrode size, air gap amount, and number of dielectric layers.

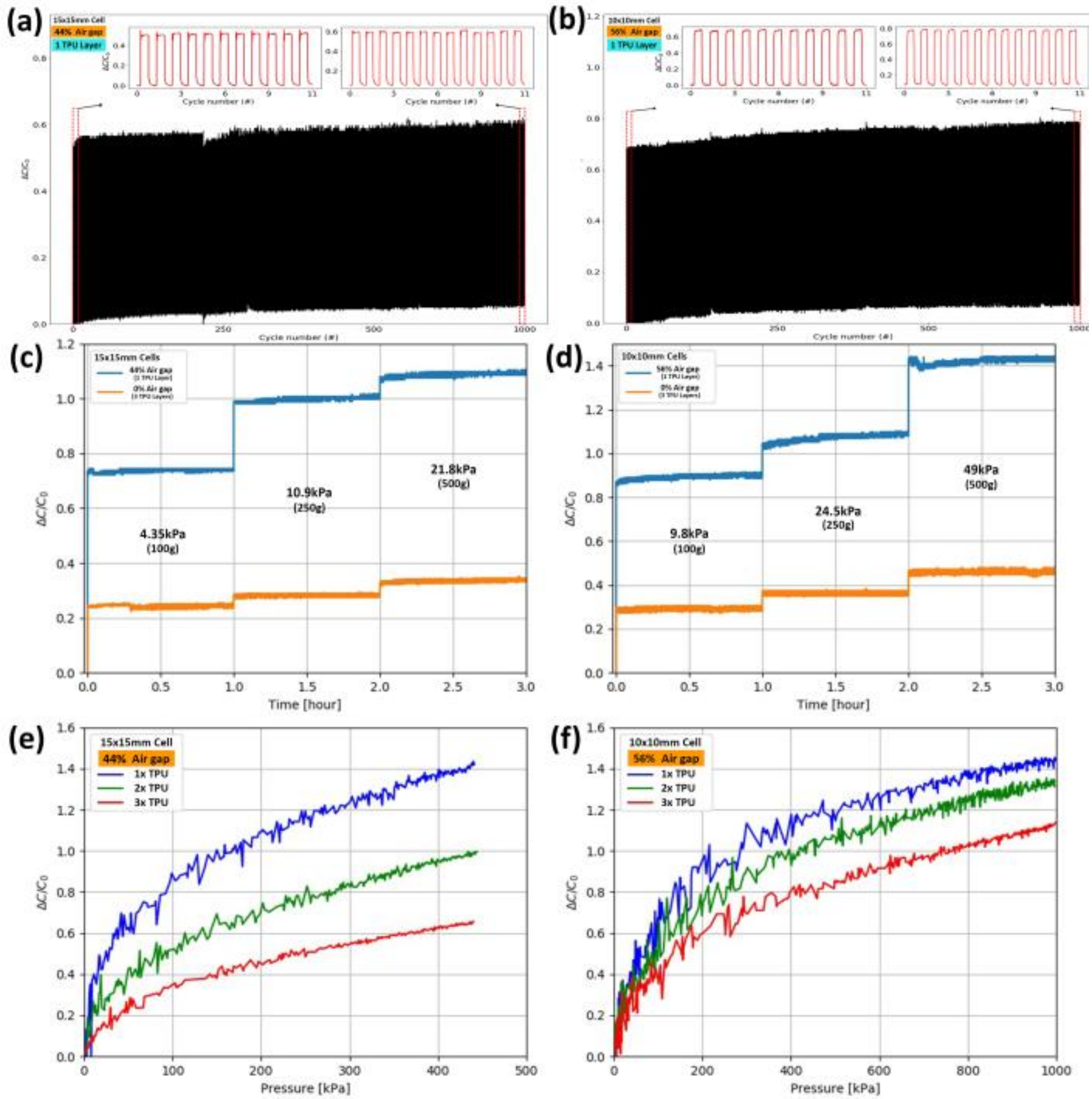

Figure 4.6 : Durability and working range test results of the most sensitive sensor specimens. (a,b) Capacitance changes of the 15 x 15 mm^2 and 10 x 10 mm^2 sensor cells when subjected to a pressure of 22.2 and 50 kPa, respectively under 1000 repeated cycles. Constant weight performance of 15 x 15 mm^2 (c) and 10 x 10 mm^2 (d) sensor cell specimens under 100, 250, and 500 g for 1 hour. (e,f) Working ranges of 15 x 15 mm^2 and 10 x 10 mm^2 sensors with varying numbers of dielectric TPU layers.

4.6 Discussion

The obtained results indicate that the created sensors, which are manufactured using a novel manufacturing approach, can compete with previously reported sensors. Furthermore, due to our scalability capabilities, any form of sensor can be created in the case of a desire. The developed manufacturing technique allows us to produce sensors with varying dimensions and air gaps. By reducing the dimensions, we can place more censor cells in arrays, allowing us to obtain high resolution from sensor mats when an object is replaced on a mat. Along with dimension variability due to the advantages of laser cutting, it is also possible to create arbitrary shapes to make your sensors more appealing.

Optical and cross-sectional microscopic images demonstrate the scalability of air amount and dielectric layers in sensor cells, which will have a significant impact on sensitivity, response time, and durability. When compared to other sensors, the response time of sensors is one of the best, thereby manufactured VR/AR components made with this technology will be competitive in the market and minimize delays during applications. Because of the flexibility of the textile structures and dielectric layer, our sensors show negligible variation over 1000 cycles. The service life of developed sensors will be long enough to fulfill market demands owing to this feature.

Furthermore, due to the superior working range of each sensor cell, mats with a high number of sensors will be able to bear tremendous pressures while maintaining their sensitivity in the majority of application areas. Aside from sensor properties, rapidity of production and a lesser amount of manufacturing steps are also essential. For Industry 4.0, less reliant on human labor manufacturing stages are desirable, thus laser cutting and heat pressure machines would suffice to construct such sensor mats. As a result, manufacturers will be able to produce high-quality sensors in large volumes at a lower cost.

5. APPLICATIONS

5.1 Object Recognition

The developed pressure sensor mats are utilized in object recognition system (Figure 5.1). The system can differentiate objects placed on the mats and determine their respective locations on the mats using their shape and weight information. Since the manufactured mats are capable of measuring the applied pressure level in each cell, the heatmap of the placed object is visualized. Then the created heatmaps are processed as an binary image and the object recognition is carried out on the obtained images by using Connected-component analysis which labels the different regions that correspond to different objects on the image. The regions are labelled according to their pixel intensity values. After identifying the shape of the object, its weight was determined by thresholding the individual cell values. To better analyze the performance of the developed object recognition system, various objects with different weights and shapes were tested.

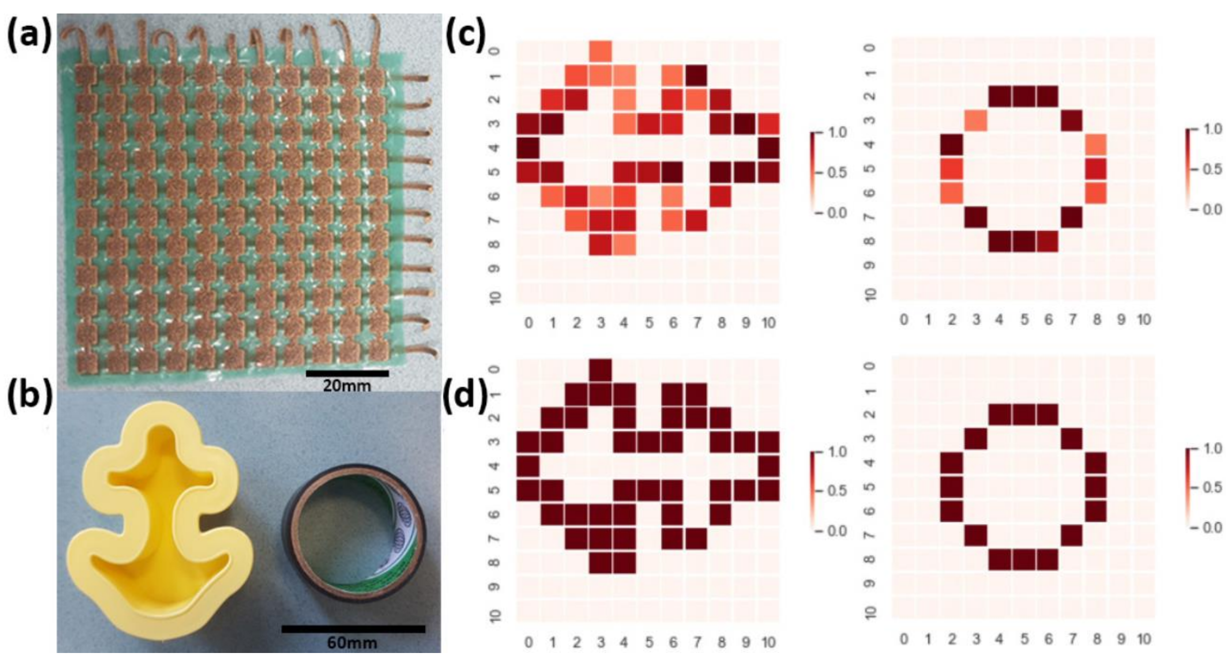

Figure 5.1 : The object recognition system developed by using pressure mat. (a) Fabricated pressure mat with 11x11 sensor arrays. (b) The objects that were used to apply pressure. (c-d) Heatmap visualization of objects over the pressure mat.

5.2 Gesture Detection and Recognition

Another application for the manufactured mat is based on gesture detection and recognition from the capacitive sensor array as shown in Figure 5.2. After the data is collected from the mat, a low pass filter is applied to the data. To find a base signal level for a cell while being in stable condition, an automatic calibration system is developed. Then, a threshold value is set for activation of each cell. A boolean map of the mat is obtained which can be used as an input for gesture detection. A consequent gesture recognition works by finding each cluster of presses in each frame and connecting them to the closest cluster in the previous frame; if none is found in a sufficiently large area a new cluster label is added. Each trace is first filtered using Kalman Filter and then processed to fit the closest described gesture. The result of processed path input obtained from the developed mat is shown in Figure 5.2(a) as a circle, and Figure 5.2(b) as a double line. Here, the user traces the mat simply with the fingers, and the trace along with its detected gesture is shown on the computer.

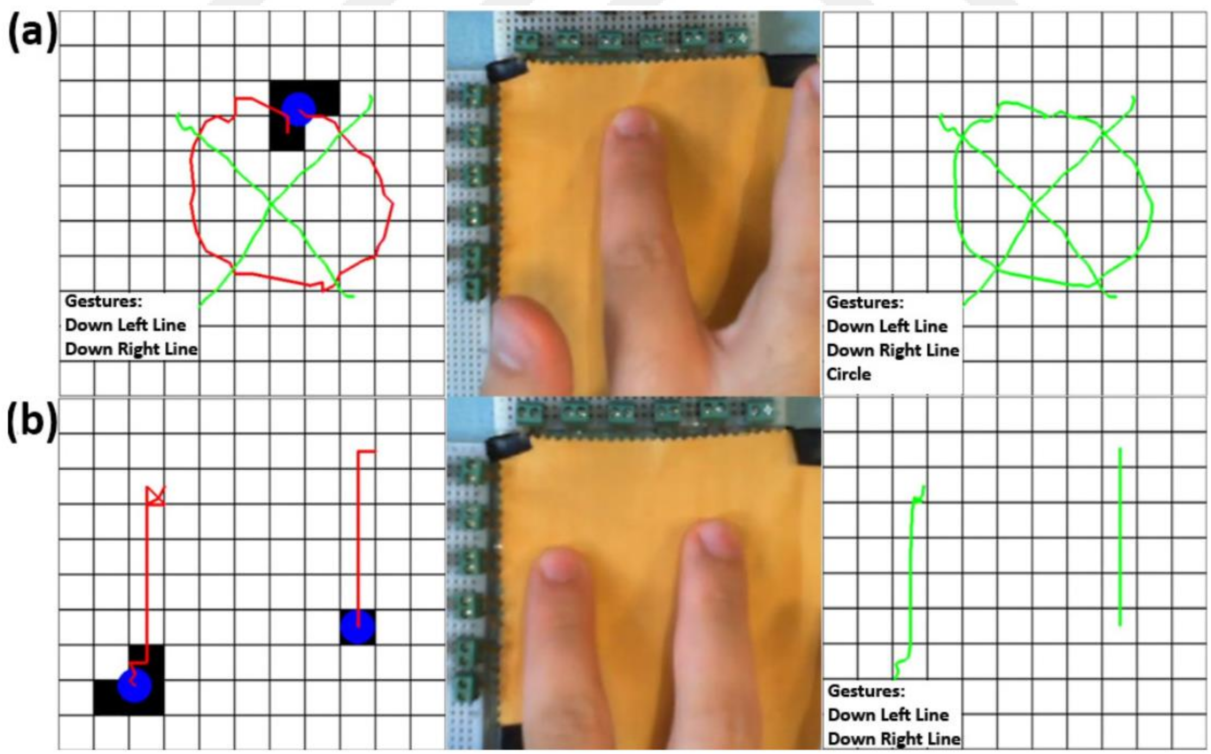

Figure 5.2 : Textile-based pressure sensing system and gesture examples. (a) Circle trace gesture recognition. (b) Double line trace gesture recognition.

5.3 Tangible Interaction Gaming Platform for Children

Game-based learning has received a tremendous research interest in modern education. One of the most prominent benefits of this sort of learning is the connection to the virtual world. In this application, a sensor mat is utilized as a tangible interaction platform that can provide both visual and audio feedback to the user. The tangible user interface is integrated with devices such as phones that realizes the functionality of the mat without needing any extra screens. The developed mat is connected to Arduino, which transfers the sensor value of each cell to the Android phone over Bluetooth using a HC-06 serial module. Several Android mobile applications focusing on Math and Alphabet Game are developed which utilize the produced mat as a playground for the children as shown in Figure 5.3(a) and Figure 5.3(b) respectively. For each application, a distinct cover which constitutes of different button positions, toy areas, etc. Are produced and positioned on top of the mat.

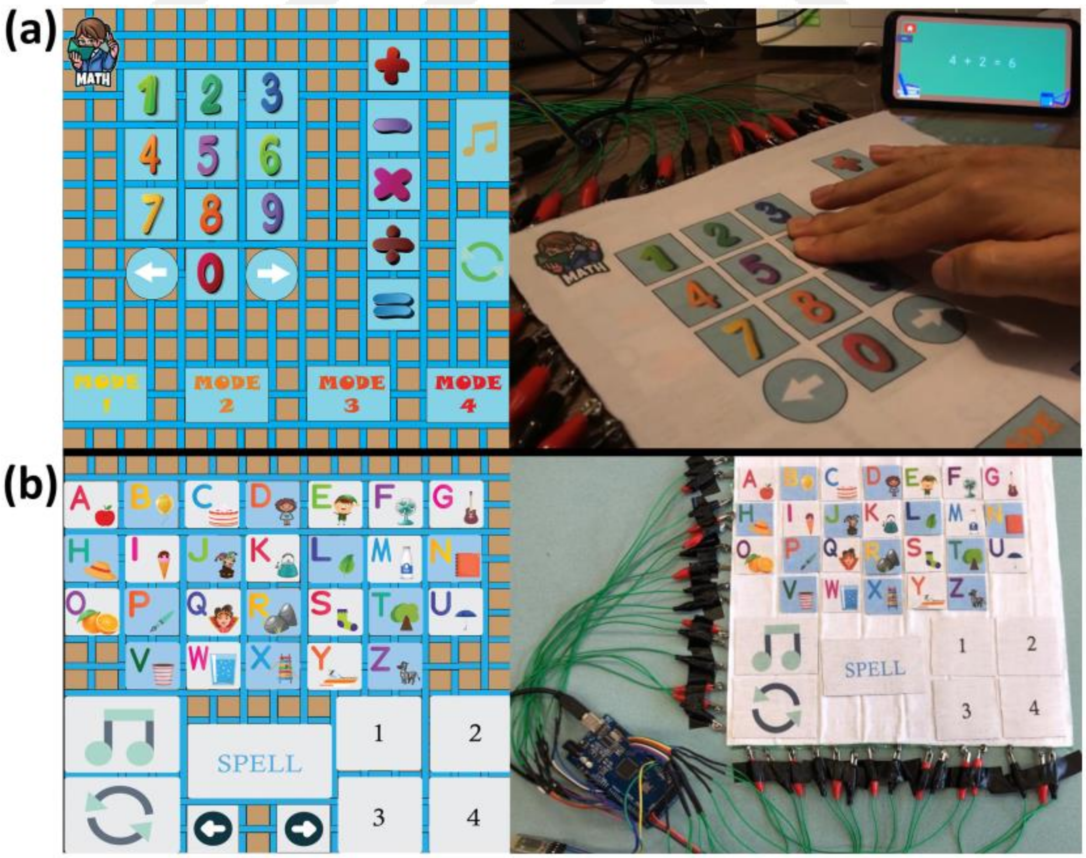

Figure 5.3 : Layout designs of tangible interaction mats on the left and the real world applications of mats on the right. (a) Math game platform. (b) Alphabet game platform.

The Math game in Figure 5.3(a) is developed for children of the age range 4 to 8. In this game, several interfaces are created. The first game mode enables the user to press any of the numbers on the mat which subsequently returns the pronunciation of the number from the phone. The second mode, on the other hand, asks the user to press the number shown in the quiz application on the phone. The third game mode provides several objects on the phone and asks the user to enter the number of the objects on the mat. The fourth game mode is developed for older children as it requires the child to enter the result of the equation on the mat.

The Alphabet Game in Figure 5.3(b) is designed for children between the age of 4 and 7. This game has 4 modes that can be chosen from the mat. In the first mode, the child presses any letter on the mat which returns the written and audio version of the letter in the display of the phone. The second mod e operates in the same manner, but here the child learns the same word starting with the corresponding initial letter. The third and the fourth mode tests the child using the letters learned in the former modes. Here, the child is requested to press the respective letter/object shown on the screen of the phone on the mat buttons.

6. CONCLUSION

In summary, we have proposed a novel textile-based pressure sensor fabrication technique for eliminating complex and time-consuming manufacturing conditions and creating sensors with desired patterns and steady characteristics. Different types of sensor cells with variable air gaps and TPU (dielectric) layers were initially created using a combination of stacking laser cut layers and a pressure plate assisted heat application technique to assess the potential application fields for each type of sensor. Afterwards, the sensors produced during the research were experimentally tested and observed to have a high and adjustable sensitivity as well as a wide working range, displaying the effectiveness of our approach. We have shown that a device sensitivity of as high as of 306.69 x 10^{-2} kPa^{-1} within the pressure range of 0-1 kPa and 9.44 x 10^{-2} kPa^{-1} for 1-30 kPa, detection range up to 1000 kPa, stable cycling performances (up to 1000 cycles), a fast response time (≈140 ms), and mechanical stability under constant deformations are achieved. Thanks to these features, our sensors are ideal candidates for effective integration with other functional devices such as e-textiles, wearable devices, and interactive software. We demonstrated the application of pressure sensor arrays for the recognition of various human gestures. Also, mechanical and computational tools enabled us to design educational mobile games, and tangible user interfaces to detect object shapes in high-resolution using pressure sensor mats. We believe that this cutting-edge manufacturing approach used to develop our sensor will meet the competitive market demands for textile-based sensor manufacturing, and opens new routes to fabricating sensors to be used in many fields such as wearable systems, rehabilitation, entertainment, and gaming.

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