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PERSPECTIVE

Soft Capacitive Pressure Sensors: Trends, Challenges, and Perspectives

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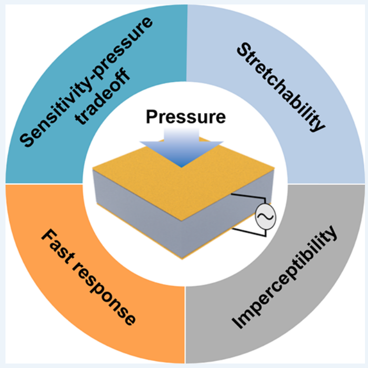
ABSTRACT: **Soft pressure sensors are critical components of e-skins, which are playing an increasingly significant role in two burgeoning fields: soft robotics and bioelectronics. Capacitive pressure sensors (CPS) are popular given their mechanical flexibility, high sensitivity, and signal stability. After two decades of rapid development, e-skins based on soft CPS are able to achieve human-skin-like softness and sensitivity. However, there remain two major roadblocks in the way for practical application of soft CPS: the decay of sensitivity with increased pressure and the coupled response between in-plane stretch and out-of-plane pressure. In addition to existing strategies of building porous and/or high dielectric constant soft dielectrics, are there any other promising methods to overcome those bottlenecks? Are there any further considerations for the widespread deployment of e-skins? This perspective aims to shed some light on those topics.**



KEYWORDS: *sensitivity, pressure range, response time, imperceptibility, stretchability*

INTRODUCTION

Soft pressure sensors capable of conforming to curvilinear and even deformable surfaces are essential components of e-skins, which are finding pervasive applications in two burgeoning areas: soft robotics and bioelectronics.[1] In response to the increasing demands for e-skins, various pressure sensing mechanisms have been explored, including piezoresistive,[2] piezoelectric,[3] capacitive,[4] ionotronic,[5] magnetic,[6] and optical sensors.[7] Among these, soft capacitive pressure sensors (CPS) came into the limelight because of their mechanical flexibility, high sensitivity, good repeatability, temperature independence, low power consumption, high spatial resolution, and suitability for large-area applications.[8] After two decades of rapid development, e-skins based on soft CPS are able to achieve human-skin-like softness and sensitivity.[9] Recent advancements in soft CPS have been well covered by several high-quality review papers.[10,11] However, there are a few remaining roadblocks in the way for practical applications of soft CPS. In this perspective, instead of offering a comprehensive review, we present a few specific challenges in soft CPS that stand out to us. After a brief summary of prior achievements of soft CPS, three outstanding issues (low sensitivity at large-pressure ranges, slow response, and obstructiveness) and their possible solutions are introduced. In the end, a critical yet unsolved challenge—stretchable CPS with discernible pressure reading—is pointed out.

PRIOR ACHIEVEMENTS OF SOFT CPS

Over the past two decades, a major focus of research on soft CPS has been increasing their sensitivity.[9] A fundamental understanding can be achieved through the following equation of a parallel plate capacitor:

$$C = k\epsilon_0 \frac{A}{d} \tag{1}$$

where C is capacitance, k is dielectric constant, ε_0 is the permittivity of vacuum, A is plate area, and d is the gap between the two parallel electrode plates. Assuming a linear elastic dielectric material between the two electrode plates, the initial sensitivity of the CPS can be derived as

$$S = \frac{d\left(\frac{\Delta C}{C_0}\right)}{dP} = \frac{1}{k_0}\left(\frac{k}{E} + \frac{\partial k}{\partial P}\right) \tag{2}$$

where P is the applied pressure and E is the compressive modulus of the dielectric material. Note that this sensitivity

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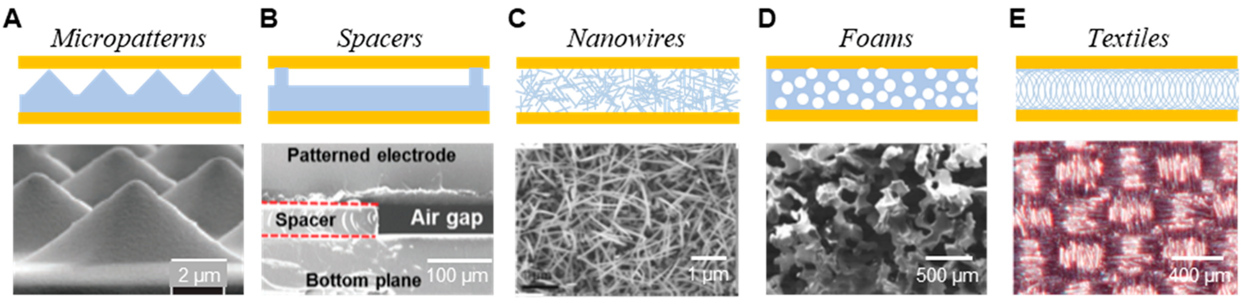

Figure 1. Cross-sectional schematic illustrations (upper row) and representative micrographs (lower row) of soft CPSs with air gaps realized through (A) surface micropatterns,[4] (B) spacers,[13] (C) nanowire networks,[14] (D) foams,[15] and (E) textiles.[16] (A) Adapted with permission from ref 4. Copyright 2010 Springer Nature. (B) Adapted with permission from ref 13. Copyright 2017 Wiley-VCH. (C) Adapted with permission from ref 14. Copyright 2018 IEEE. (D) Adapted with permission from ref 15. Copyright 2015 IEEE. (E) Adapted with permission from ref 16. Copyright 2014 Wiley-VCH.

Table 1. Summary of CPS with Both Air Gaps and High *k* Composites

fabrication	filler	matrix	structure	effective *k*	sensitivity $[kPa^{-1}]$ (pressure range)	reference number
doping	Ag nanoparticle	PDMS	foam		0.11 (<1)	17
doping	graphene	PU	wrinkle	76	1.9 (<3)	18
doping	EGaIn	Ecoflex	foam	6−12	0.292 (unknown)	12
doping	CNT	Ecoflex	foam	2−6.4	1.52 (<1)	19
oxidation		GO	foam	10	0.8 (<1.3)	22
coating	Parylene	PI	nanomesh		0.077 (<1)	20
coating	CCTO	PU	foam	18	0.73 (<1.6)	21
coating	boron nitride	PDMS	foam	1.05−1.25	0.854 (<0.5)	23

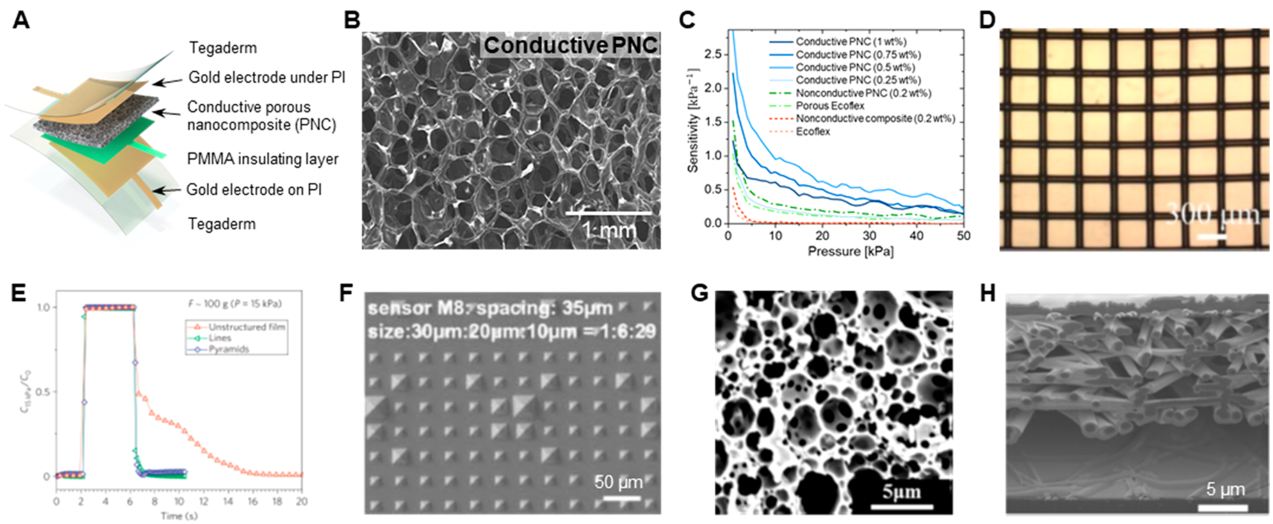

Figure 2. Strategies to improve sensitivity, response time, and imperceptibility of soft capacitive pressure sensors (CPS). (A) Schematic illustration of a hybrid response pressure sensor (HRPS), which consists of a barely conductive porous nanocomposite (PNC) and an ultrathin insulating layer (PMMA).[19] (B) Scanning electron microscope (SEM) image showing the microstructure of the PNC in the HRPS. (C) Sensitivity vs pressure curves of conventional CPS and HRPS with various CNT doping concentrations. (D) Optical image of an elastic nylon grid which helped the CPS achieve fast response.[27] (E) Experimentally measured recovery time of CPS made out of an unstructured polydimethylsiloxane (PDMS) film (red) and structured PDMS films.[4] (F) SEM images of hierarchical surface structures[28] and (G) hierarchical porous structure[29] of elastomers for the fast response of CPS. (H) Cross-sectional SEM image of ultrathin, imperceptible CPS with both electrodes and dielectrics in the form of nanomesh.[20] (A−C) Adapted with permission from ref 19. Copyright 2021 Wiley-VCH. (D) Adapted from ref 27. Copyright 2018 American Chemical Society. (E) Adapted with permission from ref 4. Copyright 2010 Springer Nature. (F) Adapted with permission from ref 28. Copyright 2018 IEEE. (G) Adapted from ref 29. Copyright 2019 American Chemical Society. (H) Adapted with permission from ref 20. Copyright 2020 AAAS.

equation only holds when the applied pressure is much smaller than the modulus of the dielectric material, i.e., when $P \ll E$.

It is obvious from eq 2 that the sensitivity can be enhanced through (1) using a soft dielectric layer to reduce the E and (2) taking advantage of the dielectrostriction effect,[12] which means a pressure-sensitive effective dielectric constant. One strategy that could achieve both goals is adding air gaps inside the dielectric or at the electrode−dielectric interface. Most obviously, porous or surface-patterned polymeric dielectrics exhibit an effective compressive modulus lower than that of their bulk counterparts. Furthermore, as most polymers have dielectric constants higher than that of air, the effective dielectric constant would enlarge with the closure of the air gaps upon compression. Figure 1 illustrates popular strategies in the literature to incorporate air gaps in dielectric polymers: micropatterned surfaces[4] (Figure 1A), spacers[13] (Figure 1B), nanowire networks[14] (Figure 1C), foams[15] (Figure 1D), and textiles[16] (Figure 1E). In addition, doping or coating polymers with high *k* or even conductive fillers may further increase the dielectrostriction effects.[12,17−23] Table 1 summarizes materials and fabrication methods to create such high *k* but mechanically soft composites. By carefully engineering the material and/or the structures, soft CPS has achieved sensitivity as high as 1.9 kPa^{-1}.[18]

However, the sensitivity enhancements through adding air gaps and improving dielectrostriction were effective only at low-pressure ranges, i.e., up to 3 kPa, as summarized in Table 1. High sensitivity cannot be maintained at large-pressure regimes because compression quickly diminishes air gaps, leaving a solid which further stiffens due to hyperelasticity and boundary confinement. Thus, as the strategies associated with adding air gaps to dielectrics are almost running out, new approaches to overcome the trade-off between sensitivity and pressure need to be invented. Additionally, while the sensitivity of CPS has been intensively studied, other important factors, such as response time, obstructiveness, and stretchability, were less discussed. For the widespread applications of CPS, major breakthroughs in materials and architectures are required to resolve these issues.

SENSITIVITY−PRESSURE TRADE-OFF

Prior soft CPS have an inherent limitation of low sensitivity at large pressure. The effective stiffness of a solid dielectric polymer increases with pressure due to the hyperelasticity of the material and its fixed top and bottom against the electrodes.[24] Although various strategies involving soft polymers, air gaps, and high *k* composites have been proposed to improve the sensitivity at small-pressure ranges (e.g., up to 3 kPa), their effects quickly vanish because even a small pressure could induce a large strain in the surface-patterned or porous dielectric, quickly closing the air gaps.

Our recent invention of a hybrid response pressure sensor (HRPS) has broken the limit set by conventional piezocapacitive pressure sensors.[19] We constructed a CPS by laminating a barely conductive porous nanocomposite (PNC) with an ultrathin insulating layer between two parallel electrodes (Figure 2A). The PNC was fabricated out of carbon nanotube (CNT)-doped Ecoflex using a nickel foam as the sacrificial template, resulting in an open cell structure with tubular ligaments and an overall porosity of 86% (Figure 2B). As the ligaments of the porous nanocomposite are resistive and the air pores generate parasitic capacitance, the PNC exhibits a hybrid response encompassing both piezoresistivity and piezocapacitivity. The ultrathin poly(methyl methacrylate) (PMMA) insulating layer is considered undeformable given its large stiffness compared to the PNC, but it is an indispensable component in HRPS because it ensures the overall sensor is still capacitive. An analytical model based on simplified circuits was built to understand the hybrid responses of the HRPS quantitatively. The model successfully explained one caveat for HRPS—there exists an optimal resistance of the PNC in terms of pressure sensitivity, which corresponds to an optimal doping concentration of the CNT (0.5 wt %), as indicated by the outmost curve in Figure 2C. When the PNC is too conductive, the piezocapacitive response is impaired, leaving the PNC a purely piezoresistive material. When it is too insulating, the piezoresistive response disappears, and the PNC becomes a conventional porous dielectric. The performance of the HRPS was compared with its conventional CPS counterparts with or without porosity (Figure 2C). It is evident that the CPS with solid dielectrics has the least sensitivity (red curves in Figure 2C). The sensitivity can be enhanced by adding porosity, but the decay with pressure is still remarkable (green curves in Figure 2C). The trade-off between sensitivity and pressure is clearly alleviated in HRPS (blue curves in Figure 2C).

We believe the HRPS provides a direction for CPS, and it is far from perfect. For example, instead of using a commercial nickel foam as the PNC template, architected conductive foams could enable more deterministic electromechanical behaviors. Strategically architected mechanical metamaterials can offer behaviors such as tunable stress−strain curve[25] and close-to-zero Poisson's ratio,[26] which are expected to be useful for enlarging the working range and possibly improving the linearity of the capacitance−pressure relationships.

Various microstructures (e.g., surface patterns and foams) have been introduced in dielectric materials to generate air gaps and improve the sensitivity of CPS. However, only a few studies have focused on engineering microstructures with a repeatable performance from sample to sample.[30] Although 3D porous structures (e.g., foams and textiles) have great potential to further improve the sensitivity of CPS, existing fabrication technologies such as electrospinning,[20] casting with removable fillers (solids and/or liquids),[31] and dip-coating on porous templates[23] cannot accurately control the size and the location of the pores, which inevitably leads to sample-to-sample variations. Because the structural uncertainty jeopardizes the repeatability of one CPS sensor to another, surface patterns fabricated with a deterministic mold have advantages over randomly porous microstructures in terms of predictable performance.[10] However, the surface structures can be easily affected during sensor packaging, i.e., when an adhesive layer is introduced between the patterned surface and the electrode.[30] Although many studies do not report the sensitivity after sensor packaging, such an issue cannot be overlooked in practice. A weak dielectric−electrode interface may also suffer from motion artifacts such as friction-induced triboelectricity.[32] In comparison, the porous microstructures are less impacted by the packaging. Therefore, surface vs bulk air gaps has their respective pros and cons, and more efforts are required to overcome their respective limitations.

FAST RESPONSE AND RECOVERY

Fast response and recovery of soft CPS are critical for the real-time detection of rapidly changing pressures. However, conventional soft CPS made out of elastomers and soft composites have innate drawbacks of slow response and slow recovery. The recovery time for a soft CPS may take up to 10 s because of the intrinsic viscoelasticity of the material and the viscoelasticity at its interface with electrodes (red curve in Figure 2E). As a result, some material and structure modifications are explored to reduce the response and recovery time.

From the material perspective, the simplest solution is to avoid using viscoelastic materials. The average response time of soft CPS made out of viscoelastic materials ranges from tens to hundreds of milliseconds alongside a slow recovery. However,

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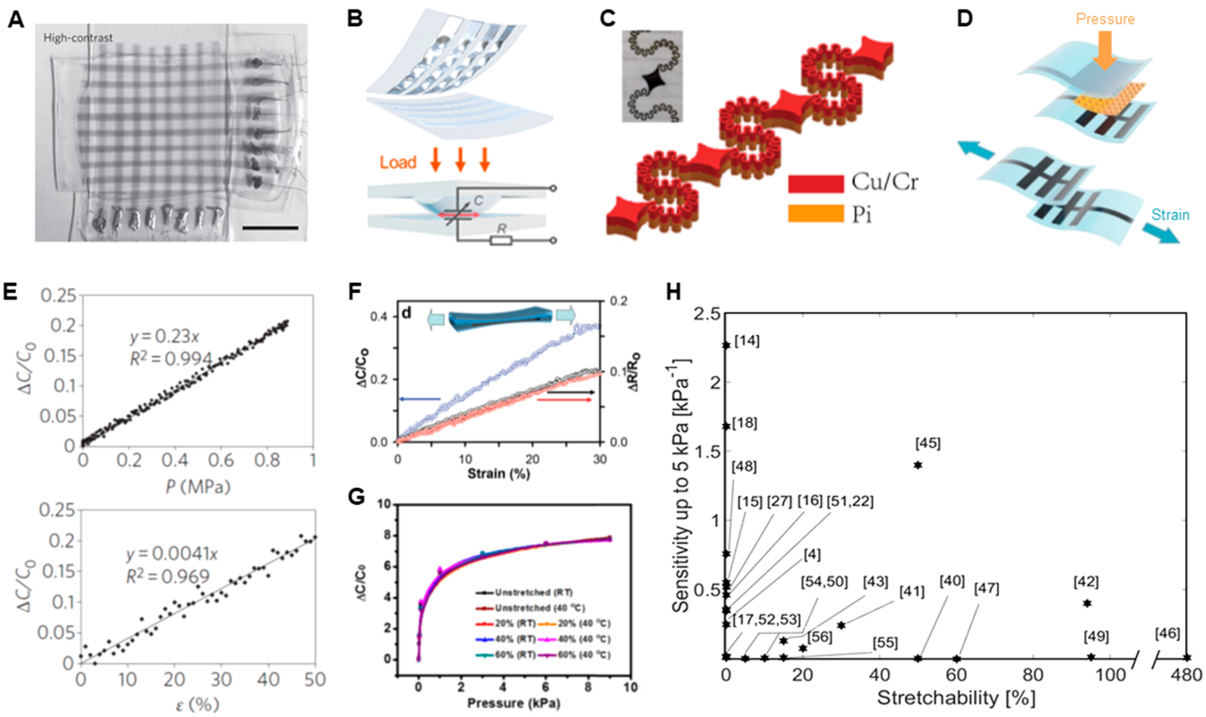

Figure 3. Stretchable electrodes used in stretchable CPSs: (A) CNT-coated PDMS,[40] (B) liquid metal,[42] (C) serpentine-shaped thin metal film,[44] and (D) sliding thin metal film.[43] (E) Relative capacitance change of a stretchable CPS in response to out-of-plane pressure (top panel) and in-plane tensile strain (bottom panel).[40] (F) Stretching response of resistive strain gauges (black and red) incorporated in a stretchable CPS to compensate for the capacitance change of the CPS (blue).[41] (G) Decoupled pressure−stretch response through strain isolation enabled by stiffened islands in a stretchable matrix.[45] (H) Ashby plot of sensitivity vs stretchability based on stretchable CPS reported in the literature. (A,E) Adapted with permission from ref 40. Copyright 2011 Springer Nature. (B) Adapted from ref 42. Copyright 2020 American Chemical Society. (C) Adapted with permission from ref 44. Copyright 2017 Royal Society of Chemistry. (D) Adapted with permission from ref 43. Copyright 2018 Springer Nature. (F) Adapted with permission from ref 41. copyright 2014 Wiley-VCH. (G) Adapted from ref 45. Copyright 2019 American Chemical Society.

sensors made out of elastic materials such as nylon grid[27] (Figure 2D) or silicon nanowire[14] networks achieved less than 10 ms response time plus a fast recovery. Yet, this simple solution has not been widely adopted because it compromises the sensitivity or sensing range of CPS due to the relatively high compressive modulus of elastic materials than viscoelastic materials. For example, the sensitivity of the CPS with the nylon grid is only 0.007 kPa^{-1} in the 1−5 kPa pressure range.[27] For the CPS involving silicon nanowire networks,[14] there is inconsistency in the capacitance-estimated dielectric layer thickness (more than 31 μm) vs the thickness of the silicon nanowire network (2 μm). Thus, some other factors, such as the natural curvature of the suspended electrodes, may affect the pressure sensing and recovery mechanisms. Given the fact that only a limited number of articles have been published on the subject, further investigation is needed to justify and guide the uses of elastic materials for CPS.

A more verified solution is the structural modification of polymers. Over a decade, numerous studies have validated that micropatterning on a polymer surface shortens the response time of CPS. For instance, elastomers with arrays of micropyramids[4,33] and microdomes[34] patterned on the surface demonstrated faster response under both loading and unloading (Figure 2E). The microstructures reduce the contact area and the deformed volume of the elastomer, which mitigates both interfacial and bulk viscoelasticity. As a result, the recovery time was shortened from over 10 s to dozens of milliseconds without compromising the sensitivity.[4] More recently, hierarchical surface structures have been reported to further shorten the response time to 20 ms (Figure 2F).[28] In addition, hierarchical porous structures may become an even more promising method to decrease the response time. Although it has not been employed for soft CPS yet, piezoresistive sensors with hierarchical porous structures have exhibited response and recovery times of fewer than 15 ms (Figure 2G).[29] The effect is attributed to a more uniform stress distribution than monomodal structures, resulting in more effective load transfer.

IMPERCEPTIBILITY

Imperceptibility is a relatively new need arising from wearable e-skins for human motion detection,[35] tactile sensing,[36] and noninvasive health monitoring.[37] When e-skins are laminated on the human body, the human perceives its obstructiveness in two scenarios: (1) the sensor physically interrupts the subject and/or (2) the subject loses some of their original sensations due to the sensor coverage. The physical interference comes from the mechanical mismatch between human skin and e-skin and may cause troubles such as skin irritation, tissue damage, and/or interfacial detachment. Therefore, the mechanical compliance of e-skins has been improved through research on soft materials and stretchable structures.[38]

However, the loss in natural human haptics, another type of obstructiveness, has not received much attention in the past. The degradation in human tactile sensation can be troublesome or even dangerous, especially when a specific human motion largely depends on the sensation. For instance, if thick or stiff sensors cover the hand, the natural tactile sensation becomes dull, leading to an unreliable grasp of objects or inaccurate operation of machines. Several methods were employed to preserve the natural sensation, such as using elastomeric substrates and/or reducing sensor thickness,[39] but these methods still compromise the natural tactile sensation.

Recently, a soft CPS with combined thinness and porosity was devised to respond to this challenge (Figure 2H).[20] Due to the compliant nanoporous structure of all layers in the sensor, the sensor-covered finger exhibited grip forces comparable to those of the bare fingers. While porous dielectric layers have been widely explored for improving compliance and sensitivity of the sensor, porous electrodes have been rarely explored for CPS. Looking into the future, other technologies for the low-cost fabrication of porous electrodes need to be developed. Also, compromised sensitivity due to the pursuit of imperceptibility shall be improved for accurate pressure measurement.

STRETCHABILITY

Achieving flexibility was a great milestone in e-skins, but stretchability has yet been fully available. Stretchable CPS can broaden the applications of e-skins in soft robotics, epidermal electronics, and stretchable touch displays. In this section, we describe the state-of-the-art stretchable CPS and point out the remaining challenges.

A big challenge for stretchable CPS was the stretchable electrodes. Unlike the dielectric layer, which can leverage many candidates of soft materials, conductive electrodes used in CPS were largely metals and indium tin oxide (ITO), which are stiff and not intrinsically stretchable. Thus, stretchable CPS only emerged after stretchable conductive materials were created.[38] Examples of stretchable electrodes for CPS include CNT-coated PDMS (Figure 3A),[40,41] liquid metal (Figure 3B),[42] serpentine metal ribbons (Figure 3C),[42] and sliding metal structures (Figure 3D).[43] However, these stretchable CPS are still immature for practical use due to the following limitations.

The most widely recognized limitation of stretchable CPS is the coupled capacitance response due to both in-plane stretch and out-of-plane pressure. When a soft CPS is stretched in-plane, both enlarged electrode area and reduced electrode distance due to the Poisson's effect of the dielectric cause an increase of capacitance. For instance, using the sensor shown in Figure 3A, the normalized capacitance change of 0.2 can be induced by either 0.8 MPa pressure or 50% stretching (Figure 3E).[40] Thus, the CPS cannot offer an accurate reading of the applied pressure based on the measured capacitance when it is subjected to simultaneous stretching and compression.

Several attempts have been made to differentiate the two responses, such as integrating a strain gauge into a CPS or employing stiffened structures for in-plane stress isolation. The added strain gauges can calibrate the in-plane stretch, which is used to compensate for the capacitance change (Figure 3F).[41] However, this strategy demands the strain gauges to be pressure insensitivity; it also adds complexity to the sensing modality as well as the sensor size. Another approach is to implement in-plane strain isolation through building CPS only on stiff islands.[45] As most deformation is accommodated by the unstiffened regions, strain in the islands is limited, hence physically isolating the CPS from in-plane strains (Figure 3G). However, this design risks lowering the spatial resolution and wrinkling the sensor due to the stiffness mismatch between the soft area and the stiff islands. More critically, this strategy requires stiff spacers around the sensing area to prevent out-of-plane deformation induced by stretching, incurring inaccurate pressure response because some of the applied pressure could be partaken by the spacers. Thus, the strain gauge and stiff island strategies have a few side effects, and there still lacks intrinsically stretchable CPS with decoupled in-plane and out-of-plane responses.

The decoupling problem should be resolved without significantly compromising the sensitivity of a stretchable CPS. Reported sensitivity vs stretchability can be summarized in an Ashby plot we constructed (Figure 3H[4,14−18,22,27,40−43,46−56]), where the pressure range is limited to be 0 to 5 kPa; that is, the sensitivities are extracted based on the slope of a straight line connecting $\Delta C/C_0$ at 0 kPa and $\Delta C/C_0$ at 5 kPa. Interestingly, there is a clear trade-off between stretchability and sensitivity. High stretchability (e.g., more than 50%) has been achieved using intrinsically stretchable electrodes, such as ionic hydrogels, liquid metals, or nanocomposites.[40,42,46,47,49] Those pioneering works mainly focused on enhancing the stretchability of CPS, without caring much for the sensitivity of CPS. The one standing out utilized the stiff island strategy,[45] which is not a complete solution as we addressed in the previous paragraph. Therefore, stretchable and accurate CPS remains to be an unmet need that demands future innovations and explorations. For example, we are currently engineering stretchable HRPS, which has the potential of offering large capacitance change only when subjected to out-of-plane pressure.

CONCLUSIONS

Soft CPS, especially stretchable CPS, is an essential enabling technology for future soft robots, bioelectronics, and expandable touch displays. High sensitivity at low pressures has been well achieved so far. The next challenge lies in the practicability of the sensor. Through this perspective, we would like to call for attention on sensitivity at high pressures with proper packaging and consistency in performance, faster response and recovery, imperceptible wear on human skin, as well as decoupled in-plane and out-of-plane responses. While we mention a few possible solutions to some of those challenges, we also try to point out their limitations and potential future directions. The improvement of CPS will further enable advanced applications such as multimodal sensing[8] and neuromorphic systems.[57] In conclusion, there is vast space for future innovations in materials, structures, manufacture, and device constructions toward mechanically soft and functionally superior CPS.

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Notes

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