Emerging Technologies in In-Situ Printed Wearable Sensors

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Abstract. Recent advancements in wearable sensors have significantly advanced the detection of physiological signals, both internally and externally to the body. The integration of innovative materials, such as flexible circuits, has allowed these sensors to achieve prolonged conformity with the monitored surfaces, thus enhancing the precision of signal gathering. In-situ bioprinting, a cutting-edge manufacturing technique, enables the direct fabrication of materials with diverse elastic properties onto specific surfaces. Sensors produced via in-situ bioprinting exhibit mechanical characteristics akin to human organs, improving their integration with the detection surface. Furthermore, the in-situ production process obviates the need for internal and external device transfer, substantially minimizing infection risks in clinical settings. The use of biocompatible inks also facilitates extended durations of wear, underscoring the profound potential of this technology. This article conducts a review of select studies to assess the current progress and technical hurdles in the domain of in-situ printed wearable sensors. It compiles the utilized printing materials, methodologies, and object tracking technologies, offering insights into the present and prospective advancements in in-situ printed wearable sensor technology.

Keywords: Wearable sensor; In situ bioprinting; Biocompatible materials; Object tracking.

1. Introduction

Wearable sensors have increasingly attracted research interest for their capability to continuously and non-invasively monitor a variety of daily activities, including physical, biological, chemical, and environmental aspects. These sensors are expected to exhibit properties such as flexibility, stretchability, high sensitivity, durability, and biocompatibility, which has led to a significant shift in sensor design from traditional rigid metals and semiconductors to softer, more flexible materials. 3D bioprinting, an innovative additive manufacturing technique, facilitates the direct in-situ production of materials like hydrogels on sensitive surfaces, including skin wounds and internal organs. This method promotes the development of seamless interfaces between biological systems and multifunctional devices, reducing the risk of infection associated with device transfer between different environments and minimizing discrepancies in mechanical properties between the sensors and human tissues. Consequently, it promises to enhance the capabilities of existing flexible sensors, particularly in terms of detection depth.

Presently, 3D bioprinting leverages two primary strategies: handheld device printing and robotic system printing. Handheld devices are already being used for direct wound dressing in surgical settings. Robotic systems, however, offer the advantage of higher precision printing without the influence of operator variability and can accommodate the printing of multi-material, complex structures. Printing directly onto irregular anatomical surfaces with robotic systems requires prior or real-time acquisition of the surface's morphological information. The selection of biologically compatible inks that can be quickly deposited or cross-linked is crucial, as is the choice of a printing method that matches the ink properties. Although this area remains predominantly experimental, numerous advanced technologies have been successfully applied in the production of certain in-situ printed sensors. Thus, this article provides a review of essential technologies for in-situ printed sensors and highlights recent designs that incorporate these advancements. It seeks to outline the evolving trends in the field of in-situ printed sensors, offering readers an advanced outlook.

2. Advanced Techniques

Current advancements have highlighted the pivotal role of 3D bioprinting in the realms of tissue engineering and the creation of biocompatible devices. Yet, its application has largely been limited to the deposition of materials onto stationary targets outside the body. This external printing process typically involves extensive durations and deleterious post-processing, aspects that stand in stark contrast to the needs of real-time, in-situ printing inside the human body. To facilitate the in-situ 3D bioprinting of sensors, it is crucial to refine prior printing approaches to eliminate harmful effects, incorporating new printing technologies and biocompatible inks. Furthermore, the dynamic nature of anatomical structures requires advancements in additive manufacturing to deposit materials on moving 3D surfaces, especially those within the circulatory system. In response, researchers have developed a closed-loop strategy, moving beyond the traditional open-loop method of designing printing paths on phantom organs, to include real-time scanning of the surface morphology for printing. This segment delves into technologies pivotal for in-situ printing, such as real-time scanning, printable electrode materials, and curved 3D printed devices, aiming to outline foundational strategies for in-situ printing on anatomical surfaces.

2.1. Real-Time Scanning

Given the potential for anatomical structures to exhibit free movement, such as the unrestricted hand of a burn patient requiring movement during therapy to retain motion range for skin grafts, or display quasi-cyclic motion like the rhythm of a beating heart, thoracic cavity movement induced by breathing, or the pulsatile throbbing of brain tissues near arteries, establishing a real-time reference surface is essential in the printing process [1]. This facilitates precise planning of the printer head’s trajectory and extrusion velocity, improving the accuracy of material deposition on anatomical surfaces [2]. The prevalent method involves integrating a stereo vision camera onto the printer to capture the target surface's contour. Nevertheless, existing research indicates that current passive stereo vision cameras often fail to meet the dual demands of a refresh rate exceeding 10Hz and sub-millimeter resolution simultaneously. The former is vital for implementing a human-in-the-loop workflow, and the latter is crucial for accurately managing material ejection or deposition. Consequently, active stereo vision technologies, like Conventional structured-light vision (SLV), are often added to enhance depth information resolution significantly. Furthermore, Zhijie Zhu and colleagues have shown that machine learning, with a pre-scanned dataset, can facilitate the real-time capture of anatomical surfaces.

2.1.1. Real-time active stereo vision

Active stereo vision techniques typically project structured light or lasers onto the surface of objects, deriving depth information by identifying the distortion of structured light or lasers across surfaces through projector-camera or camera-camera configurations. Although lasers provide clearer information, they are more expensive and slower than structured light, which, despite its lower resolution, allows for rapid, large-area scanning at a reduced cost. Accuracy demands lead most in-situ printing to employ laser-equipped devices for depth data acquisition. Two primary laser scanning strategies exist: 1) Utilizing laser stripe projection across the entire anatomical surface for immediate surface position updates and print head path and extrusion parameter real-time adjustments based on comprehensive location data; 2) Implementing local laser scanning around the print head, leveraging acquired local depth data to adjust the print head's vertical positioning. This approach, through a straightforward algorithm, dynamically adapts flat shapes to irregular surfaces, effectively printing single-layer structures or those with minimal vertical complexity.

2.1.2. AI-aided stereo vision

For anatomical surfaces with quasi-cyclic motion, the constant alterations in shape necessitate substantial computational resources for real-time active stereo vision calibration. Thus, employing a pre-processed learning dataset for print head path planning conserves computational effort. Zhijie

Zhu et al. employed this technique to bifurcate the conventional scanning and reconstruction operation into two phases: 1) offline dataset learning, and 2) learning stereo vision measurement model parameters. Initially, circular reference markers are positioned on the object's surface for scanning, establishing a link between the markers and surface morphology via structured light scanning. Subsequently, researchers rapidly develop and reconstruct the surface model for path planning by assessing the markers' relative placement and orientation through laser stereo vision, streamlining the reconstruction process.

2.2. Printable Biocompatible Material

In the process of in situ bioprinting, where printing directly occurs on the anatomical surfaces within the body, bioinks must meet specific requirements: 1) They necessitate rapid crosslinking without the need for subsequent processing. 2) The inks should match the stiffness of the targeted surface, potentially requiring a range of inks with significantly varied Young's moduli. 3) Given the internal printing environment, bioinks must generally demonstrate substantial biocompatibility and biodegradability, sometimes even supporting cellular growth.

Concerns regarding biocompatibility and the crosslinking process challenge the use of inks that rely on exogenous chemicals (e.g., chemical photosensitizers) for crosslinking in in situ applications. However, O'Connell, C.D., et al. successfully accelerated the crosslinking of photocrosslinkable materials in situ by integrating a 405-nm light source near the nozzle, illuminating the ink immediately after extrusion and before its deposition onto the target tissue [3]. Therefore, taking all factors into account, materials such as Alginate, Hyaluronic Acid (HA), Gelatin, Polyethylene Glycol (PEG), Pluronic F127, and Polycaprolactone (PCL) qualify as bioinks for in situ printing under particular conditions. Notably, silk fibroin inks [4], with their diverse formulations, water-solubility, robust and adjustable mechanical properties, and capacity for self-assembly through biophysical adsorption, are under investigation as promising bioinks for in situ printing [5].

2.3. 3D Printed Method

Currently, direct extrusion and direct inkjet systems are recognized as viable strategies for in-situ printing. The direct extrusion system, among the earliest to be developed in the field of bioprinting, continues to be prevalently used due to its cost efficiency and operational simplicity [6]. Conversely, the inkjet system, while requiring more precise control over viscosity and crosslinking of the printing materials [7], offers the advantage of drop-on-demand printing, facilitated by real-time algorithms. This feature enables dynamic path planning from live scans, thereby maintaining the accuracy of model prints without interruptions for path corrections, positioning it as an innovative printing technique [8].

Direct extrusion systems are divided into pneumatic and mechanical categories, distinguished by their power sources. Pneumatic extrusion, employing compressed air or nitrogen, exerts direct pressure on the bioink and is favored for its simplicity and low cost of production. Mechanical extrusion, powered by a device equipped with a piston or screw, facilitates both the withdrawal and deposition of bioink, contributing to cleaner ends of printed strands and thereby enhancing print fidelity. Commercially available direct extrusion printers demonstrate capabilities for sub-millimeter precision, intricate structural prints, and multi-material usage. Owing to their straightforward design, direct extrusion systems lend themselves well to DIY projects tailored to specific requirements. Although DIY printers may not match the precision of commercial models, they suffice for producing in-situ printed biosensors while considerably reducing manufacturing costs.

Direct inkjet systems precisely deposit ink in small droplets of fluid-like photopolymer onto the printing surface via a printhead. This process demands specific ink viscosities and surface tensions to ensure seamless extrusion and droplet shape retention. Inks, typically high-requirement hydrogel polymers, must crosslink upon contact with the print surface to form a cohesive structure. Printing complex three-dimensional shapes often necessitates the use of support materials, which are subsequently removed. Advances in multi-nozzle and multi-layer coating technologies have

enhanced the inkjet system's ability to accurately render complex structures, aligning with the demands of contemporary in-situ printed biosensors.

3. Result

Several sensors have been successfully fabricated and evaluated through in-situ printing on human anatomical interfaces in a laboratory setting. Others, not printed directly on human interfaces, have shown the ability to be manufactured on curved surfaces with relatively good biocompatibility, indicating their potential for direct application on human skin. These investigations provide valuable insights for the future development of in-situ printed sensors. Consequently, this section delves into the technology and performance of these sensors, highlighting their capacity to print on dynamic, irregular surfaces, the extent of in-situ printing in device fabrication, and the compatibility between the biological inks used and human tissue, as detailed in Table 1.

The range of sensors manufactured in situ encompasses humidity sensors, tactile sensors, deformation sensors, and photonic sensors. Remarkably, in-situ printed electronic tattoos and microfluidic devices also demonstrate potential synergies with these sensors and are discussed herein.

Table 1. Advanced Technologies used in Different Sensors

Device type	Print material	Print method	Printable component	Printing surface	Target tracking mothod
Humidity sensor	Polyethylene oxide (PEO) with silver flakes	Direct ink writing	Sensor materials Circuits materials	Human hand skin	3D scanning camera to dynamically track moving object
Deformation sensor	Polyacrylamide (PAM) with lithium chloride (LiCl)	Direct ink writing	Sensor materials Circuits materials	Pig lung surface	Close loop AI aided tracking moving object
Tactile sensors	Multiformula dichloromethane (DCM) and a silicone elastomer mixed with silver particles	Multi-material ink writing	Sensor layer Electrode layer Isolating layer Surporttin g layer	Human hand skin	Pre-scan object shape and pre-plan path
Photovoltaic sensor	Poly(3-hexylthiophene) (P3HT) and [6,6]-phenyl C61-butyric acid methyl ester (PCBM) Poly(ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS) Eutectic gallium indium (EGaIn) liquid metal	Layer-by-layer deposition based extrusion printing	Sensor layer Electrode layer Isolating layer Packaging materials	Hemispherical glass dome	Pre-scan object shape and pre-plan path

Electronic tattoos	Aerosol with silver nanowires	Direct ink writing	Circuits materials	Human skin	/
Microfluidic device	Sodium polyacrylate	/	Microchannel structure Surporttin g layer	Pig kidney surface	Pre-scan object shape and pre-plan path

In 2018, Zhu et al. achieved the in-situ printing of a LED for wireless power transmission on the back of a hand using a highly conductive, water-soluble ink enhanced with silver flakes in polyethylene oxide (PEO) for direct ink writing [9]. The energy-receiving coil, fabricated entirely by in-situ printing, adjusted its impedance with humidity changes, serving as a wireless humidity sensor. The printing process involved using a 3D scanning camera to dynamically track the skin surface and guide the printer's path, allowing for movement and rotation of the hand within the print area at speeds below 8 mm/s. The device remained securely adhered for more than two hours, ensuring stability, and was easily removable for recycling. The authors posit that this technology may be integrated with sweat analysis for creating a wearable device to wirelessly monitor physical exertion or stress levels.

Subsequently, in 2020, Zhu and his team printed a deformation sensor on a live pig lung's surface [10]. They developed an ionic hydrogel by dissolving lithium chloride (LiCl) in a stretchable, UV-curable polyacrylamide (PAM) matrix, which was cross-linked post-printing. The ink's elastic modulus, once cross-linked, was compatible with lung tissue, allowing the device to operate over various respiration rates. Initial scanning of a breathing pig lung created a learning dataset of time-sequenced lung shapes. By monitoring deformations of pre-placed markers on the lung and updating the lung shape in real-time, they adjusted the printing path accordingly. The printed Electrical Impedance Tomography (EIT) sensor featured a hydrogel sensing layer and multiple copper electrodes, maintaining a stable interface even under significant deformation. The device included a peripheral circuit for data collection and control, featuring a microcontroller, waveform generator, and a voltage-controlled current source (VCCS), and could be non-invasively removed post-printing. In 2017, Guo et al. proposed an in-situ printing method for tactile sensors on the hand, using a sinter-free nanomaterial ink of adjustable viscosity in a multi-material 3D printing setup with four independent nozzles [11]. This sensor, consisting of multiple layers including electrodes and an isolation layer, was printed with an ink formulated from dichloromethane (DCM) and a silicone elastomer mixed with silver particles, achieving high conductivity and a modulus matching that of the skin. They successfully printed the sensor on fingertips to detect and differentiate human movements and envisage developing an electronic skin capable of mapping pressure with high spatial resolution.

In 2018, Sung Hyun Park and his team successfully accomplished the complete in-situ 3D printing of photovoltaic sensor arrays on curved surfaces [12]. They employed a photoactive layer composed of a blend of poly(3-hexylthiophene) (P3HT) and [6,6]-phenyl C61-butyric acid methyl ester (PCBM), along with poly(ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS) as the transparent anode and eutectic gallium indium (EGaIn) liquid metal as the cathode. Printed at room temperature on a hemispherical glass surface, the inks' surface tension and adhesion to the substrate maintained the structural integrity on the curved surface. Post-printing, the device was encapsulated with a UV-curable solution to shield it from oxygen and humidity degradation. Although not yet applied in situ on human skin, the technique's similarity to current human-surface in-situ printing methods and its proficiency in printing on curved surfaces indicate its potential for human skin application.

Significant advancements have also been made in the field of in-situ printing of electronic components for sensors. Nicholas X. Williams and his team formulated silver nanowire inks for the direct writing of electronic tattoos, capable of creating conductive traces at low temperatures without requiring harmful post-processing and retaining high electrical performance after extensive bending

[13]. With a drying time of less than 2 minutes, this ink is exceptionally well-suited for integration with other 3D-printed sensor components on delicate surfaces, facilitating the development of comprehensive wearable devices. Additionally, Manjot Singh and colleagues innovated a fully 3D-printed microfluidic device for the kidney's surface [14], aimed at isolating clinically significant metabolic and pathophysiological biomarkers. Through conformal printing, a microchannel area made of sodium polyacrylate was precisely printed on the kidney to extract heat shock protein 70 (HSP-70) and kidney injury molecule-1 (KIM-1) from the renal cortex. This device holds the promise of integration with in-situ printed chemical sensors to detect biochemical markers, paving the way for an integrated, in-situ printed wearable device.

4. Conclusion

This article comprehensively reviews recent advances in in-situ printing techniques for wearable sensor devices, addressing the criteria for printability and biocompatibility, and highlights state-of-the-art technologies meeting these prerequisites. The review suggests that 3D printing technology, enhanced by AI, which facilitates real-time tracking directly on dynamic human anatomical surfaces, is evolving and shows promise for broad future applications. Presently, the focus of in-situ printed wearable sensors is predominantly on external body surface printing. While fabricating devices for internal body monitoring presents significant clinical potential, the challenging internal bodily environment poses unresolved technical issues. Current in-situ printing predominantly employs hydrogel-based inks, selected for their mechanical compatibility with human tissue; however, aspects such as durability and electrical conductivity demand further validation. Developing biocompatible, high-performance inks suited for the internal body environment remains a pivotal challenge for advancing in-situ printed wearable sensors. Looking ahead, combining in-situ printing of crucial sensor parts with the integration of pre-manufactured components offers a cost-effective and practical approach to crafting in-situ printed wearable sensors. Despite the potential value of achieving comprehensive in-situ printing for wearable sensors, research in this domain is limited, indicating a significant gap in implementing this technology on human anatomical surfaces.

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