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AI-Based Metamaterial Design for Wearables

*Defne Yigci, Abdollah Ahmadpour, and Savas Tasoglu**

Continuous monitoring of physiological parameters has remained an essential component of patient care. With an increased level of consciousness regarding personal health and wellbeing, the scope of physiological monitoring has extended beyond the hospital. From implanted rhythm devices to non-contact video monitoring for critically ill patients and at-home health monitors during Covid-19, many applications have enabled continuous health monitorization. Wearable health sensors have allowed chronic patients as well as seemingly healthy individuals to track a wide range of physiological and pharmacological parameters including movement, heart rate, blood glucose, and sleep patterns using smart watches or textiles, bracelets, and other accessories. The use of metamaterials in wearable sensor design has offered unique control over electromagnetic, mechanical, acoustic, optical, or thermal properties of matter, enabling the development of highly sensitive, user-friendly, and lightweight wearables. However, metamaterial design for wearables has relied heavily on manual design processes including human-intuition-based and bio-inspired design. Artificial intelligence (AI)-based metamaterial design can support faster exploration of design parameters, allow efficient analysis of large data-sets, and reduce reliance on manual interventions, facilitating the development of optimal metamaterials for wearable health sensors. Here, AI-based metamaterial design for wearable healthcare is reviewed. Current challenges and future directions are discussed.

1. Introduction

Continuous monitoring of physiological parameters has remained an essential component of patient care. Enabling the use of more accurate and sensitive tools for monitoring and intervention, advancements in engineering and clinical medicine have improved patient outcomes significantly over the past century. Continuously tracking congestion in heart failure patients have reduced hospitalizations;[1] early detection of sepsis using wearable wireless monitors at intensive care units (ICUs) has decreased length of hospital stays;[2] and real-time continuous glucose monitoring has improved glycemic control for type 2 diabetes mellitus (DM) patients.[3] With an increased level of consciousness regarding personal health and wellbeing, the scope of physiological monitoring has extended well beyond the hospital and proactive healthcare is no longer limited to routine check-ups. Instead, used not only by patients but also by millions of seemingly healthy individuals, smartwatches, jewelry, and other accessories have been developed to track a wide range of physiological parameters including movement, heart rate, respiratory rate, cardiac cycle, vocal cord vibration, blood oxygen saturation, blood glucose, electrodermal activity, and sleep patterns.[4–9] Moreover, given the widespread acceptance of these tools, the development of wearable sensors that accurately and continuously record physiological data have gained substantial momentum over the past decades, giving rise to electronic skin (e-tattoos), textile-based sensors, and biofluidic wearable sensors among other applications.[10–12] However, the performance of these wearable

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Table 1. Summary of metamaterials commonly used in wearables.

Metamaterial	Construction	Properties	Limitations	Ref.
Acoustic metamaterials	Subwavelength metaatoms	• Negative dynamic mass • Negative equivalent density • Negative bulk modulus • Negative refractive index	• Frequency dependence • Difficult to achieve structural complexity with current fabrication methods	[14]
Auxetic metamaterials	Polymeric materials with kirigami-inspired construction	• Negative Poisson's ratio	• Structural stability • Limited material choice	[15]
Electromagnetic metamaterials	Metallic and/or dielectric structure at subwavelength scale	• Negative refractive index • Negative permeability • Total absorption	• Complex and costly fabrication • Challenging device integration	[16]
Flexible mechanical metamaterials	Various materials and design strategies can be employed	• Negative density • Negative Poisson's ratio • Negative compressibility • Nonlinear responses • Shape-morphing ability • Topological protection	• Prone to altered properties due to fabrication errors • Manufacturing constraints limit complexity • Difficult rational design	[17]
Piezoelectric metamaterials	Piezoelectric element integrated structures	• Enhanced wave propagation • Tailored piezoelectric response • Electro-mechanical coupling • Negative Poisson's ratio	• Scalability challenges	[18]
Plasmonic metamaterials	Metallic nanostructures	• Plasmonic resonance • Adjustable optical response • Subwavelength resolution • Surface-enhanced sensing	• Losses and damping effect • Fabrication challenges • Sensitivity to environmental conditions • Limited bandwidth	[19]
Thermal metamaterials	Various materials with integrated thermal elements	• Thermal cloaking, focusing, or rectification	• Narrowband operation • Scalability challenges • Limited applications	[20]

devices has been limited by the intrinsic qualities of materials used in their fabrication. To address this, metamaterials have emerged as promising solutions.

Metamaterials are artificially-constructed composites, designed to exceed properties of naturally occurring materials.[13] The enhanced functionality of metamaterials stems from their inherent characteristics such as negative Poisson's ratio, negative refractive index, enhanced wave propagation, non-linearity and subwavelength propagation (**Table 1**). Moreover, metamaterials offer unique control over electromagnetic, mechanical, acoustic, optical, or thermal properties of matter, enabling advanced applications for wearables.[14–20] For example, using auxetic metamaterials can improve sensor performance in stretchable strain sensors by eliminating the intrinsic sensitivity limit of traditional materials.[21] Moreover, auxetic metamaterials have a negative Poisson's ratio which enables 2D expansion, thereby demonstrating a 24-fold sensitivity improvement over conventional sensors. Alternatively, for metamaterials with properties like negative refractive index and band gap, mechanical wave propagations can be manipulated to enable optimized energy harvesting.[22] Specifically, 2D octagonal phononic crystals (PnCs) have been used and harvesting power has been recorded to be 22.8 times higher than that of conventional materials. Additionally, various metamaterial-based antennas have been developed to establish wireless body area networks (WBANs) and have improved wireless communication, widened the operating band, or enabled reconfigurability.[23] Finally, by allowing patient-specific adjustments (i.e., position adjustment for joint movement), low-temperature thermoplastics (LTTPs) have been used to fabricate electronic assistive devices with superior user comfort.[24]

3D printing, additive manufacturing, and advancements in other fabrication methods have accelerated progress in metamaterial construction, with molding-sintering, cutting-molding, cavity injection, and drilling being used for dielectric metamaterial construction; photolithography, shadow-mask lithography, electron beam lithography, imprint lithography, polymerization, multilayer electroplating for flexible metamaterial construction; fused deposition modelling and stereolithography for acoustic metamaterial construction; and material jetting, selective laser melting, selective laser sintering, and fused deposition modelling for auxetic metamaterial construction.[25–27] Despite developments in fabrication and manufacturing methods, metamaterial design has relied heavily on manual design processes, missing out on opportunities for better optimization, more complex design, and enhanced functionalities. Artificial intelligence (AI)-based tools can be leveraged to achieve a higher degree of functionality in metamaterial design, particularly for wearables. By supporting faster exploration of design parameters, allowing efficient analysis of large data-sets, and reducing reliance on manual interventions, AI-based design can enable more optimal metamaterial designs to be achieved, thereby expanding applications for wearable technologies and beyond. Here we review artificial intelligence (AI)-based

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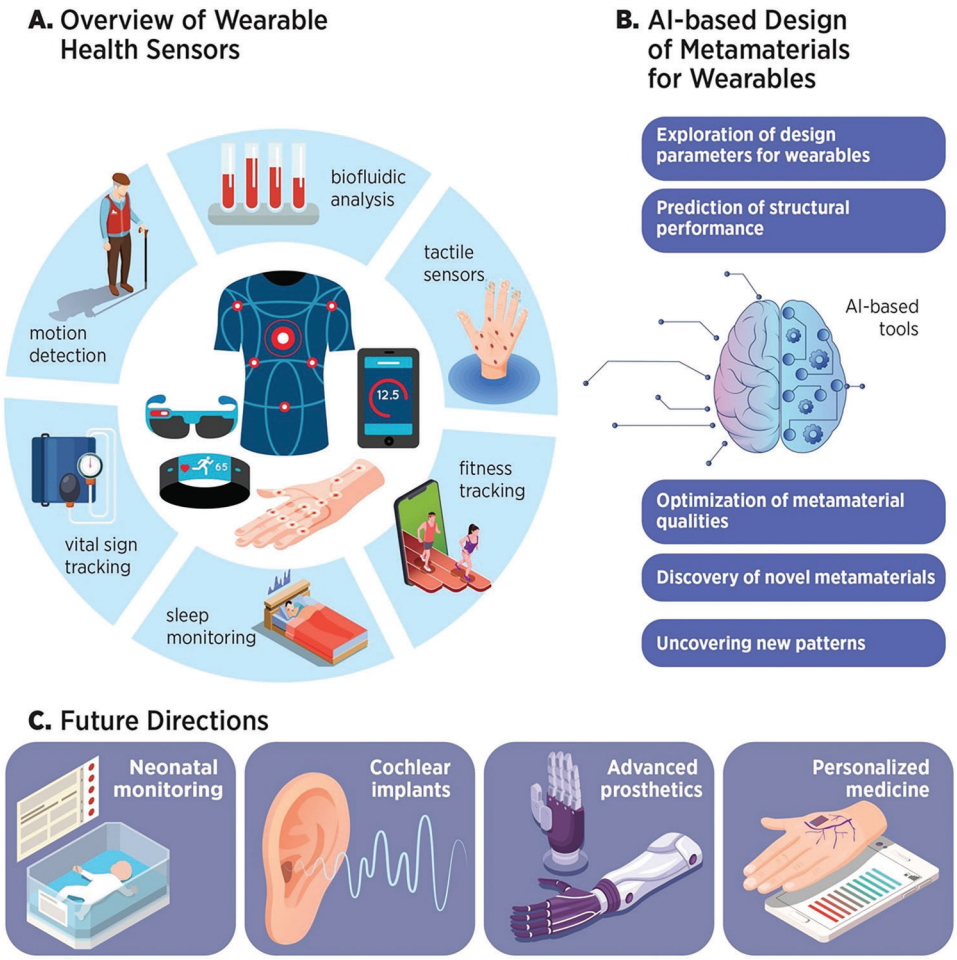


Figure 1. Overview of AI-based metamaterial design for wearables. A) Current applications of wearable sensors. Examples of wearable sensors include smart textile, mount-on skin-like sensors, smartwatches or wristbands, shoes, eyewear. Applications include fitness tracking, sleep analysis, vital sign monitoring, motion and fall detection, biofluidic analysis, and tactile sensors. B) Integration of AI-based metamaterial design in wearable sensor development to enable exploration of design spaces, optimization of parameters, uncovering of patterns, prediction of structural performance. C) Future directions for wearable sensors using AI-based metamaterial design: physiological monitoring at neonatal intensive care, development of advanced cochlear implants to restore natural hearing, construction of cutting-edge prosthetic designs with improved neural interfaces, tactile senses, and mobility, and applications in personalized medicine. Some elements in Figure 1 were designed using resources from freepik.com.

metamaterial design for wearable healthcare devices (**Figure 1**A,B) and discuss future directions (Figure 1C) regarding the use of AI-based metamaterial design for wearables in healthcare and medicine.

2. AI-Based Metamaterial Design

State-of-the-art metamaterial technology improves wearable sensors for healthcare measurements, including heart pulse monitoring, blood pressure tracking, and analyte detection in healthcare and point-of-care testing.[28–31] The improvement of metamaterial technology is achieved through the careful design of an optimized structure. By considering the unique requirements of the wearable sensor's environment, the design of the metamaterial can be fine-tuned to maximize its effectiveness and functionality. Metamaterials acquire their properties not from the inherent characteristics of the bulk materials, but rather from their artificially engineered internal geometry comprising multiple sub-elements or cells which are typically organized in regularly repeated patterns.[32,33]

Traditional design approaches for metamaterial structures and machines often rely on manual operations, which can be effective in certain conditions but may not ensure optimal efficiency across all scenarios.[34] Machine Learning (ML) techniques enable the exploration of vast design spaces, uncovering patterns and optimizing parameters that may not be readily apparent through manual methods alone.[35] By employing iterative data-driven algorithms, these methodologies enable computers to uncover latent insights without the need for explicit programming guidance on where to search which proves highly effective for efficient metamaterial parameter estimation.[36] ML finds application in material and structure science across three primary categories: predicting structural performance, discovering new materials, and designing materials with desired performance characteristics.[37] Regression and probabilistic algorithms are employed within these categories to systematically evaluate

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diverse combinations of structures and components. Ultimately, these algorithms aid in the selection of materials and their corresponding structures, ensuring the achievement of desired performance attributes. The careful selection of algorithms for ML systems in material selection and structural design is crucial, as these algorithms greatly influence the design capability and accuracy of predictions. Probability algorithms are primarily utilized for designing novel materials and structures,[37] whereas regression, clustering, and classification algorithms are employed for predicting properties of materials and structures at different scales. ML excels in tackling non-linear problems by effectively handling noisy and incomplete data with its inherent flexibility, symbolic reasoning capabilities, and explanatory power, and once properly trained, ML models can achieve high-speed generalization and accurate predictions.[38]

The literature contains three primary application processes of ML in architected structures, namely data analysis, algorithm development, and model evaluation.[38] The data analysis process involves data preprocessing and structure characterization to analyze objectives and identify key features. Raw data in materials and structures are often acquired from experimental calibration or numerical simulations, leading to challenges of incompleteness, inconsistency, and high noise. Data cleaning plays a crucial role in identifying inaccurate, incomplete, incorrect, and irrelevant portions of the data, enabling modification or replacement of noisy data.[39–41] The algorithm development process in architected structures can be divided into two subcategories: supervised and unsupervised components. Supervised ML encompasses regression and classification, while unsupervised ML involves clustering and probability estimation. In the pursuit of pattern recognition and knowledge extraction from vast datasets, ML constructs models that deliver dependable and consistent outputs. By utilizing black-box algorithms to establish intricate connections between input parameters and output results, ML generates sets of linear or nonlinear functions that surpass the capabilities of traditional statistical methods.[42–45] The model evaluation process aims to assess the performance of ML models by comparing the generalization errors between calculated tests and predicted responses. Models should demonstrate accuracy not only with existing data but also when applied to unseen data. Testing data is utilized to validate the models' discriminative capabilities using performance indices, employing methods such as bootstrapping, cross-validation, or hold-out.[46–49]

3. Applications of Wearables in Healthcare and Medicine

Continuous health monitoring plays a crucial role in modern healthcare, enabling real-time assessment of physiological changes and early detection of pathological conditions (Figure 1).[50–54] Accurately tracking health or disease progression allows personalized and proactive measures to be taken, thereby improving overall health outcomes. A great physiological sensor exhibits high sensitivity, accuracy, and reliability, integrates seamlessly into the daily life, and captures a wide range of physiological signals in a non-disruptive manner. Wearable health sensors offer distinct advantages over traditional sensors as they are often integrated with mobile platforms facilitating user experience and can overcome specialized equipment requirements. With the use of metamaterials, wearables have become increasingly lightweight, flexible, and accurate.[10] AI-based design of metamaterials can improve wearable sensor functionality even further.[34]

3.1. Monitoring Vital Signs, Cardiovascular Health, and Drug Metabolism

Continuous blood pressure (BP) measurement can allow the early detection of hypertension and potentially early-stage cardiovascular disease.[55] Piezoelectric metamaterials have been used to fabricate non-invasive, cuffless, wearable, arterial pulse-based BP sensors in various forms including thin-film array sensors, epidermal sensors, Poly(vinylidene fluoride) (PVDF) sensors, and braces, overcoming many drawbacks (limited sustained power, slow response times, temperature or operating voltage dependence) of conventional wearable sensors.[56–60] Despite the accuracy and user-friendliness of manually designed piezoelectric platforms, alterations made to the structure of piezoelectric elements can result in limitations such as significant power consumption and fatigue. These limitations can be overcome using AI-based metamaterial design for wearable sensors. In fact, an AI-based metamaterial design was developed for a wearable BP sensor. To optimize piezoelectric metamaterial design for BP sensors and enable higher functionality, an AI-based structural comparison study was completed (**Figure 2**).[61] Data simulations and visualizations demonstrated that the electrical potential (calculated using stress simulations) generated by traditional square-shaped elements were lower compared to all other conformations. As a result of Bayesian optimization and ML driven regression model analyses, honeycomb-metamaterials proved superior to traditional models in generating output potentials. Further assessments revealed that the honeycomb structure retained the ability to produce double the electric potential of traditional models, offering promising new avenues for wearable BP sensor design.

Besides piezoelectric metamaterials, plasmonic metamaterial textiles have also been used to track vital signs such as temperature, heart rate, and respiratory rate.[62–65] In fact, plasmonic metamaterials have been employed to evaluate physiological and pharmacological analytes in sweat non-invasively using surface-enhanced Roman scattering (SERS).[63] Moreover, to prevent potentially destructive strains and large deformations, finite element model (FEM)-based stress analysis was conducted prior to plasmonic metamaterial design. The final product allowed for monitoring of drug (nicotine) concentration found in sweat, establishing a proof-of-concept continuous monitoring tool for personalized therapeutic medical applications. Despite these advancements, the potential of plasmonic metamaterials in wearable healthcare devices has not been fully realized yet. Furthermore, by employing an iterative transfer matrix approach to train an ML algorithm in evaluating the optical characteristics for a meta-plasmonic biosensor, a detection sensitivity 13 times greater than that of conventional designs was achieved.[66] Although the use of chiral plasmonic metamaterials in wearables is an area of active research, AI-based design strategies have significantly reduced computational costs for chiral plasmonics design. Moreover, to improve sensing of biomolecular enantiomers, an

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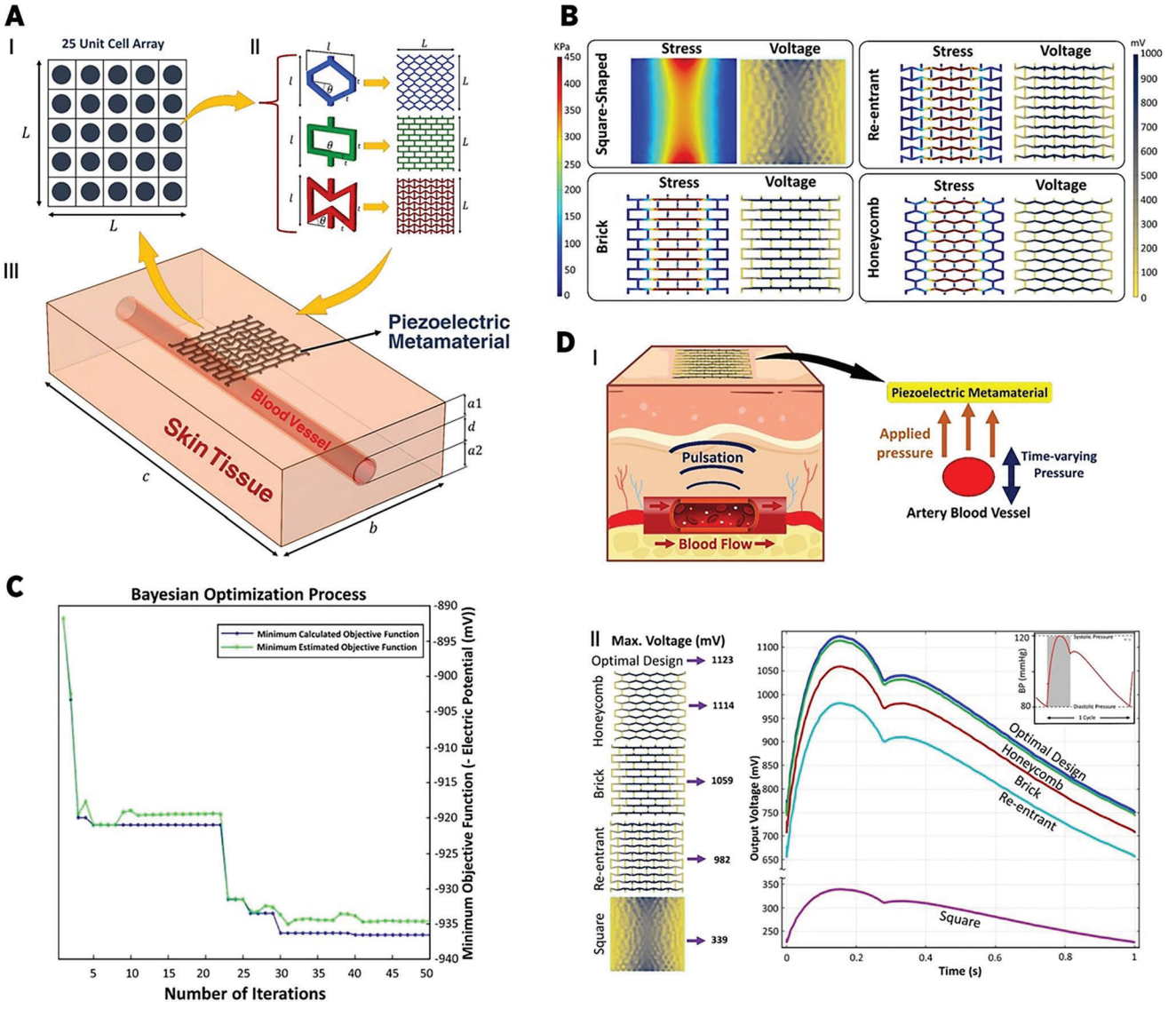


Figure 2. Piezoelectric metamaterial design for wearable arterial BP sensor. A) 3D Sensor simulation model. (I) Piezoelectric unit cell dimensions, (II) honeycomb, brick and reentrant models with variable angle unit of cell, θ, (III) sensor model on skin tissue model. B) Stress analysis and voltage simulation for square, re-entrant, brick, and honeycomb structures with Von Mises stress and electric voltage distributions. C) Maximization of output voltage using Bayesian optimization. D) Output voltage BP simulations. I) Schematic model for BP variation inside vessel, II) Diastolic and systolic BP and output electric voltage for square, re-entrant, brick, and honeycomb structures calculated using FEM. Adapted with permission.[61] Copyright 2023, American Chemical Society.

end-to-end functional bidirectional deep-learning (DL) algorithm was implemented.[67] While this method required prior experimental or FEM-generated data set, the model was able to recognize, generalize, and detail chiroptical response of various metamaterial geometries, demonstrating high potential for wearable metamaterial design with enhanced functionalities.

Other strategies have also been employed to enable multimodal health monitoring using wearables. Overcoming complex fabrication demands, a low-cost high-precision semisolid extrusion (SSE)-based 3D-printed epifluidic electronic skin (e^3-skin) was developed to enable multimodal health surveillance (**Figure 3**).[68] Electrochemical sweat biosensors including glucose, alcohol, and pH sensors as well as vital sign tracking including temperature and pulse sensors were incorporated into the e^3-skin to allow for comprehensive and seamless health monitoring. Finite element analysis was employed to analyze deformation behavior and thereby enable reliable radial pulse monitoring when elastically stretched against a rigid body. Data collection of both vital signs and electrochemical analytes was coupled with ML to accurately (>90%) predict behavior response (i.e., inhibitory control) following alcohol intake. In addition to analyte monitoring and vital sign tracking, plasmonic metamaterials have been used to develop wearable electrocardiogram (ECG) sensors. For example plasmon-like textiles

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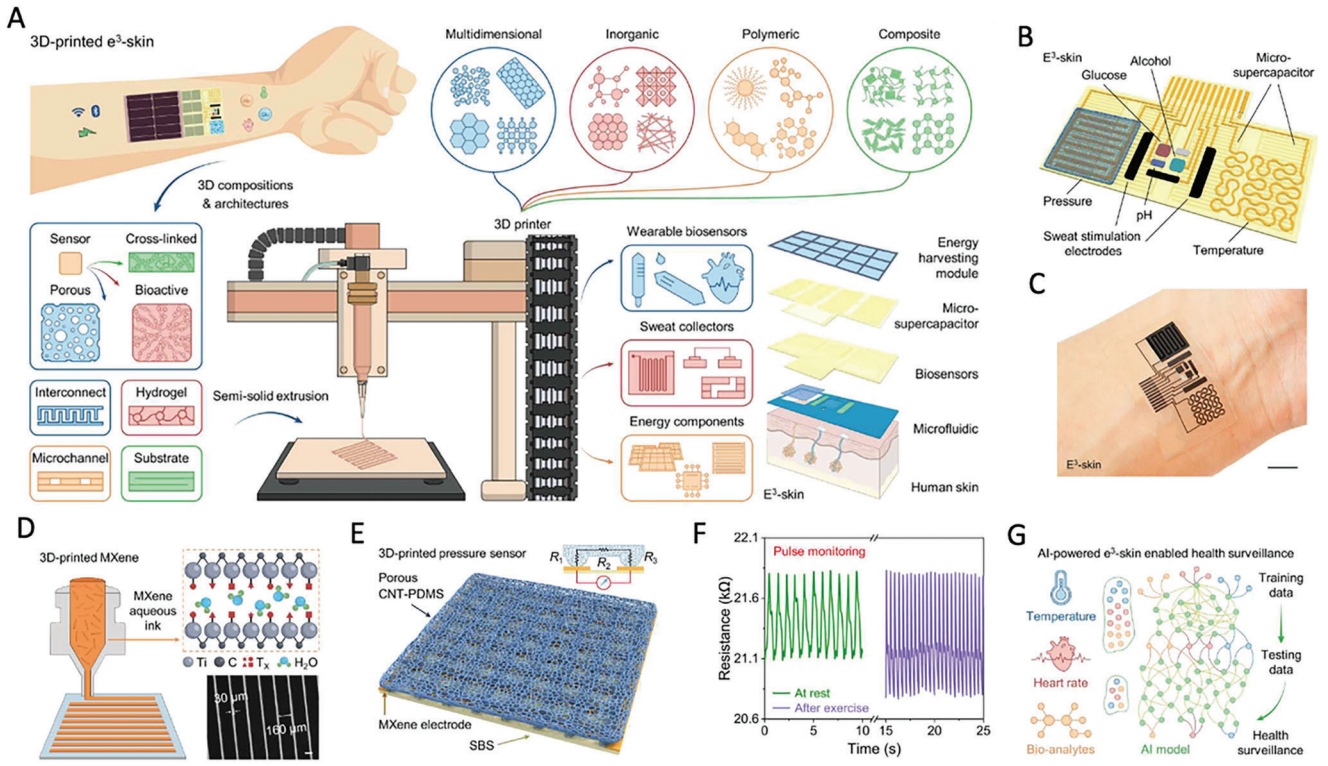


Figure 3. Schematic representation of e^3-skin. A) SSE-based 3D printed fabrication of e^3-skin using versatile and customizable inks. B) e^3-skin structure depicting biochemical and biophysical components that enable multimodal physiological monitoring. C) Optical image of fully assembled e^3-skin on human subject. D) 3D-printed MXene filaments of e^3-skin. E) Components and structure of 3D-printed pressure sensor. F) Human subject radial pulse monitoring at rest and post-exercise using pressure sensor. G) ML-based behavioral analysis system of e^3-skin. Adapted under the term of Creative Commons Attribution License 4.0 (CC BY).[68] Copyright 2023, The Authors, published by American Association for the Advancement of Science.

have been fabricated to act as wearable ECG sensors, enabling security in WBANs and allowing wireless power transfer.[69] The metamaterial design was achieved using a numerical optimization procedure and not only offered a threefold enhanced transmission efficiency but was also able to overcome energy-inefficiency, a major limitation of conventional WBANs. Similarly, auxetic metamaterials were used to construct skin-mounted ECG monitors and auxetic serpentine network hygroscopic wearable ECG sensors.[70,71] While expected PQRST wave response, prevention of skin irritation, noise reduction at long term use, and resistance to environmental factors was achieved, AI-based design can be utilized to further improve capabilities of metamaterial-based wearable ECG sensors. For example, a back propagation neural network (BPPN) was coupled with a genetic algorithm (GA) to introduce a data-driven countermeasure to optimize perforated auxetic metamaterial design.[72] Parameters of perforated auxetic metamaterial with peanut shaped pores impacting Poisson's ratio were identified as configuration (*a*), size (*b*), and length (*L*) and the model offered inverse design capabilities where parameters could be determined for any desired Poisson's ratio, thereby enabling rapid estimation of design parameters for desired characteristics of 2D metamaterials. Similar AI-driven models could be utilized for auxetic metamaterial design to achieve superior qualities through more efficient design processes.

3.2. Monitoring Movement and Sensory Parameters

For neurodegenerative and cerebrovascular disease patients, continuous health monitoring can drastically improve long-term disease progression, advance quality of life, and prevent complications by enabling early detection and timely intervention.[73–75] In this regard, various forms of wearable devices have been developed to allow continuous monitoring of movements, sleep, and relevant biomarkers.[76–79] Specifically, stretchable strain sensors have been used to detect motion and tremor, despite some limitations such as lack of uniformity or low sensitivity. Several strategies have been employed to overcome these limitations. For example, a self-powered strain sensor-based wearable device has been developed using piezo-transmittance and auxetic structure to monitor human motion, achieving high uniformity.[80] Alternatively, a conductive single-wall carbon nanotube network on polydimethylsiloxane (PDMS) thin film with a PDMS auxetic frame was used to reduce structural Poisson's ratio for a wearable motion sensor and demonstrated 24-fold higher sensitivity and high cyclic duration compared to other stretchable strain sensors.[21] The causal relationship between the mechanical properties of metamaterials under deformation and functional properties of stretchable electronics were also demonstrated, suggesting that enhanced mechanical properties of metamaterials can drastically transform capabilities of

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wearable sensors. To improve or alter mechanical properties of metamaterials, AI-based strategies can be employed.

For instance, using Bayesian optimization brittle polymers were fabricated at different length scales to produce recoverable and supercompressible materials (**Figure 4**A).[81] By reducing time spent on experimental validation, the strategy has allowed the exploration of new avenues in metamaterial design. Other strategies have also been employed to achieve metamaterial designs with enhanced functionalities. Novel microfibril design was validated using Bayesian optimization and FEM to generate optimally adhesive microfibrils, revealing ML-derived optimal structures.[82] Alternatively, efficient mechanical metamaterial actuators were designed using a deep neural network trained to identify functional regions of structures.[34] New structures were also generated using a Monte Carlo method without soft modes, thereby eliminating the need to impose restrictions and enabling the assessment of a wider phase space. Alternatively, a combination of computational algorithms and a four-tile DL model were used to predict unusual combinations of properties (such as double-auxetic yet stiff models) of multimaterial mechanical metamaterials, allowing the exploration of various design requirements with a wide range of elastic properties (Figure 4B).[83] By integrating such computational strategies into design processes, higher functionality has been achieved for various applications and similar strategies can be applied for wearable metamaterial sensor design processes.

In addition to motion sensors, wearable tactile sensors have also been developed using stretchable, flexible, or auxetic metamaterials to overcome limitations (such as limited range or lower sensitivity) of conventional sensors. Traditionally, tactile sensors have aimed to sense various types of mechanical stimuli such as pressure, strain, shear, and vibration to mimic slow and fast adapting skin receptors (i.e., Meissner, Merkel, or Pacinian corpuscles).[84] The ability to differentiate between mechanical stimuli using artificial textiles or skin-like wearables can significantly improve the quality of life for amputees or skin-damaged patients.[85] Such developments can also restore sensory feedback mechanisms when embedded in prosthetic devices. In this regard, numerous bio-inspired tactile wearable sensors have been developed. Some examples include, threshold switching memristors that have been used to mimic key nociceptor adaptations like threshold or sensitization phenomena,[86] wearable ultra-thing tactile sensors with pseudocapacitive motion detecting capabilities that can be worn for extended periods of time.[87] Moreover, a human skin-inspired multi-layer heterogeneous multilayered structure was developed using flexible mechanical metamaterials to exhibit locking behavior based on force sensing ranges.[88] The model achieved multiple sensitivities at various force ranges using a magnetic field-based transduction strategy. Employing another approach, a force-sensing joint wearable with an embedded electromyogram (EMG) sensor was fabricated using a soft auxetic metamaterial array and metamaterial capacitive sensor.[89] Alternatively, fractal metamaterials were designed using experimental, hierarchical theoretical, and FEM models as well as an automatic design tool for 3D printing, achieving 360% stretchability.[90] Hopfield network encoded neuromorphic metamaterials have been used to develop a system with mechanosensing and simultaneous learning abilities, further increasing the capabilities of tactile sensors.[91] Although arbitrary force range sensing,[88] increased compliance and conformity to curved surfaces,[89] bionic-stress matching and imperfection insensitivity[90] were achieved using conventional design strategies, AI-based design optimization has not been explored thoroughly for wearable tactile sensors despite attracting attention in other fields. For example, to enable faster multi-dimensional problem analysis, a hybrid ML and FEM-based flexible metamaterial design process was developed to construct operational insect wings.[92] An inverse design framework utilizing Spearman correlation analysis and ML regression models was developed and a thin-walled flexible unit with exceptional stress recovery, load carrying, and energy absorption qualities were generated.[93] As such, wearable sensor design can greatly benefit from similar strategies to better control design parameters.

4. Challenges & Future Directions

Metamaterials designed using AI-based tools can easily outperform those created using bio-inspired or human intuition-based approaches. Utilization of AI-based strategies in metamaterial design can help develop optimal structures for wearable sensors, advancing user satisfaction, increasing sensitivity, and improving functionally. However, several challenges have to be considered when using AI-based strategies in metamaterial design (**Table 2**). Large data sets and sometimes data preprocessing are required to train many AI based algorithms.[94] To overcome this limitation, DL-based methods can be utilized.[95] Alternatively, a system identification step using few sample responses to collect data required for the ML step can be employed.[96] However, these, especially DL-based strategies can limit scalability as they are often characterized by complex architecture. Besides data requirements, AI-based metamaterial design can involve highly complex design spaces to support numerous design variables, which can result in high computational costs. To address this, an AI-based approach has employed dimensionality reduction techniques using a pseudoencoder, reducing computational time significantly.[97] Another important challenge associated AI-based metamaterial design is fabrication constraints. While AI-driven metamaterial designs might appear superior to conventional ones, high complexity at fabrication can limit applications. Moreover, manufacturing limitations should be considered in order to develop functional metamaterial design. Finally, cost effectiveness, long term reliability, maintenance requirements, and integration with existing systems should be considered at wearable metamaterial design.

While challenges remain, capitalizing on novel algorithms and models, AI-based metamaterial design frameworks can prove useful in many application domains in healthcare and medicine (Figure 1C). Moreover, wearable wireless sensors can be designed particularly for neonatal intensive care units (NICUs) to embody multiple functionalities (vital sign, ECG, analyte monitors) without compromising on accuracy and user-experience (for premature newborns).[98,99] Besides NICU applications, metamaterials have recently been used to construct cochlear implant models with a wide audible range compared to conventional models.[100] For such models, AI-based optimization can significantly enhance functionalities and facilitate reconstruction of natural hearing. Alternatively, AI-based metamaterial design can allow sensors to achieve

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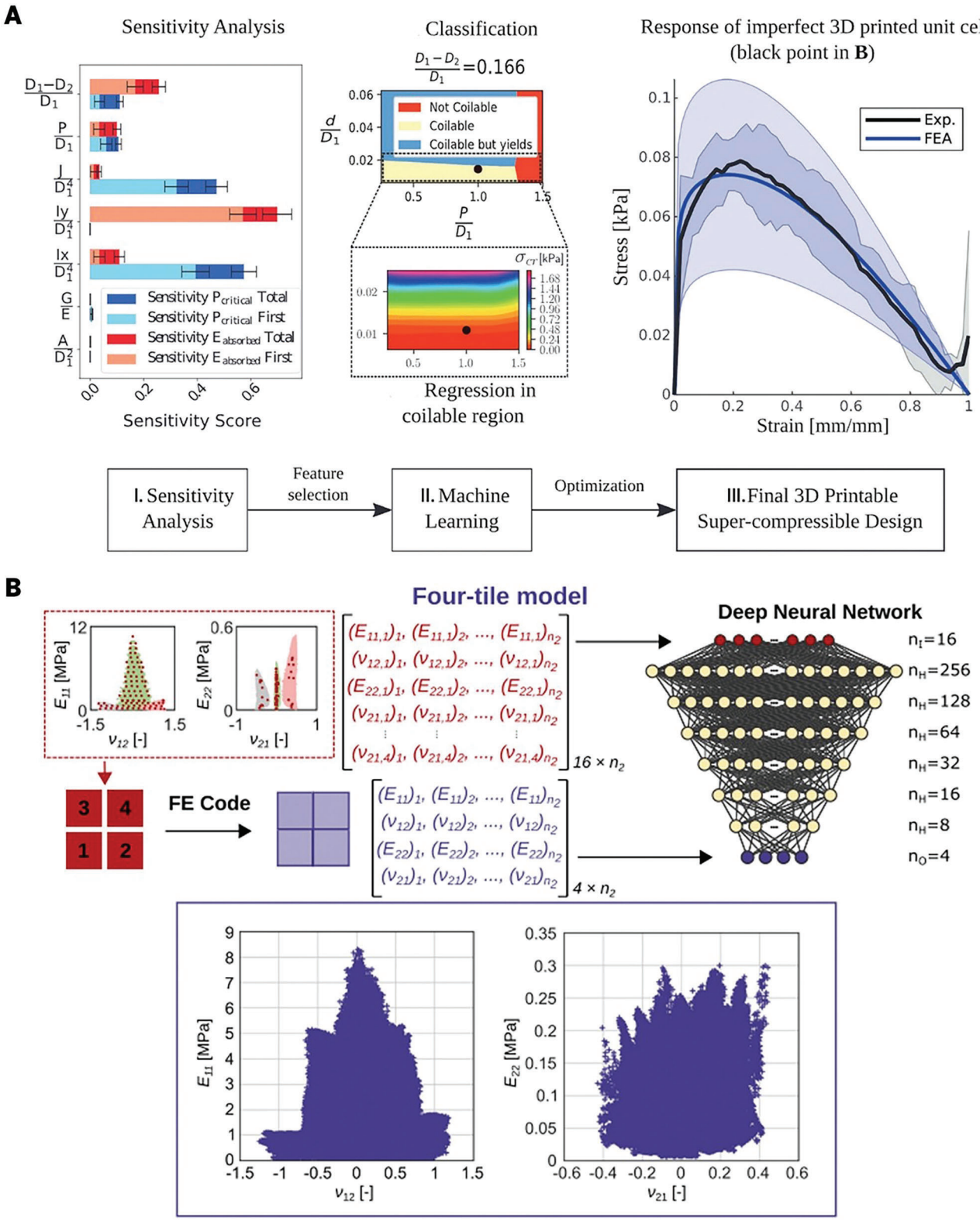


Figure 4. AI-based metamaterial design strategies to develop A) fully recoverable, super-compressible (100%) metamaterials. Adapted under the term of Creative Commons Attribution License 4.0 (CC BY).[81] Copyright 2019, the Authors, published by Wiley-VCH. B) multi-material metamaterial lattice structures using DL. Adapted under the term of Creative Commons Attribution 4.0 International License.[83] Copyright 2022, The Authors, published by SpringerNature.

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Table 2. Current challenges for AI-based metamaterial design strategies for wearable sensors and potential solutions are listed.

	Challenges	Potential Solutions	Ref.
AI-based design	Large data sets may require extensive data preprocessing	DL-based methods	[94–96]
	Complex design spaces can increase computational costs	Dimensionality reduction techniques	[97]
Fabrication	Potential discrepancy between structural assumption and performance	Alterations on assembly strategies	[37, 106]
	Scaling challenges (potential metamaterial function alteration when drastically scaled up)	Composites of multiple metamaterials to achieve desired function	[37]
	Complex or multi-step fabrication demands	3D printing applications	[68]

major goals of assistive robotics. Furthermore, metamaterials have already been used to enable grasping motions for different objects through mechanical metamaterial sensing, improve user comfort with auxetic metamaterials, and develop artificial skin sensation pathways composed of tactile sensors.[101–103] These functionalities can be improved further using more optimized metamaterial-based sensors and facilitate fully-functional neural interfaces for prosthetics. In addition to NICU-specific applications, hearing aids, and assistive robotics, AI-based metamaterial design can also improve applications in personalized medicine. For example, novel approaches to personalized drug delivery using an acoustic metamaterial-based transdermal pharmaceutical monitoring and controlled drug delivery[104] and contactless wound monitoring through intelligent bandages[105] have been developed recently. Improvements as well as potential commercialization of such models can be achieved using AI-designed metamaterials by rapidly refining desired qualities of materials.

5. Conclusion

Wearable health sensors have become an integral part of continuous health monitoring. As well as improving user experience, the use of metamaterials in wearables has expanded the functionality of sensors significantly. AI-based design of metamaterials can enable wearable health sensors to achieve their highest potential by facilitating optimal design parameters. Using AI-based metamaterial design, wearable health sensors can be used in a multitude of applications including NICU sensors, cochlear implants, assistive robotics, and personalized medicine.

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Conflict of Interest

The authors declare no conflict of interest.

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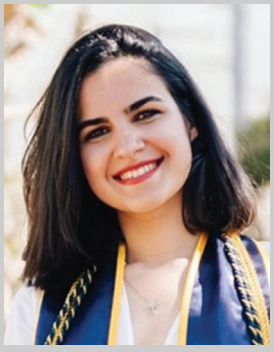
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