REVIEW ARTICLE

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A Brief review on metamaterials applied to the healthcare field

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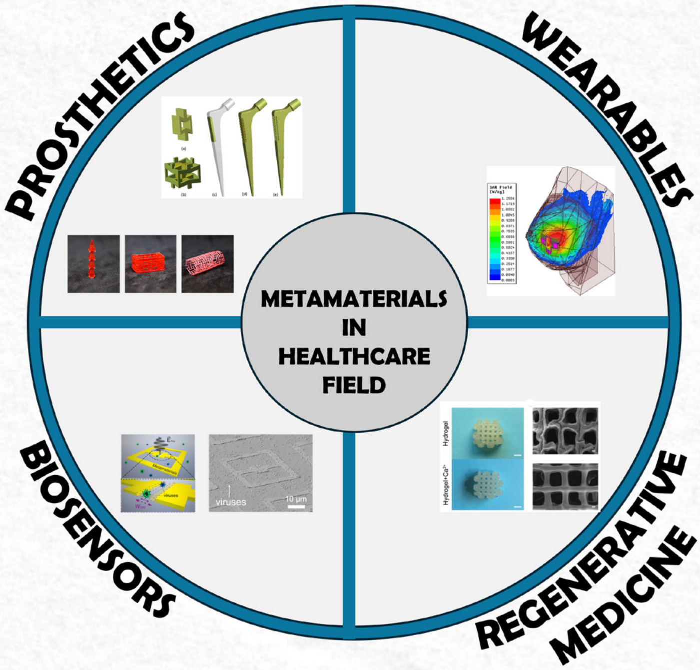

Abstract: Metamaterials refer to any modification of the physical behavior of an existing material through the structured arrangement of repetitive patterns, procedurally generated, which can directly influence its response to deformation, thermal dissipation, and vibrational control. This creates possibilities for solutions that were previously difficult to achieve using conventional materials such as metals, ceramics, polymers, and their composites. The use of this technology has gained momentum with the advent of 3D printing, which has made it possible to apply and create these structures for practical validation. The first structures were modeled at the beginning of the last century, such as the creation of patterns to generate anomalous properties, with diverse applications in fields like optics, thermodynamics, and mechanics, as it allows for material design tailored to specific applications. As a result, applications have expanded to various scales, from millimeter-engineered materials to the nanoscale, drawing the attention of researchers from different fields, including healthcare. This interest stems from the vast array of possibilities and innovations driven by advancements in materials and additive manufacturing, combining these fields to generate increasingly adaptive solutions. In this paper, the concept of metamaterials will be introduced, followed by an exploration of various applications of this technology, including medical equipment, devices, prosthetics, orthotics, and implants, as well as potential future applications of this technology in healthcare.

Keywords: Metamaterials. 3D Printing. Advanced Healthcare. Advanced Materials.

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Introduction

Metamaterials can be characterized as artificial materials with distinct properties not found in conventional materials, specifically designed to perform targeted functions(1). The first documented study on the development of this type of material was conducted in 1898 by Jagadis Chunder Bose, a physicist researching electromagnetism. Bose proposed the creation of a material with repetitive helix-shaped structures that could modify the behavior of microwaves(2). This theory laid the foundation for the basic concept of characterizing a metamaterial: the presence of a repetitive structure with a unitary geometry, arranged throughout the model, specifically designed to alter the behavior of a physical property.

Following these theories, new applications emerged, gradually attracting researchers from various fields of physics, who applied the principles of structured materials to phenomena such as deformation control and the manipulation of other types of waves, such as light, sound, and thermal flows(3). However, the complexity of these structures made them difficult to manufacture, which delayed the practical application of metamaterials until the early 21st century. The resurgence was driven by the advent and popularization of 3D printing, which allowed for greater design freedom, enabling the first metamaterial cells to move from theoretical models to physical prototypes, validated through practical testing.

General Classification of Metamaterial

Metamaterials can be subdivided according to their application(4), including thermal, electromagnetic, mechanical, and acoustic categories. In general, their properties involve generating a response characterized by negative coefficients, leading to unnatural behaviors. An example is auxetic materials, which expand along multiple axes without a reduction in cross-section, due to the distribution of deformation through specifically designed cells within the material(5)(6).

Another fundamental classification pertains to the number of axes in which the unit cell is present in the material(7) which can be in two-dimensional (planar), or three-dimensional (Figure 1).

For electromagnetic metamaterials, also could be classified by Permittivity (ε) a fundamental electrical property that describes a material's ability to polarize in response to an applied electric field. Simply put, this property indicates how easily a material can be polarized, leading to the formation of electric dipoles and by magnetic permeability (μ), a magnetic property that defines a material's ability to magnetize under the influence of an applied magnetic field. This characteristic reflects the ease with which magnetic dipoles can form within the material(8)

The combined analysis of ε and μ enables the classification of materials into four distinct categories, represented by quadrants in a Cartesian graph(9). In this context, the values of ε and μ define the electromagnetic properties and specific behaviors of each class:

Quadrant I ($\varepsilon>0$, $\mu>0$): Represents conventional materials, encompassing most naturally occurring substances.

Quadrant II ($\varepsilon<0$, $\mu>0$): Includes metamaterials with a negative refractive index, known for unique phenomena such as negative refraction and perfect focusing.

Quadrant III ($\varepsilon<0$, $\mu<0$): Comprises another type of metamaterial with a negative refractive index, exhibiting properties similar to those in Quadrant II.

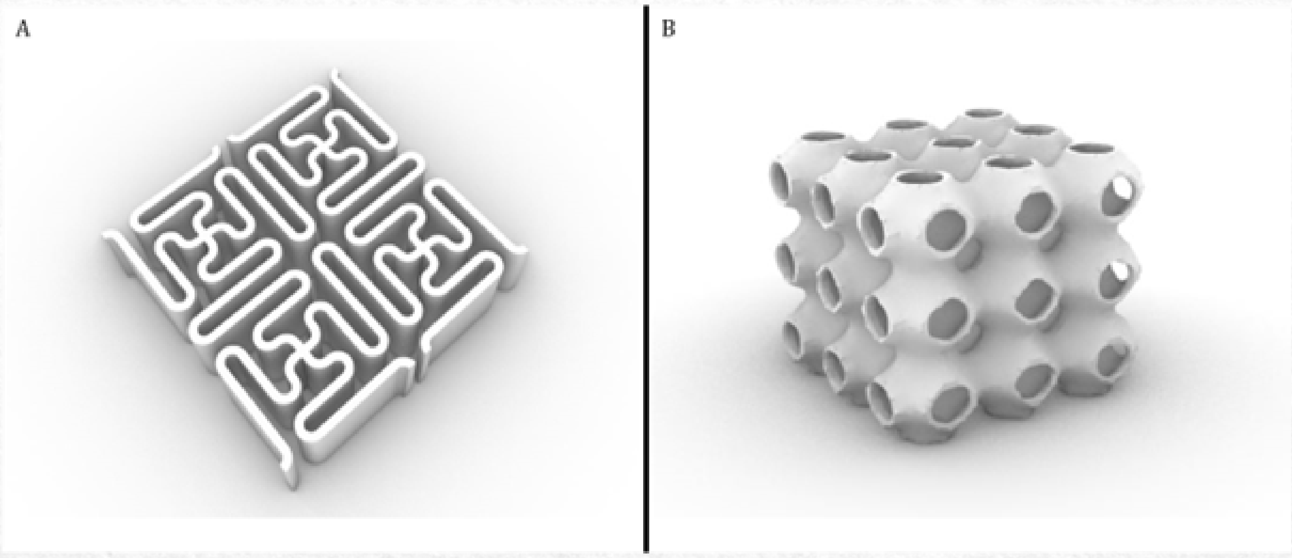

Figure 1 - Representation of different cellular configuration types, A planar cell and B a 3D cell.
Source: Author

Quadrant IV (ε>0, μ<0): Contains metamaterials that are less explored but show significant potential for specific applications.

In addition to classifying materials, the values of ε and μ are directly related to various physical quantities that influence the behavior of electromagnetic waves. For instance, the refractive index of a material is determined by these two parameters, with metamaterials located in Quadrants II and III exhibiting a negative refractive index, enabling phenomena such as anomalous refraction(10). The impedance of a material, which establishes the relationship between the electric and magnetic fields of an electromagnetic wave, is also significantly influenced by ε and μ. Furthermore, the phase velocity of an electromagnetic wave in a medium depends directly on these values. In metamaterials with a negative refractive index, the phase velocity may become negative, resulting in counterintuitive properties.

This framework for classification and analysis provides a robust theoretical basis for studying and developing advanced materials with engineered electromagnetic properties. Metamaterials have revolutionized fields such as optics, telecommunications, and energy, enabling the emergence of innovative applications and cutting-edge technologies(11)

Thermal Metamaterials

Natural materials typically exhibit isotropic properties regarding their thermal dissipation behavior (12), meaning that all portions of a material dissipate thermal energy uniformly throughout its volume. Thermal metamaterials are designed to modify this isotropic behavior into a controlled anisotropic response(13), enabling the internal heat flow of a piece to be altered through the arrangement of the material's internal structures, such as the behavior seen in carbon nanotubes.

Examples of functionalities for this type of material include thermal filters(14), structures that facilitate the flow of specific bands of thermal radiation through an insulating medium, enhancing the efficiency of thermosensitive devices such as certain categories of solar panels. These structures typically consist of stacked plates made from two or more materials, creating patterns that, under the effect of heating, allow the selection of the wavelength spectrum that can pass through the assembly.

Other possibilities include flow control structures(15), which regulate thermal dissipation to maintain the functionality of temperature-sensitive components, such as electronic or optical devices (16), preventing overheating or enabling their use in harsh conditions.

Lastly, there are metamaterials with shape memory properties, where heat alters their structure. An example is engineered polymers, which deliberately change their form to selectively modify the behavior of lenses(17).

Electromagnetic Metamaterials

The primary function of electromagnetic metamaterials is to modify behaviors related to electromagnetism, enabling the alteration of electromagnetic fields and wave behavior by manipulating two fundamental physical principles: electromagnetic permittivity and permeability(18). These properties describe how a material is affected by an electromagnetic field and how it responds to magnetization. Such control allows the replication of the functionality of well-known devices, such as antennas and satellites, at much smaller scales, reducing the number of components required for their operation(19).

Among the applications are electromagnetic filters(20), which block the propagation of specific wave sizes, thereby enhancing the efficiency of sensors and electromagnetic induction devices, such as fast-charging batteries. In addition to filters, metamaterials can be designed to absorb(21) or reflect electromagnetic fields(22), making them useful in creating barriers and protective shields, especially for high-power field applications, such as MRI machines and other medical imaging devices.

Optical Metamaterials

Optical metamaterials can be considered a variation of electromagnetic metamaterials, as they fundamentally aim to alter the natural behavior of materials concerning their interaction with waves. However, in this case, the waves pertain to light and its emission spectra, such as infrared, ultraviolet, and others(23). To achieve this, the refractive and absorption coefficients of the material are manipulated.

Applications in this category include the selective variation of focal points(24), which allows for the creation of multifocal or controlled monofocal points, even in flat lenses. This technology can produce more effective and compact lasers, color filters (25) that block specific light spectra to reduce interference in optical sensors, and cloaking cells(26), which are designed to deform light projected onto an object. These cells function as a form of camouflage by bending light to create an illusion of transparency, preventing direct interaction with the light and allowing visibility of what lies behind the object.

Mechanical Metamaterials

Mechanical metamaterials exhibit significant variation from the principles of operation of other metamaterials, as they generally work with structures at the millimeter scale. This is because they aim to modify properties more related to material deformation and stiffness(27), thus, their unit cells do not need to be as small as those of other metamaterials, which must be produced at the same scale as the phenomena they are designed to interact with(28).

Among the applications are auxetic cells(29), which alter deformation behavior, create impact-resistant structures(30), controlled points of elastic deformation for the generation of hinges, and adaptive structures(31) that facilitate the biomechanical interaction of prosthetics and orthotics(32).

In addition to auxetic properties, these materials can exhibit other interesting behaviors, such as shape memory(33), which allows for the creation of predetermined patterns that change in response to applied forces. This capability enables the development of self-compensating structures and stress converters that, like auxetics, manipulate the forces acting on the material to cancel stress dissipation through inversion. This is achieved by employing structures with variable stiffness points through the combination of independent plates(34).

Acoustic Metamaterials

Similar to mechanical metamaterials, this category operates on the principle of varying responses to deformation and stiffness(35). However, the application of their cells focuses on the control, modulation, cancellation, and amplification of sound waves, utilizing variations in the vibration patterns of the components to manipulate sound wave propagation in space(36). This capability allows for directing sound toward a specific point or altering its amplitude to change the frequency through the vibrations of the metamaterial cell itself, as well as isolating frequencies to prevent distortion in sensors.

Examples of applications include acoustic lenses(37), which can generate directed pulses of vibration to focus the action of sound waves, much like a lens does for a light beam. This prevents dispersion and enhances precision, and this characteristic can be replicated across various frequency ranges, improving the quality of sensors that utilize sound waves, such as ultrasound machines and echography devices.

In terms of modulation, acoustic metamaterials can produce absorbers and acoustic filters(38) that cancel or impede the transmission of noise, reducing interference and enhancing the sensitivity of devices that rely on sound to capture information, such as radars and other echolocation devices.

Metamaterials Applied in the Healthcare Field

As observed, despite the exploratory nature of this research, several interesting applications for this technology can already be identified, particularly in newer areas such as wearables, adaptable and intelligent prosthetics, biosensors, cellular scaffolds, and other implantable devices(39).

In the realm of wearables, examples include equipment for real-time monitoring of biological signals(40). These devices serve to monitor critically ill patients, potentially reducing the response time of medical teams, as well as tracking patients with chronic conditions such as diabetes, arrhythmia, and other diseases requiring continuous treatment, or to detect illness in a more efficient way, like exams breast cancer(41), exemplified in the Figure 2.

This kind of devices present groundbreaking advancements in healthcare and communication

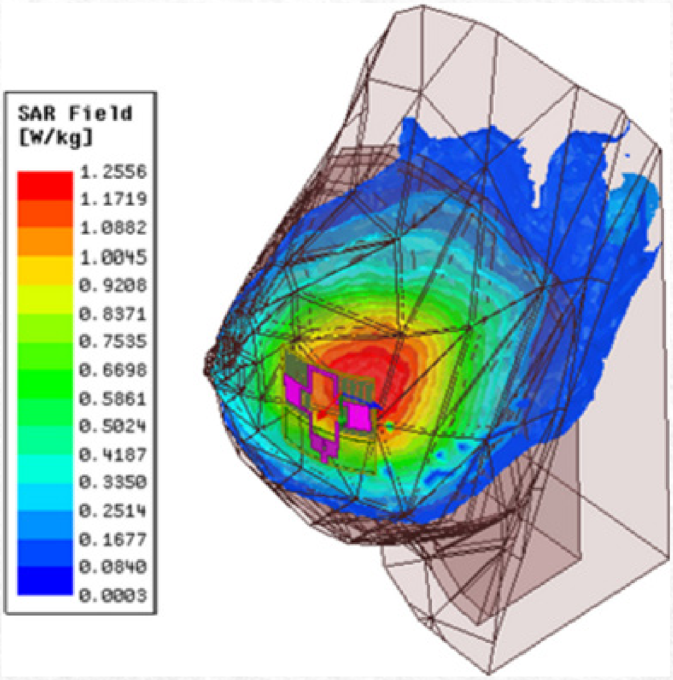

Figure 2 - SAR Field simulation of a bend metamaterial antenna for breast cancer detection. Source:(41)

systems. A notable development, for example, is a wearable pad inspired by metamaterials, designed to enhance the coupling of electromagnetic radiation with biological tissues at 2.4 GHz(42). Another application in the safe field is a dielectric metamaterial pad that significantly improves signal penetration in biological tissues, achieving over a 4 dB increase, thus offering a practical solution for diagnostic and therapeutic medical systems.

For transmission specifically, novel metamaterial-based antennas and sensors for 5G, 6G, IoT, and medical devices exhibit compact, broadband, and cost-effective designs(43), generating fractal geometries and CSRR structures enhance performance and energy efficiency, highlighting metamaterials' pivotal role in developing eco-friendly, self-powered wearables for advanced healthcare and communication systems.

Besides the studies in the modifications of electromagnetic fields, to improve the efficiency of wearables, the use of artificial intelligence (A.I) was being applied to explore new solutions in the use of metamaterials in this filed, for example, using a AI-driven methodologies to optimizes wearable sensors, enabling rapid exploration of design parameters and enhancing sensitivity, weight, and usability. These approaches facilitate applications in neonatal intensive care, assistive robotics, and personalized medicine(44).

In terms of applications for prosthetics, metamaterials contribute to the development of prostheses with varied mechanical properties that adapt to the stresses encountered in the model, like natural bone(45) or improve the comportment of stress distribution(46), exemplified in Figure 3 and Figure 4 respectively.

This modulation allows for the identification of diverse mechanical properties, minimizing phenomena such as stress shielding(47), which occurs when metallic materials with higher elastic modulus capture stress on bones, leading to localized bone fragility(48). Additionally, techniques such as texturing can enhance the integration of the prosthesis with bone(49), and the incorporation of drug or bioactive material deposition points(50), can reduce rejection by the immune system and prevent infections(51).

Still in the field of prosthetics, we can highlight more specific applications, like the use of metamaterials to develop biomimetic tendons and other soft tissues(52).

Figure 3 - Application of metamaterials in the field of prosthetics and implants. Source: (45)

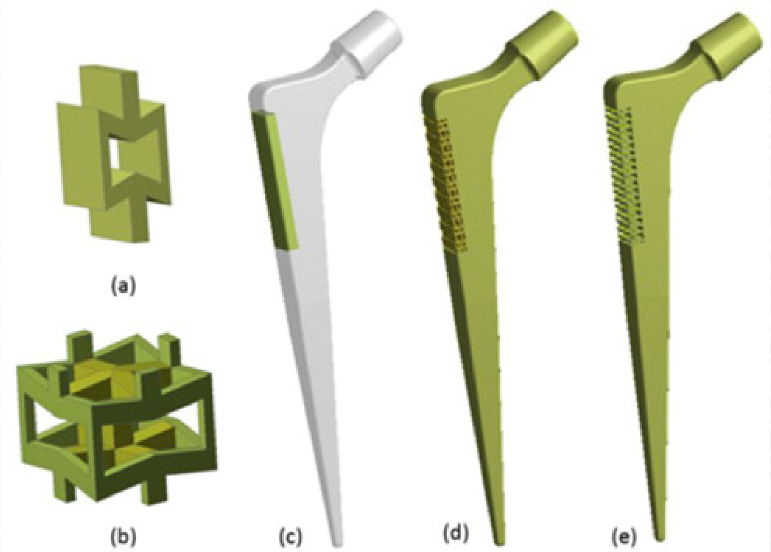

Figure 4 - Application of mechanical metamaterial cell for improving load transfer at proximal-lateral region of the femur. Source: (46).

This technology enables the creation of synthetic fibers made from polymers, and through engineered cell design, it alters deformation behavior to closely resemble that of muscular tissue. This capability allows for the replacement of damaged tendons and cartilage, promoting recovery for athletes and accident victims while avoiding the removal of healthy tissue. These synthetic fibers can be implanted alongside the patient's tissue, functioning as grafts.

Focusing on the use of 3D printing, it can be employed for the use of metamaterials for improve the osseointegration in 3D-printed implant screws, which are typically metallic, used frequently in orthopedics(53). These screws often cause "stress shielding" and postoperative loosening, impacting long-term fixation(54). To address these issues, some strategies could be used like voronoi and other lattice structured materials(55), such as Fischer-Koch S, Octet, Diamond, and Double Gyroid. These porous structures help reduce "stress shielding." Furthermore, bone regeneration on the surface of the screws has increased by a factor of 1 to 50, enhancing the integration between the screw and the bone tissue(56), Figure 5, show some of the cells applied in the implant.

Other materials, such as polymers, can also be utilized in this prosthetic filed. When combined with techniques like topological optimization, they can create solutions such as the dynamic topological optimization of a transtibial orthopedic implant, 3D printed with adjustable isotropic porous metamaterials, to improve the weight-bearing capacity of the bone structures in the residual limb allowing the implant to withstand varying forces during the gait cycle, enhancing its functionality and adaptability(57).

Beside the use for internal prosthetics, the use of metamaterial could be extended to limb substitution, like the use for development of a prosthetic liners for residual limbs to improve comfort and stability, ensuring better load distribution(58) and the use of cellular auxetic mechanical metamaterials to create flexible joints in soft robotic hands, inspired by human finger joints, offering adjustable stiffness and large bending angles(59), showed in Figure 6.

In the field of biosensors, metamaterials play a crucial role in developing rapid, compact, and more efficient tests through the creation of nanosensors capable of detecting the presence of specific molecules. These sensors can identify viruses and other pathogenic agents(60), as well as proteins and enzymes in blood(61). This represents an advancement over conventional tests, as they require significantly smaller quantities of material for detection, making the tests more reliable, quicker, and reducing patient discomfort (Figure 7).

At last, in the field of regenerative medicine, metamaterials are being applied in tissue scaffolds, creating structures that promote tissue differentiation and facilitate interaction and maturation among cells(62). Through planned structuring, these scaffolds enable the development of bioabsorbable structures with temporary support, allowing the desired tissue to form. They serve as a framework for spheroids(63), which, upon maturation, completely absorb the scaffold, leaving only the newly formed tissue in place (Figure 8).

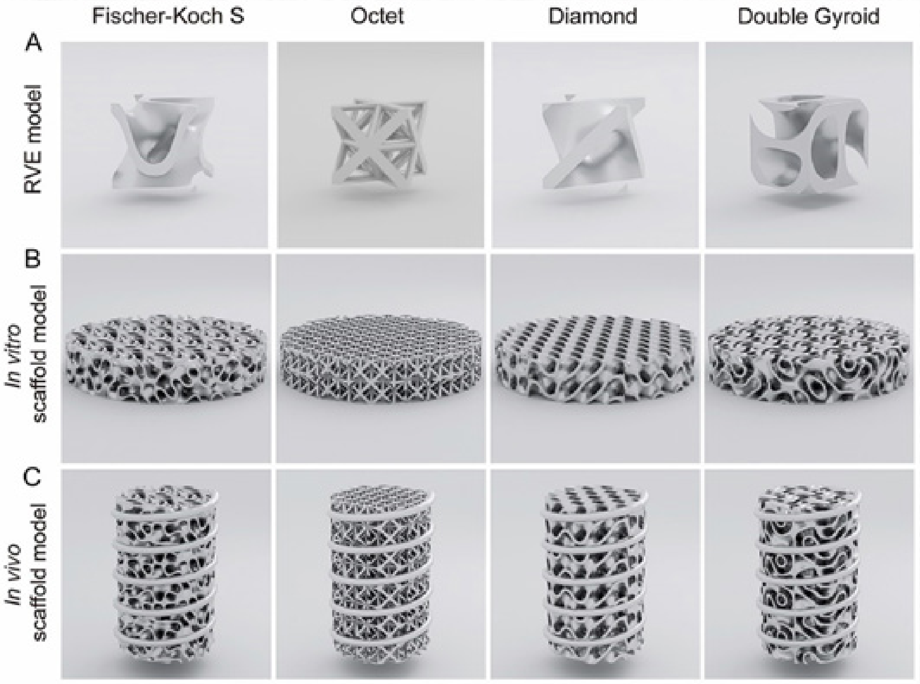

Figure 5 – Mechanical metamaterial cells applied in bone implant to increase osseointegration. Source(56).

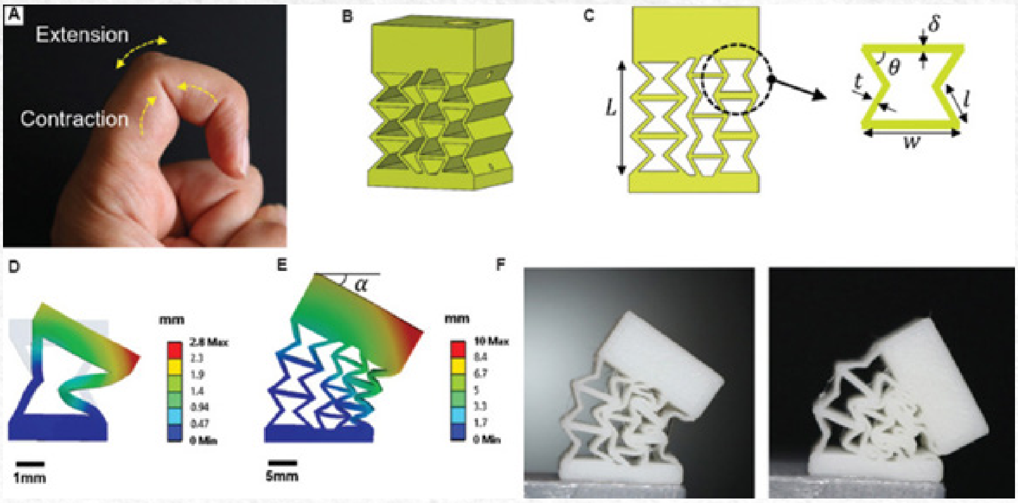

Figure 6 – Metamaterial joint for a soft robot prosthetic hand. Source:(59)

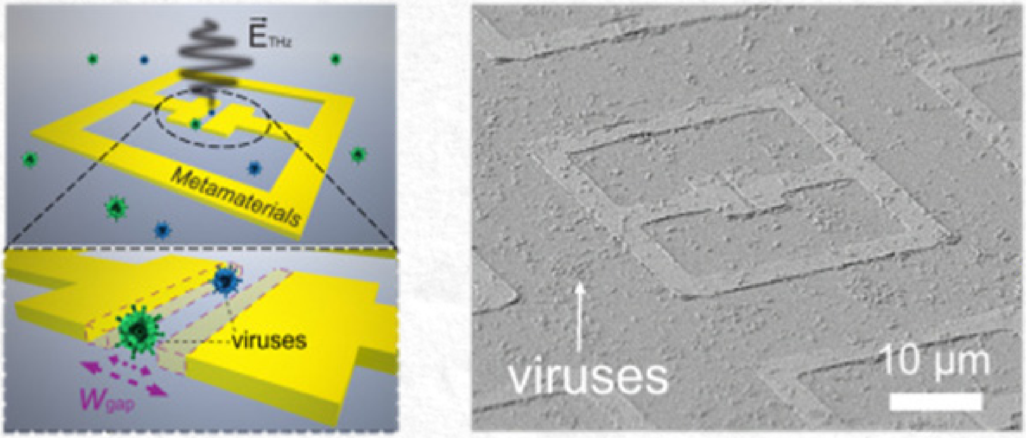

Figure 7 - Application of metamaterials in biosensors virus identification. Source: (60)

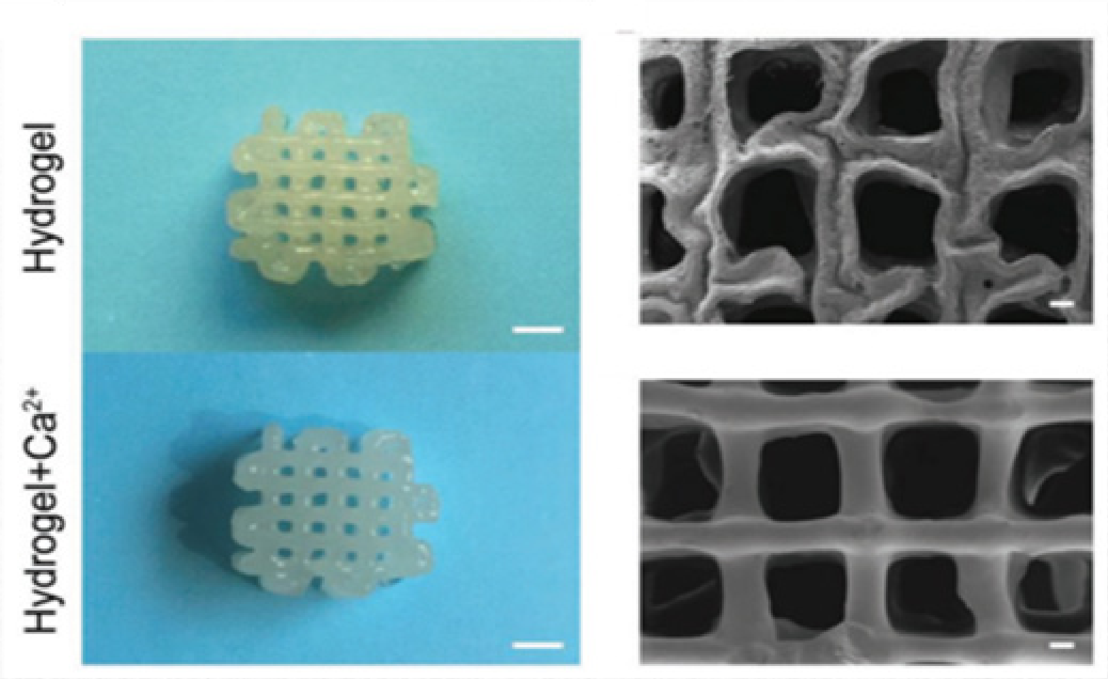

Figure 8 - Application of metamaterials in tissue scaffolds. Source: (63)

Conclusion

The great potential for advancement in the use of metamaterials is certainly enhanced by the popularization of the use of three-dimensional printing technology, with the healthcare sector being a great entry possibility for this type of technology, largely due to its multidisciplinary nature. The use of metamaterials is undoubtedly transformative, due to its capability to develop personalized solutions and improve the adaptability of materials applications, with lead to a great advantage in detriment of other solutions, in terms modification and adaptability.

However, its widespread adoption faces significant challenges, especially in terms of scalability, due to the manufacturing complexity and costs associated with using disruptive technology such as 3D printing. While these technologies hold immense promise, enabling advancements such as personalized prosthetics, real-time monitoring devices, and rapid pathogen detection, translating them into accessible and economically viable solutions remains a considerable hurdle. Addressing these barriers will require ongoing innovation in manufacturing processes and strategic investment. Despite these challenges, the trajectory of these technologies suggests a future where their integration into healthcare systems becomes not only feasible but indispensable, offering profound improvements in patient care and quality of life.

This progress will enhance our longevity and quality of life, aligning with contemporary measures and the integration of information technology into daily life. It represents a natural evolution of existing equipment, such as probes, smartwatches, rapid tests, and other devices.

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Declarations

Conflict of Interest

All authors declare no conflict of interests.

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