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SURVEY

Design, Analysis and Applications of Wearable Antennas: A Review

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ABSTRACT Wearable antennas are the vital components for Body Centric Communication (BCC). These antennas have recently gained the attention of researchers and have received a great deal of popularity due to their attractive characteristics and opportunities. They are fundamental in the Wireless Body Area Networks (WBANs) for health care, military, sports, and identification purposes. Compared to traditional antennas, these antennas work in close proximity to the human body, so their performance in terms of return loss, gain, directivity, bandwidth, radiation pattern, efficiency, and Specific Absorption Rate (SAR) is influenced by the coupling and absorption of the human body tissues. Additionally, in the design of these antennas, size, power consumption, and speed can also play a paramount role. In most cases, these antennas are integrated into the clothes, or in some cases, they may be fixed over the skin of the users. When these characteristics are considered, the design of wearable antennas becomes challenging, particularly when textile materials are examined, high conductivity materials are used during the manufacturing process, and various deformation scenarios have an impact on the design's performance. To enhance the overall performance of the wearable antennas and to reduce the backward radiation towards the human body, metamaterial surfaces are introduced that provide a high degree of isolation from the human body and significantly reduce the SAR. This paper discusses the state-of-the-art wearable/textile/flexible antennas integrated with metamaterial structures composed of wearable/flexible substrate materials, with a focus on single and dual band antenna designs. The paper also reviews the critical design issues, various fabrication techniques, and other factors that need to be considered in the design of wearable/textile/flexible antennas. All the designs presented in this work are of the recent developments in wearable technology.

INDEX TERMS BCC, WBAN, SAR, metamaterial, wearable/textile/flexible antennas.

I. INTRODUCTION

Recently, Body Centric Wireless Communication (BCWC) has become one of the most important parts of the fourth generation (4G) mobile communication systems. The fifth generation (5G) is an encouraging technology which will not only fulfil the need of a high data rate for mobile phones and similar devices but also enable incorporation with different high added value services [1]. The IEEE 802.15 standardization group has been established to standardize applications intended for on, off, and in-body communication due to the growing interest in antennas and wave propagation for body centric communication systems [2]. BCWC is a type of communication which is used to connect devices

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which are worn on or in the body, or between the two people in close proximity. It is further divided into three different categories according to the mean of communication, they are on-body, in-body and off-body communication [3], [4], [5]. On-body communication describes the wireless communication between the body-mounted devices. In-body communication takes place between the base units or mobile devices that are nearby and the body-worn gadgets. The communication between on-body gadgets and medical implants is referred to as in-body communication [6]. Body worn wearable technologies have drawn significant research interest in the past decade because of their functionalities and abilities they can be used in a number of specialized fields that apply body centric communication systems such as in health care industry as a wearable tool to detect the vital health problems of the patients, recovery rooms, clinics, operations theatres, homes, and even on the move. Besides, miniaturized antennas are used in military applications for camera and microphone module for the transmission of data [7]. Additionally, these antennas can also be used for youngster, aged persons, and athletes for the monitoring purpose. The typical applications of wearable antennas are portrayed in Fig. 1. A brief overview of these applications is summarized in Table 1. In order to connect these technologies to other data acquisition stations antennas are needed to be connected to these stations. To attain this, wearable antennas have attracted considerable attention and can play a paramount role in on-body centric communication and have gained more attention in research. These antennas are made up of wearable textile, flexible and fabric materials, and therefore, the characteristics of these materials are manipulated [9]. These antennas are so designed to enable communication to its source stations while worn on human body or when the users are moving.

TABLE 1. Summary of the applications of the wearable antennas [8].

Field	Applications
Medical/healthcare	Endoscopy, GPS trackers, glucose monitoring, breast cancer detection, wearable thermometers, patient monitoring, oximetry, and wearable Doppler units are all examples of wearable/textile antennas in medical health care.
Military/Rescue	Wearable antennas can be used in the bulletproof jacket of a soldier, which can be used to check the effectiveness of the bullet when the soldier is shot. Furthermore, it transmits the message via radio waves to the base to keep track of the fatigue of the piolet. Besides, they can be used in the battle field, smart cloths, and fire detection
Entertainment	Wearable devices can be used in smartwatches, LED dresses, music jackets, video disc and intelligent shoes.

Likewise, certain performance-based improvements are also mandatory to make a clear function characteristic of a body worn antenna. Since these antennas functions in the proximity of human body and due to the loading effect of the lossy human body make the design of these antennas more challenging. Thus, for suitability, these antennas need to be user friendly, durable, low-cost, low weight,

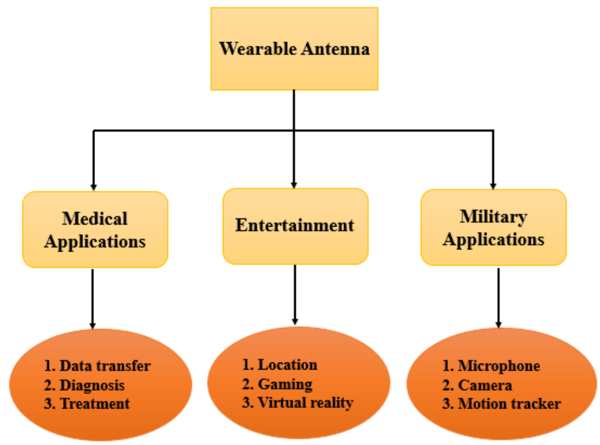


FIGURE 1. Overview of the applications of wearable antenna.

comfortable, maintenance free, compact, and require no installation, because the performance of the antenna changes when operates in the free-space and when placed on other places. Similarly, due to the absorption of water contents and the physical changes on human body will make a significant change in the overall performance of the antenna [10]. The variation in the design of these antennas depends on the operating range of frequencies, the strength of transmission and the environment in which the antenna operates. However, the overall performance of the antenna is totally dependent on the dielectric material used. For the design of the antenna the dielectric material characteristics in terms of its capability to adjust to severe circumstance such as bending, crumpling and stretching consequences, and conductive materials in terms of high tolerance to degradation due to mechanical deformation and resistance [11]. Furthermore, the design of wearable antennas need the understanding of electromagnetic properties of the material used on which the profile of the antenna generally depends on such as the permittivity, the loss tangent, and the thickness of the substrate used [12]. Wearable materials are generally the nonconductive and conductive textiles (electro-textile) Nonconductive textile material are usually used in the design of wearable antennas to reduce the weight and profile of the antenna such as felt [13], silk, nylon [14] and leather [15], wash cotton [16], Denim, Polymer, fleece and Paper are used as a substrate material [17], [18]. Besides, due to the low dielectric constant Jeans [19], and polyethylene terephthalate (PET) [20], are widely used wearable substrate materials. The conductive textile (e-textile) material which are designed by mixing the polymer threads or conductive metal with normal textiles. These conductive textiles material is Flectron [21], Zelt [22], pure copper [22], taffeta [24] and Sheildith [25]. These materials are flexible, and durable which are suitable for body worn application and has a significant contribution in the wearable context. The characteristics of conductive textiles are such that in order to minimize losses, they provide low and stable electrical resistance. To design a high-performance antenna system the substrate must be lightweight and flexible [26], [27]. There are several methods of finding the dielectric properties of textile material as reported for example in [28]. While designing these antennas it must be ensured that the radiator would not cause any adverse effect to the living bodies [29]. In the design wearable antenna, to make the antenna durable for a given applications the substrate selection is a crucial stage. Generally speaking, textiles have a very low dielectric constant, which lowers surface wave losses and broadens the antenna's impedance bandwidth [30]. The main issue in body worn antenna is the reliability of properties of across changing environment. It mainly addresses such as humidity, temperature and proximity of people as well as wash cycles etc. [31]. Likewise, when multiple wearable antennas/sensors are used in a specific application, the placement and distance between the sensors are the main factors to enhance the effectiveness of the system. For example in [32] the authors designed an UWB health monitoring system by using multiple wearable sensors at different positions and distances to classify/track various daily life activities leading to healthier lifestyle. In addition, most wearable antennas have linear polarization, and due to the human body movement polarization mismatches occur. The authors in [33] introduced a wearable pattern diversity dual polarized button-type antenna for on-/off body communication that is flexible in terms of application band, communication mode, and polarization state in order to reduce the polarization mismatch. The proposed work performs consistently under various bending and tilting circumstances.

Wearable antennas operate close to a lossy human body, which has an impact on the antenna's efficiency, driving point impedance, bandwidth, and gain. When electromagnetic waves are used for communication, some of the radiation is focused on the human body, passes through the skin, and is absorbed by the body, having negative health effects. In addition to bending and crumpling consequences and flexibility, the wearable antennas should also comply with high efficiency and low specific absorption rate (SAR). SAR is the amount of energy absorbed by the human body per unit mass and is measured in W/kg. This issue has been significant for the past few years, and various regulating agencies have established a safe limit for the SAR for these antennas [34], [35].

To address the above-mentioned problems, various techniques have been proposed in the past. In [36] the authors have designed an ISM band wearable antenna by using a pair of strip lines for isolation between the feedlines and bandwidth enhancement. It has been noticed that the main contribution of the proposed approach is to enhance the bandwidth without any significant improvement in the SAR reduction. In [37], the authors employed a fractural slot loaded approach to attain multiband response. Moreover, the bandwidth enhancement is achieved at the cost of structural complexity. A truncated ground approach is used in [38] to reduce the SAR of a meander line antenna for wearable applications. However, the substrate is 1.6 mm thick FR-4 which is not appropriate for wearable applications. Other techniques for SAR reduction include variation in the antenna feed point or orientation, and the insertion of an EM wave absorber [39]. Perfect electric conductor (PEC) reflectors are also used as a supplementary antenna element to increase the effective radiation efficiency and reduce the SAR of wearable antennas [40]. However, the use of PEC reflectors adversely affects the low profile characteristic. Ferrite sheets are also used for SAR reduction of antennas; however, they result in a higher integration cost and bulky volume, making the antenna unsuitable for body-worn applications [41].

Metamaterials have been widely used in the design of wearable antennas for gain enhancement and isolation of the human body from backward radiation over the last two decades. Metamaterials, are a collection of several distinct components formed from conventional materials like metal or plastic and are artificially engineered materials having unusual properties not available in nature [42], [43], [44]. These metamaterials, including electromagnetic bandgap (EBG) structures, high impedance surfaces, and artificial magnetic conductors (AMC), are integrated as advantageous designs for body-worn antennas [45]. The prominent characteristics of the EBGs are their surface wave band gape and in-phase reflection. In the surface wave band gap, the EBG behaves as a high-impedance surface (HIS) and hence can minimize the effects of antenna radiation on the human body. Also, HIS behavior improves the isolation between the multiple antenna elements, thus resulting in mutual coupling reduction and impedance matching. The in-phase reflection characteristic combines the antenna currents and the image currents constructively, resulting in the gain enhancement of the antenna based on such an EBG. In general, these materials have many promising features. They can enhance the overall performance of the tiny antennas, reduces the side and back lobes radiation towards the human body and hence minimize the SAR and protect the human body tissue from the harmful radiations [46], [47], [48], [49], [50].

The goal of this review work is to outline recent developments in the field of wearable antennas for body-centric communication as well as other important factors. Additionally, the significance of combining metamaterial surfaces into wearable/textile/flexible antennas will be demonstrated by highlighting the previous studies. The rest of the work is organized as follows. Section II focuses on the critical design issues and challenges in the design of wearable antennas. Section III illustrates the suitable conductive and non-conductive materials for the design of wearable antennas and their impact on the performance of the wearable antennas by providing several antennas fabricated on various materials. In Section IV, it is detailed how the human body interacts with the antenna and how it affects the antenna's overall performance. Section V focuses on the specific absorption rate (SAR) analysis and explains various techniques for reducing the value of the SAR. The effect of bending with various radii tested on antennas is examined in Section VI. Section VII focuses more on the various fabrication methods for the wearable antennas. Thereafter, Section VIII focuses on the importance of metamaterial in wearable applications. Section IX concludes the entire article.

II. DESIRABLE CHARACTERISTICS AND CRITICAL DESIGN CHALLENGES

Recently, wearable antennas have attracted increased interest because they are designed to work while being worn and are integrated into the clothing, which is a desirable feature for the military and hands-free applications [51]. Second, a serious issue known as fading, which causes the signal strength to decline, occurs when mobile devices travel over a distance comparable to the wavelength. This multipath fading can be overcome by using antenna diversity. However, in order to achieve antenna diversity, at least half a wavelength separation between each antenna is required, which is impossible for small form factor handheld devices, further limiting the use of antenna diversity. On the other hand, the antenna diversity can be employed on large scale body worn wearable system [20]. Additionally, due to the increasing demand from the rapidly developing wireless communication industry, body-worn wearable textile antennas have also attracted attention in the consumer electronic sector. The desirable characteristics of the body worn antennas which are common to all application are: robust, light weight, inexpensive, no maintenance and set up required and unobtrusive. The critical design factors that can influence the performance of the wearable textile antenna are summarized below:

A. MATERIALS

Wearable antennas are designed to work while being worn, and can be employed in the context of WBAN. Suitable materials (conductive and non-conductive) must be utilized in their design as these antennas operate in the proximity of human body. The electrical and dielectric properties of wearable materials for body-worn antennas are a major issue, because the properties of some wearable materials are not readily available. The dielectric properties of the textile fibers have been studies by many researchers and various measurement techniques for different cases has been presented [34]. Thus, choosing an appropriate material for the design of these antennas is a challenging task.

B. INTERACTION OF THE HUMAN BODY WITH THE ANTENNA

Another problem that needs to be considered in the design of wearable antennas is the interaction of the human body with the antenna, because of the complex permittivity and conductivity of the human body tissues, can have a strong reaction to the waves propagating around the antenna. When the antenna is in close contact with the human body, the antenna resonant frequency will alter with respect to that in the free space and cause a large detuning towards the lower frequency due to the high dielectric constant of the human body tissue [52]. Furthermore, because the human body is lossy, some of the radiated power will be absorbed by the human body, resulting in a decrease in the gain of the antenna [53].

C. PROXIMITY OF HUMAN BODY

When the antenna operates in the proximity of the human body, some of the radiation in the backward direction gets absorbed into the human body tissue, resulting in severe health implications. Therefore, special care should be given to the power absorbed by the human body, which is called the SAR. In essence, the SAR helps in quantifying the power absorbed per unit mass of the tissue and to meet the standard defined by the international organization to shield the human body from dangerous radiation. Thus, while designing body-worn antennas, numerous factors such as the antenna's radiation properties, the input impedance matching capabilities, and the power absorbed by the antenna should be considered [54], [55].

D. VARIATION IN DIMENSIONS

The movement of the person and posture will result in bending, stretching, and twisting, which are typical for wearable antennas, as a result the antennas geometry is susceptible to distort or bend, which has a negative impact on the performance characteristics of the antenna. Therefore, even when utilizing the same material, it will be exceedingly difficult for the antenna to produce the same radiation properties [56], [57].

E. ABSORPTION OF WATER AND MOISTURE

Body-worn antennas comprised of textile materials have a few microscopic holes and are vulnerable in extreme weather conditions because the fibers are constantly exchanging water molecules with the air and establishing equilibrium with the humidity and temperature in touch with it. These microscopic pores are capable of readily absorbing moisture and water, which alters the electromagnetic characteristics, raises the dielectric constant, and causes loss. As a result, the resonance frequency shifts and the impedance bandwidth changes [58].

F. EFFECT OF THE ENVIRONMENT

The performance of the body-worn antenna may be impacted by environmental factors such as the temperature tolerance of the material used, the durability to numerous bending, its resistance to physical abrasion, and the operational environmental stress [59].

There are some common requirements that need to be taken into account for wearable antenna design in addition to the general requirements, which are application specific and are discussed above. These consist of:

1. To be comfortable for users, these antennas must be light in weight and compact in size.
2. These antennas are desirable to have consistent resistance to bending and stretching.

3. These antennas shall be designed carefully in order to minimize the backward radiations towards human body, to comply with the safe SAR limit defined by international regulations.
4. These antennas must have low maintenance and fabrication costs and require no setup to operate.

III. MATERIALS SELECTION

The materials employed in traditional antenna designs might be uncomfortable and are not appropriate for body-worn antennas. To address this problem an appropriate textile material can be used in the design of them. The conductive (e-textile) materials possess the characteristics of an imperfect and anisotropic electric conductor. Therefore, these conductive materials have different conduction properties than those of traditional conductors used in conventional antenna design. The electrical and dielectric properties of some materials is also not available in the material library, which is also an issue for the antenna engineers [60], [61].

The two most important materials which impact the overall performance of the wearable antennas are the conductive (radiating element) and non-conductive (substrate) materials. The substrate materials are chosen on the basis of dielectric properties, deformation (i.e. bending, crumpling, twisting, and stretching), susceptibility to miniaturization and durability in the external environment, while the conductive materials are chosen on the basis of electrical conductivity. Initially, it is necessary to choose the most appropriate substrate material for supporting the layers before selecting a conductive material for the radiating parts, such as the feed line, patch, and ground plane. By using these materials, the wearable antennas will satisfy the need for comfort and protect the users from harmful radiation. Moreover, the selection of material is chosen on the basis of the mentioned properties to guarantee acceptable gain, high efficiency, and an adequate bandwidth [62], [63].

A. NON-CONDUCTIVE MATERIALS

Non-conductive (substrate) materials or smart fabrics can play an important role in the design of wearable antennas. These materials must have minimal dielectric loss, thermal expansion coefficient, and relative permittivity [64], to attain better efficiency, durability and adequate bandwidth. The non-conductive material chosen for the design has an impact on the wearable antennas' overall performance. These materials are not only limited to supporting the radiating element, but they also affect the antenna performance parameters such as return loss (S_{11}), bandwidth, and efficiency [51], [65], [66]. In addition, the substrate material is very critical in terms of operation, wear ability, and fabrication. Permittivity, thickness, loss tangent, and flexibility should all be considered while selecting the substrate material. These factors are very important because they have an impact on the antenna performance, such as the thickness of the material and permittivity has an impact on the bandwidth. The efficiency is impacted by the loss tangent. The lower the value of the loss tangent, the more efficient the antenna will be. Similarly, the antenna adapts to the users due to its flexibility. As a result, a suitable substrate material must meet both the electrical and mechanical specification of the design.

Before designing the antennas, it is essential to characterize the properties of the substrate materials because the properties of the materials change depending on the materials selection and frequencies used [67], [68]. Table 2 provides an overview of the factors that the researchers considered when designing wearable antennas.

Different designs of antennas fabricated on various wearable substrate/textile substrate materials are depicted in Fig. 2.

B. CONDUCTIVE MATERIALS

All the antennas require conducting materials for the ground plane as well as for the radiating element. Wearable antennas must have suitable radiating elements and ground planes made of conductive materials to ensure proper antenna radiation characteristics. For the wearable/textile antennas, conductive materials (electro-textiles) are used to function as fully flexible and wearable antenna designs. The current flowing through the conductor, which is responsible for radiation, depends on the conductivity of the material. The conductivity is the ability of the material to allow the flow of charges through it unopposed. The conductivity of the material is measured in Siemens per meter (S/m). The electrical conductivity of the perfect electric conductor (PEC) is infinite, which is ideally used in the design of antennas. But in practice, all the materials have limited conductivity. For instance, the conductivity of the commonly used copper material is 5.8×10^7 S/m. For the wearable antennas, conductive textile (e-textile) materials are used. Thus, materials having relatively greater electrical conductivity are preferably used. Therefore, the conductive materials used in the design of wearable or flexible antennas must have high conductivity. Therefore, it is necessary to characterize the electrical properties of these materials [51]. Additionally, for the conductive fabrics, the following are the essential requirements for the design of wearable antennas:

1. ***Homogeneity*:** It is necessary that the resistance variation over the material be small and be homogenous across the antenna area
2. ***High Conductivity*:** These materials should have a lower surface resistivity (1 Ω/Sq.) to minimize losses
3. ***Flexibility*:** These materials should be flexible enough so that the antenna cannot be distorted when worn on the human body
4. ***Elasticity*:** These materials should be elastic so that the characteristics of the antenna does not alter when bent, stretched, crumpled or compressed

The electrical conductivity of the material used can play an important role in attaining the desired performance from the antennas. Four various types of electro-textile materials which have been reported in the literature and are widely used as a radiating element and as a ground plane are Zelt,

TABLE 2. Summary of the dielectric properties of the wearable/textile substrates.

Ref	Non-conductive Material	Relative Permittivity (ε_r)	Loss Tangent (tan δ)
[24]	Felt	1.3	0.044
[69]	Silk	1.75	0.012
	Felt	1.22	0.016
	Cordura	1.60	0.0400
	Moleskin	1.45	0.05
	Jeans	1.7	0.025
	Panama	2.12	0.05
	Tween	1.69	0.0084
	Polyester (100 %)	1.90	0.0045
	Quartz @ Fabric	1.95	0.0004
	Cotton	1.60	0.0400
[70]	Felt	1.38	0.023
	PTFE	2.05	0.0017
	Fleece	1.17	0.0035
	Perspex	2.05	0.0017
	Moleskin	1.45	0.05
	Tween	1.69	0.0084
	Panama	2.12	0.018
	Silk	1.75	0.012
[71]	Felt	1.3	0.02
[72]	Silk	1.2	0.054
	Leather different type	1.83-2.39	0.049-0.071
	Cotton	1.54	0.054
	Polyester foam	1.02	0.00009
	Felt	1.36	0.016
	Fleece	1.2	0.004
	Neoprene Rubber	5.2	0.025
[73]	Denim	1.4-2	0.0093
	Neoprene	5.2	0.03
	Cotton	1.6, 1.54	0.04, 0.058
	Panama	2.12	0.018
	Polyester	1.9	0.0045
	Silk	1.75, 1.2	0.012, 0.054
	Leather	1.8-2.95	0.049-0.16
	Moleskin	1.45	0.05
	Velcro	1.34	0.006
	Felt	1.36, 1.38	0.016, 0.023
	Fleece	1.17, 1.2	0.0035, 0.004
	Tween	1.69	0.0084
[74]	Rubber	3.94	0.016
[75]	PDMS	2.8, 2.8	0.02, 0.0013

Flectron, Shieldit, and Taffeta are shown in Fig. 3. All these materials can be cut and sewn just like ordinary fabrics.

The Taffeta and Shieldit are the polyester-based fabrics, with the former being coated with pure copper and the latter plated with copper and nickel, in addition to hot melt adhesive on one side. The Flectron and Zelt, on the other hand, are nylon-based fabrics; the former has a copper-only coating, while the latter has a tin- or copper-coated coating. The conductivity of the conductive materials can be calculated by using the following equation.

$$\sigma = \frac{1}{(\rho^{\tau})} \tag{1}$$

where, ρ is the surface resistivity and τ is the thickness of the material. The properties of the four materials mentioned above are summarized in Table 3.

As a conclusion, for the wearable antennas to give an efficient electromagnetic radiation and acceptable performance they will need low-loss dielectric material as a substrate and a highly conductive material as a radiating part.

IV. IMPACT OF HUMAN BODY ON WEARABLE ANTENNAS

The human body has a heterogeneous, lossy character and acts like an irregularly shaped medium. The conductivity of the human body depends on the permittivity and frequency used. For instance, the minimum value of conductivity is 0.10 S/m for breast fat and the maximum value is 3.46 S/m for the Eye (Aqueous Humor) part of the body at the 2.45 GHz operating frequency. The interaction between the antenna and the human body must therefore be taken into account for body-worn antennas. The overall performance of the antenna, such as the radiation pattern, bandwidth, resonant frequency, and especially the efficiency, may vary due to the complex permittivity and conductivity of the human body [97]. All of these performance parameters will change significantly when the antenna is placed in close proximity to the human body. In order to better understand how the human body affects the antenna performance, two different types of numerical models known as "phantoms" have been distinguished and reported by the researchers in the literature. These body phantoms are categories as theoretical phantom and the voxel phantom (realistic model), which essentially employs simulated biological tissue and the actual physical structure, respectively [98], [99], [100]. Fig. 4 and 5 represent the human body physical models, while Fig. 6 illustrates the theoretical phantom model consists of various tissue layers.

The voxel phantom (a realistic model) is non-homogenous and comprised of several elements, which consist of the complex permittivity and conductivity of the human body tissue. Using these models, better results can be obtained. However, more computational resources and greater processing power will be needed for the numerical simulation. Therefore, to reduce the computational resources and processing time, it is preferable to model a simple 3D single-layer (homogenous) and multi-layer (heterogeneous) human body phantom. The single layer model consists of a single dielectric material and the multi-layer model is composed of different human

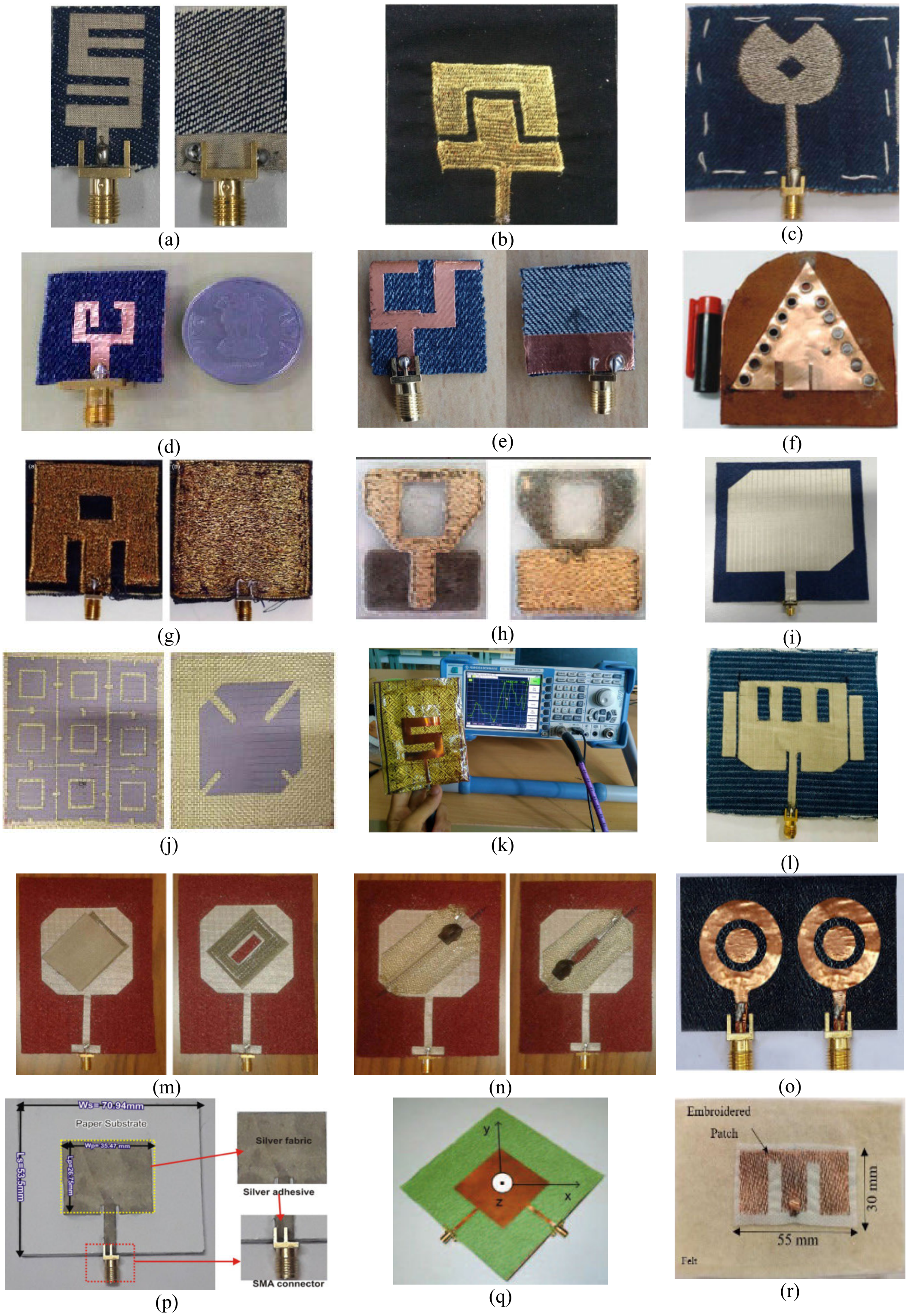


FIGURE 2. Different wearable antenna designs fabricated on various textile substrate (a) inverted e-shaped on Denim [76] (b) textile antenna on woven cotton cloth [77] (c) embroidered wearable antenna [78](d) textile antenna on jeans [79] (e) textile ultra-wideband (UWB) antenna on jean [73] (f) wearable antenna on leather [15] (g) low profile textile antenna on cotton [80] (h) flexible antenna constructed on PDMS [81] (i) reconfigurable frequency textile antenna on felt [82] (j) AMC backed dual-polarized planar textile antenna on felt [83] (k) soft wearable antenna on silk [84] (l) fully textile antenna on Denim [85] (m) polarization reconfiguration wearable antenna on Velcro [86] (n) polarization reconfiguration wearable antenna on zip [86] (o) UWB wearable MIMO on jeans [87] (p) paper based wearable antenna [88] (q) two-port on body MIMO on fleece [89] (r) e-shaped antenna on felt [90].

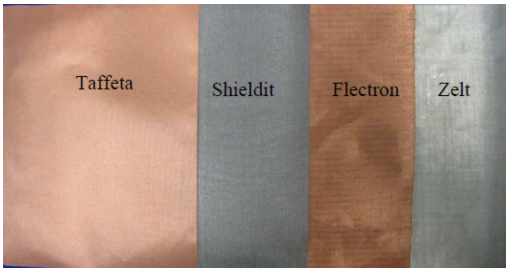


FIGURE 3. Samples of Zelt, Flectron, Shieldit And Taffeta, conductive materials [51].

TABLE 3. Summary of the characteristics of the conductive materials.

Ref	Conductive Fabric	Conductivity (σ) [S/m]	Thickness [mm]	Surface Resistivity (ρ) [Ωm]
[34]		1x 106	0.06	<0.01
[91]	Zelt	1.75x105	0.0635	--
[92]		5.88 x 107	0.11	0.05
[93]	Flectron	5.88 x 107	0.03	--
[94]	Shieldit	6.67 x105	0.17	<0.1
[95]		1.18 x105	0.17	<0.05
[92], [94], [96]	Taffeta	2.5 x105	0.08	0.05

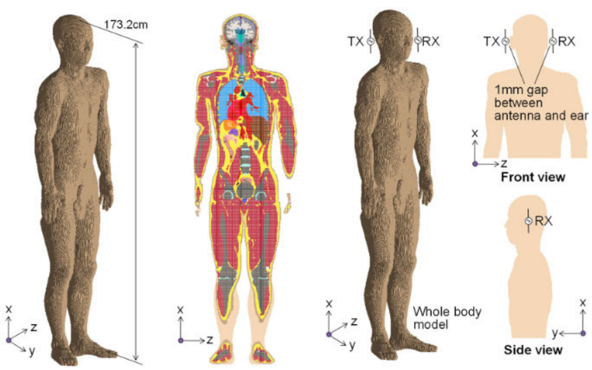


FIGURE 4. Human body physical model (voxel model) [99].

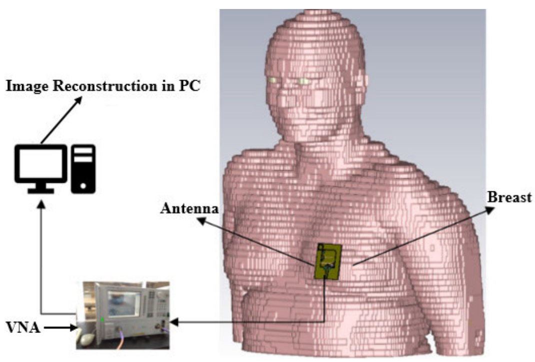


FIGURE 5. Simulation setup of a female physical body voxel model [100].

body tissues such as muscle, fat, skin, bone, and any other in the commercially available simulation software. To simulate the human body arm, four-layered spherical phantoms are mostly used [34], [54], [101]. For the flat body section such as the chest, a heterogeneous three-layer model is used [102]. A seven-layer heterogeneous model is frequently used for the human body head [103]. The dielectric properties of the tissues can be found in [44], [98], [105], and [106].

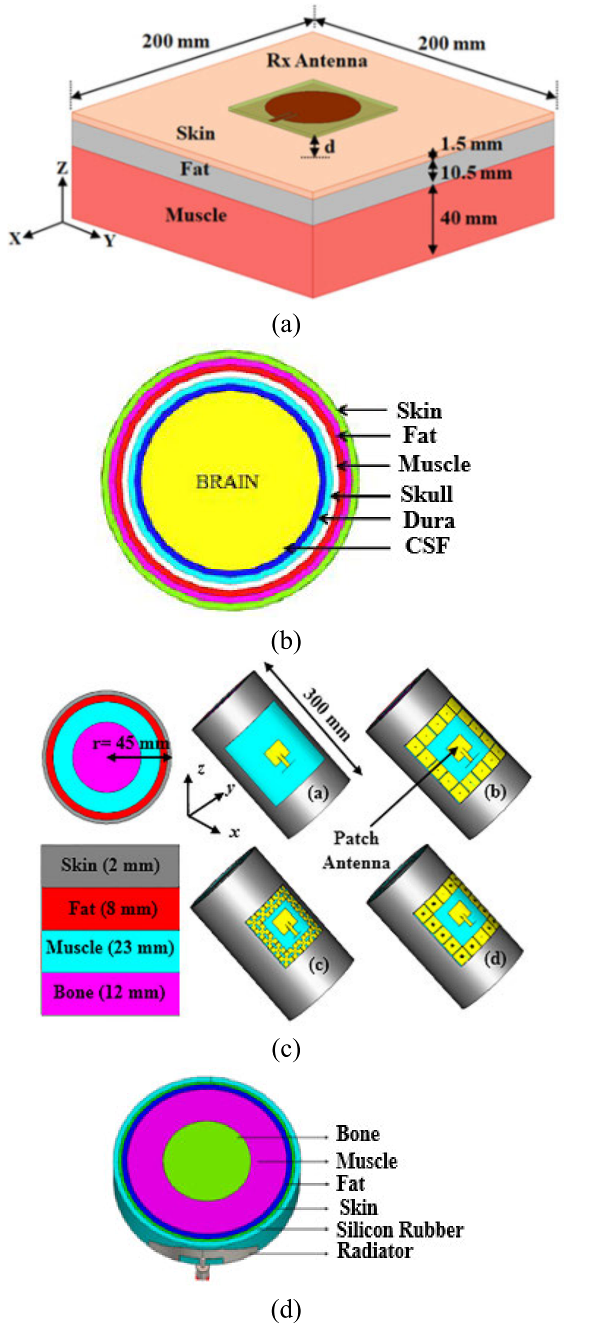


FIGURE 6. Simplified human body model a) three-layer chest [102] (b) a seven-layer head [103] (c) a four-layer arm [34]; and (d) a four-layer cylindrical wrist [104].

The authors of [107] carried out a thorough investigation utilizing numerous homogeneous models of human body tissue. The accuracy, computational effectiveness, processing speed, and resolution of the results produced by the software using the human body model were the primary focus of the study, followed by experimental validation. These models were used to assess the overall performance of the antenna before being put into a physical (realistic) model.

In [108], the effect of human body on the overall performance of the patch antenna such as efficiency, resonant frequency and radiation pattern has been presented. For the analysis a three-layer human body model consisting of skin, fat and muscle tissue is taken into account. In the proposed study the effect of the individual tissues such as skin, fat and muscle in the proximity of human body has been considered. The antenna is first excited for a single band with a central frequency of 5 GHz in the free space when there is no human body in contact with the antenna, and then the antenna is exited for the same frequency in the proximity of human body and the impact of the human body tissue on the overall performance of the antenna has been analyzed. The effect of the outer most layer of the human body based on the high water contents is considered first. The proposed antenna is placed directly in contact with the human body with a skin layer thickness of 1 mm, 2 mm, 5 mm and 10 mm, respectively. It was observed that the skin has a very marginal impact on the bandwidth. In addition, the return loss is not highly affected by the thickness of the skin (Fig. 7). However, the radiation pattern is greatly affected and even worst when the thickness of the skin layer increases (Fig. 8). This shows that increase the thickness of the skin layer will result in more side lobes emerged behind the main lobe, and hence the radiation pattern is highly affected.

In order to examine the impact of the human body on the performance of the proposed antenna, a three-layered human body model made up of skin, fat, and muscle with corresponding thicknesses of 2 mm, 3 mm, and 5 mm is placed on top of it. Fig. 9 and 10 represent the results, respectively. Hence employing the three-layer model has a significant impact on the radiation properties of the proposed antenna compared to the single-layered model.

Similarly, the authors in [109] proposed a compact single-layer textile MIMO antenna for body-worn applications, in which they investigated the influence of the human body on the performance of the MIMO antenna. A four-layered human arm model comprised of bone, muscle, fat, and skin tissues has a thickness of 13 mm, 20 mm, 5 mm, and 2 mm, respectively. The material properties at 2.45 GHz are illustrated in Table 4 [109]. The S-parameters when the antenna is fully in contact with the human body arm model are illustrated in Fig. 11. Due to the high permittivity loading, a frequency detuning of the central frequency of around 250 MHz is observed, relative to the resonance when the same antenna was studied alone. In addition, due to the body loss, the isolation is increased by 5 dB. As the bandwidth of the antenna in free space is adequate, it is worth mentioning that after the frequency shift, i.e., from

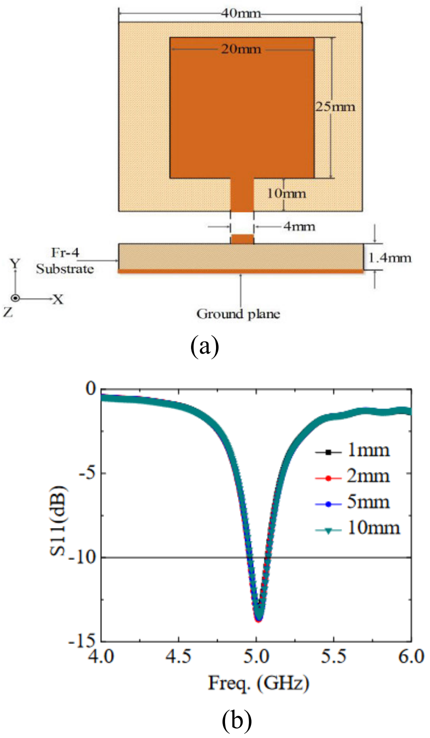


FIGURE 7. **(a) Design architecture of the proposed antenna (b) simulated s_{11} when the antenna is placed on human body with various thicknesses [108].**

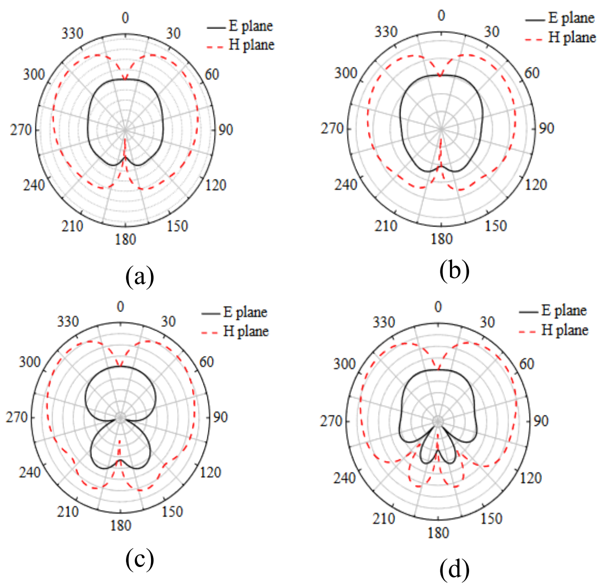


FIGURE 8. **Polar plots radiation pattern in both e and h planes on skin tissue with a thickness of (a) 1mm (b) 2mm (c) 5mm and (d) 10mm 108].**

2.4 to 2.5 GHz, the antenna is still well matched and performing
well.

In [110], a flexible circularly polarized monopole antenna for off-body communication is presented. The influence of the human body on the performance of the antenna is inves-

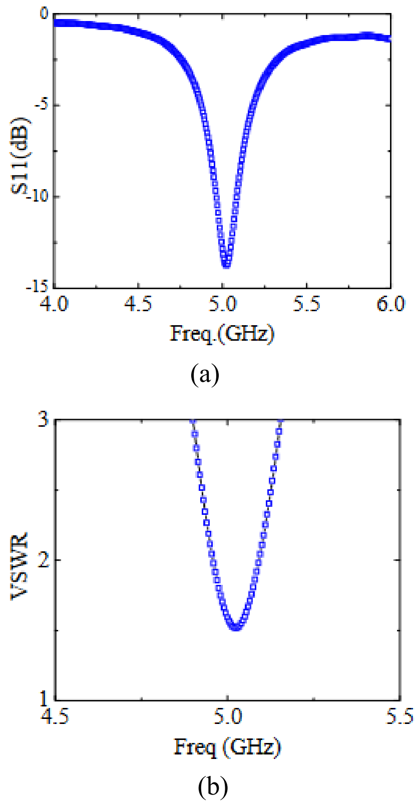


FIGURE 9. Simulated results of the antenna placed on a three-layered model (a) S_{11} (b) VSWR [108].

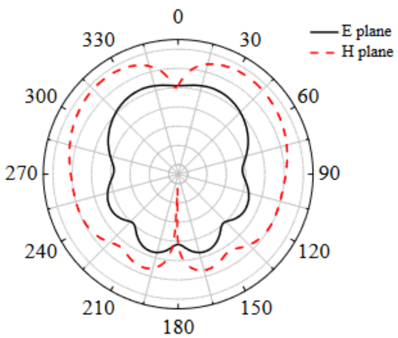


FIGURE 10. Radiation pattern polar plots both *E* and *H* planes [108].

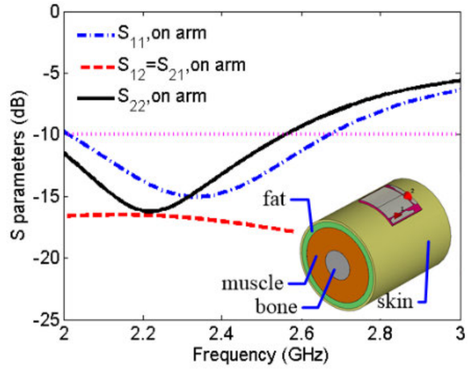


FIGURE 11. S-parameters of MIMO antenna placed on a four layered human body model arm [109].

tigated by considering a there layered human body phantom (chest) as illustrated in Fig. 12. The dielectric properties at the desired frequency (5.8 GHz) and the thickness of each layer are taken from [111], and are given in Table 5. To reduce the computational resources and processing time, the human body is simplified to a 100 × 100 mm2 dimension.

Due to the movement of the human body, the separation between the antenna and the human body will also vary, and hence the *S*-parameters, gain, and the axial ratio (AR) of the proposed antenna with various separations (*do*) are studied. As shown in Fig. 13(a), the proposed antenna has a robust impedance match. However, there is a large variation in the distance between the antenna and the human body. Moreover, Fig. 13(b) illustrates that when the antenna gets close to the phantom, the axial ratio bandwidth of the antenna decreases. The adjusted do is set to be within 2–4 mm in order to attain the entire band coverage and pure circularly polarized (CP) performance. This separation can be guaranteed only by thin clothes having various thicknesses. Furthermore, it was observed that when *do* increased, the gain was reduced. So, to make a trade-off between the axial ratio (AR) performance and the bore side gain, the separation between the antenna and the human body phantom was kept $do = 3$ mm.

Likewise, the authors in [112] investigated a flexible antenna with metamaterial for WBAN applications. The antenna was constructed to work in the proximity of the human body and due to the fact that some part of the electromagnetic energy is absorbed or reflected by the human body, the antenna was examined in the proximity of the human body and the impact of the human body on the performance of the antenna was studied. For the analysis, the CST MWS human

TABLE 4. Dielectric properties of tissues of the arm at 2.45 GHz [109].

Parameter	Skin	Fat	Muscle	Bone
Permittivity (ε_r)	37.95	5.27	52.67	18.49
Conductivity (S/m)	1.49	0.11	1.77	0.82
Density (kg/m^3)	1001	900	1006	1008

TABLE 5. Dielectric properties and thickness of the human body tissues at 5.8 GHz [111].

Parameter	Muscle	Fat	Skin
Relative Permittivity (ε_r)	48.49	4.96	35.12
Conductivity (S/m)	4.96	0.29	3.71
Thickness (mm)	20.0	10.0	1.3

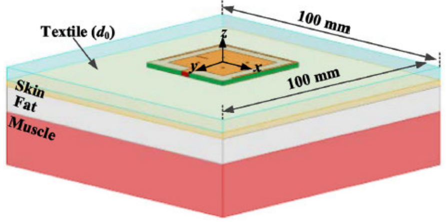


FIGURE 12. Schematic of the three layer human body model chest [110].

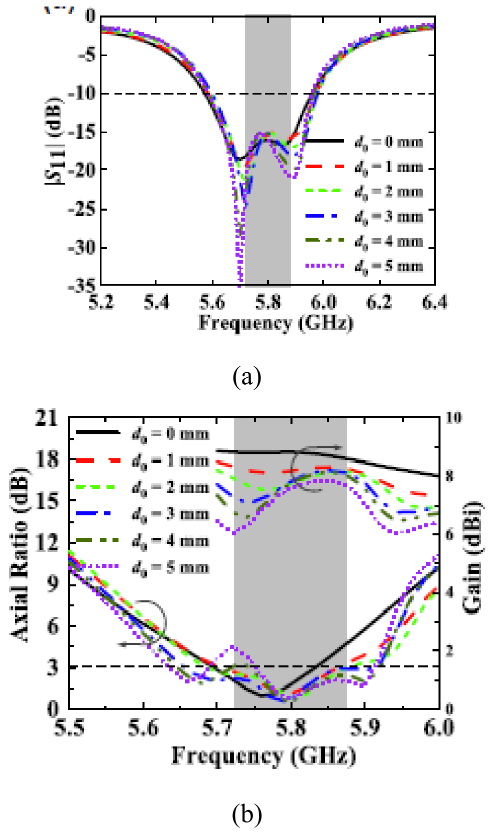


FIGURE 13. Simulated results of the antenna with various separation distances from the three layer human body phantom chest (a) S-parameter (b) axial ratio and gain [110].

body model Gustav, as shown in Fig. 14(a), was considered. To reduce the simulation complexity and processing time, the model was simplified into four simple layers, such as bone, muscle, fat, and skin, only. The distance between the antenna and the human body is critical [113], therefore, to assure that the proposed antenna works properly, it is placed at a separation distance of 5 mm. The simulated results of the proposed antenna with and without the human body model are presented in Fig. 14(b), in which the curves free space (FS) and on body (OB) refer to the results attained when the antenna was in the middle of the simulation area (area under test) and was placed on a human body model (Gustav), respectively. Because the permittivity of the human body model is greater than that of the polyamide substrate used, it was discovered that when the antenna was placed at a separation on a human body model, its operating frequency decreased from 2.6 to 5.8 GHz to 2.2 and 5.6 GHz, respectively. Besides, reflection coefficient and VSWR, other parameters such as gain and radiation pattern of the proposed antenna were also analyzed.

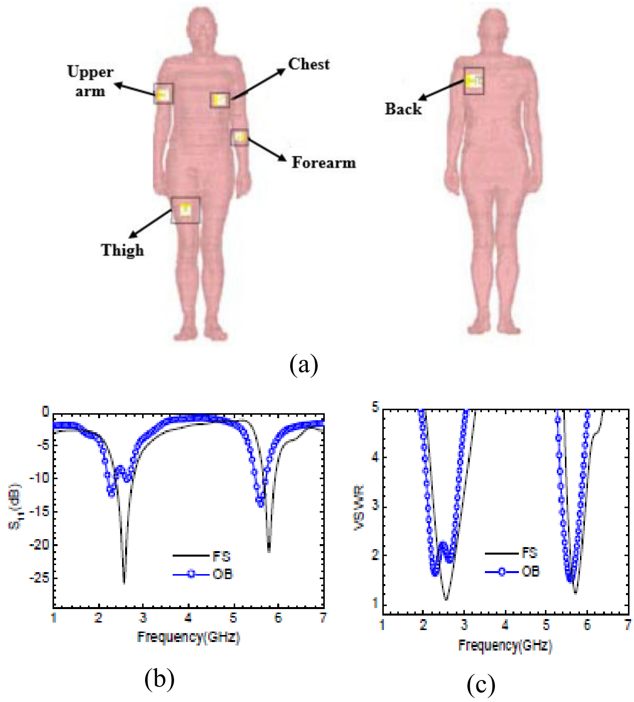


FIGURE 14. Comparison of the simulated results with and without the gustavo model (a) proposed antenna placed at various positions of the model (b) S-parameters (s11) (c) VSWR [112].

The radiation pattern of the proposed antenna is highly affected by the human body compared to the radiation pattern in the middle of the simulation as depicted in Fig. 15. Due to the impact of the human body model, radiation in both the principal (E and H) planes is observed. The comparative analysis in terms of radiation is summarized in Table 6.

TABLE 6. Summary of performance comparisons of the antenna is in free space and on the human body FOREARM [112].

Freq.	Gain (dB)		Rad. Eff (%)	
(GHz)	Free Space	On Body	Free Space	On Body
2.4	1.2	-4.1	82.3	12.9
5.8	1.6	2.3	82.4	31.5

Similarly, in [114] the authors presented a flexible dual-band meander line monopole antenna for healthcare applications. The performance of the antenna is studied on a human body part, the chest and arm. For the human body's chest (flat body model) and arms (cylindrical body model), a three-layered body structure comprised of skin, fat, and muscle was used to investigate the performance of the antenna. It was observed that the antenna in free space showed good

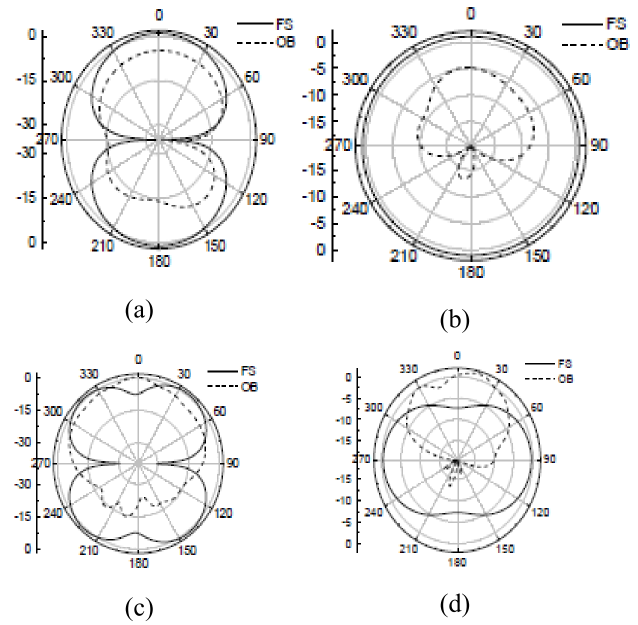


FIGURE 15. Comparison of the radiation pattern polar plots at 2.4 GHz when the antenna is mounted (a) on various parts of the human body (b) in the middle of the simulation area (c) and (d) *E* -plane in (a) and (c), *H* -plane in (b) and (d) [112].

impedance matching in both the lower and upper frequency bands. The antenna is placed over the human body models and an air gap is introduced between the antenna and the human body, representing the utilization of the comparable thicknesses of multiple textile layers because textile materials usually have a dielectric constant close to zero. The air gap between the antenna and the human body was adjusted to 3, 5 and 10 mm. Due to the strong mutual coupling, when the antenna is adjusted at a distance of 3 mm from the human body, which is very close to the human body and due to the strong mutual coupling, the impedance matching is significantly affected. However, when the distance between the antenna and the human body was increased, the impedance matching was marginally affected, and the antenna was nearly decoupled when the distance between the antenna and the human body was adjusted to 10 mm. Fig. 16 shows the simulated reflection coefficient of the proposed antenna at various separations from the human body models. In addition, the lossy nature of the human body tissues makes the radiation pattern wider and a wide bandwidth is obtained when the antenna is positioned on the human body. As a result, the power is approximately radiated in all directions, resulting in an omnidirectional radiation pattern in both bands (Fig. 17).

V. SPECIFIC ABSORPTION RATE (SAR)

Because of widespread concerns about the health effects of radiation and legal requirements around the world, antenna designers, engineers, and researchers have always been concerned about radiation absorbed by the human body tissue. The protection of the human body from dangerous radiation must therefore be taken into account in addition to the

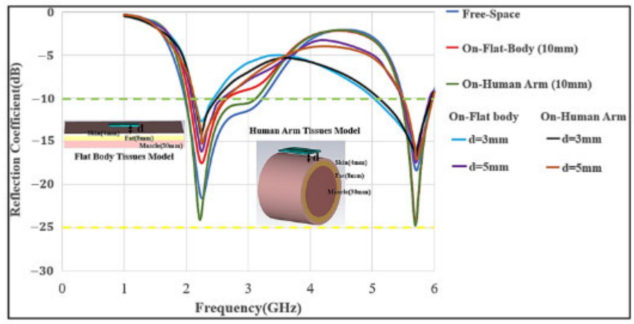


FIGURE 16. Optimization of the reflection coefficient of the proposed antenna in free-space, on chest, and arm models with different positions on the body (3 mm, and 5 mm) [114].

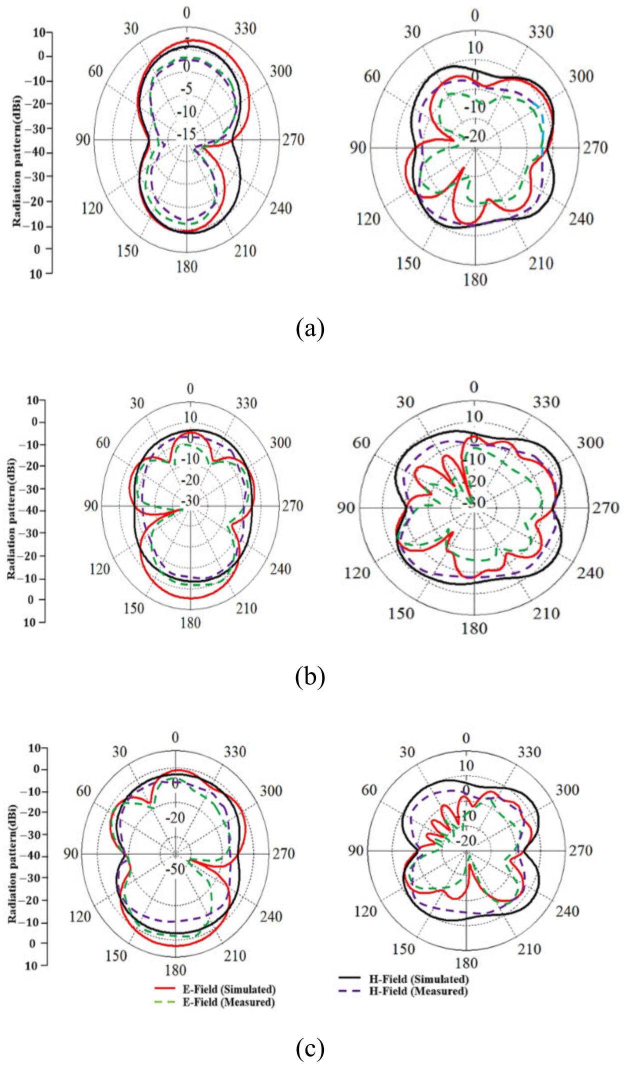


FIGURE 17. Radiation pattern polar plots in both principal planes at both frequency bands, the lower frequency (left side), the upper frequency (right side), (a) in free-space (2.2 GHz and 5.6 GHz), (b) on-chest (2.3 GHz and 5.7 GHz), (c) on-arm (2.2 GHz and 5.7 GHz) [114].

compatibility of wearable antennas. The SAR is required to calculate the amount of electromagnetic power absorbed by human body tissue. It is generally defined as the rate of absorbed radiation per unit mass of human body tissues when they are exposed to an electromagnetic field. The SAR is either averaged over the overall body or a small volume of the human body tissues. The SAR can be expressed mathematically by using the following relationship [34], [115]:

$$\mathrm{SAR} = \frac{\sigma\, |E|^2}{\rho} [\mathrm{W/Kg}] \tag{2}$$

The ρ represents the density of tissue, E is the Root Mean Square (RMS) electric field and σ is the conductivity of tissue. The SAR is directly related to the tissue conductivity absorbing the radiations and negatively related to the density of the tissue. Regarding the safety of the human body, two safety restrictions have been defined by the international standardization authorities. The maximum safety limits defined by the IEEE C95.1-1999 is less than or equal to 1.6 w/kg for any 1 g of tissue and the safety limit defined by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) is less than or equal to 2 w/kg for any 10 g of tissues [85]. In order to protect the human body from harmful radiation, the absorption of power must be less than or equal to the aforementioned safety standards. Before employing the antenna for WBAN applications, the safety limit must be determined and verified. The choice of phantoms and tissues differs by group because the human body phantom has complex permittivity and conductivity. The size, composition of tissues, and separation factor of the human body phantom all play significant roles, and decreasing the distance between the antenna and the human body has a significant impact on the SAR value [80], [116], [117].

The authors in [112] investigated the SAR of the proposed dual band antenna at 2.45 and 5.8 GHz by employing the antenna on a human body model considering the 1 g and 10 g of tissues while assuming the input power taken for the antenna was 0.5 watts. The distribution of SAR (Fig. 18) and the maximum values of SAR at two distinct frequencies for 1 g and 10 g of tissues are summarized in Table 7. It is observed form the table that 1 g of human body tissues absorbed more radiation than 10 g of tissues. As the conductivity of the human body tissues at 5.8 GHz is greater than at 2.45 GHz, and hence the tissues at 2.45 GHz is exposed to more electromagnetic radiation than at 5.8 GHz. Furthermore, it is observed that the peak SAR for 1 g of human body tissues is 17.50 w/kg. This shows that the SAR of the proposed antenna at 2.4 and 5.8 GHz frequencies is very high and above the specified thresholds defined by the regulatory authorities, and therefore, additional measures have to be taken to reduce the SAR to the safe limit.

The SAR of wireless power transfer systems, which use different antenna scenarios for body-worn devices, was averaged over 1 g of tissue studies and analyzed in 102]. For the analysis, a three-layer human body tissue model comprised of skin, fat, and muscle; hand, head, and torso are taken into consideration, assuming a maximum of 1 watt of excitation power. The peak SAR value of 14.26, 12.41, 8.50, and 2.08 watts per kilogram was observed when the antenna was placed in proximity of three layer models: hand, head, and torso, respectively. The SAR distribution for the system for various antenna situations is shown in Fig. 19. It was evident that the SAR in all the four cases was on the higher side and needed to be within the safer limit defined by the IEEE C95.1-1999 standard (1.6 W/kg).

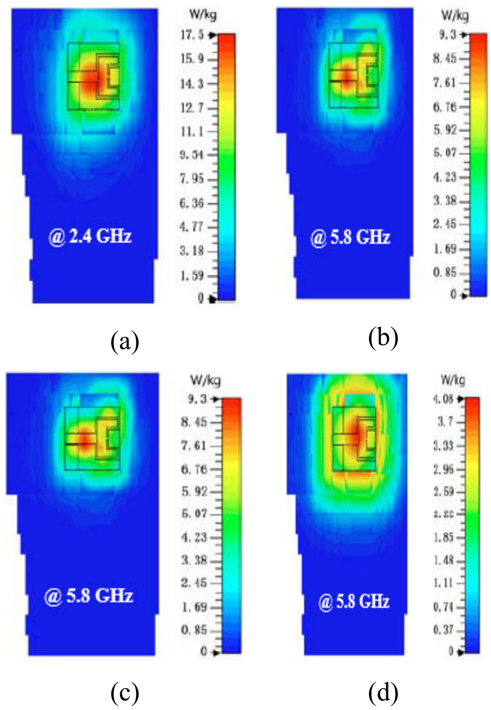


FIGURE 18. The distribution of SAR (a) and (b) refer to 1 g of tissue, while (c) and (d) refers to 10 g of tissues [112].

TABLE 7. Summary of the SAR values assuming input power of 0.5 watt [112].

SAR (W/kg)	@ 2.45 GHz	@ 5.8 GHz
1 g	17.5	9.3
10 g	8.99	4.08

The authors of [118] conducted the SAR analysis of the wearable antenna pressure sensors for elderly fall monitoring. For the SAR analysis, a three-layer human body phantom comprised of skin, fat, and muscle layers was established in the CST MWS simulation software (Fig. 19a). The dielectric properties of the tissue at the desired frequency (2.45 GHz) are taken from [120]. The proposed antenna was analyzed for 1 g and 10 g of human body tissues. It was observed that when the antenna is placed in the proximity of human body phantom greater amount of electromagnetic energy is absorbed in the human body tissue resulting a higher value of the SAR, as shown in Fig. 19(b) and c for 1 g and 10 g of human body tissues, respectively.

Besides, the literature has reported on the SAR analysis of numerous single-band and multi-band antenna designs with

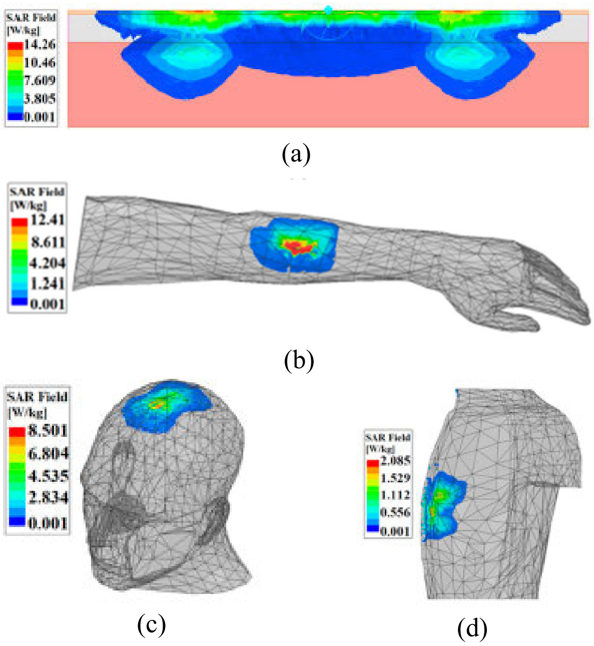


FIGURE 19. SAR distribution on various human body tissues (a) three-layer model (b) hand (c) head and (d) torso [102].

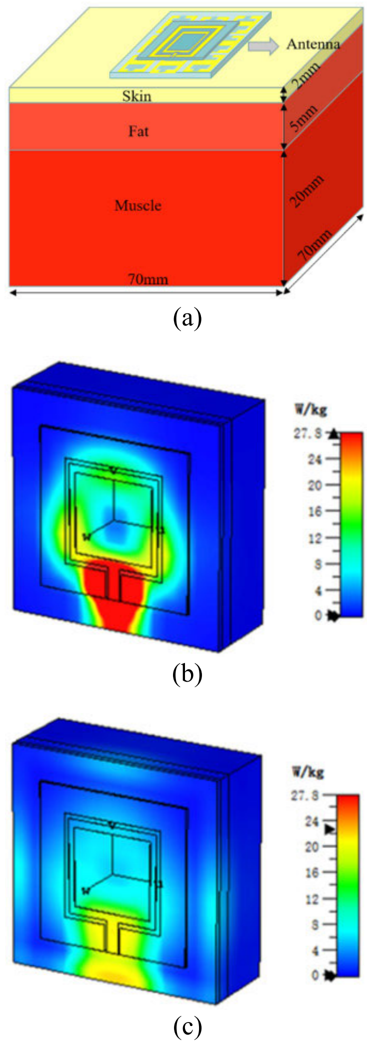


FIGURE 20. (a) Three layer body phantom with antenna (b) SAR for 1 g tissue, (c) SAR for 10 g of tissue [118].

various layouts and feeding processes. It has been shown that for the same size antenna, phantom arrangement and operating frequency, the patch antennas have equal SAR. However, with a different feeding mechanism (aperture coupled), the SAR value is increased despite the fact that the antenna is being placed twice away from the human body phantom. Therefore, it is worth mentioning that, in addition to the operating environment, the SAR value also depends on the type and shape of the antenna. Furthermore, the SAR of multiband antennas is usually higher at the higher frequencies, whereas patch antennas working at lower frequencies give a low value of SAR [22], [24], [120], [121], [122].

VI. EFFECTS OF BENDING ON WEARABLE ANTENNAS

Wearable antennas are employed in different parts of the body depending on the requirements of the application. As a result, the antenna design experiences various structural deformation (bending) with the different movements of a human body. Due to the bending deformation, the performance of the wearable antennas becomes critical because bending can have a variety of effects on the antenna's structural properties. The requirement for wearable antenna is that its performance must be consistent with respect to various deformations. Therefore, it is essential to study the effect of bending on the overall performance of the antenna.

In [123], the authors have proposed a wearable flexible antenna with a simple design operating in the ISM 5.8 GHz frequency band. To study the effect of bending on the performance of the antenna, the proposed antenna is examined using eight cases of different radii of bending deformation along the x-axis and y-axis, using HFSS simulation software. The eight bending effects are illustrated in Fig. 20. To validate the simulated results, the prototype of the proposed antenna is used for bending (Fig. 21). The comparison of the return loss (S_{11}) between the simulated and measured results with various degrees of bending is illustrated in Fig. 22. It was observed that by reducing the bending radius 40 mm (x-axis) and 80 mm (y-axis) to 20 mm (x-axis) and 50 mm (y-axis), the resonance frequency of the antenna shifts around 20 MHz and 50 MHz, respectively. Furthermore, it was observed that the resonance frequency varies slightly when the radius is further reduced from 25 mm (x-axis) and 60 mm (y-axis) to 10 mm (x-axis) and 40 mm (y-axis). However, it was studied that the bandwidth varies a bit. Consequently, the -10 dB bandwidth is close 400 MHz in all the bending scenarios.

In [34], the design and analysis of a textile patch antenna operating at the ISM frequency band (2.4 GHz) are discussed. A 3 mm thicker wash cotton textile material is used as the substrate material in the design of the antenna, while a conductive

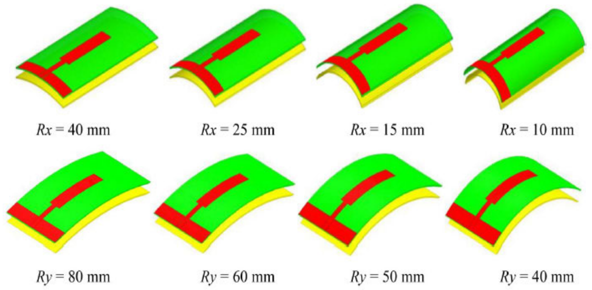


FIGURE 21. Bending Of the proposed antenna at different radii along *X* and *Y* axis [123].

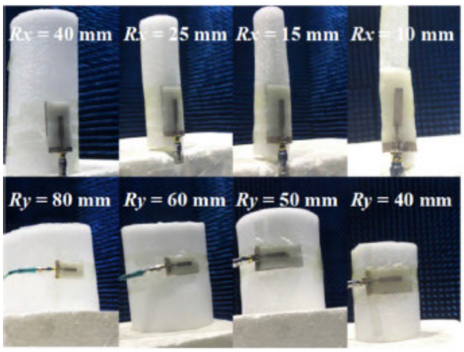


FIGURE 22. Prototype of the proposed antenna at various degree of bending along *X* and *Y* axis [123].

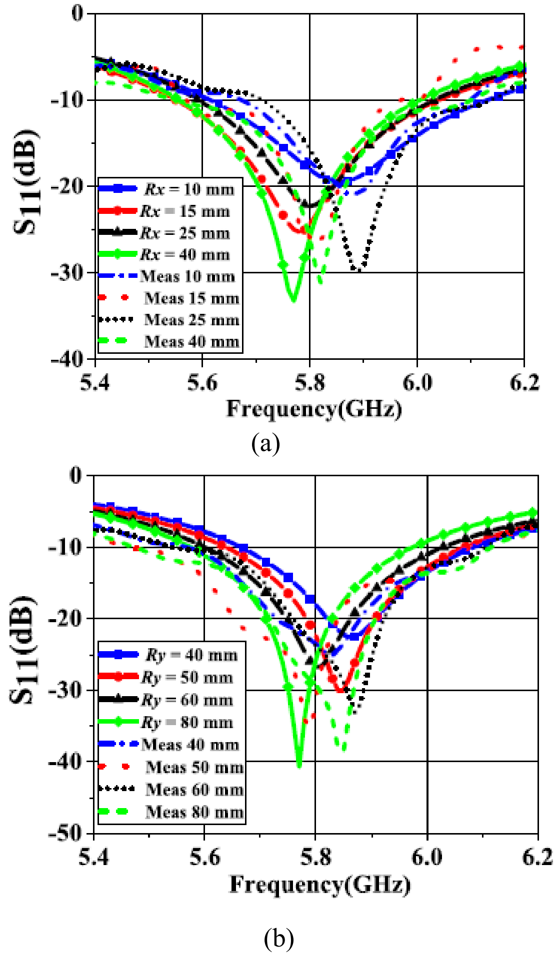


FIGURE 23. Simulated and measured return loss of the proposed antenna under various bending scenarios (a) along *x*-axis (b) along *y*-axis 123].

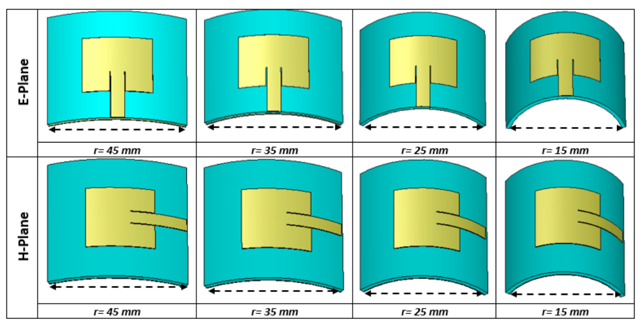
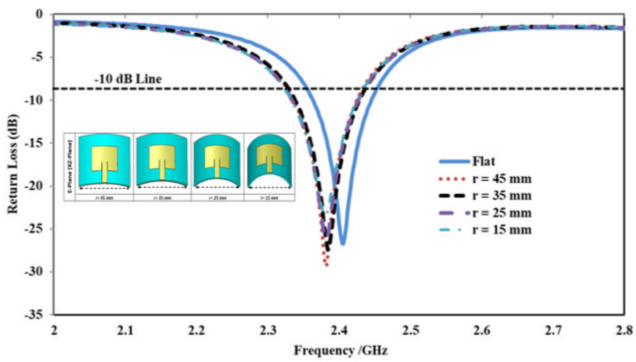


FIGURE 24. *E* and *H* -planes bending of the proposed antenna at various radii [34].

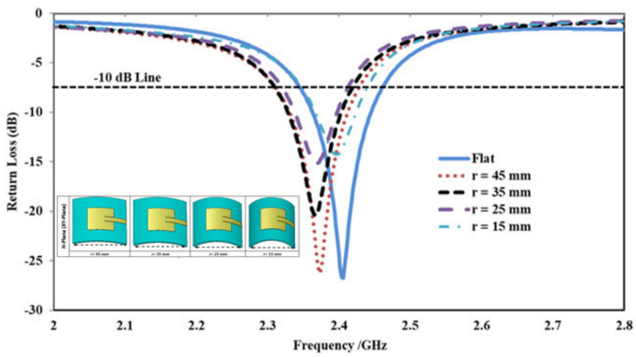
fabric (Zelt) is used as a ground plane and radiating element. In this work, the effect of bending at four different radii, such as 15, 25, 35, and 45 mm in E and H-planes, is demonstrated and compared with the antenna in flat condition. The bending of the antenna in both the E and H-planes is illustrated in Fig. 23, and the resultant simulated reflection coefficient in both the planes is depicted in Figure 23. It is observed from Fig. 24(a), that the proposed antenna provides a good impedance match with a return loss of (<-10 dB) irrespective of the E-plane bending radius. Furthermore, the antenna gives an enhanced impedance matching with a return loss of (<-10 dB) at 45 mm bending in the H-plane, as shown in Fig. 24(b), as compared to other bending radii such as 35, 25 and 15 mm. In addition, it was observed that in both E and H-plane bending scenarios, the resonance frequency is slightly shifted to the left compared to the flat counterpart. Moreover, it is worth mentioning that under all the bent scenarios in both the principal planes, the fractional bandwidth of the bent antenna remains unchanged.

A research work is conducted on wearable MIMO antenna for diversity performance enhancement in 124]. The antenna is designed on a semi-flexible Rogers 5880 substrate material using CST MWS. The effect of bending on the performance of the antenna is analyzed and practically validated by curving the antenna across two different radii 20 and 25 mm (average wrist size of an adult) along the x- (R_x) and y-(R_y) axis. Fig. 25(a) and b describes the reflection coefficient at all the bending radii and the transmission coefficient at the extreme bending along the x-and y-axis, respectively.

By decreasing the curving radii in the x-axis, the resonance frequency and impedance matching are marginally affected. In addition, a shift from -40 to -34 dB is observed in the reflection coefficient (S_{11}) when the antenna is bent at 20 mm (extreme case) as compared to the antenna in flat condition. It is pertinent to mention that the mutual coupling

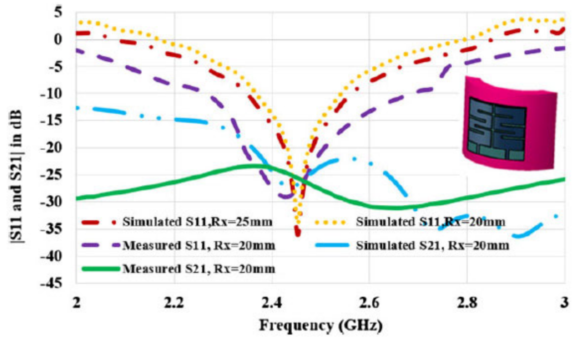


(a)

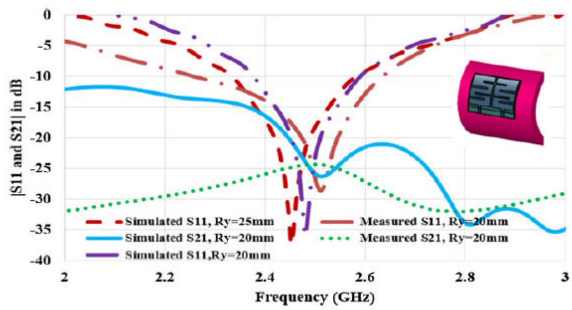


(b)

FIGURE 25. Return loss comparison of the proposed antenna in flat and bent conditions at various radii in (a) *E* -plane (b) *H* -plane [34].

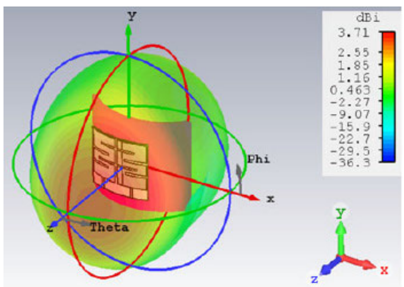


(a)

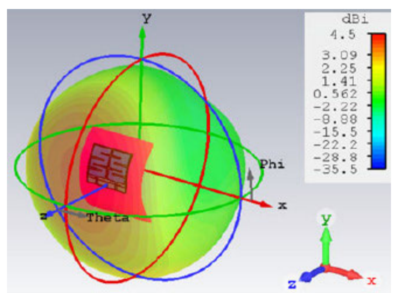


(b)

FIGURE 26. Effect of bending on S-parameters of the proposed wearable MIMO antenna along (a) *x*-axis (b) *y*-axis [124].



(a)



(b)

FIGURE 27. 3D radiation pattern when the antenna is curved along (a) *X* -axis (b) Y -axis [124].

is not affected when the antenna is curved along the *x*-axis. Furthermore, a frequency detuning in the upward direction is observed when the antenna is bent, reducing the radii along the *y*-axis. When the antenna was curved at 20 mm, a degradation in reflection coefficient from −40 to −34 dB was observed compared to its flat counterpart. This effect is mainly observed due to the deviation in the gap between the open-end slots and their width. However, it is worth mentioning that due to the wide band performance of the antenna, it can still efficiently cover the entire ISM band. Moreover, due to the y-axis bend, the mutual coupling is also affected. It was concluded and observed that the smaller radius has a greater effect on the antenna performance than the larger radius. In the proposed work, the reflection coefficient for all the bending conditions along both the axis is well below −10 dB, which shows that the proposed antenna well maintained the reflection coefficient irrespective of bending conditions.

Besides, in the proposed research work, a 3D radiation pattern for both the deformation conditions has also been presented (Fig. 26). A reduction in diversity was observed when the antenna was bent along the *x*-axis as compared to the flat antenna design. Furthermore, when the antenna is bent along the *y*-axis, a stable response to the radiation pattern is established.

A small, dual-band wearable antenna for WBAN applications that operates at 2.45 and 5.8 GHz is reported in [120]. The fabricated photographs of the proposed antenna are shown in Fig. 27. The bending effect on the performance of the antenna is studied with various degrees of bending along both the axis (x-and y-axis). The study was carried out using the typical bending radii of 60, 40, and 40 mm, which are usually used for wearable applications. Fig. 28 compares the return loss (S_{11}) of the proposed antenna with flat and curved scenarios of varying radii. A slight variation in the return loss (S_{11}) is observed for all bending conditions when compared to the antenna in flat scenario at both the lower (2.45 GHz) and upper (5.8 GHz) frequencies. Moreover, it was seen that the variation at a higher frequency (5.8 GHz) is quite more sensitive than at the lower frequency (2.45 GHz). In addition, it was found that the working bandwidth for all the bending curvatures provides an adequate bandwidth and fully satisfies the WBAN application at both the frequencies (2.45 and 5.8 GHz). Based on the aforementioned, it was concluded that the antenna is a good candidate for body-worn applications.

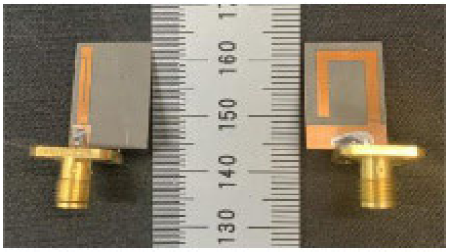


FIGURE 28. Photograph of the fabricated prototype of the proposed antenna [125].

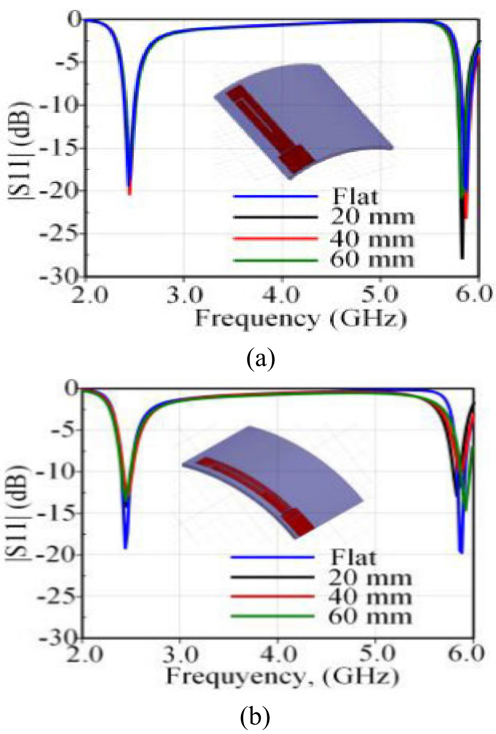


FIGURE 29. Comparison of the S-parameters of the proposed antenna with various bending curvatures (a) *X* -direction (b) *Y* -direction [125].

The authors in [3] presented an AMC-based wearable antenna for IoT applications. The antenna operates at two distinct frequency bands (2.45 and 5.8 GHz) and is printed on a semi-flexible substrate. The effects of bending on the performance of the proposed antenna were carried out using various bending curvatures (i.e., 30, 60, and 90 mm) along the x-axis (B_x) and y-axis (B_y), as illustrated in Figure 28. Fig. 29 depicts a comparison of the proposed antenna's reflection coefficients at various bending curvatures in the x and y directions. A stable reflection coefficient was observed even when the antenna was curved at 90 mm. Furthermore, it was observed that in x-direction bending, the lower band (2.45 GHz) is almost negligibly affected (Fig. 30a). However, a slight shift towards the lower side was seen in the higher frequency band (5.8 GHz). Similarly, when the antenna was bent in the y-direction at various bending curvatures, it was seen that the reflection coefficient is slightly affected when bent in the y-direction (Fig. 30b). This affects in both the x- and y-axes is insignificant, and therefore the antenna can be suitably used for wearable applications.

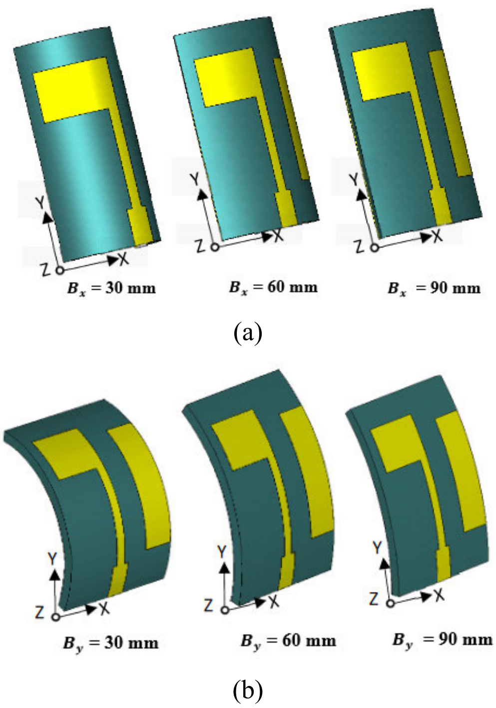


FIGURE 30. Bending of the antenna in various B_x and B_y along (a) *X* -direction (b) *Y* -direction [3].

A tri-band textile dipole antenna fabricated on a low-loss Denim textile material and operating in the 2.4, 5.25, and 5.75 GHz frequency bands was presented in article [7]. The influence of bending on the performance of the antenna was investigated by applying different deformations. The proposed antenna is bent around a foam cylinder of various curvatures, such as 3, 5, and 7 cm. The comparison of the measured return loss of the antenna in normal conditions and when the antenna is bent at various curvatures is shown in Fig. 31. It was seen that the return loss is slightly shifted for all the bending conditions compared to the antenna when

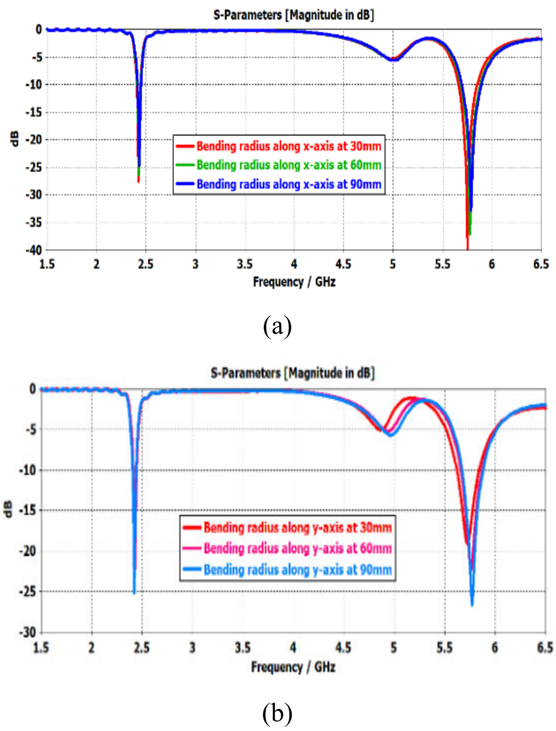


FIGURE 31. Effect of various bending curvature on the reflection coefficient of the antenna along (a) *X* -axis (b) *Y* -axis [3].

relaxed (normal condition), however this shift is negligible and has no impact of the antenna's functionality in the desired frequency bands. Furthermore, it was observed that due to the stable performance of the antenna, the impedance bandwidth at the proposed frequency bands remained the same compared to the antenna when it is in a normal state. The proposed antenna was found to be highly robust, with stable performance regardless of bending condition.

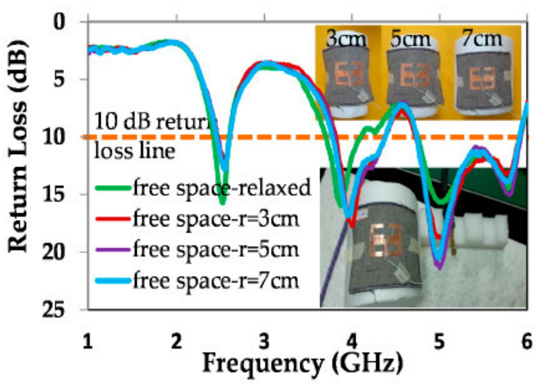


FIGURE 32. Return loss comparison of the antenna in normal and bent antenna [7].

The authors in [57] proposed a compact dual-band antenna operating on the 900 MHz and 2450 MHz frequency bands on a flexible Roger substrate. The performance of the proposed antenna was analyzed under bending conditions in the *x*- and *y*-directions (Fig. 32). The simulated and measured results of the proposed design in the *x*- and *y*-directions are depicted in Fig. 33(a) and b, respectively. It was observed that due to bending along both axes, the antenna shows a strong agreement between the simulated and measured results. The measured bandwidth of the antenna when bent along the *x*-direction is 245 and 720 MHz, while it gives a bandwidth of 270 and 585 MHz when bent along the *y*-direction, for this specific geometry of the antenna.

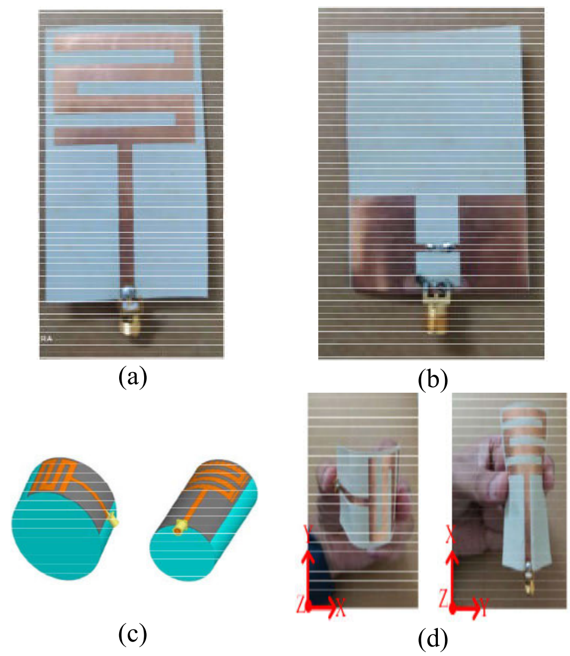


FIGURE 33. Prototype of the antenna (a) front view (b) back view (c) simulation setup (d) measurement setup for bending analysis [57].

The authors in [76] conducted an experiment in which the bending of the antenna in both the vertical and horizontal directions was analyzed (Fig. 34). A foam cylinder having diameters of 140, 100, 80, and 70 mm was taken into consideration in order to perform the experiment. These various diameters were taken in order to verify the impact of various bends on the performance of the antenna and to test whether the resonant frequency is stable under bending conditions, which is needed for a reliable wearable antenna. Fig. 35 elaborates on the return loss characteristics that were analyzed and measured when the antenna was bent at various radii in both the horizontal and vertical directions. It was seen that by reducing the bending radii, the return loss is slightly shifted in the upward direction. Considering the bending in the horizontal direction and taking the curving radius of 50 mm, a frequency shift of 5 MHz was observed towards the higher frequency, which is inconsequential, and the performance of the antenna is stable (Fig. 35b). In addition, it was concluded that the antenna functions well within the desired frequency band without considerable frequency detuning even when the antenna is bent and irrespective of bending directions. The

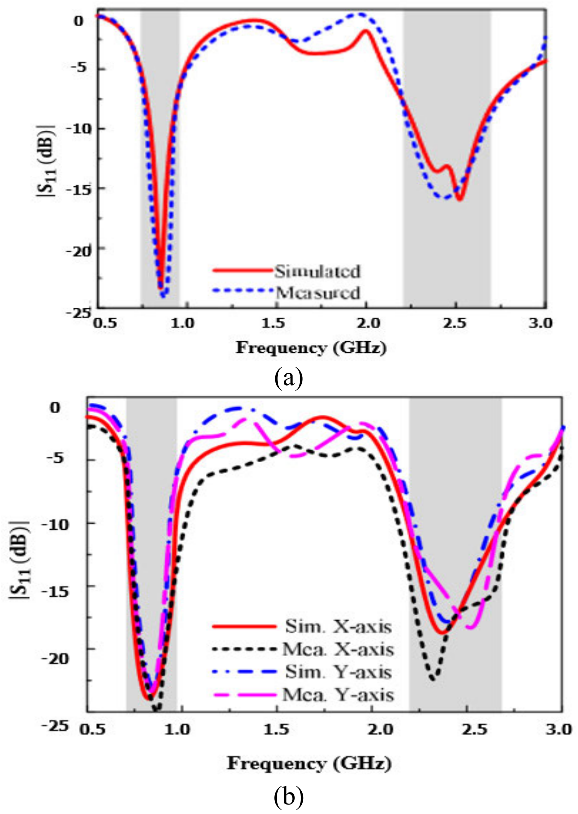


FIGURE 34. S-parameters comparison of the simulated and measured results (a) antenna in flat condition (b) antenna bent along *X*-and *Y*-axis [57].

comparison of the measured bandwidth of the antenna in flat and bent conditions is summarized in Table 8.

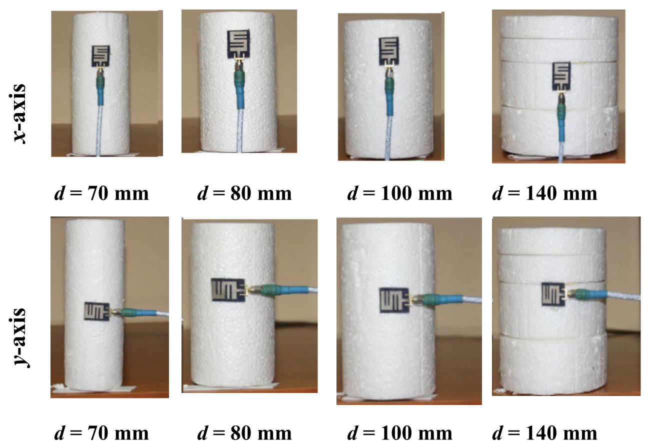


FIGURE 35. Experimental setup depicting antenna deformation at various radii in the *X*- and *Y*-directions [76].

The authors in [126] described a study on metamaterial-based dual band antennas on Jeans textile substrates. To investigate the effect of bending on the performance of the antenna, the antenna is bent according to the various human body postures. For analysis, the proposed antenna was bent at four different radii (R), such as 30, 60, 105, and 205 mm (Fig. 36).

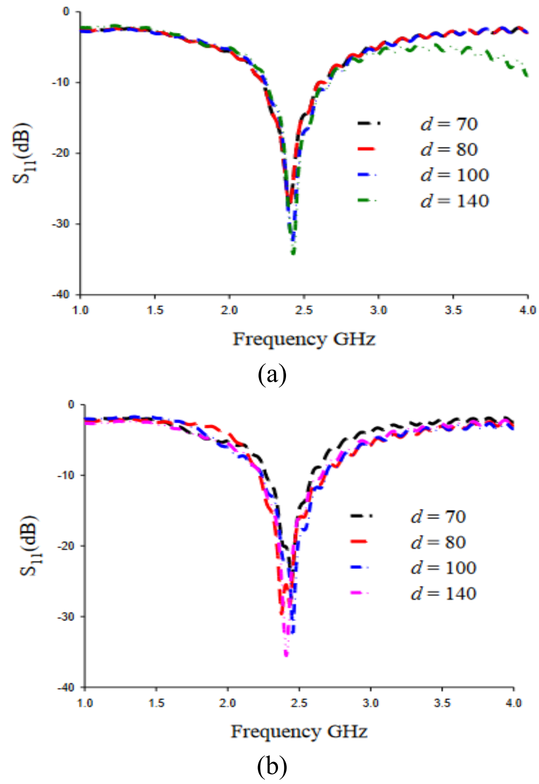


FIGURE 36. Measured return loss comparison at various bending deformation along (a) *x*-axis (b) *y*-axis [76].

The simulated return loss (S_{11}) of the antenna with and without bending is illustrated in Fig. 37. It was observed that due to bending, the upper as well as the lower band bandwidth are affected. It was further seen that when the antenna was exposed to extreme bending ($R = 30$ mm), a frequency range coverage of (2.67–2.93) GHz and (4.12–5.41) GHz was observed. However, when the antenna was bent by a large radius ($R = 205$ mm), a frequency range coverage of (1.1 – 3.0) GHz and (4.65 – 6.55) GHz was observed. In addition, it was analyzed that due to bending, the field pattern was also changed and hence the operating bandwidth was affected. It was concluded that the bandwidth was badly affected when the antenna was exposed to extreme bending ($R = 30$ mm).

The bending effects on the performance of the wearable/textile antennas were studied in this section. Besides bending deformation, the dielectric properties and the radiation around the human body tissue are some of the aspects that also need to be addressed. Wearable antennas are intended to be curved and conformed to specific structures throughout the activity, and hence the impact of severe bending conditions also needs to be studied. In view of the bending analysis presented in this research work and reported in the literature, it is observed that in all the bending cases, the resonant frequency is slightly shifted either below or above the desired frequency. The summary of the effects of bending on the performance of wearable/textile antennas studied in

TABLE 8. Comparison of the measured bandwidth of the flat antenna and the bent antenna [76].

Curving Direction	Bending radii (mm)	Bandwidth (MHz)	Measured Band (GHZ)
Flat (Normal)	--	360	2.23 – 2.59
Horizontal (*x*-axis)	35	290	2.28 – 2.57
	40	330	2.24 – 2.57
	50	360	2,23 – 2.59
	70	350	2.25 – 2.60
Vertical (*y*-axis)	35	340	2.23 – 2.57
	40	340	2.24 – 2.58
	50	350	2.23 – 2.58
	70	360	2.26 – 2.62

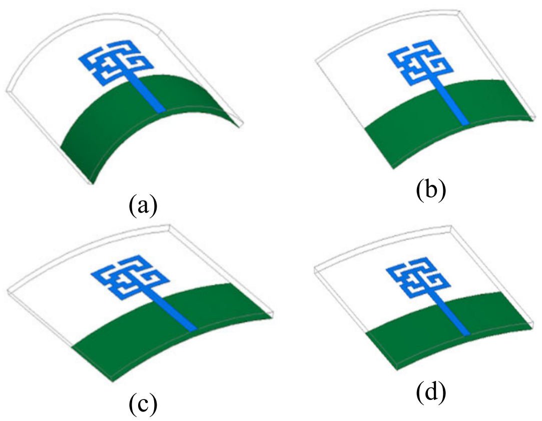


FIGURE 37. Illustration of the antenna of the different deformation at various radii (a) 30 mm (b) 60 mm (c) 105 mm and (d) 205 mm [126].

TABLE 9. Summary of the effect of bending on the performance of wearable antennas.

Ref.	Dielectric Substrate	Bending Radius (mm)/Degrees/ Direction	Bandlimits/ Bandwidth (MHz)	Applications
[24]	Polyester Fabric	Y- and Z-axis	1198 - 2055	Ulta-Wide Band (UWB)
[34]	Wash Cotton	35, 25, 15	2350	ISM Band
[57]	Flexible Roger 5880	*X*- and *Y*-axis	245 and 720 270 and 585	GSM, WiFi
[76]	Denim	70, 50, 40, 35	2400	ISM Band
[80]	Cotton	*X*- and *Y*-axis	2450	ISM Band
[100]	Denim	150°, 90°, 60°, 10°	7000 - 28000	UWB, WBAN
[116]	Felt	*X*- and *Y*-axis	2450, 5800	ISM Band, 5G
[117]	Polyester Felt	--	23000 – 30000 24500 - 28000	5G
[122]	Jeans	--	3090 – 3040 4230 - 5650	5G lower band, WiMAX
[125]	Semi-flexible	*X*- and *Y*-axis 60, 40, 20	2400 – 2540 5720 - 5940	WBAN
[3]	Semi-flexible Roger 3003C	*X*- and *Y*-axis 90, 60, 30	Not Specified	IoT
[126]	Jeans	*X*- and *Y*-axis 70, 50, 40, 35	60, 2760	WLAN, WiMAX
[127]	Felt	80, 60, 40	24500	WLAN, LTE
[128]	Felt	55, 45, 39	2400	ISM Band

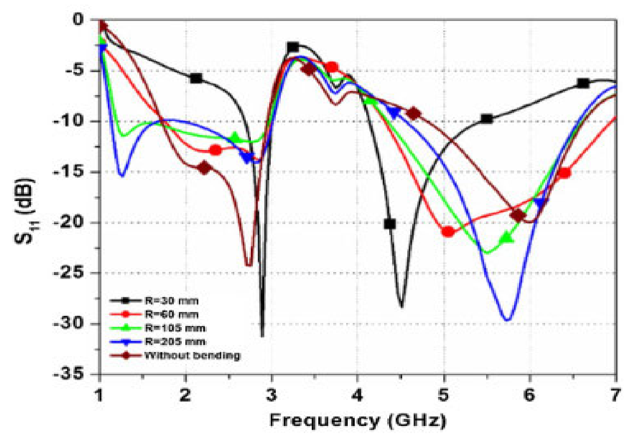


FIGURE 38. Return loss (s_{11}) comparison of the proposed antenna with and without bending at different radii [127].

this work and which are reported in the recent literature is given in Table 9.

The analysis of the abovementioned literature shows that in addition to the choice of the materials used in the design, the effect on the performance matrices also depends on the geometrical layout of the wearable antenna.

VII. WEARABLE ANTENNAS FABRICATION TECHNIQUES

Fabrication methods can play an important role in the design of wearable/textile antennas. It is vital to employ an appropriate fabrication approach in order to give outstanding stability and excellent performance for the wearable/textile/flexible antennas. Additionally, the fabrication techniques can affect precision, cost, and processing time. Researchers and antenna designers have suggested a number of fabrication techniques in response to the demand for wearable antennas. Some of the most popular and widely used methods for designing wearable/textile antennas are listed below [62], [129], [131], [132], [135], [136]. These techniques are dependent on the substrate used for the antenna's design.

(i) Screen-Printing
(ii) Inkjet Printing
(iii) Sewing/stitching and Embroidery Processes

Wearable/textile antennas that are affordable, reliable, and comfortable can be created using the aforementioned fabrication techniques, and users can be able to wear them with regular clothing. Below are the details of each of the fabrication techniques which are mentioned above.

A. SCREEN PRINTING

Screen printing is a cost-effective, fast and easy method that has been employed by many electronic manufacturers and antenna designers [62]. This method can be used to design lightweight, low-cost, and flexible wearable antennas. In this technique, ink is forced through a screen to attach to the affixed substrate with the wiper blade being driven downward. The ink is forcefully released onto the exposed portion of the substrate via the screen to create the proposed pattern [137]. The screen is constructed from a mesh of fabric threads and set up so that the non-image portion is covered with emulsion while the picture portion is left uncovered. This method is one of the most adaptable due to its ability to print images on most of the substrate materials. Additionally, this process has also been used to materials made of polyester and stainless steel. In order to create wearable antennas, three different types of screen printing techniques have been identified and are currently being used. These methods include rotary, flatbed, and cylinder ones. The flatbed approach is regarded as a standard method among all of these. Fig. 38 depicts the process of screen printing as well as the wearable antenna prototypes that were made using this technique.

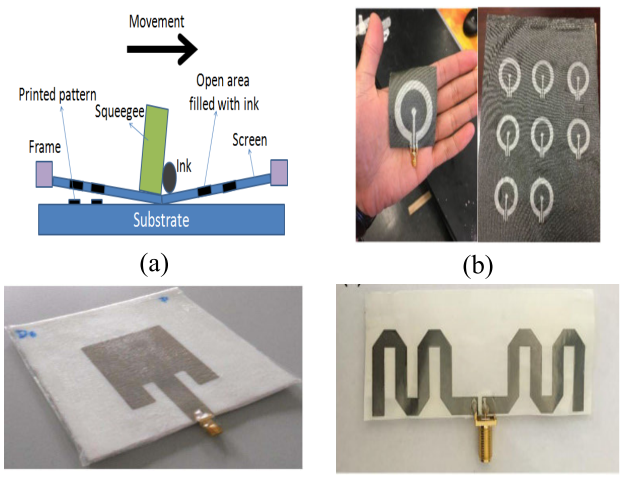


FIGURE 39. (a) Screen-printing process [131] (b) Screen-printed antenna on (nylon/spandex) substrate [132] (c) Screen-printed wearable patch antenna [133] (d) Meandered line textile antenna [134].

The primary disadvantage of screen printing is the low printing resolution. This technology is restricted to printing a specific number of layers, and the thickness of the conductive layers cannot be altered. These reasons make the technology the least acceptable.

B. INKJET PRINTING

Another sort of fabrication technique used to make flexible antennas is inkjet printing, which is regarded as one of the most widely used and reasonably priced printing technologies because of its dependability and quick designing speed [62], [138]. The accuracy of this method is remarkable and can yield a pattern with extremely high precision because the ink droplet used during the production process little, such as a few picoliters [139]. Conductive inks, such as silver nanoparticles, are used in this method. The inkjet printing is further subdivided into two categories, such as drop on demand and continuous inkjet [140], [141].

The inkjet printing technique is considered one of the most cost-effective printing techniques because the specially designed printer can only project one ink droplet from the nozzles to the intended region without any waste. Due to this advantage, the inkjet printing technology is a noticeable benefit compared to the conventional etching and milling methods used in the industry, and is used as an alternative to these techniques. However, some conductive ink varieties have huge particle sizes, which cause nozzle obstructions, rendering this technology inappropriate. Which is the main drawback of this technology. Fig. 39 shows a few inkjet printing wearable/flexible antennas prototypes.

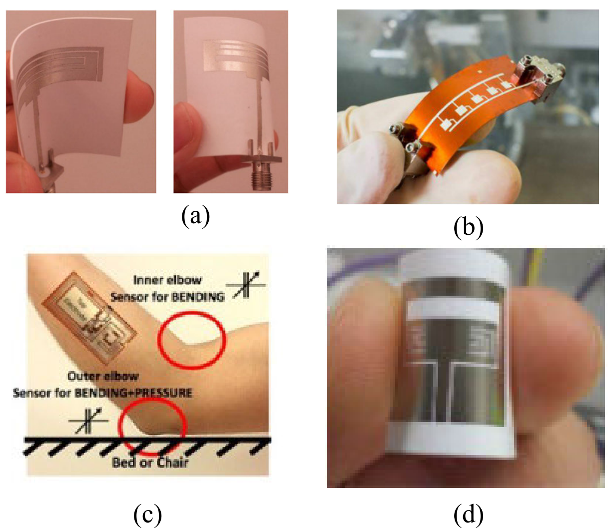


FIGURE 40. Antenna prototypes using inkjet printing techniques (a) flexible antenna on synthetic paper substrate [136], [137], [138], [139], [140], [141], [142] (b) flexible linear array [137], [138], [139], [140], [141], [142], [143] (c) loop antenna on a smart bandage [138], [139], [140], [141], [142], [143], [144] (d) flexible antenna on PET film [139], [140], [141], [142], [143], [144], [145].

C. SEWING/STITCHING AND EMBROIDERY PROCESS

This method is based on the traditional way of stitching and sewing and is currently being used in a number of wearable and flexible antenna applications. In this technique, the conductive fabric material thread is used to embroider the required shape of the conductive parts directly onto nonconductive materials. The antennas have also been directly embroidered onto a nonconductive wearable fabric using technology-supported equipment for embroidery. For wearable electronics, it is necessary to be flexible and comfortable, and therefore, embroidered antennas successfully address this issue due to the fact that the radiating part is directly integrated into clothing. However, the stitching causes creases in the cloth, which gives the antenna its deformed appearance. Furthermore, the spacer textile substrate cannot be used with this method [62], [131], [146]. Wearable antennas, typically made with embroidery, are managed by sewing machines and computer-aided design (CAD) software (Fig. 40). The process involves importing the layout's image into the CAD program, which then creates a digitized design from it. This digital design is then transferred to the sewing machine as a guide note. The stitching gap, yarn tension, and embroidery speed must all be precisely regulated prior to starting the embroidery process.

It is important to note, however, that for simple patch structure, the radiating thread can also be manually embroidered. This technique is utilized frequently in flexible electronics nowadays because it offers a better solution than conventional antennas due to the embroidered shape, which is more elastic and flexible than antennas with radiating sections composed of metal [147]. Fig. 41 shows a few of the antennas that were created utilizing the embroidery techniques.

FIGURE 41. Embroidery machine [148].

Besides, a method based on *Substrate Integrated Waveguide (SIW)* for fabrication of wearable antennas has also been reported in the literature [130], [154]. Similar to that, the most current literature also presents a fabrication technique known as *Adhesives*. These simple fabrication techniques are utilized to link the various antenna sections, including the substrates, vias, connectors, cables, and radiating elements [129], [155]. Additionally, [129], [156] offer the Direct *Cutting approach*, which is an easy and inexpensive way to design wearable/textile antennas. The earliest Radio Frequency Identification (RFID) tags were created using this technique and were constructed of copper sticky tape. A different fabrication technique known as Direct Handwriting is described in [129] and is used for the design of wearable antennas.

Since these approaches must be simple to integrate, affordable, and accurate for WBAN systems, it be concluded that the fabrication processes are highly challenging. Direct handwriting approaches, for example, have drawn a lot of attention because to how simple and inexpensive they are to fabricate. However, these techniques are not yet fully developed and

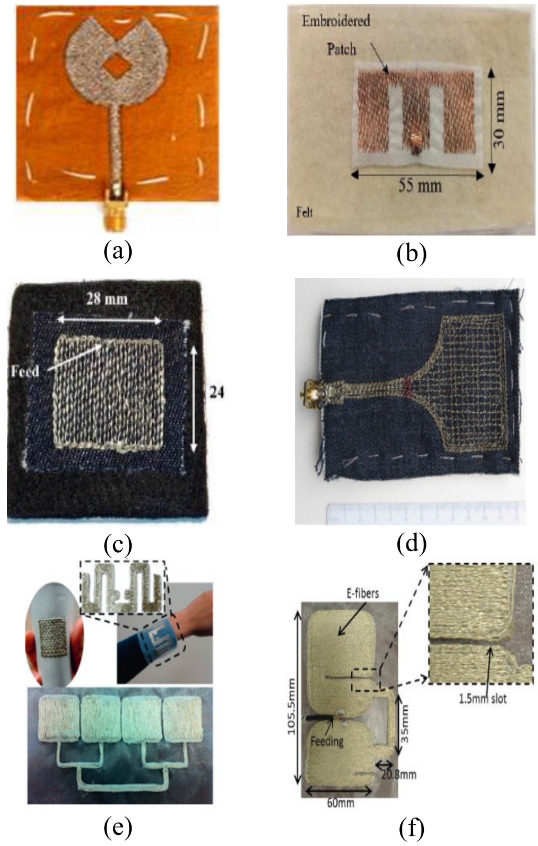


FIGURE 42. Antenna prototypes of embroidered antennas using sewing/stitching techniques (a) Textile UWB antenna using conductive threads [149] (b) E-shaped antenna using flexible felt [90] (c) Microstrip patch antenna using felt [150] (d) Wideband textile planar monopole [151] (e) Textile surfaces [152] (f) Multiband textile antenna on E-fiber [153].

deployed, despite the need for their potential use in body-worn devices.

VIII. IMPORTANCE OF METAMATERIALS IN WEARABLE APPLICATION

In the previous research study, several antenna designs for wearable applications were presented [76], [95], [157], [158], [159], [160]. However, due to certain shortcomings of these antenna designs may further restrict the uses of these antennas in wearable electronics, such as:

- Due to the bidirectional radiation characteristics, the SAR level was raised while in close proximity to human body tissues.
- Since they were not low-profile and conformal, it was challenging to incorporate them into clothing and the human body.
- The majority of the radiation was directed toward the human body due to the near-omnidirectional radiation characteristics, which substantially altered the radiation pattern and thus reduced the antenna's overall performance.
- The size of these designs was very large.

TABLE 10. Performance analysis of single band wearable antenna with and without metamaterials.

Ref	Antenna without Metamaterial						Antenna with Metamaterial					
	Gain (dBi)	Rad. Eff (%)	S_{11} (on body)	Peak SAR (W/kg)		Frequency (GHz)	Antenna Topology	Gain (dBi)	Rad. Eff (%)	S_{11} (on body)	Peak SAR (W/kg)	
				1 g	10 g						1 g	10 g
[13]	−7.46	7.91	Shifted	4.13	1.52	2.45	Monopole	4.07	38.84	Stable	0.021	0.007
[34]	6.54	60.66	-do-	--	7.95	2.4	Rect. Patch	7.31	74.04	-do-		1.79
[47]	6.1	52	-do-	--	8.16	2.4	-do-	7.3	74	-do-	--	1.77
[54]	1.28	90	-do-	15.2	4.51	2.4	Monopole	6.49	84	-do-	0.807	0.4
[157]	2.0	--	-do-	7.78	--	2.4	-do-	7.5	71	-do-	0.028	--
[158]	4.2	--	-do-	6.19	2.70	2.45	-do-	7.8	--	-do-	0.036	0.013
[159]	1.1	--	-do-	1.88	--	2.45	-do-	3.7	--	-do-	0.683	--
[164]	--	--	-do-	--	--	2.45	-do-	7.47	--	-do-	<0.15	--
[165]	1.41	29.17	-do-	1.62	--	2.45	-do-	1.68	98.06	-do-	1.48	--
[166]	2.1	61.77	-do-	--	4.56	2.45	Dipole	5.43	95.07	-do-	--	0.03

TABLE 11. Performance analysis of dual- band wearable antenna with and without metamaterials.

Ref	Antenna without Metamaterial						Antenna with Metamaterial					
	Gain (dBi)	Rad. Eff (%)	S_{11} (on body)	Peak SAR (W/kg)		Frequency (GHz)	Antenna Topology	Gain (dBi)	Rad. Eff (%)	S_{11} (on body)	Peak SAR (W/kg)	
				1 g	10 g						1 g	10 g
[28]	--	--	Shifted	13.85	7.81	2.45	Coplanar Patch	--	--	Stable	0.079	0.043
	--	--		20.29	6.80	5.80		--	--		0.127	0.090
[46]	2.0	--		--	11.6	2.40		4.9	--	-do-	--	1.90
	1.74	--	-do-	--	18.3	5.20	Dipole	6.15	--		--	0.92
[112]	1.25	82.3	-do-	17.50	8.99	2.45	Monopole	5.2	61.3	-do-	2.48	0.7
	1.66	82.4		9.3	4.08	5.80		7.7	66.2		3.33	0.71
[167]	-0.6	--	-do-	7.23	4.18	2.45	planar	4.5	--	-do-	0.972	2.8
	1.7	--		7.23	2.06	5.80	inverted-F	5.6	--		0.668	1.51
[168]	2.5	65	-do-	38.9	15.6	2.45	(CPW) fed	5.1	70	-do-	0.035	0.018
	3.45	75		37.4	8.03	5.80	monopole	8.45	87		0.014	0.032
[169]	1.13	84	-do-	8.4	--	2.45	Monopole	5.67	78	-do-	0.35	--
	3.03	92		17.5	--	5.80		6.89	80		0.39	--
[170]	2.41	--	-do-	--	--	2.45	Printed	6.43	--	-do-	--	0.018
	3.58	--		--	--	5.80	monopole	6.85	--		--	0.016
[171]	6.55	60.2	-do-	--	5.88	2.40	Patch	7.22	62.2	-do-	--	1.97
	6.17	62.6		--	11.0	5.40		7.39	64.7		--	1.18
[172]	-0.52	66	-do-	14.07		2.45	CPW	1.7	--	-do-	1.49	--
	0.8	80		15.49		5.80	Monopole	8.1	--		1.45	--

- These antenna designs have a poor front-to-back ratio (FBR) and a narrow bandwidth.
- Due to the wearable antennas being worn on the human body or as a part of the clothes, the performance of the antenna is degraded.

As briefly discussed in Section-I, metamaterials have been incorporated into wearable/textile/flexible antennas in order to overcome the aforementioned issues. These materials are used to give a high degree of isolation of the human body from the antenna, and to reduce the SAR level to the safety threshold. Additionally, when the antenna is bent, performance suffers in terms of the resonance frequency shift. As a result, metamaterial can play a vital role in restraining the performance of the antenna when bent.

Metamaterials are increasingly being used in the design of body-worn antennas. The first metamaterial-based wearable antenna with a frequency of 2.45 GHz was proposed and explored in [161]. The traditional rigid FR-4 substrate material was used in the proposed design. The antenna was not truly a wearable antenna because the substrate used was inflexible. However, the primary goal of the study was to investigate the impact of the metamaterial on the performance of the antenna. The antenna was fabricated on the thin FR-4 substrate, and the EBG structure was integrated into the ground plane of the antenna by etching. The introduction of the EBG resulted in an increase in impedance bandwidth, an increase in overall gain, a reduction in size, and a decrease in backward radiation.

The extended version of the work presented in [161] was put forward in [162]. In this paper, a fully metamaterial-based wearable antenna design using copper tape as a conducting component of the antenna and fleece material as a substrate was discussed. It was observed that by adding the metamaterial into the antenna, the size of the antenna was reduced by 30 % and the impedance bandwidth was enhanced by 50 %. In addition, the impact of bending along both the principal (E & H) planes on the input matching and impedance bandwidth without and with EBG was studied in [163]. It was observed that when the antenna was H-plane bent, it had a little impact on the performance compared to the E-plane bending. This was due to the fact that the E-plane bending changed the resonant length. Besides, an improved performance and good impedance matching were observed when the EBG was integrated into the antenna.

The in-depth analysis of the EBG based wearable antenna was conducted by the authors in [28]. In which they proposed a dual band coplanar antenna design operated on 2.45 and 5.8 GHz frequency bands and was printed on felt textile substrate. The antenna was incorporated by an array of 3 × 3 wearable EBG structure. The reflection phase characteristics of the EBG was studied using the suspended strip line methods. It was analyzed that by incorporating only a 3 × 3 array of the EBG elements resulted in minimizing the radiation in the backward direction by over 13 dB, increasing the gain of the antenna by around 3 dB while decreasing the value of the SAR significantly. In addition, the bending of the antenna in both E and H-planes were also investigated and it was examined that the EGB integrated antenna gives better overall performance compared to the conventional counterpart.

Researchers continued to investigate and experiment on numerous metamaterials, their integration with various types of antenna designs, and the impact of the number of unit cells utilized in the array after the successful integration of the EBG structures into the wearable antennas. Additionally, the researchers and antenna engineers looked at several metamaterial combinations with various textile/wearable/flexible antenna designs and tested them on the human body phantom, where the antenna's on-body performance was evaluated. Additionally, they combined several EBG configurations with bent antennas and examined the results. Table 10 and 11 respectively summarize the performance analysis of several single-band and dual-band antennas with and without metamaterials for body-worn applications.

IX. CONCLUSION

Wearable/textile antennas are the vital components of the wearable and portable electronics. They are a good replacement for the outdated wireless sensor network technologies due to their low cost, versatility, light weight, and conformal design. The purpose of this article was to give readers the general understanding of the wearable/textile antennas and their applications in the military, sports, and health sectors. The critical design issues and challenges such as material selection, interaction of the human body with the antenna, variation in dimensions, and effects of the environment on the performance of wearable antennas have been covered in detail. The material selection is one of the most important factors in the design of a wearable antenna; therefore, the two types of materials, namely conductive and non-conductive, have been thoroughly discussed. It was discovered that the loss tangent and permittivity are the important factors to take into account while selecting a good substrate material. The substrate is an essential component of wearable antennas, hence materials that provide higher efficiency and wider bandwidth should be used to construct these antennas. It was also mentioned that a thicker, low-permittivity substrate would offer a wider bandwidth and reduce losses. Thus, it is concluded that a variety of potential conductive and non-conductive materials have been employed in the design of wearable antennas. Additionally, to attain the antenna design to satisfy the specification of wearable antennas, testing with the proximity of the human body has to be done. Consequently, it was studied how the antenna and the human body interact. The voxel and equivalent tissue models for the on-body analysis were presented, and the antenna performance on various human body parts was examined. It was found that the complex permittivity and conductivity of the lossy human body has an impact on the performance of the antenna, such as radiation pattern, resonant frequency, bandwidth, and efficiency in particular. Moreover, wearable antennas must adhere to safety limitations regardless of the kind and shape of the antenna design due to widespread worries about the health effects of radiation and illegal requirements throughout the world. The article provide a summary of the concerns regarding the harmful radiation absorbed by the human body tissues and the protection methods from the harmful radiation. It is also examined that how well the antennas performed when they were curved at different radii. It was discovered that bending affects the radiation pattern and detunes the resonance frequency. Various fabrication techniques that can be crucial in achieving outstanding stability and excellent performance from the perspective of wearable antennas were also discussed, and the benefits and limitations of each technique were explained. It is expected that the overall performance of the antenna will be affected by coupling of the antenna with the human body and absorption of electromagnetic waves by the human body tissues.

Therefore, in order to provide a high degree of isolation between the antenna and the human body and to enhance the performance of the antenna, various approaches have been used in the past, such as ferrite sheets, truncated ground, PEC reflectors, fractural slot loading, etc., however, these techniques have the limitations of bulky size, structural complexity, higher integration cost, and wearing discomfort. In the last two decades, metamaterials have been extensively utilized in the design of wearable antennas to enhance their overall performance, which includes higher bandwidth, directivity, and gain, good radiation efficiency and front-to-back ratio (FBR), and a reduced SAR value. The impact of employing metamaterials on the performance of the wearable antennas is summarized in Tables 10 and 11. In view of the above-mentioned facts, it was concluded that metamaterial-based antennas are good candidates for wearable applications.

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