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BENDING AND CRUMPLING DEFORMATION STUDY OF THE RESONANT CHARACTERISTIC AND SAR FOR A 2.4 GHZ TEXTILE ANTENNA

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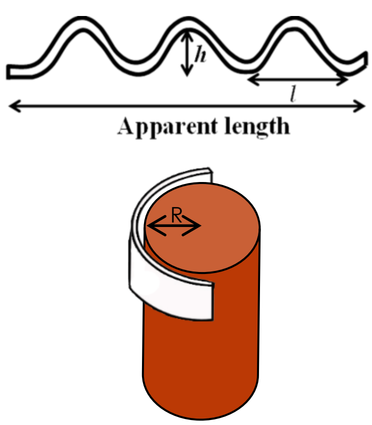
Graphical abstract



Abstract

Over recent years, there has been an explosive growth of interest in the development of flexible wearable antennas due to rapid growth in Wireless Body Area Network (WBAN) applications. However, the antenna is subjected to deformation when being worn by users. Therefore, it is compulsory to analyze the absorption of electromagnetic (EM) radiation and the antenna performances as a function of the deformation conditions since the antenna is not in its normal flat conditions anymore. In this paper, two types of deformations; bending and crumpling are analyzed by means of CST Microwave Studio. The peak SAR_{10g} demonstrates increment up to 65.7 % and 48.7 % under bending and crumpling deformation respectively. Moreover, the crumpling is more sensitive to the geometrical shape and composition of the exposed body area if compared to bending. Moreover, the detuning effects of the resonant frequency are more significant for crumpling cases.

Keywords: Electromagnetic wave absorption; SAR (Specific Absorption Rate); electromagnetic radiation; dipole antennas; electromagnetic fields

Abstrak

Kebelakangan ini, terdapat percambahan minat di dalam pembangunan antena-antena boleh pakai yang fleksibel disebabkan oleh pertumbuhan pesat di dalam aplikasi *Wireless Body Area Network*. Walau bagaimanapun, antena tersebut terdedah kepada kecacatan ubah bentuk apabila dipakai oleh pengguna. Justeru, adalah wajib untuk menganalisis penyerapan radiasi elektromagnetik *(EM)* dan prestasi antena berdasarkan keadaan ubah bentuk kerana antena itu tidak lagi berada dalam keadaan normalnya yang rata. Dalam kajian ini, dua jenis ubah bentuk; lenturan dan kedutan dianalisis dengan menggunakan *CST Microwave Studio*. Maksimum SAR_{10g} menunjukkan peningkatan sehingga 65.7 % dan 48.7 % masing-masing untuk ubah bentuk lenturan dan kedutan. Selain itu, ubah bentuk kedutan adalah lebih sensitif kepada bentuk geometri dan komposisi kawasan tubuh badan yang terdedah jika dibandingkan dengan lenturan. Tambahan pula, kesan peralihan frekuensi resonan adalah lebih ketara bagi kes kedutan.

Kata kunci: Penyerapan gelombang elektromagnetik; SAR (Specific Absorption Rate); sinaran elektromagnet; antena dwikutub; medan elektromagnet

1.0 INTRODUCTION

Over recent years, there has been an explosive growth of interest in the development of flexible wearable antennas due to rapid growth in Wireless Body Area Network (WBAN) applications [1]. It has been recognized that an effective wearable antenna should possess flexibility and elasticity structure criteria in order to ensure it is comfort to the user. Therefore textile antenna is a promising candidate since it can be fully integrated into intelligent garments, known as wearable electronic systems [2].

However, this flexibility criteria leads to the formation of bending and crumpling due to the complex shape and curvature of human body. In addition, the human body movement will also expose the antenna to such deformation. The antenna deformation may degrade the antenna performance. Researches in [3–5] reported that the resonant frequency, input matching and impedance bandwidth of the antenna fluctuates remarkably when the antenna is exposed to bending and crumpling. Based on [6-7], circular polarization antennas lose their polarization property when bent. Other than that, authors in [3, 8–10] have compared the effects of bending towards conventional and Electromagnetic Band Gap (EBG) antenna. They found that under bending conditions, reflection coefficient responses for the EBG antenna are more stable than the conventional patch antenna. In [11], the authors concluded that for the studied of 2.05 GHz Coplanar Waveguide (CPW) monopole antenna, the antenna performances modifications under crumpling deformations are greater than bending.

Furthermore, even in the normal flat condition, degradation of the wearable antenna performance is expected since the antenna is mounted close to the human body [12-13]. But there is another major concern which is the potential of adverse health effect from the backward radiation that goes towards the human body. The health effect usually measure by Specific Absorption Rate (SAR). The SAR quantifies the power absorbed per unit mass of tissue. SAR is the standard unit used to measure the rate of energy absorbed by the human body when exposed to the electromagnetic radiation. The maximum permissible exposure limits to the RF energy which have been set by International Committee for Non-Ionizing Radiation Protocol (ICNIRP) and Institute of Electrical and Electronics Engineers (IEEE) for the head and trunk is 2 W/kg over 10 g mass of tissue for the general public exposure. Hand held and body worn electronic devices must comply with this basic restriction in order to avoid excessive heating in the human biological tissue. The formula for SAR calculation as follows:

$$SAR = \frac{\sigma |E|^2}{\rho} \quad \text{(W/kg)} \qquad (1)$$

where,

σ : conductivity of the tissue (S/m),
ρ : mass density of the tissue (kg/m^3)
$|E|$: total RMS electric field strength (V/m)

In [9], authors demonstrate that an EBG structure could provide lower SAR due to reduced backwards radiation from the dual frequency band textile antenna. Moreover, authors [14] show that the localized SAR of the designed flexible foam material-based substrate decreases with increasing dimensions of the ground plane. Whereas our previous work [15] has briefly investigated the bending effects towards SAR using the same textile antenna as in this paper.

Up to date, there are very limited number of researches that focuses on the near-field effect of the crumpling and bending towards the SAR. Therefore, the interaction between the deformed antenna and the user body is investigated in this paper in terms of resonant frequency detuning, electric field behavior and SAR value.

2.0 METHODOLOGY

The numerical simulations are performed by using Finite Integration Technique (FIT) by means of CST Microwave Studio. A more generic sources which is a dipole antenna is used as the radiating sources to allow comparison with previous research and keeps the exposure system simple and repeatable [16]. The 2.4 GHz textile antenna is made of denim as the substrate and copper tape as the conducting element [17]. The 50 ohm SMA connector is soldered to the feeding line. The antenna is crumpled and bent by controlling the parameters below as illustrated by Figure 1. The parameters are controlled according to the values in Table 1 and Table 2 respectively.

For bending, the antenna is bent around a cylinder of radius *R* (Figure 1(b)). Small bending radius, *R* indicates a high curvature while large *R* represents low curvature. Only E-plane bending (antenna bent along xz-plane) is studied in this paper. Research in [15] has shown that antenna bending in the E-plane has higher SAR value if compared to the bent antenna along the H-plane. This bending radius is chosen as to replicate a normal deformation scenario when the antenna is worn on the human arm. Four cases, Case 1 to Case 4 are considered for each of the bending and crumpling cases to represent ascending order in the amount of bending and crumpling. Meanwhile, flat indicates a normal planar orientation of the antenna.

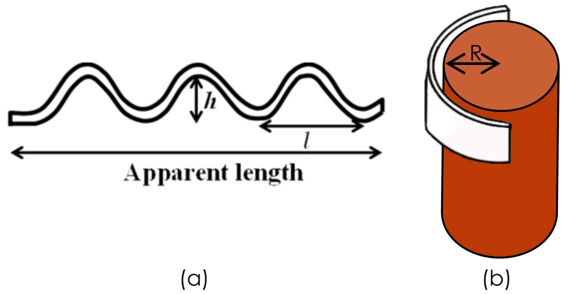


Figure 1 Depiction of the (a) crumpling parameter, and (b) bending parameter

Table 1 Crumpling parameters and the antenna dimension after exposed to crumpling [a]

	Crumple height, *h*	Crumple length, *l*	Apparent length
Flat	N/A	N/A	140
Case 1	11	40	133.24
Case 2	11	18	115.19
Case 3	11	10	90.23
Case 4	11	8	79.28

[a]All dimensions are in millimeter (mm).

Table 2 Bending parameters and the antenna dimension after exposed to bending [a]

	Bending radius, *R*	Apparent length	Apparent dipole arm length
Flat	N/A	140	85
Case 1	80	124	81.17
Case 2	70	119.12	80.02
Case 3	60	111.77	78.28
Case 4	50	100.08	75.47

[a]All dimensions are in millimeter (mm).

After the antenna is bent and crumpled in free space, a high resolution 3D voxel human body model is imported into the simulation as depicted by Figure 2. Gustav male model is used in this simulation which consists of 32 types of human biological tissues. The electrical properties of all the tissues are defined at 2.4 GHz [18]. In this study, the antenna is placed at several distances from the human arm, *d*; 1, 5, 10, and 20 mm as illustrated by Figure 2. These distances are chosen by considering the thickness of the clothing and air gap that may exist between the antenna and the human body. The antenna is positioned on the arm because the result in [15] has shown that the absorption will be higher in the arm area due to less fat tissue. Therefore the arm position is critical in order to characterize the worst case scenario.

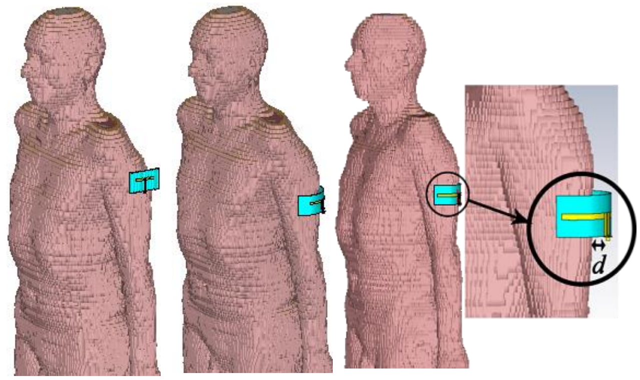


Figure 2 Depiction of the crumpled and bent antenna placed close to human arm and the distance, *d*

3.0 RESULTS AND DISCUSSIONS

3.1 Resonant Characteristics

In this section, the effects of bending and crumpling will be discussed in terms of the resonant frequency and bandwidth when the antenna is in free space and at several distances from the human body. In free space scenario, the antenna resonant frequency is shifted to the higher frequency by 520 MHz when exposed to crumpling deformation as depicted by Table 3. This is because the antenna apparent length has become much shorter when crumpled as shown in Table 1. Whereas, the bending only reduce the reflection coefficient value of the antenna without shifting the antenna resonant frequency. This is due to the smaller changes in the apparent length of the antenna. Besides that, the -10 dB bandwidth of the antenna has gradually decreased as the bending and crumpling conditions become more extreme.

Table 3 The antenna resonant frequency for bending and crumpling condition in free space

		f_r (GHz)	S_{11} (dB)	Bandwidth (MHz)
Flat		2.44	-48.78	390
Bending	**Case 1**	2.44	-43.40	360
	Case 2	2.44	-41.50	360
	Case 3	2.44	-31.89	358
	Case 4	2.44	-27.78	350
Crumpling	**Case 1**	2.46	-32.32	371
	Case 2	2.56	-24.39	370
	Case 3	2.74	-16.16	330
	Case 4	2.96	-13.19	261

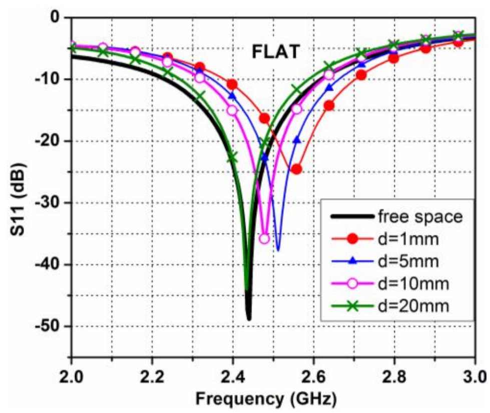


Figure 3 The antenna resonant frequency for flat case and placed at several distances from human arm

from the human arm. The graph shows that in flat condition, the antenna reflection coefficient is better when the distance between the antenna and the human body, *d* is increased. Moreover, the resonant frequency varies with the changes of the separation distance between the antenna and human body, *d* whether the antenna is in flat or bent condition, as shown by Figure 3 and Figure 4.

However, by comparing Figure 3 and Figure 4, we can see that the detuning of the resonant frequency is enhanced when the antenna is bent. In this paper, only bent Case 4 graph is shown since the other cases exhibit similar trend. Besides that, the Case 4 graph in Figure 4 shows that when the antenna is bent, the antenna reflection coefficient is better when the antenna is closest to the human body.

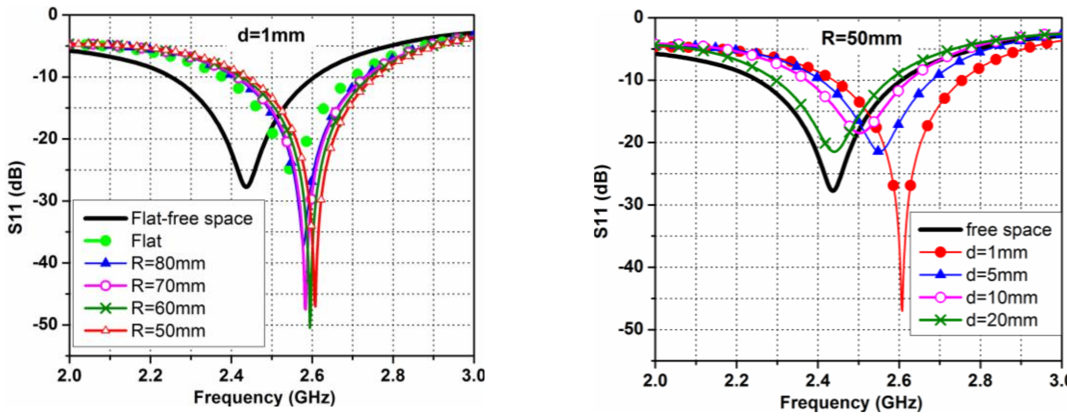


Figure 4 The antenna resonant frequency for all bending cases at 1 mm distance and the bent antenna (Case 4) placed at several distances from human arm

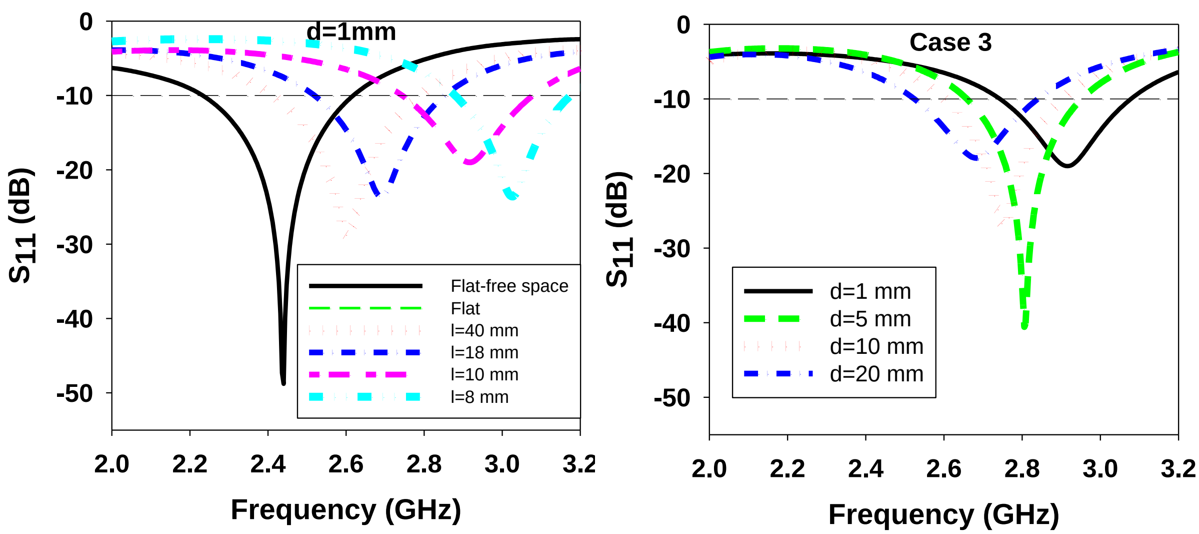


Figure 5 The antenna resonant frequency after crumpled with varying *l* at 1 mm antenna-body distance and crumpled Case 3 antenna placed at several distances from human arm

Figure 3 illustrates the resonant frequency when the normal flat antenna is placed at various distances

Furthermore, when comparing the graph for bent and crumpled antenna at *d*=1 mm in Figure 4 and Figure 5, it can be seen that the amount of crumpling deformation has significant effect on the resonant frequency compared to the bending cases. Different crumpling cases will result in huge shift of the resonant frequency even though the distance between the antenna and body, *d* is the same. In addition to that, the graphs also show significant changes in the operating frequency when the antenna is placed closer to the body. This is true for all flat, bent and crumpled conditions.

Generally, the presence of the human body has further shifted the antenna resonant frequency and the highest shift of the resonant frequency is observed for Case 4. However the detuning effect is more prominent when the antenna is crumpled and positioned closest to the human body.

3.2 Electric Field Intensity (Free Space)

Firstly, the antenna electric field behaviour when deformed in free space will be studied to provide better understanding on their behaviour when placed close to the human body. The effect of bending and crumpling is compared and the effect is further discussed in this section. Table 4 shows the electric field behaviour for the textile antenna under bending and crumpling deformation in free space environment. It can be seen that in normal flat case, the maximum field existed at the centre between the dipole arms. As the antenna crumpled and as the crumple become more extreme, the electric field is concentrating at the end of the dipole arm and at the feeding line close to the SMA port. On the other hand there is negligible effect on the electric field behaviour of the antenna for bending deformation cases, in which the maximum peak of electric field remains at the centre of the dipole arm.

Flat

Case 1

Case 4

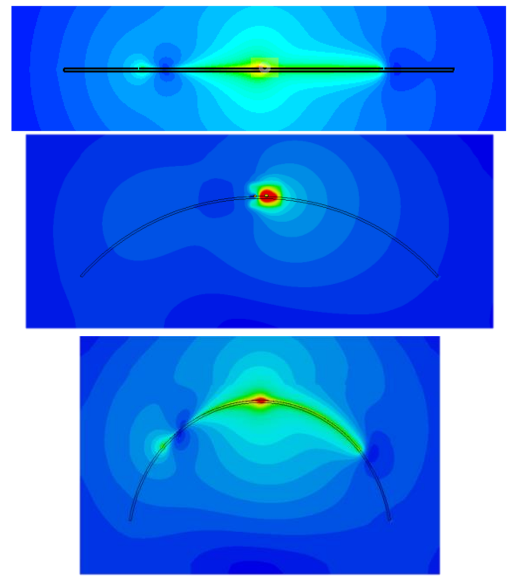
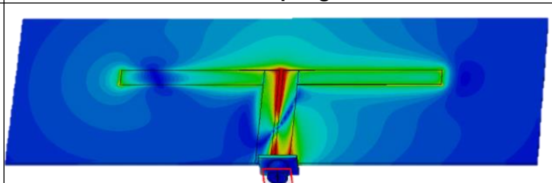
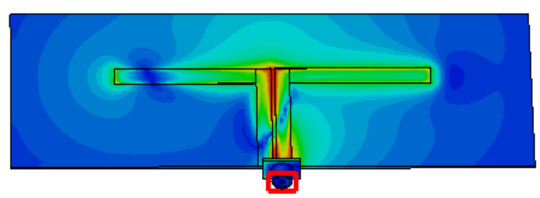
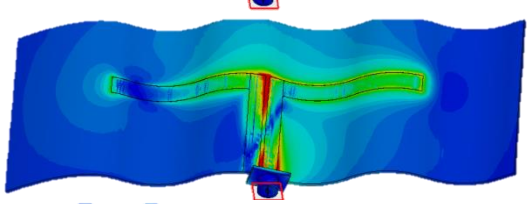
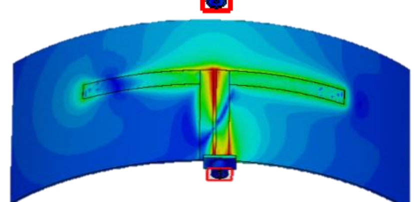
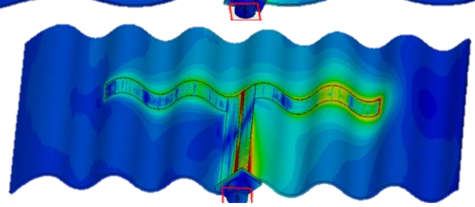
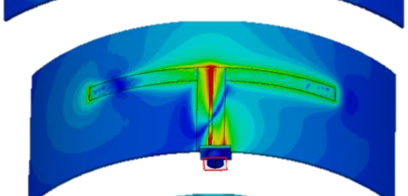
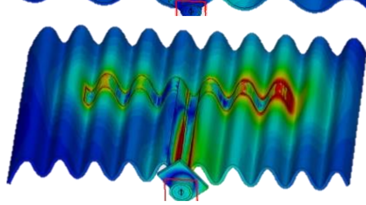
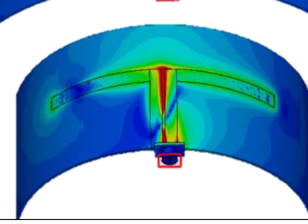


Figure 6 The antenna electric field at y-plane for flat and bent cases

Table 4 The electric field behavior of the antenna exposed to crumpling and bending deformation in free space

	Crumpling	Bending
flat		
Case 1		
Case 2		
Case 4		

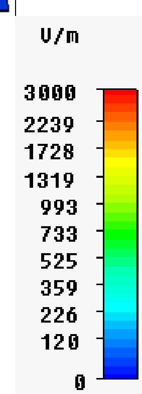


Table 5 Peak SAR_{10g}, peak SAR_{1g}, peak point SAR and their positions for 2.4 GHz textile antenna under bending and crumpling conditions [a].

	Bending					Crumpling				
	Peak SAR (W/kg)			Peak SAR_{10g} position	Peak SAR_{1g} & point SAR position	Peak SAR (W/kg)			Peak SAR_{10g} position	Peak SAR_{1g} & point SAR position
	10g	1g	Point SAR			10g	1g	Point SAR		
Flat	16	41.38	2107	fat	skin	16	41.92	2106.61	fat	skin
case1	22.03	57.1	4727.69	fat	skin	13.96	34.71	251.6	fat	skin
case2	23.56	59.82	1972.22	fat	skin	16.83	41.77	345.75	fat	skin
case3	24.44	62.44	3279.69	fat	skin	21.29	51.9	501.27	fat	skin
case4	26.51	66.22	1831.67	fat	skin	23.79	58.19	12169.9	fat	skin

[a]The accepted power for all cases is normalized to 1 Watt.
[b]The distance and position of the antenna is kept constant throughout the simulation at 1 mm from the body (arm).

Correspondingly, the electric field behaviour at y-plane under bending deformation is also shown in Figure 6. The value is normalized to the same scale as in Table 4. It can be seen that the electric field intensity for Case 4 is higher than Case 1. Therefore it is expected that the antenna backward radiation towards the body is higher for Case 4.

3.3 Specific Absorption Rate

In this section, the effects of bending and crumpling deformation with the close proximity of human body will be discussed in terms of the EM absorption and the penetration of the radiation into the human tissues. The effects of different crumpling and bending cases when placed at 1 mm from the human arm towards the SAR value is summarized in Table 5. The accepted power has been normalized to 1 W for all cases investigated. From Table 5, the highest SAR_{10g} and SAR_{1g} is observed when the antenna is bent (Case 4). This is due to the increment in the antenna backward radiation when the antenna is bent. Bending has enhanced the peak SAR_{10g} and SAR_{1g} by 65.7 % and 60 % respectively. On the other hand, the crumpling deformation increases the peak SAR_{10g} and SAR_{1g} by 48.7 % and 38.8 % respectively. In addition to that, the peak SAR_{10g} and SAR_{1g} for the textile antenna exposed to bending deformation is gradually increased from Case 1 to Case 4. Whereas for crumpling deformation, the peak SAR_{10g} and SAR_{1g} has slightly dropped for Case 1 and then continue to increase from Case 2 until Case 4. This may be due to the position of the port that has move away from the body due to the crumpling.

Table 5 also summarizes the peak SAR_{10g} and SAR_{1g} location inside the human tissues. Fortunately, the peak is around the surface layer only. No deep penetration is observed when the antenna is bent and crumpled. For all flat, bending and crumpling cases, the peak SAR_{10g} is found at the fat tissue layer, whereas the peak SAR_{1g} is found in the skin tissue. Furthermore, the position and distance between the antenna and the human body is varied and the results are presented in Figure 7 and Figure 8 are for bending and crumpling cases respectively at slightly different arm position.

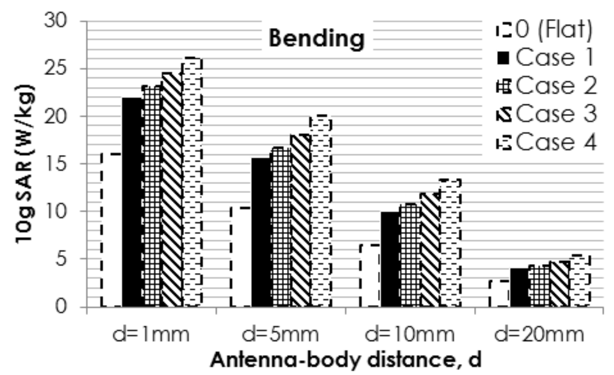


Figure 7 The peak 10 g SAR value under bending deformation with the variation of antenna-body distance, *d*

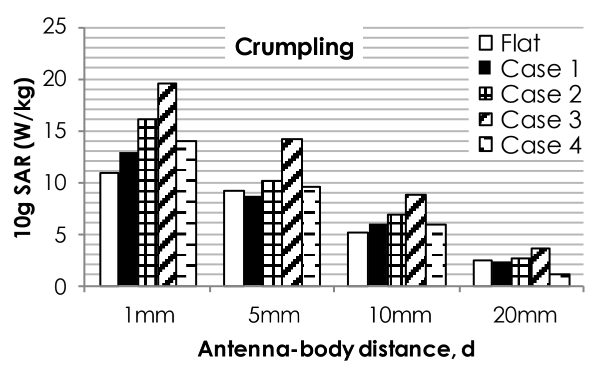


Figure 8 The peak 10 g SAR value under crumpling deformation with the variation of antenna-body distance, *d*

By referring to Figure 7, it can be seen that even at different separation distances and position, the antenna still exhibit the same trend of increasing peak SAR_{10g} value when bending towards the body. Whereas, the antenna crumpling possess slightly different trend of SAR. In this position, the peak SAR_{10g} is gradually increased from Case 1 until Case 3 and then slightly dropped in Case 4 (Figure 8). However the value for Case 4 is still higher than the flat case for *d*= 1, 5, 10 mm. This is happening because of the different in anatomical shape of the exposed human body. Moreover, it can be observed that the electromagnetic absorption for antenna exposed to crumpling deformation is highly influenced by the on-body position of the antenna if compared to the bending which is insensitive to different on-body position.

4.0 CONCLUSION

The effects of bending and crumpling deformation towards the antenna resonant characteristics, electric field behaviour, peak SAR and EM penetration depth have been studied in this paper. When comparing these two types of deformation, it can be concluded that crumpling has greater detuning effect on the antenna resonant frequency, bandwidth and reflection coefficient values. Both deformations will shift the resonance to higher frequency due to the changes in the apparent length of the antenna. Additionally, the electric field behaviour of the antenna has been altered and thus enhances the absorption of the EM radiation by the human body.

Furthermore, the peak SAR_{10g} is increased for up to 65.7 % and 48.7 % under bending and crumpling deformation respectively. Moreover, the crumpling is more sensitive to the geometrical shape and composition of the exposed body area if compared to bending. Besides, increasing the antenna-body distance, *d* will lower the SAR value but still possess the same trend of SAR increment when the bending and crumpling amount is increased.

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