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Development and printing of three-dimensional electrodes for the high body adhesion of smart wear

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Abstract

Herein, we investigate the effects of 3D printed electrodes on electrophysiological signals and identify the important design elements required for manufacturing better electrodes for high body adhesion for smart wear. Ten electrodes of different shapes (plain, check, stripe, circular, radial cut-out) and thicknesses (0.5 mm and 1.0 mm) were manufactured. The electrodes were evaluated by testing on 20 healthy individuals (10 men and 10 women). To measure the electroencephalogram (EEG) of the participants, we used BIOS-S8 (BioBrain Inc., Korea), an 8-channel polygraph for multibody signal measurement. Data were analyzed using the SPSS 26.0 statistical program. The EEG values were significantly activated according to gender. For the male participants, relative alpha (RA), relative slow theta (RST), relative mid theta (RMT), and the ratio of SMR-mid beta to theta (RSMT) values were highly activated and for the female participants, RA, relative fast alpha (RFA), and relative slow theta (RSA) values were highly activated. There were no significant gendifferences in the EEG of both genders for the 10 types of electrodes. However, for the female participants, the 'RA' indices showed a significant difference based on electrode shape on the right temporal lobe (T4), but there was no significant difference based on the thickness. There was a significant difference in the subjective preference of the electrodes also. In the subjective evaluation, it was found that the differences based on the shape and thickness of the electrodes were sensitively recognized.

Keywords: Smart wear, 3D printing, Electrode shape, High body adhesion, Electroencephalogram (EEG)

Introduction

In the last decade, Korea's medical expenses burden has increased the fastest among major organization for economic cooperation and development (OECD) countries due to an aging society and an increase in chronic diseases, such as hypertension, diabetes, and cardiac disorders. Such medical expenses and health concerns have brought public attention to healthcare that can manage and prevent the occurrence of diseases (Han & Kim, 2020; Jang & Cho, 2019). Therefore, studies on wearable biosignal monitors for real-time observation of people's health and prompt reactions in emergencies are being actively conducted (Ates et al., 2021; Devi et al., 2023; Kim et al., 2019, 2021; Lee & Cho, 2019; Lu et al., 2020; Sprogis et al., 2019).

Currently, wearable biosignal monitoring is being conducted through devices such as smartwatches, smart belts, and smart clothing. In particular, smart clothing mostly measures biosignals by connecting sensors with electrodes to clothing. In this case, sensors are highly important for the measurement of stable and precise signals within the body, so various crafting methods for such electrodes have been continuously studied (Banitaba et al., 2023; Jang & Cho, 2019; Kang et al., 2008; Seoane et al., 2013; Song et al., 2010; Takagahara et al., 2014; Yapici & Alkhidir, 2017). Electrodes are devices that deliver electrical signals from within to the outside of the body by monitoring the potential difference that occurs because of the many electric fields on the skin. Currently, data are obtained by sensing the potential difference of the delivered signal, and various biosignals, such as the electrocardiogram (ECG) and electromyogram (EMG), can be analyzed using these data. To date, diverse types of electrodes, such as gel electrodes, metal electrodes, and fiber electrodes, have been used to measure biosignals. Gel electrodes, which are mainly used in medical centers, are disposable, require frequent replacement, and cause environmental problems. Moreover, they exhibit side effects, such as skin irritations and itchy skin rashes, when used for long durations; therefore, dry electrodes such as metal plates, flat plates, and fiber electrodes have been developed. However, not only are metal electrodes hard and cold where they contact the skin, but they also have a low adhesive force, making it difficult to obtain biosignals in body areas with high curvature. Therefore, many studies have been conducted recently to develop fiber electrodes that do not cause discomfort upon contact and are easy to attach to clothing (Lee, 2010; Lee & Cho, 2019; Pani et al., 2019). A major problem that occurs when wearing smart clothing that uses fiber electrodes is that precise and stable biosignals can be obtained in an upright posture, but not during active motion as the electrode detaches from the body, leading to noise and inaccurate measurement. In addition, when applied to smart clothing, the wearer may experience discomfort due to sensor contact.

Therefore, electrodes that can measure stable and precise data, as well as enhance wearing comfort, need to be developed. For this purpose, studies on the material and design of electrodes and their contact with the body (Jang, 2006; Jeong & Yang, 2012; Jeong et al., 2010), the design of electrodes that contact the body (Cho et al., 2018; Cömert et al., 2013; Lee, 2010; Song et al., 2010), and the optimal location of electrodes for high adhesion (Cho et al., 2010; Cho & Cho, 2015; Cho & Lee, 2015; Mohindra et al., 2007; Self et al., 2006; Tysler et al., 2007), etc. are being conducted in the fashion industry. Specifically, Jeong et al. (2010) suggested an optimal contraction rate and smart design for the precise measurement of ECG by applying different contraction rates. Cho et al. (2018) confirmed that solid electrodes produce signals of better quality than flat electrodes by examining six types of electrodes crafted through a combination of electrode size and composition (flat/solid). Cho and Cho (2015) used body mapping technology to examine the rate of change of body surface and clothing and suggested that the front of the chest and beneath the shoulder blade are the optimal locations for electrodes that are least affected by body movement. In previous studies, it was found that the design, structure, and location of the electrode had an important influence on obtaining high-quality signals by a resulting increase in the contact surface area by increasing the adhesion between the skin and the electrode, and by reducing the electrical noise. However, there are no studies on applying the electrode structure to smart clothing by modifying the electrode structure; in particular, there is no research that we know of on the development of an electrode shape with high adhesion to the body by applying 3D printing. Moreover, few studies have objectively analyzed the effect of electrode sensors on overall comfort. Therefore, a 3D printed electrode structure with high adherence and comfort upon contact needs to be developed for the precise measurement of biosignals, and the subtle differences must be effectively verified. Such subtle differences while wearing functional clothing have been recently detected using physiological signals such as brain wave electroencephalogram (EEG) and electrocardiogram (ECG) (Bang & Kim, 2012; Jeong & Kim, 2009; Krzemińska et al., 2023; Lee & Lee, 2021; Lee et al., 2019). These brain waves are signals that reflect physiological responses and psychological status and respond immediately upon external stimuli, allowing the analysis of comfort sensation that is swiftly changing (Han & Chun, 2019).

Therefore, in this study, in order to develop a 3D printed electrode structure with excellent adhesion and contact sensation that can be applied to smart wear, various types of electrode sensors were attached to the skin and EEG measurements and subjective sensation evaluation were conducted. At this time, by analyzing men and women who have differences in the sense of external stimuli, we attempted to find a form of electrode sensor with excellent adhesion and comfort sensation according to gender, and provided fundamental data so that this could be used when designing fabric electrode sensors.

Methods

Participants

Twenty healthy adults in their twenties (10 males and 10 females) without a brain or cognition-related disease and medical history were selected to participate in this experiment. Based on previous research (Lee, 2016, 2020; Lee & Lee, 2020a, b), there are statistically significant differences in tactile sensation with respect to gender among demographic characteristics. Therefore, in this study, we divided the participants into male and female groups for experimentation and analysis. The experimental procedures related to subjective evaluation and EEG measurements were explained to them before the experiment, and consent forms were signed by all participants. The experimental procedure was approved by the Institutional Review Board (IRB) (No. 202106-HR-013-01). Moreover, all participants were given ample sleep the day before the experiment and banned from consuming alcohol, caffeine, medicine, prohibited from excessive exercise to reduce interference with the nervous system. On the day of the experiment, participants were excluded from the experiment if their health and fatigue conditions were abnormal to minimize the effect of physical conditions related to concentration. The characteristics of the participants' bodies are shown in Table 1, body mass index (kg/m^2) and total body fat (%) were measured using InBody (Inbodyco., Ltd., Korea).

Experimental electrodes and evaluation of flexural modulus

The electrode sensors for measuring biosignals used in this experiment were designed considering various motions and three-dimensional human body shapes. Two types of thicknesses (0.5 and 1 mm) and five shapes (plain, check, stripe, circular, and radial

Table 1 Physical characteristics of participants (N = 20)

Participants	Age (years)	Height (cm)	Weight (kg)	Body mass index (kg/m^2)	Total body fat (%)
Male					
Mean (SD)	21.80 (1.01)	176.60 (4.12)	70.23 (6.28)	23.7 (1.86)	21.9 (3.18)
Female					
Mean (SD)	21.50 (0.98)	162.25 (3.97)	52.05 (5.82)	20.1 (3.85)	23.1 (4.79)

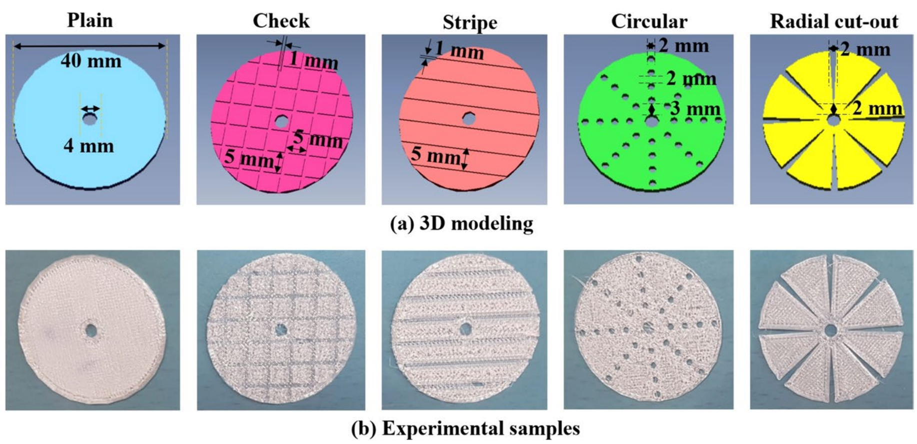

Fig. 1 3D modeling results and produced experimental samples

cut-out) were combined, totaling ten types. Based on the preliminary experiments, we chose 0.5 mm and 1.0 mm as thickness variables because they allowed for successful printing while maintaining good adhesion.

The 3D printed electrode sensors used in this experiment were circular with a diameter of 40 mm, with a circular hole of 4 mm diameter at the center of the base type (plain), while the other four types (check, stripe, circular, and radial cut-out) retained the same outer 40 mm circle but the inner shapes were varied. Moreover, the thickness of the electrode sensors was 0.5 mm and 1.0 mm for each shape. The plain type uses the original circle of 40 mm diameter, the check type has horizontal and vertical 1 mm grooves at 5 mm intervals, and the stripe type has horizontal 1 mm grooves at 5 mm intervals. The circular type has four small holes with a 2 mm diameter at 2 mm intervals on a radial shape every 45°, and the radial cut-out has cuts of 2 mm width 2 mm away from the center of the circle at 45° intervals. The electrode sensors were modeled using the Geomagic Design X program (3D Systems, Inc., Korea), and were 3D printed using a 3D printer (CUBICON Single Plus 3DP-310F) and Cubicreator Program. An FDM-type 3D printer was used, and the printing directory was confirmed and saved via G-code using the view mode of slicing software before printing. As the printing material selected TPU because it has been evaluated to offer superior flexibility, recovery, durability, and thermal comfort compared to other non-breathable materials commonly used in recent sensor applications (Jung & Lee, 2022; Lee et al., 2022). The printing conditions were set as 100% inner density, discharge temperature of 230 °C, bed temperature of 65 °C, printing speed of 15–30 mm/s, and layer height of 0.15 mm for better printing quality. Experimental samples were crafted as shown in Fig. 1b, and the experiment was carried out.

Flexural modulus refers to stiffness or softness, and it is a critical factor not only for evaluating flexibility but also for adhesion to the skin. Therefore, the flexural modulus of the electrode sensors was analyzed in this experiment. The experimental method and crafting of the samples were carried out following ASTM D 790-99, the testing standard for curvature evaluation of unreinforced material and plastic. Sample sizes were $127 \times 12.7 \times 5$ mm and $127 \times 12.7 \times 10$ mm, span length was 80 mm, and the descent rate of crosshead was 2.1 mm/min for three-point bending evaluation. The flexural modulus for the ten sensors is shown in Table 2, and it differs according to sensor thickness and shape, with plain type displaying the highest flexural modulus for 5 mm thick sensors followed by circular, radial cut-out, and check and stripe types. Meanwhile, the circular type had the highest flexural modulus for the 10 mm sensors followed by plain, radial cut-out, check, and stripe types. The sensors with lower flexural modulus are more flexible, meaning that check and stripe types were the most flexible for both thicknesses. In addition, the flexural modulus was greater for the 10 mm sensors than for the 5 mm sensors for all types of sensors. This concurs with the results that flexural modulus increases with thickness (Lee & Lee, 2020a, b), and confirms the reduction in flexibility as the thickness increases.

Experimental equipment and procedure

Electroencephalography according to the adhesion of each electrode sensor was recorded using an eight-channel data acquisition system BIOS-S8 (BioBrain Inc., Daejeon, Korea). As shown in Fig. 2 (Lee & Lee, 2021), electroencephalography was measured at seven locations according to the International 10–20 System (Jasper, 1958): F3 (left hemisphere, frontal lobe), F4 (right hemisphere, frontal lobe), T3 (left hemisphere, temporal lobe), T4 (right hemisphere, temporal lobe), O1 (left hemisphere, occipital lobe), O2 (right hemisphere, occipital lobe), and Cz (crown). The reference electrode at A1 was attached behind the left earlobe, and the ground electrode was attached to the forehead.

The EEG signals were digitized at a sampling frequency of 250 events/s (250 Hz). The relevant frequencies were filtered using a time-series biosignal data analysis program (BioScan, BioBrain), and EEG rhythm data were recorded in the frequency domains. Spectrum values, which reflect the quantitative value of the EEG rhythm, were then calculated. The EEG was batch-analyzed using an analysis program on indices defined according to wavelength (Kim, 2016), including the relative theta power spectrum(RT), relative alpha power spectrum (RA), relative beta power spectrum (RB), relative gamma

Table 2 Flexural modulus of experimental electrodes (unit: MPa)

Shape	Thickness	
	5 mm	**10 mm**
Plain	53.58	78.84
Check	10.74	15.80
Stripe	10.50	12.04
Circular	46.34	84.28
Radial cut-out	34.18	47.00

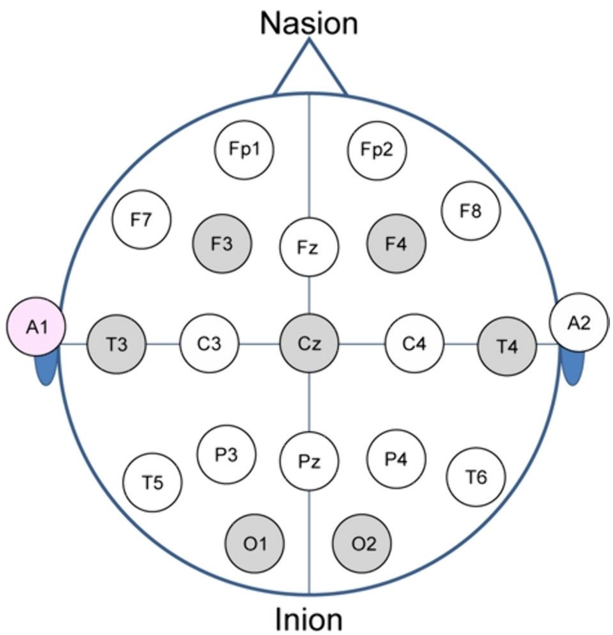

Fig. 2 EEG measurement locations

Table 3 Analysis indices for the EEG

Abbreviation	Full terminology	Frequency range
RT	Relative Theta Power Spectrum	(4–8 Hz)/(4–50 Hz)
RA	Relative Alpha Power Spectrum	(8–13 Hz)/(4–50 Hz)
RB	Relative Beta Power Spectrum	(13–30 Hz)/(4–50 Hz)
RG	Relative Gamma Power Spectrum	(30–50 Hz)/(4–50 Hz)
RFA	Relative Fast Alpha Power Spectrum	(11–13 Hz)/(4–50 Hz)
RSA	Relative Slow Alpha Power Spectrum	(8–11 Hz)/(4–50 Hz)
RLB	Relative Low Beta Power Spectrum	(12–15 Hz)/(4–50 Hz)
RMB	Relative Mid Beta Power Spectrum	(15–20 Hz)/(4–50 Hz)
RHB	Relative High Beta Power Spectrum	(20–30 Hz)/(4–50 Hz)
RST	Ratio of SMR to Theta	(12–15 Hz)/(4–8 Hz)
RMT	Ratio of Mid Beta to Theta	(15–20 Hz)/(4–8 Hz)
RSMT	Ratio of (SMR–Mid Beta) to Theta	(12–20 Hz)/(4–8 Hz)
RAHB	Ratio of Alpha to High Beta	(8–13 Hz)/(20–30 Hz)

power spectrum (RG), relative fast alpha power spectrum (RFA), relative slow alpha power spectrum (RSA), relative low beta power spectrum (RLB), relative mid beta power spectrum (RMB), relative high beta power spectrum (RHB), the ratio of the sensorimotor rhythm (SMR) to theta (RST), ratio of mid-beta to theta (RMT), ratio of SMR-mid beta to theta (RSMT), and ratio of alpha to high-beta (RAHB). The frequency range of each index is listed in Table 3. To reduce individual differences in the EEG analysis index (Suh et al., 2011), 91 values (7 measurement locations × 13 analysis indices) were analyzed by subtracting the basal EEG value from the experimental EEG.

The experimental procedures are set with reference to previous studies (Choi et al., 2014; Lee & Cho, 2015; Lee & Lee, 2020a, b; Park & Lee, 2021), and was shown in

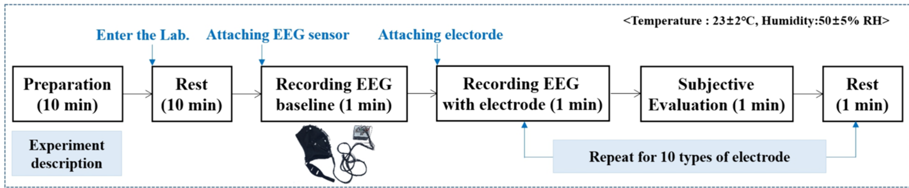

Fig. 3 Experimental protocol

Fig. 3. EEG measurements according to electrode sensor type were conducted in a laboratory set at room temperature of 23 ± 2 °C and relative humidity of 50 ± 5%. After entering the laboratory, the participants were briefed on the overall experimental procedure and cautions. After a 10 min break, participants sat comfortably in a chair to reduce noise in the EEG data and were fitted with special fabric caps to which EEG electrodes had been attached (BIOS_Dry_8, Biobrain, Daejeon). First, Base EEG in the relaxed state was measured for 1 min without attaching experimental electrode. Then experimental electrode was placed on the brachioradialis, both ends of the experimental electrode were pressed with the thumb and index fingers of the right hand to attach the experimental electrode to the brachioradialis, and then the EEG was measured for 1 min. The data used excluded the first and last ten seconds of the measurement duration. After measuring the EEG, subjective evaluation was conducted using four questions on "skin adhesion," "feeling of contact," "flexibility," and "overall comfort," and was conducted using a 7-point Likert scale ranging from 1 point for "strongly disagree" to 7 points for "strongly agree." Afterward, a minute break was given. The electrode sensors were placed on the participants using an altered Latin square design to minimize the effect of ordering.

Data analysis

All measured data were statistically processed using SPSS 26.0 (IBM, New York, USA). T-tests of individual samples were utilized to analyze differences in EEG indices according to gender, and ANOVA and Duncan post-hoc tests were conducted to analyze differences in EEG indices according to the ten types of electrodes. Additionally, correlation was conducted to examine the relationship between EEG indices value data and subjective evaluation data. Significance was set at $p < 0.05$.

Results and discussion

EEG changes upon attaching electrodes according to gender

To examine whether the sensor causes discomfort and irritation when the developed electrode sensor is closely attached to the skin, changes in the EEG index according to the presence or absence of contact with the electrode sensor were analyzed. As shown in Table 4, 18 EEG values showed a statistically significant difference ($p < 0.05$). Significant differences were extracted from the frontal lobe (F), temporal lobe (T), and crown (Cz), and the indices were relative alpha (RA), relative fast alpha (RFA), relative gamma (RG), relative slow theta (RST), relative mid theta (RMT), and the ratio of SMR-mid beta to theta (RSMT).

Table 4 T-test results of changes in EEG indices according to gender to contact with electrode sensor

EEG index_sensor position	Men Mean (SD)	Women	*t*
RA_F4	−0.021 (0.06)	0.001 (0.02)	−3.579***
RA_T4	−0.029 (0.15)	0.025 (0.08)	−3.046**
RFA_Cz	−0.002 (0.02)	0.005 (0.01)	−2.460*
RSA_F3	−0.007 (0.04)	0.004 (0.02)	−2.436*
RSA_F4	−0.017 (0.04)	0.001 (0.01)	−4.295***
RSA_Cz	−0.018 (0.04)	0.006 (0.01)	−5.583***
RG_T3	0.005 (0.03)	0.006 (0.04)	2.277*
RG_Cz	0.003 (0.03)	0.005 (0.03)	2.078*
RST_F3	0.011 (0.15)	−0.051 (0.17)	2.784*
RST_T3	0.034 (0.14)	−0.068 (0.17)	4.653***
RST_T4	0.030 (0.15)	−0.046 (0.12)	4.037***
RMT_F3	0.007 (0.18)	−0.090 (0.30)	2.757*
RMT_T3	0.028 (0.18)	−0.113 (0.27)	4.442***
RMT_T4	0.044 (0.21)	−0.062 (0.13)	4.259***
RMT_Cz	0.017 (0.20)	−0.055 (0.20)	2.465*
RSMT_F3	0.018 (0.33)	−0.141 (0.46)	2.806*
RSMT_T4	0.075 (0.35)	−0.108 (0.24)	4.280***
RSMT_Cz	0.035 (0.35)	−0.073 (0.34)	2.214*

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

Firstly, when analyzing the results of RA, RFA, RSA, and RG, as can be seen in the Table 4, RA, which signifies rest, RFA, which signifies calmness and concentration, and RSA, which represents relaxation are more activated for women compared with men. Specifically, areas of activation were the frontal lobe of the right hemisphere (F4) and the temporal lobe of the right hemisphere (T4) for RA, the crown (Cz) for RFA, and the frontal lobe (F3, F4) and crown for RSA. Generally, alpha waves are generated in a comfortable state (Lee, 2014), implying that women feel relaxed when electrode sensors are placed and pressed on the skin. Meanwhile, the RG index decreased at the temporal lobe of the left hemisphere (T3) and crown (Cz) for women. The RG index, which signifies a high level of cognition, anxiety, and stress, is deemed preferable when lower, meaning that pressing the electrode sensor on the skin reduced cognitive pressure and stress, enhancing comfort. These results are consistent with the research results (Park & Lee, 2021) that wearing partially functional compression pants inside a wearable robot helps to reduce gamma waves that provide tension, arousal, excitement, and anxiety.

In conclusion, the activation of alpha and gamma waves differed according to gender, as the electrode sensors developed for measuring biosignals were pressed on the skin. In particular, female participants did not feel discomfort due to the sensors and suggested possibilities of reduction in anxiety, stress, and tension as well as an increase in comfort.

Meanwhile, the RST, RMT, and RSMT indices that correlate with concentration are higher in males than in females. Specifically, the RST index was highly active in the frontal lobe of the left hemisphere (F3) and the temporal lobes of both hemispheres. RMT and RSMT indices showed that male theta waves were highly active in the frontal lobe of the left hemisphere(F3), temporal lobe of the right hemisphere(F4), and the crown(Cz), confirming clear differences based on gender. Therefore, it was shown that males tried to respond to each electrode sensor at a higher concentration, and females participated in the experiment with less tension and stress.

EEG changes according to electrode sensor types

As the previous statistical results showed a difference in EEG according to gender, further analysis was performed on each gender group to determine whether there was a difference in EEG according to the sensor type (10 types). Males showed no statistical difference in EEG according to the sensor type. Contrarily, females showed no significant difference according to the electrode sensor thickness (2 types), but there was a significant difference in EEG values according to the electrode sensor shape (5 types) ($p < 0.05$). As shown in Fig. 4, the index shows a significant difference in the RA index, indicating stability and rest, and the alpha value shows high levels of activation in the temporal lobe of the right hemisphere (T4).

On comparing the results based on the shape of the electrode sensor, there were differences in the RA index for plain, check, radial cut-out, and circular shapes. Upon closer inspection, the subjects who participated in the experiment recognized the differences between plain and check, plain and circular, check and radial cut-out, and check and circular among the five electrode types. That is when the sensor type check was placed on the brachioradialis (horizontal radius of curvature 3.36 cm, vertical radius of curvature, 15.55 cm) of the participants the difference could be detected, and the average value was significantly higher than when plain, radial cut-out, and circular were placed. Furthermore, when the electrode sensor type check was placed on the brachioradialis, it adhered tightly to the skin and thus was more comfortable than other electrode types. This is because the check shape has a grid-shaped groove and can be bent in various directions up, down, left, and right, and can be deformed to suit the curvature of the body. The results of this study concur with that of a study that showed that softer and less stiff materials increase the alpha wave, relieving tension and providing comfort (Lee, 2014). This is also consistent with the research (Cho, 2006) that alpha waves increase when positive stimuli are presented, and therefore, it can be interpreted that the tight adhesion and flexibility of the check helps to increase comfort. In addition, in the

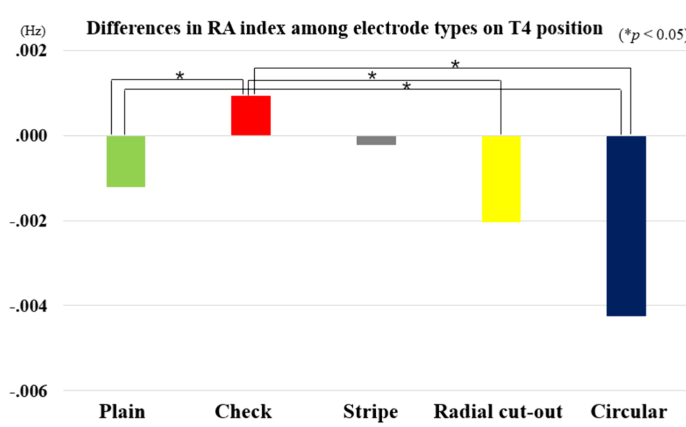

Fig. 4 Differences in RA index among electrode sensor types on T4 position

subjective evaluation (Table 7), Check type showed the highest adhesion to skin, flexibility, and good contact, as well as the highest overall comfort. Subjective sense recognized Check electrode sensors as a positive stimulus, and it is considered to have increased alpha waves. The adhesion of the sensor was found to be more affected by the shape than the thickness of the electrode.

Subjective evaluation according to electrode types

An analysis was conducted on the subjective evaluation results of men and women according to contact with the electrode sensor. As shown in Table 5, three subjective evaluations of “skin adhesion,” “feel on contact,” and “overall comfort” except for “flexibility” show significant differences ($p < 0.05$). Specifically, in the “skin adhesion”, “feel on contact,” and “overall comfort” items, women showed higher average values than men. It can be interpreted that when the electrode sensor was placed on the skin, women felt that it had excellent skin adhesion, good contact, and generally felt more pleasant. That is, in the subjective evaluation, women responded more sensitively and positively to the adhesion of the electrode sensor compared to men.

Thereafter, ANOVA was used to examine the difference in subjective evaluation according to the type of electrode for each male and female, a statistically significant difference was found ($p < 0.05$), as shown in Tables 6 and 7, respectively. Specifically, we found that there were significant differences in the subjective evaluation items of skin adhesion, feel on contact, flexibility, and overall comfort for both men and women. When the thickness of the electrode sensor was thin (0.5 mm), the average value for all subjective evaluation items was high for both men and women.

In particular, for women, as recorded in Table 6, there was a significant difference according to the shape of the electrode sensors. For skin adhesion, plain, check, and stripe types (0.5 mm) were evaluated as excellent with a score of at least 6.1. In addition, the feel on contact, flexibility, and overall comfort were evaluated as excellent for the 0.5 mm check shape. These results were evaluated in the same manner as the EEG results. In the case of the circular shape, the subjective evaluation and brain wave results were evaluated as the worst regardless of the thickness.

Conversely, as shown in Table 7 for male evaluations, 0.5 mm plain and check types have the best adhesion, 0.5 mm plain and stripe types have the best feel on contact, 0.5 mm check type the best flexibility, and 0.5 mm plain for best overall comfort; the preference for a 1.0 mm circular type was low. In conclusion, the 0.5 mm check and stripe types, which were highly preferred by both males and females, had a flexural modulus value of 10.7 MPa, 10.5 MPa by objective measurement. This was lower than

Table 5 T-test results of subjective evaluation according to gender to contact with electrode sensor

Subjective evaluation items	Men Mean (SD)	Women	*t*
Skin adhesion	4.39 (1.77)	5.18 (1.50)	-3.406^{**}
Feel on contact	4.80 (1.29)	5.38 (1.20)	-3.291^{**}
Overall comfort	4.76 (1.33)	4.98 (1.30)	-1.180^{*}

* $P < 0.05$, ** $P < 0.01$

Table 6 Subjective evaluation of females according to electrode changes

Evaluation items	Thickness 1.0 mm					Thickness 0.5 mm					*F*
	Mean (SD)										
	Plain	Check	Stripe	Radial cut-out	Circular	Plain	Check	Stripe	Radial cut-out	Circular	
Skin adhesion	4.20 (1.62) AB	5.40 (1.26) BC	5.20 (1.14) ABC	4.60 (1.71) AB	3.90 (1.73) A	6.10 (1.00) C	6.30 (0.67) C	6.10 (1.45) C	5.00 (0.74) ABC	5.00 (1.25) ABC	3.683*
Feel on contact	4.70 (1.34) A	5.30 (0.95) ABC	5.10 (0.88) AB	5.10 (1.29) AB	4.70 (1.25) A	6.00 (0.94) BCD	6.50 (0.53) D	6.20 (0.79) CD	5.30 (1.49) ABC	4.90 (1.10) A	3.392*
Flexibility	2.30 (0.67) A	4.20 (1.23) B	4.10 (0.99) B	4.70 (0.95) B	2.40 (0.52) A	6.10 (0.88) CD	6.80 (0.42) D	6.20 (0.63) CD	5.70 (0.48) C	4.60 (0.70) B	38.221**
Overall comfort	4.20 (1.23) A	5.00 (1.05) AB	4.80 (0.79) A	4.50 (1.27) A	4.00 (1.25) A	5.90 (0.88) BC	6.30 (0.67) C	5.90 (1.20) BC	4.60 (1.51) A	4.60 (1.07) A	4.943**

* $P < 0.05$, ** $P < 0.01$, Duncan test results (A < B < C < D)

Table 7 Subjective evaluation of males according to electrode changes

Evaluation items	Thickness 1.0 mm					Thickness 0.5 mm					*F*
	Mean (SD)										
	Plain	Check	Stripe	Radial cut-out	Circular	Plain	Check	Stripe	Radial cut-out	Circular	
Skin adhesion	3.50 (1.43) AB	4.70 (1.25) BCD	4.90 (1.37) BCD	3.60 (1.58) AB	2.70 (1.34) A	6.00 (1.05) D	6.00 (1.25) D	5.10 (1.45) CD	3.70 (1.89) ABC	3.70 (1.95) ABC	5.717**
Feel on contact	4.70 (0.95) BC	4.50 (1.18) BC	5.30 (0.82) CD	4.10 (1.20) AB	3.30 (0.95) A	5.80 (1.14) D	5.40 (1.17) CD	5.90 (1.10) D	4.10 (1.10) AB	4.90 (1.00) BCD	6.016**
Flexibility	2.50 (0.85) A	4.20 (1.32) B	4.80 (1.40) B	4.30 (1.34) B	2.20 (0.92) A	6.10 (0.74) CD	6.50 (0.97) D	6.30 (0.82) CD	5.30 (1.83) BC	4.50 (1.27) B	15.420**
Overall comfort	4.70 (1.16) BCD	4.50 (1.18) ABC	4.80 (1.14) BCD	4.00 (1.33) AB	3.40 (1.26) A	6.00 (1.05) E	5.50 (1.27) CDE	5.70 (0.82) DE	4.60 (0.97) BCD	4.40 (1.26) ABC	4.687**

** $P < 0.01$, Duncan test results (A < B < C < D < E) the values for the other electrode types (34.2–53.6 MPa). This indicates that the check and stripe types possess softer and more flexible properties than other forms, and it is deduced that these characteristics are directly connected to subjective senses, as shown in the responses.

Correlation between EEG changes and subjective evaluation according to electrode sensor types

To determine the relationship between EEG changes and subjective evaluation of electrode sensors, correlation analysis was conducted according to gender. As a result, as shown in (Table 8), in the female group, there was a statistically significant difference between RA index in the right hemisphere temporal lobe area (T4) and subjective evaluation items (skin adhesion, feel on contact, flexibility, and overall comfort) according to electrode sensor shape (5 types). That is, in the case of the female group, when the electrode sensor was in the 'Check' form, the RA index in the right hemisphere temporal lobe (T4) and the subjective evaluation items 'skin adhesion' ($r = 0.275$, $p < 0.01$), 'feel on contact' ($r = 0.221$, $p < 0.01$), 'flexibility' ($r = 0.185$, $p < 0.05$), and 'overall comfort' ($r = 0.262$, $p < 0.01$), it was found that there was a positive correlation between them. In other words, it was found that when the type of electrode sensor was 'Check', 'skin adhesion', 'feel on contact', 'overall comfort' were excellent, it was flexible, and the brain wave value of 'RA' was highly activated. On the other hand, in the male group, there was no statistically significant correlation between EEG values and subjective evaluation items according to electrode sensor type.

Table 8 Correlation between EEG changes and subjective evaluation of females according to electrode sensor types

	RA_T4 (Plain)	RA_T4 (Check)	RA_T4 (Stripe)	RA_T4 (Radial cut-out)	RA_T4 (Circular)	Skin adhesion	Feel on contact	Flexibility	Overall comfort
RA_T4 (Plain)	1								
RA_T4 (Check)	−0.312*	1							
RA_T4 (Stripe)	−0.235	0.228	1						
RA_T4 (Radial cut-out)	0.218	−0.419*	−0.249	1					
RA_T4 (Circular)	0.435*	−0.523*	−0.252	−0.267	1				
Skin adhesion	0.134	0.275**	0.188	0.082	0.056	1			
Feel on contact	0.150	0.221**	0.189	0.164	0.081	0.739**	1		
Flexibility	0.034	0.185*	0.136	0.165	0.053	0.581**	0.535**	1	
Overall comfort	0.092	0.262**	0.150	0.093	0.035	0.757**	0.765**	0.590**	1

* $P < 0.05$, ** $P < 0.01$

Conclusions

In this study, it was analyzed the effects of electrodes for measuring biosignals manufactured in different shapes and thicknesses through EEG and subjective sensory evaluation using neurophysiological evaluation methods. it was found that the activated EEG index was different according to gender. Therefore, it is considered that it would be more efficient to design the electrodes differently for genders developing the electrodes because biosignals measured for men and women have different EEGs, even if they are the same electrode. Also, in the EEG change according to the type of electrode(shape and thickness), in the case of women, there was a significant difference according to the shape of the electrode, but no significant difference according to the thickness of the electrode. Therefore, the shape of the electrode is the most important factor to consider in manufacturing electrodes to minimize the inconvenience caused by the electrode sensor and comfortably measure biosignals in daily life. it was confirmed that the subjective sensory evaluation showed sensitivity to all types of electrodes and recognized their differences. Herein, a new attempt was made for meaningful product evaluation by developing 3D printed electrode structures with excellent contact comfort and analyzing its effect through EEG. These results can be utilized in the development of various smart clothing, and are expected to reduce the wearer's discomfort from contact with sensors. However, this study concluded by testing electrode design for better adhesion and overall comfort in 20 individuals in their twenties. Further studies on electrode design with various age groups and more test participants are required to reach an optimal design. Additionally, in this study, the effect of the electrode sensor was verified in only one brachioradialis location in the stationary state. In follow-up studies, it would be necessary to observe various body parts with different curvatures and changes during various movements. These results are expected to be utilized to develop a fabric-type electrode that reflects the optimal electrode shape, and it would be possible to develop an integrated fabric-type smart clothing that can acquire high-quality biosignals without time and space constraints.

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Author contributions
OL and HL were responsible for experimental design and conduct, OL was responsible for data analysis and manuscript writing, and HL was responsible for data analysis and manuscript review. All authors read and approved the final manuscript.

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Availability of data and materials
The data used in this study cannot be disclosed because the patent is in progress and subsequent studies are in progress. However, if there is a legitimate request and the author's organization approves it, the corresponding author can provide it.

Declarations

Ethics approval and informed consent
This study was approved by the Institutional Review Board (IRB) from Kumoh National Institute of Technology (Approval No. 202106-HR-013-01).

Competing interests
The authors declare that there is no conflict of interest.

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