A Pre-Gelled EEG Electrode and Its Application in SSVEP-Based BCI

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***Abstract*— Electroencephalogram (EEG) electrodes are critical devices for brain-computer interface and neurofeedback. A pre-gelled (PreG) electrode was developed in this paper for EEG signal acquisition with a short installation time and good comfort. A hydrogel probe was placed in advance on the Ag/AgCl electrode before wearing the EEG headband instead of a time-consuming gel injection after wearing the headband. The impedance characteristics were compared between the PreG electrode and the wet electrode. The PreG electrode and the wet electrode performed the Brain-Computer Interface (BCI) application experiment to evaluate their performance. The average impedance of the PreG electrode can be decreased to 43 kΩ or even lower, which is higher than the wet electrode with an impedance of 8 kΩ. However, there is no significant difference in classification accuracy and information transmission rate (ITR) between the PreG electrode and the wet electrode in a 40 target BCI system based on Steady State Visually Evoked Potential (SSVEP). This study validated the efficiency of the proposed PreG electrode in the SSVEP-based BCI. The proposed PreG electrode will be an excellent substitute for wet electrodes in an actual application with convenience and good comfort.**

***Index Terms*— Pre-gelled (PreG) electrode, hydrogel, electroencephalogram (EEG), brain-computer interface (BCI).**

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I. Introduction

EEG has been widely studied in clinical medicine and BCI because of its noninvasive characteristics. Silver/silver chloride (Ag/AgCl) electrodes and conductive paste are commonly used sensors for acquiring a high-quality signal.

Often, the electrode placement and gel injection require a professional operation. The presence of hair, which is almost nonconductive, makes the placement and preparation of EEG electrodes more cumbersome. The contact between the scalp and the electrode relies on the penetration of the conductive paste. The direction of the needle and the amount of the conductive paste need to be constantly adjusted and controlled to connect the scalp and the electrode simultaneously without causing a short circuit between adjacent electrodes. BCI systems based on wet electrodes are too complicated to be promoted.

To facilitate EEG acquisition and simplify the operation of electrode placement, semi-dry electrodes or dry electrodes without conductive paste or gel operation are a solution to the problem. To reduce or eliminate the interference of hair, most of the dry electrodes adopt a comb-like structure [1]–[3] to pass through hair and make direct contact with the scalp. Without conductive paste's assistance, the conversion of electrons and ions at the electrode/skin interface becomes difficult [4], [5]. The contact impedance of electrode/skin is high [6], which can reach 100KΩ @ 100Hz, or even higher. Fiedler *et al.* performed special research on the relationship between impedance and pressure [7], [8]. To maintain a small contact impedance, a certain pressure on the electrode is required. The wearing comfort level is poor since most of the dry electrode is made of hard material.

To improve the contact between dry electrodes and scalps, researchers have proposed many solutions. One method is to modify the electrode structure. For instance, adjusting the number or size of the comb teeth increases the comb teeth' density to make a brush-like electrode [9], [10]. Researchers also make the comb teeth of the electrode into a spring column or a telescopic elastic structure like a claw [11]–[15]. Another method is altering the materials. Some researchers have developed electrodes made of conductive rubber combined with carbon nanotubes, graphene, conductive coatings, metal fibers (such as nano-silver wire), and other modified polymer materials [16]–[20]. These improvements in structure and materials optimize the contact impedance and wearing comfort to some extent. However, Young's modulus of the materials that contact the scalp, either spring-supported metal or conductive modified polymer, is tens of MPa or even higher [8], [21]. However, Young's modulus of the head skin is in the range of 0.1-1MPa [22]. Therefore, when the comb teeth contact the scalp with a certain pressure, the deformation is mainly on the skin. The subjects have to endure a certain amount of skin deformation to obtain a lower contact impedance. Therefore, such electrodes are discomfort. It is only suitable for short-term use.

Semi-dry electrode is a compromise between dry and wet electrodes [23]. This type of electrode uses a capillary or microporous structure [24]–[26] to deliver water or electrolyte to the scalp to replace the conductive paste. It solves the problem of the residual conductive paste after the use of a wet electrode. A storage cavity and a certain amount of water or electrolyte are the common structures of these kinds of electrodes. To avoid deforming to squeeze out water, the material of the electrodes is rigid. For some semi-dry electrodes, pressure must be precisely controlled to avoid a short circuit caused by an excess electrolyte [27], [28]. Hydrogel is a flexible material with a three-dimensional polymer chain network [29] that can moisturize the hair and scalp without a short circuit, and improve comfort level when used to EEG semi-dry sensors. Some researchers have tried to replace sticky conductive pastes with conductive hydrogels. S. Toyama, *et al.* developed a non-adhesive solid-gel chip for noninvasive BCI, proving to work well for practical BCI and was useful for bedridden patients [30]. However, the hair has to be put aside before installing the cylindrical solid-gel chip due to the flat interface of the hydrogel electrode, which may be a troublesome operation of a subject with thick hair/high-density EEG recording. Pedrosa *et al.* proposed a novel alginate-based hydrogel with viscous liquid as an alternative to the traditional conductive paste [31]. The liquid hydrogel can transform into a solid hydrogel rapidly and enable faster and easier cleaning of the scalp after the recording procedure. There were also some disadvantages of the hydrogel, such as a prolonged preparation time similar to conductive paste, a special designed hydrogel cavity to reduce the risk of gel leakage. Sheng *et al.* developed claw-like and patch-like electrodes ionic-hydrogel for electroencephalography recording at the hairy and hairless regions, respectively, which achieved comfort and good contact with skin [32]. However, the soft hydrogel also has to rely on the container to maintain its designed shape. In conclusion, the semi-dry electrode has a lower impedance than that of the dry electrode but is no more convenient than the dry electrode. The new generation semi-dry electrode based on hydrogel has realized the balance of comfort level and impedance to a certain extent.

In this paper, an EEG electrode consisting of a hydrogel probe and an Ag/AgCl electrode named the Pre-gelled (PreG) electrode was designed and developed to improve the BCI system's convenience. The PreG electrode is a kind of semi-dry electrode with a replaceable hydrogel probe. The hydrogel probe was made into a cone shape with a specified size. The proposed device has the advantages of a simple structure, short preparation time, stable impedance performance, no residue after use, and no need to clean the head and electrode, which permits rapid application in the BCI systems.

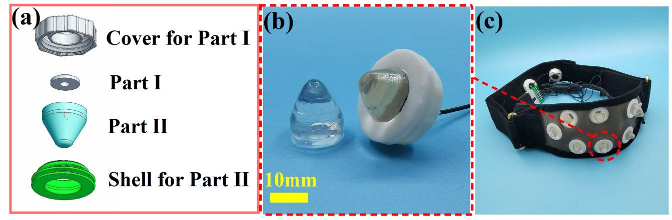

Fig. 1. (a) Schematic diagram of the PreG electrode. It consisted of, from top to down, a cover, a plane Ag/AgCl electrode, a hydrogel probe, and a bowl-shaped shell. (b) The fabricated hydrogel probe (left) and the PreG electrode (right). (c) The PreG electrodes were installed on the EEG headband.

II. Materials and Methods

A. The Design of the PreG Electrode

The PreG electrode mainly consisted of a part I- Ag/AgCl electrode and a part II- hydrogel probe. A bowl-shaped shell and a cover were 3D printed to package the hydrogel probe and the Ag/AgCl electrode, as shown in Figure 1(a). The sintered Ag/AgCl electrode with a diameter of 8 mm was glued on the cover. The hydrogel probe was designed as a cone shape, which could coordinate with the bowl-like shell to fix the hydrogel probe on the Ag/AgCl electrode. The conical tip makes it is easy to be put into the hair. The basal diameter and the height of the proposed cone shape hydrogel probe are both 13mm $\pm$ 0.5mm. After filling in the hydrogel probe, the shell and the cover could be buckled together by screwing. The cover and the shell could be repeatedly opened and closed to replace the hydrogel probe. After being put into the package, the cone's tip sticks out of the shell by approximately 8 mm. The fabricated hydrogel probe and the PreG electrode are shown in Figure 1(b). An additional ring groove is reserved around the shell. The ring groove makes it easy to install on an EEG headband, as shown in Figure 1(c).

B. The Preparation of Hydrogel Probe

The hydrogel mainly comprises the following components with a mass ratio: carrageenan (Shandong Yaheng Biotechnology Co., LTD) (8 %), water retention agent (Glycerol, Sinopharm Chemical Reagent Co. LTD) (35 %), NaCl conductive salt (0.9 %), and deionized water(rest). Carrageenan is a commonly used additive in the food industry, such as jelly, fudge, ice cream, etc. Glycerin is often added as a moisturizer in skin care products. Recently, Glycerin has been a popular candidate applied in the hydrogel EEG electrode to improve the moisturizing ability [33]. The preparation process of the hydrogel probe in this paper mainly included the following steps: Firstly, weighing the raw materials according to the proportion, adding the water retention agent into the carrageenan, fully stirring and uniformly mixing to obtain a mixture A; Secondly, adding the NaCl conductive salt into deionized water, heating, stirring and dissolving to obtain a mixture B; Thirdly, adding mixture A into mixture B, mixing them uniformly by heating and stirring to obtain hydrogel material in a liquid state; Lastly, pouring the liquid into a mold. All the heating processes were carried out in an enclosed reactor to maintain the mass ratio nearly unchanged. After cooling and demolding, a flexible elastic hydrogel cone is produced. In this way, the hydrogel probe can be prepared in large quantities.

C. Impedance Test

To compare the performance of the hydrogel probe (corresponding to the proposed electrode) and conductive paste (corresponding to the wet electrode), the impedance test was carried out on the subjects' heads with the same Ag/AgCl electrodes. The testing was realized by replacing the hydrogel probe with the commercial conductive paste (purchased from ZPtec, Wuhan, China). The impedance measurement was conducted with commercial equipment (Neusen.U08). The equipment provided a 7.8 Hz, 48 nA peak-to-peak square wave current to test the impedance. The impedance of each channel was calculated by monitoring the voltage difference between the working electrode and the reference electrode. The module's working state could be switched between "impedance test" and "EEG recording" through software.

Firstly, the impedance of the PreG electrode was measured. An 8-PreG electrode was assembled on a headband and placed on the subjects' heads. Since the electrode was pre-gelled, the headband could be applied by the subjects themselves. The electrodes were placed according to the 10-10 international standards on PO5, PO3, POz, PO4, PO6, O1, Oz, and O2. The reference electrode and the ground electrode, both using the PreG electrodes, were placed on the forehead. The initial impedance of 8 channels was recorded as soon as the EEG headband was worn. Each channel's impedance was recorded once every six minutes. The mean impedance and standard deviation of all 10 subjects' all channels were calculated, and the impedance of long hair (six female subjects with hair length more than 20cm) and short hair subjects (four male subjects with hair length shorter than 5 cm) was compared. To verify the continuous employment duration of the PreG electrode, a representative subject performed a six-hour impedance test. Each channel's impedance was recorded once every 1 hour. Identical measurements were conducted of the wet electrode by replacing the hydrogel probe with the commercial conductive paste.

The PreG electrode and wet electrode were chosen to perform the impedance test in a random order for comparison. If the PreG electrode was tested first, the Ag/AgCl electrode which remained on the EEG headband would be cleaned after removing the hydrogel probe. The commercial conductive paste was injected into the Ag/AgCl electrode's shell after the subject's hair and the Ag/AgCl electrode were completely dried. If the wet electrode was tested first, the subjects were asked to wash their hair after the experiment, and the Ag/AgCl electrode must be cleaned. The PreG electrode test was conducted after both the subject's hair and the Ag/AgCl electrode were dried entirely. There was no need for cleaning hair before the first experiment no matter which kind of electrode was used.

D. Moisture Test

The initial mass of six hydrogel probes was weighed. The hydrogel probes were then placed in a constant temperature oven with a temperature of 36 °C and relative humidity of 15.4%. The mass of the hydrogel probes was weighed once an hour. The mass variance was monitored for approximately 12 hours, and the variation relative to the initial mass was calculated.

E. Open Circuit Potential Test

A minimum and stable potential difference between recording electrodes is expected to acquire high-quality EEG signals. Nonpolarizable electrodes are preferred to the EEG recording [34]. The open circuit potential (OCP) is to evaluate the polarization characteristics of an electrode-electrolyte system.

The OCP test was referred to the method described in [35]. A pair of PreG electrodes, with their hydrogel probes contacting face to face, was connected to an electrochemical workstation (CHI750E, Chenhua Inc., China) after 5min rest. The potential between the electrodes was tested at a sampling rate of 1Hz. The test lasted 10 minutes. Four PreG electrode couples were tested. Four Ag/AgCl electrode couples used in the PreG were placed on conductive paste (ZPtec, Wuhan, China) to conduct the OCP test for comparison. The average OCPs across four PreG electrode couples and four Ag/AgCl electrode couples were calculated. The standard variation of the average OCP across the recording time was also calculated. To evaluate the stability of the polarization potential, the potential drift [34] was calculated and compared between the Ag/AgCl electrode and the PreG electrode.

F. Elasticity and Plasticity Test

To mimic the pressure loaded on the electrode during the wearing and adjusting process, a typical pressure range according to [8] was loaded on the hydrogel probe. This pressure range can balance the impedance and the comfort level of a dry or semi-dry electrode. The transient force applied on the hydrogel probe was to mimic adjusting operation by pressuring the PreG electrode to squeeze hydrogel against the head to decrease impedance. As a static and stable scene needs to be established to conduct the test to control the force and the time, the tips of the hydrogel probes were placed on the porcine skin to simulate an electrode–skin interface, though the elastic modulus of the porcine scalp was found to be almost twice the values of the human scalp [36]. Different kinds of pressures were applied, and the dimension changes were measured to assess the mechanical characteristics. A transient pulsed pressure was applied to evaluate the hydrogel probe's elasticity. Namely, a force of 1 N was repeatedly applied and removed (press for 6 s, release for 6 s) 30 times to observe the hydrogel probe's elasticity or rebound properties. Then, a constant force of 0.25N was applied to the hydrogel probe placed on the porcine skin for 2 hours to observe the hydrogel probe's and the porcine skin's deformation under long-term pressure. To compare the deformation caused by the electrodes, dry electrodes (purchased from Florida Research Instruments Inc., Florida, USA) were placed at the side of the hydrogel probes, and an identical constant force of 0.25N was applied for 2 hours, as shown in Figure 6(b).

The hydrogel probes were placed on a glass plate to assess the deformation characteristics of the hydrogel probes under different pressures. Vertical forces 0. 25 N, 0.5 N, 1 N, and 2 N were applied to the hydrogel probes, respectively. The dimension variances after 1 hour and 2 hours were measured. Besides, the Young modulus of the hydrogel blocks was tested roughly as shown in **Figure S1** in the Supplementary Materials.

G. BCI Test

The SSVEP-based BCI task was used to verify the signal acquisition capability of the developed PreG electrode. Ten subjects, including six females with long hair and four males with short hair, took part in the experiment. Their ages ranged from 22 to 42. All of the subjects were healthy and had normal or corrected-to-normal vision. All experiments were approved by the Research Ethics Committee of Tsinghua University (N0.20200020). Informed consent was obtained from all participants. No scalp cleaning or special scalp preparation was performed on the scalp before the tests. The PreG electrode and wet electrode were chosen to perform the experiment in identical order with the impedance test. An 8-channel EEG headband was used to assemble the PreG electrode and wet electrode. A commercial wireless amplifier with a sampling rate of 1kHz and a common-mode rejection ratio (CMRR) of 120 dB was used (provided by the Neuracle Technology Company, Changzhou, China). The montage of electrodes was the same as that in the impedance test.

A 4 × 10 matrix consisting of 40 flickering stimuli (including numbers 0-9, letters A-Z, “,”, “.”, spaces, and backspaces) was displayed on a 24.5-inch screen with a refresh rate of 60 Hz. The frequency ranged from 8Hz to 15.8 Hz with an interval of 0.2 Hz, and the phase difference between adjacent frequencies was 0.5 π. The stimulus of fixed frequency and phase was realized by sinusoidal modulation of each target’s brightness on the screen (brightness range: 0-255). Each trial included a 1s-long visual cue, 4s-long stimulation, and 1s-long feedback. Each block contains 40 trials (40 targets). Six blocks were performed of each kind of electrode of each subject. A trigger box (provided by the Neuracle Technology Company, Changzhou, China) was used to synchronize the stimulation with the EEG signal in this experiment. An optical sensor connected to the trigger box with a USB cable was placed at one of the corners of the stimulation screen to collect the trigger. Then, the trigger box sent the trigger to the recording computer with an RS485 line. This configuration avoided the event information loss and ensured the stimulation’s stability for a wireless communication system. The connection schematic diagram of the trigger transmission is shown in **Figure S2**. The stimulation interface is shown in Figure 2. The subjects were asked to sit 50 cm in front of the screen. Before the SSVEP-based BCI experiment, the impedances were checked and adjusted to below 150 kΩ, and the EEG waveforms were inspected visually simultaneously. This process may spend about 3-5minutes. The adjusting process is shown in **Video 1** in Supporting Materials.

At the beginning and end of the BCI experiment, the subjects were requested to fill in the comfort questionnaire

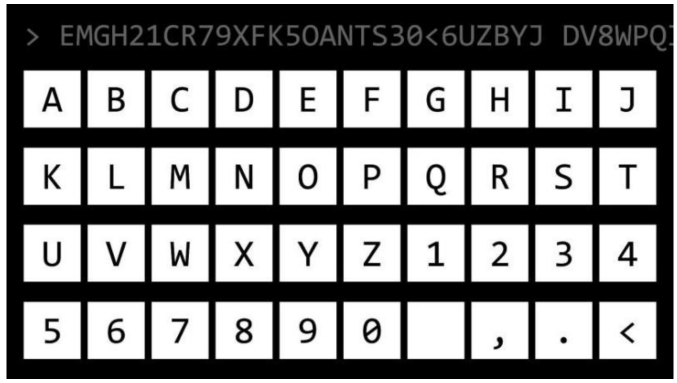

Fig. 2. 40 targets stimulation interface of SSVEP-based BCI system.

referred to [37]. The comfort level was divided into four levels: Comfortable without pain; A little pain, Acceptable pain, Discomfortable with pain. “Comfortable without pain” means no feel to the subjects. “A little pain” means slightly uncomfortable to the subject. “Acceptable pain” means that the subject feels discomfortable and endured pain. “Discomfortable with pain” means that very uncomfortable and painful. In addition, the questionnaire on the preference of the two types of electrodes was required to complete after the experiment. To be more specific, the subject had to decide the preference of the electrode under two cases: consider (1) Only comfort; (2) Both comfort and convenience. For both case (1) and case (2), three choices were provided, including Wet electrode, PreG electrode, and Both well. Only one choice can be made for each case. “Both well” means no preference between the two electrodes.

Filter bank canonical correlation analysis (FBCCA) was used to calculate the average classification accuracy and information transmission rate (ITR) of all subjects [38]. The significance of the difference ($p < 0.05$ indicated a significant difference) between the PreG electrode and the wet electrode was evaluated by one-way repeated-measures analysis of variance (ANOVA) at 4s data length. The statistical analyses were conducted using SPSS software (IBM SPSS Statistics, IBM Corporation). To better analyze the characteristics of SSVEP, the amplitude spectra and signal-to-noise ratio (SNR) of fundamental and harmonic components (from fundamental frequency to fourth harmonic) were calculated using the 4s data length. Firstly, the raw EEG data were downsampled to 250Hz. Secondly, the downsampled data were processed by a notch filter. Thirdly, the data were filtered by a band-pass filter (8-90Hz). Fourthly, the standard Canonical Correlation Analysis (CCA) method was used to find the optimal linear combination coefficients of EEG signal and the predefined sinusoidal reference signals to maximize the correlation between them for SSVEP detection [39]. Thus, a CCA-based spatial filter can be obtained and then the 8-channel data were processed by the CCA-based spatial filter. Lastly, the amplitude spectrum y(f) was calculated by fast Fourier Transform (FFT), and the SNR in decibels (dB) was defined as the ratio of y(f) to the mean value of the eight neighboring frequencies [40]. The flow chart of the calculation process is shown in Figure 3. One-way

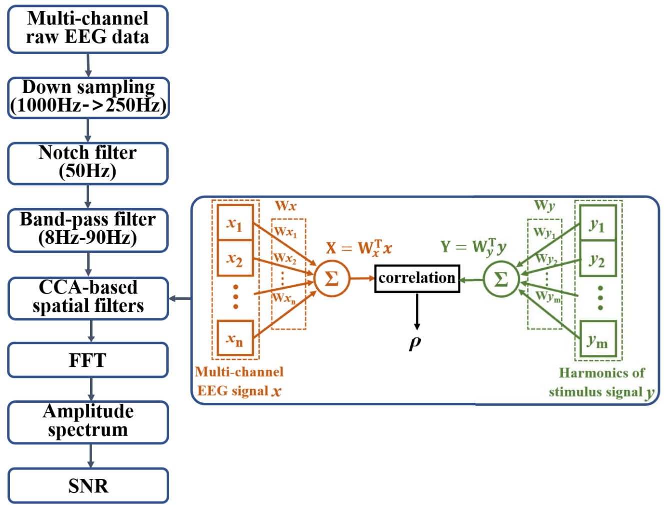

Fig. 3. The flow chart of the process to calculate the amplitude spectrum and the SNR.

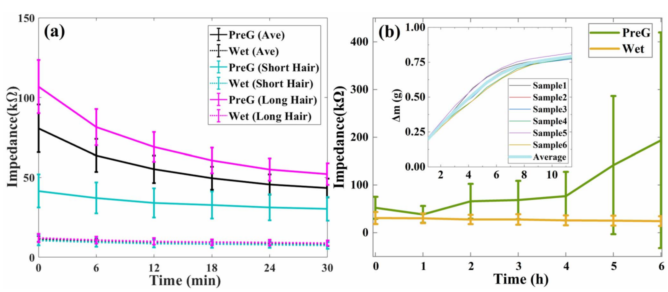

Fig. 4. (a) The average impedance variation in 30 min of the PreG electrode (solid black line) and wet electrode (black dotted line) of all subjects, short hair subjects (solid blue line and blue dotted line), and long hair subjects (solid pink line and pink dotted line). (b) The impedance variation of the PreG electrode and wet electrode over 6 hours. The inset is the mass loss versus time.

repeated-measures analysis of variance (ANOVA) was also used to test the difference of amplitude and SNR between the PreG electrode and the wet electrode at different frequencies.

$$SNR = 20log_{10}\frac{8\times y(f)}{\sum_{k=1}^{4}[y\,(f-0.25\times k)+y(f+0.25\times k)]} \quad (1)$$

III. Results and Discussion

A. Contact Impedance

The average impedance of the PreG electrode is 43 ± 6 kΩ, and the average impedance of the wet electrode is 8 ± 1 kΩ as shown in Figure 4(a). The impedance of the PreG electrode is higher than that of the wet electrode, especially at the initial time. The initial average impedance of the proposed device is 81 kΩ. The impedance of the PreG electrode shows a decreasing trend within the first hour. The conductive paste was injected into the hair, however, the hydrogel probe was placed on the top of the hair. It took more time for the PreG electrode to wet the hair and scalp than the wet electrode. After checking the subjects' hairstyle and impedance, we found that the hair length or thickness had a noticeable effect on the PreG electrode impedance. As shown in Figure 4(a), the average impedance on six long hair subjects is obviously higher than that of the four short hair subjects. Since the moisture of the hydrogel probe is limited, long or thick hair needs more time to wet through than short hair. The PreG electrode performed better on short hair subjects. Either the initial impedance or the time spent to reach a stable impedance was less than that of the long hair subjects. According to [41], the amount of hair between the scalp and the electrode does affect the impedance values. Thus, it is best to push aside the hair before placing the PreG electrode to decrease the impedance and the stable period. A 6-hour impedance monitoring in Figure 4(b) shows that the average impedance of the PreG electrode decease to 38 kΩ 1 hour later. The average impedance of the electrodes is no more than 76 kΩ during the first 4 hours. The increase in impedance after one hour, we speculate, is mainly caused by the deformation of the PreG electrode. The inset in Figure 4(b) shows the mass loss versus time. The water contention will exhaust in 8 hours in an environment that mimics body temperature. During the first 4 hours, as the water content of the hydrogel was not less than 41%, the impedance of the electrode remained at a stable value. As the electrolyte in the PreG electrode continuously evaporated, the impedance of the PreG electrode began to increase. The PreG electrode could maintain low impedance for at least 4 hours. This is enough for most of the current BCI applications.

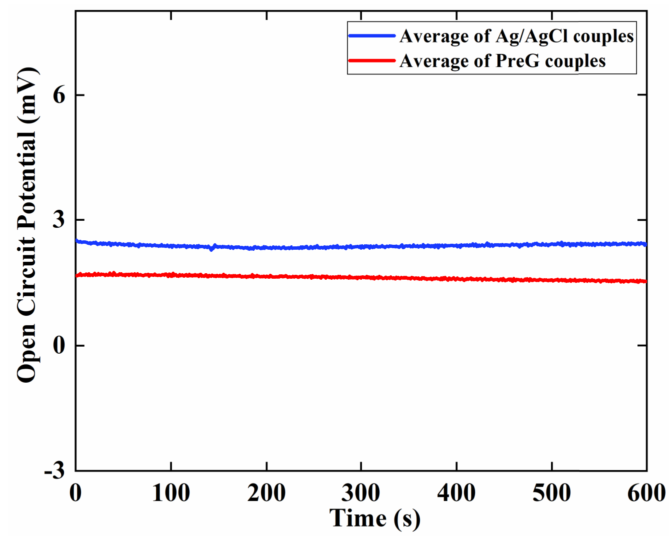

Fig. 5. The average open circuit potentials of PreG electrode couples and Ag/AgCl electrode couples.

B. Open Circuit Potential

The average open circuit potentials of four PreG electrode couples and four Ag/AgCl electrode couples are displayed in Figure 5. The average OCPs of PreG electrode couples and Ag/AgCl electrode couples are 1.62mV ± 0.052mV and 2.39mV ± 0.038mV, respectively, which is low enough for most biopotential amplifiers [42]. The potential drift was also calculated of the PreG electrode and the Ag/AgCl electrode to evaluate the stability of polarization potential, which is important in EEG signal recording [43]. The potential drifts of the

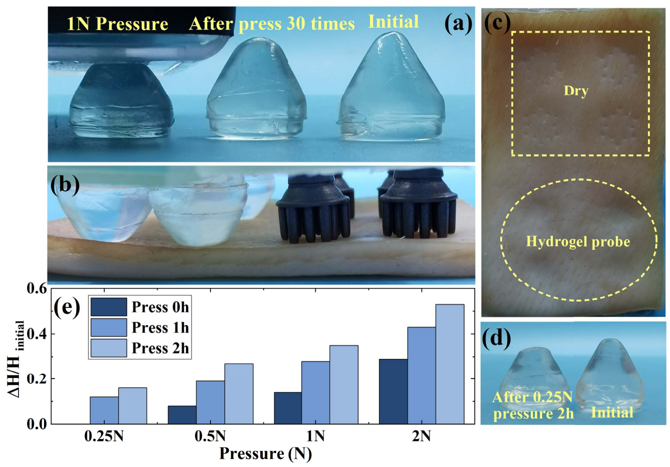

Fig. 6. (a) The deformation of the hydrogel probe under a force of 1N (left) and the resilient hydrogel probe after a transient force of 1N (6s press and 6s release) 30 times (middle) and the initial hydrogel probe (right). (b) The hydrogel probe and the dry electrode were pressed on the porcine skin under a constant force of 0.25N. (c) The indentation on the porcine skin surface of hydrogel probes and dry electrodes under the constant force of 0.25N after 2 hours. (d) Deformation of the hydrogel probe under the constant force of 0.25N after 2 hours (left) and the initial hydrogel probe (right). (e) The ratio of height variance to the initial height of the hydrogel probe under 0.25N, 0.5N, 1N, 2N after 1 hour and 2 hours.

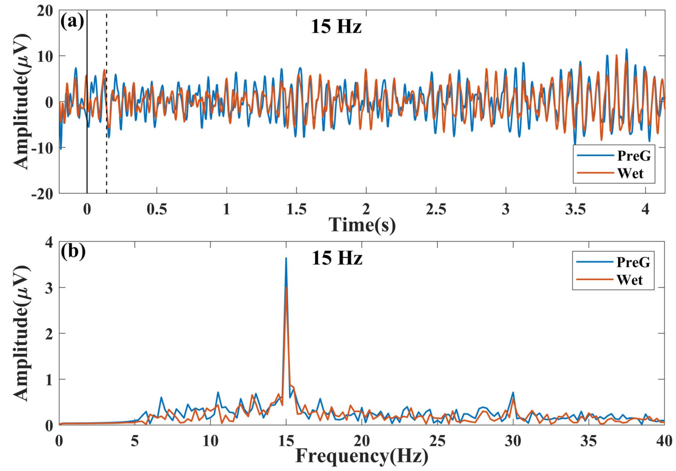

Fig. 7. (a) Temporal waveform and (b) Amplitude spectrum of SSVEPs at 15Hz from Oz channel averaged across six blocks of one typical subject. The black solid line represents the stimulus onset, and the black dashed line represents the latency of the EEG response [37].

PreG electrode and the Ag/AgCl electrode are 0.023mV/min and 0.024mV/min, respectively. These results indicate that the PreG electrode is applicable for high-quality EEG recording.

C. Elasticity and Plasticity

The elasticity of the hydrogel probe is demonstrated in Figure 6(a). The left hydrogel probe was under 1N pressure. The middle one was a hydrogel probe after repeated pressing (1N with 6s press and 6s relax) 30 times. No obvious deformation could be observed compared to the right one, which was an original hydrogel probe. The hydrogel probe had good elasticity and resilience. This meant that the PreG electrode could self-adapt the head surface in a certain range. The deformations of the porcine skin and hydrogel probe under a force of 0.25N after 2 hours are shown in Figure 6(c) and Figure 6(d), respectively. Both types of electrodes left indentations on the porcine skin. The dry electrode left a few little, and deep indentations, The indentations made by the PreG were flat and shallow. Compared with the hard dry electrode, the hydrogel probe was flexible, and it deformed when it was pressed to the porcine skin, which meant a greater contact area and minor intensity of pressure. Commonly, it was the intensity, not the pressure itself, that makes one feel uncomfortable. Therefore, the hydrogel probe's elastic and flexible characteristics endow it with a more comfortable wear feeling than the hard dry electrode did. The primary deformation of the hydrogel probe occurred to the height and the tip area. The bottom of the hydrogel cone changed little. The height variance under long continuous forces was tested and is shown in Figure 6(e). The height was lower than the initial height when the hydrogel probe underwent a constant long-term force. The height variance increases with the increased force. The deformation reaches a certain level and is maintained under a certain pressure. The probe deformed after one hour of continuous pressure. The deformation will decrease the pressure on the probe and scalp interface. Then the decreased press will cause the PreG electrode impedance to increase. The deformed hydrogel probe is shown in **Figure S3**. The pressed state of the electrode is reflected in the impedance test result.

D. BCI Performance

The temporal waveforms and amplitude spectra of SSVEPs using the PreG electrode and the wet electrode are shown in Figure 7(a) and (b), respectively. The time-domain signal and the frequency-domain spectrum of 4-second-long SSVEP at 15Hz from the Oz channel of one typical subject were extracted and calculated by averaging six blocks with two types of electrodes. The data were filtered by a band-pass filter (6Hz-40Hz) to observe the characteristics of SSVEP. According to the results, both PreG electrode and wet electrode could record the SSVEP signal clearly, and the response peaks at 15Hz (wet: 2.998μV vs PreG: 3.640μV) and 30Hz (wet: 0.567μV vs PreG: 0.714μV) can be observed in the amplitude spectrum.

The average classification accuracy and ITR of the BCI system based on the 40 target SSVEPs of the PreG electrode and wet electrode are almost equal, as shown in Figure 8(a). As the data length increasing, the accuracy increases. In addition, the ITR reaches a peak at approximately 1.8 seconds. The PreG electrode and the wet electrode have the same trend of average classification accuracy and ITR with increasing data length. One-way repeated-measures ANOVA shows that there is no significant difference in the average classification accuracy ($F(1, 9) = 1$, $p = 0.343$) and ITR ($F(1, 9) = 0.987$, $p = 0.346$) between the two electrodes with a 4s data length, as shown in Figure 8 (b). The results reported in [37] indicated that there was no significant correlation between classification accuracy and impedance for dry electrodes and

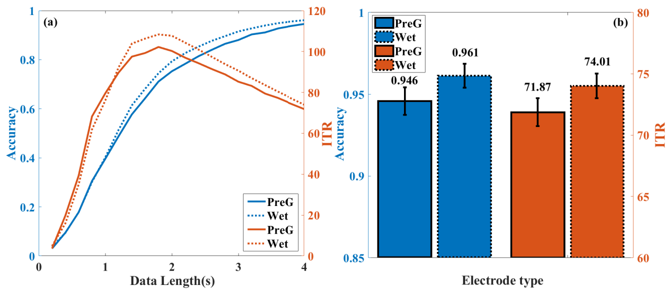

Fig. 8. (a) The results of the average classification accuracy rate and ITR of the PreG electrode and wet electrode with different data lengths. (b) The average classification accuracy rate and ITR of the PreG electrode (blue bar) and wet electrode (orange bar) with 4s data length. The solid box corresponds to the PreG electrode, the dotted box corresponds to the wet electrode.

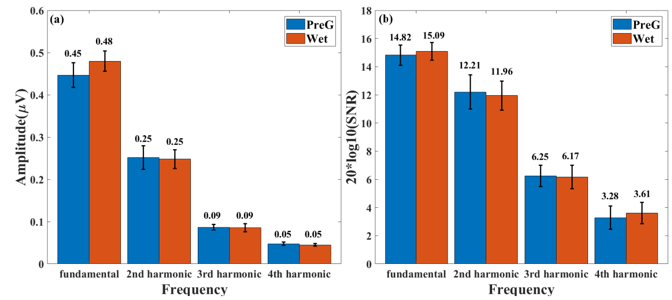

Fig. 9. (a) The amplitude of fundamental frequency, 2nd harmonics, 3rd harmonics, and 4th harmonics component of the SSVEP signals acquired by the PreG electrode and the wet electrode. (b) The signal-to-noise ratio of the fundamental frequency, 2nd harmonics, 3rd harmonics, and 4th harmonics components of the SSVEP signals acquired by the PreG electrode and the wet electrode.

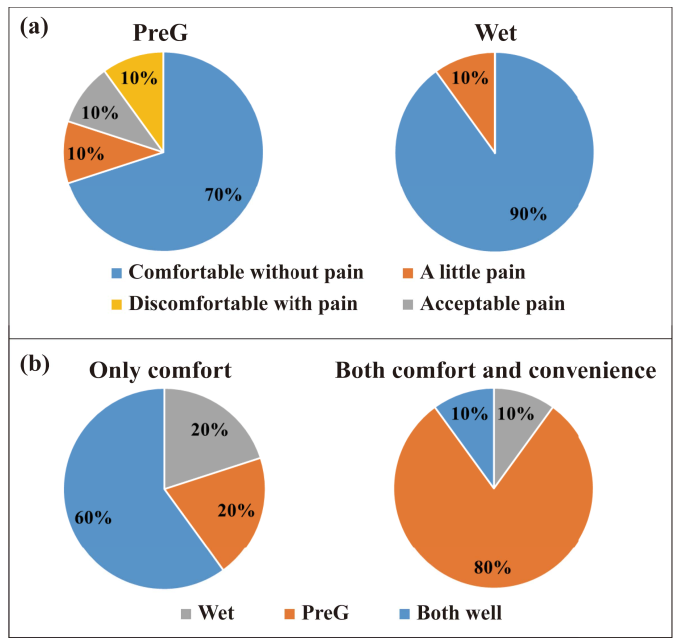

Fig. 10. (a) The proportion with the different comfort levels of subjects of the PreG electrode and the wet electrode; (b) In the case of the only comfort considered, the subjects' preference of these two types of electrodes, and in the case of both comfort and convenience considered, the subjects' preference of these two types of electrodes.

wet electrodes (average impedance of 261.67 ± 28.74 kΩ for the dry electrode and 19.63 ± 1.20 kΩ for the wet electrode). Thus, the impedance of the PreG electrode was acceptable for the BCI system.

The average amplitude and SNR of the 40-target SSVEP of the PreG electrode and wet electrode were calculated from the fundamental to the fourth harmonics component. Figure 9 (a) shows that the fundamental component has the highest amplitude, and the amplitude of harmonics of both the PreG electrode and the wet electrode decrease as the response frequency increasing. One-way repeated-measures ANOVA results show no significant difference of amplitude between the PreG electrode and the wet electrode (fundamental: $F(1, 9) = 3.18$, $p = 0.108$; 2nd harmonics: $F(1, 9) = 0.088$, $p = 0.774$; 3rd harmonics: $F(1, 9) = 0.062$, $p = 0.810$; 4th harmonics: $F(1, 9) = 0.398$, $p = 0.544$). The corresponding SNR of the PreG electrode and the wet electrode also decreases as the response frequency increasing. One-way repeated-measures ANOVA results also show no significant difference of SNR between the PreG electrode and the wet electrode (fundamental: $F(1, 9) = 0.234$, $p = 0.640$; 2nd harmonics: $F(1, 9) = 0.283$, $p = 0.608$; 3rd harmonics: $F(1, 9) = 0.011$, $p = 0.918$; 4th harmonics: $F(1, 9) = 0.136$, $p = 0.721$). In brief, the performance of these two types of electrodes in classification accuracy and ITR at full-band shows no significant difference. The amplitude and SNR also show no significant difference at full-band. Therefore, the developed PreG electrode has a similar EEG signal capture capability to the wet electrode.

Regarding the PreG electrode, 70% of subjects felt comfortable without pain, while for the wet electrode, 90% felt comfortable, 10% of subjects even felt discomfort with pain, while 0% for the wet electrode, as displayed in Figure 10(a). Thus, the comfort level of the proposed device still needs to be improved. In addition, the subjects' options for these two types of electrodes in two cases in the questionnaire were recorded. In the case of only considering comfort, 60% of subjects thought both types of electrodes could be accepted. In another case of comprehensively considering comfort and convenience, 80% of subjects tended to choose the PreG electrodes, as shown in Figure 10(b). The residues after the use of these two types of electrodes are shown in **Figure S4**. The PreG electrode left a little residue, while the wet electrode left gels on the scalp and hair. It must be washed away with water. Therefore, the proposed PreG electrode is a more popular and convenient substitute than the wet electrode.

IV. Conclusion

In this paper, a PreG EEG electrode was proposed, prepared, and demonstrated on a scalp with hair. Compared with the comb-like dry electrode, the PreG electrode was elastic and flexible and had lower impedance. Compared with the wet electrode, the PreG electrode did not need to wash hair after use. The convenience of simple operation made it more welcome by the subjects. The elastic hydrogel probe made most subjects feel comfortable. However, the impedance and comfort level of the PreG electrode were inferior to those of the wet electrode. The performance of the PreG electrode in the BCI application was quite good compared with the wet electrode. For the simple operation process and no cleaning of the electrode after use, researchers or experimenters in the BCI experiment preferred to use the PreG electrode. Even so, new hydrogel materials or recipes need to balance the mechanical and electrical characteristics. An ideal PreG electrode should have a lower impedance, be softly elastic without plastic deformation, and last enough long time.

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