Conductive Rubber Electrodes for Earphone-Based Eye Gesture Input Interface

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ABSTRACT

An eartip made of conductive rubber that also realizes bio-potential electrodes is proposed for a daily-use earphone-based eye gesture input interface. Several prototypes, each with three electrodes to capture Electrooculogram (EOG), are implemented on earphones and examined. Experiments with one subject over a 10 day period reveal that all prototypes capture EOG similarly but they differ as regards stability of the baseline and the presence of motion artifacts. Another experiment conducted on a simple eye-controlled application with six subjects shows that the proposed prototype minimizes motion artifacts and offers good performance. We conclude that conductive rubber with mixed Ag filler is the most suitable setup for daily-use.

Author Keywords

EOG; electrode; conductive rubber; earphone; eye gesture.

ACM Classification Keywords

H.5.2 Information interfaces and presentation (e.g., HCI): Input devices and strategies

INTRODUCTION

Headphones, including earphones, are commonly used devices since they allow us to enjoy music anytime, anywhere. Their ubiquity and long term use provide interesting possibilities for advanced services. For example, continuous health monitoring using headphones is an important application [16]. Since headphones are always placed where the user can access them easily and quickly though they attract no visual attention, various interaction interfaces that can be used anytime anywhere will be provided if they offer input functionalities. While some headphones in the market already offer input functionality via buttons, work continues on creating new interaction styles with headphones. For example, touch sensors have been attached to earphones; they need little force to operate [2]. Other headphones recognize head gestures and so offer eye-free interaction [1]. Facial movement can be detected by a photo interrupter installed inside the earphones [21]. A proximity sensor mounted on an earphone detects which side of the head it is worn on [11]. A simple circuit can detect the tapping command on general headphones [9].

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Bio-potential measurement is another approach for equipping headphones with input functionality. Electromyogram (EMG) has been measured using earphones equipped with conductive foils to recognize facial movements [19]. EOG, one of the known eye tracking techniques, is based on the potential of the retina. Though electrodes are attached around eyes generally, it is shown that EOG can be detected by electrodes placed on headphones [8] and also earphones [10].

There are many wearable eye-based interaction techniques such as [6], as well as several EOG-based interaction techniques [3, 8, 10]. Since such EOG-based techniques do not obstruct the user's view and require only headphone use, the user will extract great benefits if they suit everyday life. Unfortunately it is difficult to use the last technique because the earphones must be custom made [10] which makes their cost rather high.

In this paper, we focus on an earphone-based eye gesture input interface and propose conductive rubber eartip electrodes suitable for daily-use. Experiments with several prototypes were conducted to compare their characteristics.

RELATED WORKS

Ears have a wide variety of shapes as demonstrated by their use for biometric authentication [17]. Since accurate EOG measurement requires continuous proper contact between the electrodes and the skin, it is difficult to provide a universal setup for many users, which is the reason why custom-made earphones were used in [10].

Flexible electrodes can resolve the issues of various kinds of conventional bio-potential electrodes (see [12] for detail). Textile-based electrodes, one major form of flexible electrodes, are often made of silver-coated thread. They have been applied to shirts [14] and bed sheets [15] to capture electrocardiogram (ECG), and also a head cap to measure EOG [23]. Textile electrodes are hopeful materials, however they are not suitable for earphone use due to the size and complicated surface of the inner ear.

Rubber substrates with conductive fillers are good candidates for flexible EOG electrodes. Various materials have been used as the filler; carbon black is the dominant choice. Ag can be used to improve conductivity but it degrades flexibility. Conductive rubber has been already applied as bio-potential electrodes. Pt-catalyzed silicon rubber [13] and conductive

Figure 1. Prototypes tested. Starting from the left, "Rubber", "Disc", "Mold" and "Spring". Each pair of earphones has at least 3 independent electrodes.

rubber with nickel-coated graphite as the filler [18] have been used for ECG capture. Black carbon filler was tested for capturing electroencephalogram (EEG) [7]. Moreover, EOG has also been captured by rubber electrodes around the eyes using an AC coupled arrangement [22]. Since most in-ear earphones have a rubber eartip for fixation and isolation, conductive rubber seems most suitable to replace the conventional eartip in realizing an EOG electrode. It should be noted that EOG is generally measured by a DC coupled amplifier because the DC level of EOG directly matches eye angle. If AC coupling is used, a high pass filter of extremely low frequency is employed. Many bio-potential signals including ECG and EMG have been captured using AC coupling-based techniques and indeed the studies mentioned above lie in the AC domain. In DC-coupled measurements, the stability of electrode potential, which is a result of an electro-chemical reaction between electrode and electrolyte is a quite important factor. This is because the electrode potential is directly added to the measured signal.

Various techniques have been applied for evaluating new electrodes. Impedance while attached to the skin is one of the indexes, e.g. [13, 20]. Such electrical specifications are easy to evaluate, however it is just one of the factors that impact the measured bio-potential. Visual evaluation of measured signals is often conducted, e.g. [13, 18], however it tends to be subjective. The correlation and spectrum of the signals measured by new and reference electrodes [5], and RMS values introduced by artifacts in measured signals [20] have been used as objective evaluations. Unfortunately, the large variations in the signal make the evaluations problematic. Electrical reactions between electrode and skin and the electrical phenomenon inside the body are not always the same, so the measured signals can differ with every trial. It has also been mentioned that electrode performance is enhanced by prior skin preparation [12] which complicates reliability in daily use.

EXAMINED PROTOTYPES

There are many requirements for daily-use earphone-based EOG electrodes such as accurate capture in DC-coupled setting, one setup that suits many users, comfortable to wear, and easy to use. Using conductive rubber eartips of in-ear earphones as electrodes is proposed to meet the requirements. Four types of prototypes including the proposal in Figure 1, "Rubber", "Disc", "Mold" and "Spring" were developed to compare their performances.

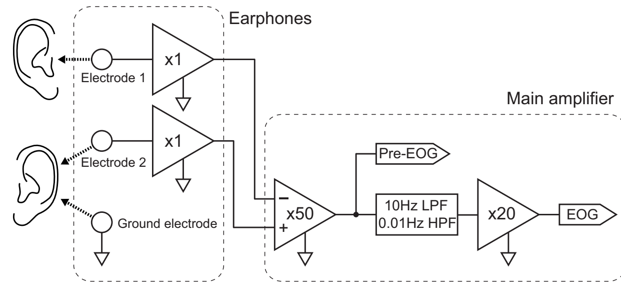

Figure 2. Simplified schematic for EOG measurement. Electrodes 1 and 2 are placed on different sides (right and left) and ground electrode can be placed on either side.

Two different conductive fillers were tested in "Rubber", so that five electrode setups were examined. Each earphone has at least one electrode and a pair of earphones have three electrodes, one works as ground and the other two which are placed at each earphone detects EOG. Each earphone has a pre-amplifier and so acts as an active electrode.

"Rubber"

Our proposal, "Rubber", is based on an in-ear canal earphone with a support to fix itself in the ear canal. Both the eartip and the support are made of conductive rubber and work as independent electrodes. Two filler configurations were examined; carbon which is commonly used and a mixture of carbon and Ag which is often used as bio-potential electrode; the two types were labeled "C rubber" and "Ag rubber", respectively. Though conductivity is high if the filler consists of only Ag, we found that such an eartip was too hard to wear comfortably.

"Disc"

"Disc" is made of small Ag/AgCl disc electrodes (widely used in bio-potential measurements) mounted on a intra-concha earphone. Each earphone has three disc electrodes, some of them are electrically shorted to keep contact to the skin.

"Mold"

Custom earphones completely fit the user's ears offer high comfort and isolation and are often used by musicians. "Mold" devices were constructed on a shell customized to fit the individual. The electrode consisted of Ag/AgCl ink. This prototype was same as that tested in [10].

"Spring"

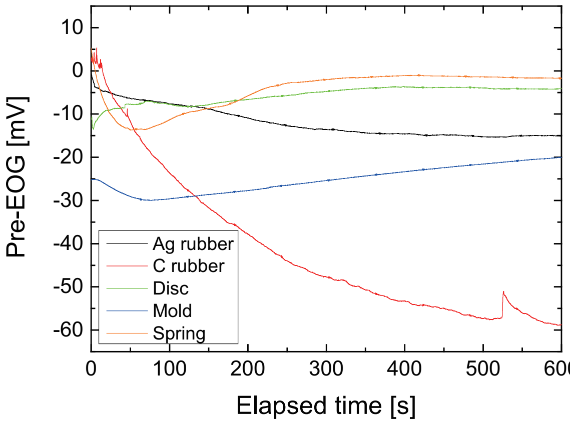

Figure 3. An example of Pre-EOG which represents the balance of electrode potentials. Except for "C rubber", all signals have small values.

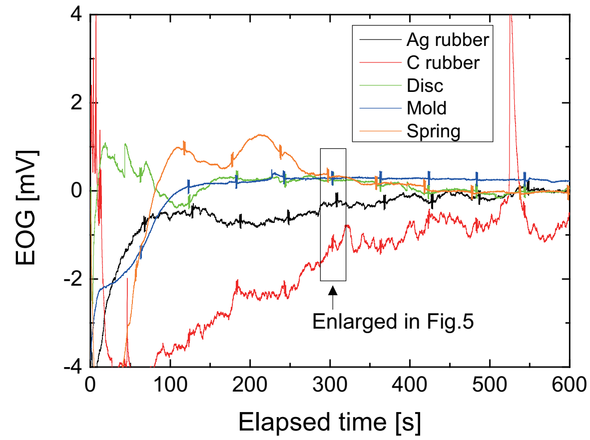

Figure 4. An example of EOG according to Figure 3. Eye movements every one minute are found as small and quick swings. Baseline stability differs with the prototype.

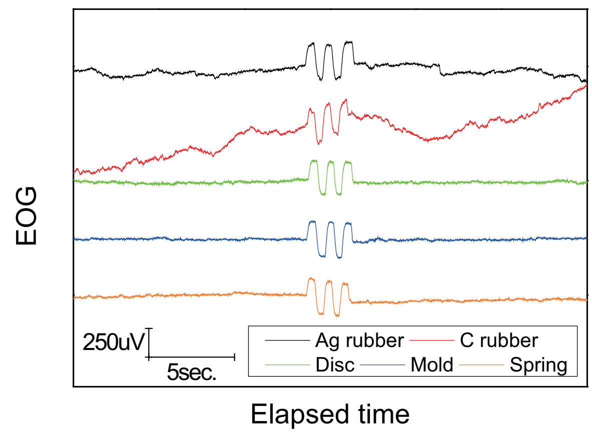

Figure 5. Observed EOG in a part of Figure 4. Eye movements are clearly found in all prototypes; some prototypes offer excellent stability.

"Spring" was implemented on an intra-concha earphone; three thin springs were mounted around each earphone, which is same as "Disc". Each Ag/AgCl coated spring works as an electrode. The springs bend to provide contact with various shapes; they apply pressure to the skin.

EVALUATION

It is difficult to evaluate the electrodes as mentioned above since simultaneous trials with multiple setups are impossible. We conducted two evaluations; basic and practical, with multiple trials to enhance evaluation reliability. The basic evaluation focuses on the characteristics of each prototype. The practical evaluation examines compatibility with many users in actual use.

Basic evaluation

The prototypes were connected to the test circuit shown in Figure 2. EOG and Pre-EOG which indicates the imbalance on electrode potential, were recorded with 200Hz sampling. The experiment was conducted with one particular subject over a 10 day period. All setups were examined each day and the testing order was shuffled (10 records for each prototype). The subject worn the prototype after wiping his ears with alcohol and kept gazing straight forward for 10 minutes. During the experiment, he moved his eyes right and left to maximum extent every minute.

Balance of electrode potentials

Figure 3 shows an example of a recorded Pre-EOG. Electrodes of Ag/AgCl or Ag yield small signals while carbon outputs much larger signals. Since large imbalance between electrode potentials can saturate the amplifier and introduce large drift, electrodes with such characteristics are not suitable as bio-potential electrodes. In Figure 3, no signal was saturated however "C rubber" saturated the amplifier several times in this experiment (exceeded $\pm$100mV in this setting).

Measured EOG

Figure 4 shows an example of EOGs corresponding to Figure 3 and a part of it is enlarged in Figure 5. In Figure 4, the values approach zero due to the high pass filter. Even though baseline stability differs with the setups, the eye movement is clearly captured by all setups. In these figures, upper indicates that the eye moves to the right.

The amplitudes of EOG during eye movement right to left is the same value for all setups, about 250μV. The amplitudes were manually measured from all records and the averages and standard deviations (SD) are shown in Figure 6. For "C rubber", the signal was saturated and no eye related signal was seen on some days. Since it is known that the amplitude of EOG can change with room illumination level, it is natural that the amplitude varies. A key finding is that each setup tested can capture EOG at the same level, even if the electrode positions differ slightly in each setup. This means the comparison mainly involves baseline stability or noise.

Stability of baseline

Figures 4 and 5 indicate that baseline stability varies markedly. Good baseline stability is desired to recognize eye movements correctly. SD in 5-second time window was used as an index of stability. Since sudden or pulse-like artifacts are sometimes observed in bio-potential signals, e.g. "C rubber" at 530s in Figure 4, the median of the SDs over the 10-minute measurement period was used in this evaluation,

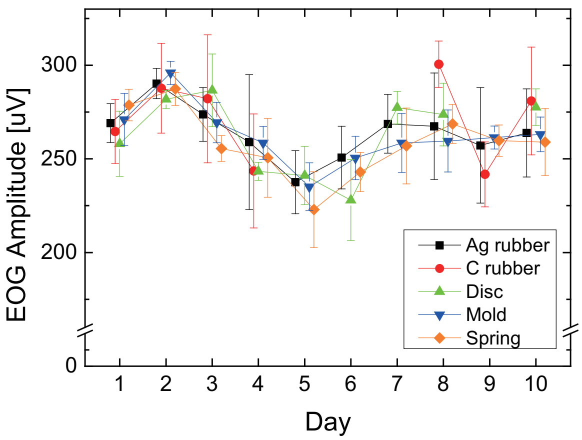

Figure 6. Measured EOG amplitude. Though the values change with day slightly, all prototypes capture the eye movements to the same level.

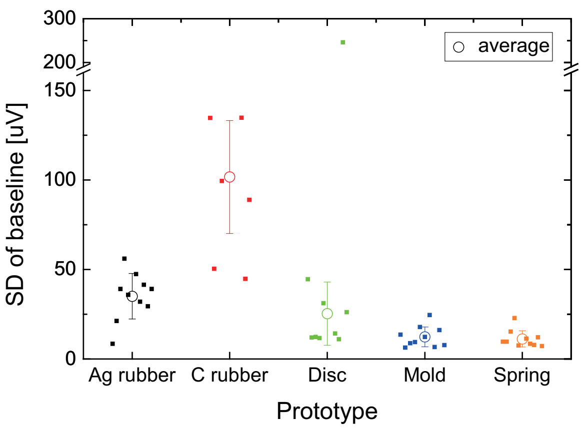

Figure 7. SD median represents stability of the baseline. Right two prototypes show excellent performance. Though "Ag rubber" is inferior compared with the two, the difference is not critical.

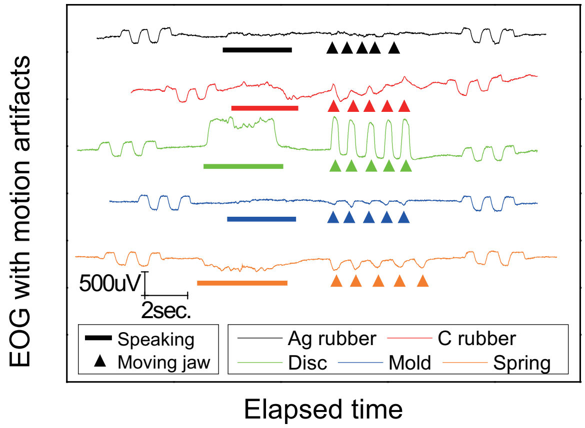

Figure 8. Measured EOG during motions. While "Disc" introduces quite large motion artifact, "Ag rubber" and "Mold" have high tolerance.

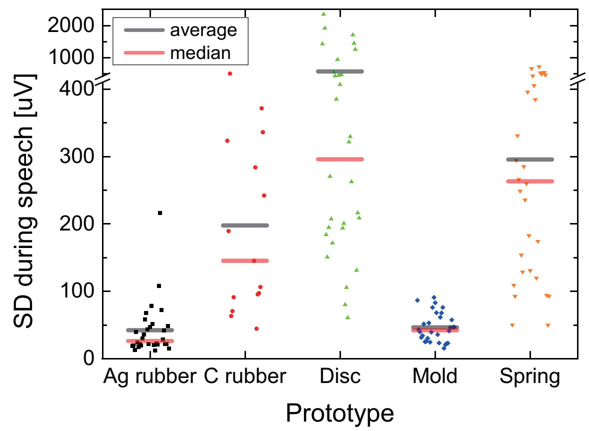

Figure 9. SD during speech section. Artifacts with "Ag rubber" and "Mold" are smaller than others

which also eliminates the effect of eye movement every one minute. The median values and their averages are shown in Figure 7. Data was dropped if the signal was saturated because the corresponding SD was calculated as 0. A outlier due to strong hum noise is shown for the "Disc" setup but such points were not used in calculating the average.

"Mold" and "Spring" always offered stable baselines and while "C rubber" was always noisy. The baseline for "Disc" was sometimes noisy. "Ag rubber" was noisy compared with the best two prototypes, but it is not so critical because the amplitude of EOG to be recognized is much larger in many cases. The SD values decrease over the last 5 minutes, but the tendency remained the same.

Motion artifact

Considering usage in everyday life, electrodes must be robust in suppressing the effects of motion artifacts. If motion artifacts are not negligible, false positives will often occur. After the previous experiment, the subject kept wearing the prototype to check for motion artifacts. He spoke for several seconds and opened/closed his jaw 5 times. Before and after the motions he moved his eyes. This sequence was repeated three times per day so that a total of 30 records was obtained for each setup. An example of measured EOG is shown in Figure 8. The thick lines represent speech sections and the triangles represent jaw movements. Figure 9 shows SD value calculated for speech section and Figure 10 shows the plot of the amplitude of artifact introduced by open/closing jaw as manually measured from peak-to-peak values.

"Disc" exhibits quite large artifacts and their values exceed the amplitude related to eye movement. In "C rubber" and "Spring", many motion artifacts match the signal level of eye movement. On the other hand, motion artifacts were few and small with the "Ag rubber" and "Mold", with "Ag rubber" demonstrating excellent performance.

Practical Evaluation

The first experiment showed that "Mold", examined in previous research [10] offers good performance while the "Ag rubber" proposed here is comparable. If "Ag rubber" offers high compatibility with different users, which is one of the remaining requirements, it will be a suitable setup for daily-use. In this evaluation, six subjects participated using an eye-controlled application to evaluate compatibility and robustness against motion artifacts. All subjects were male

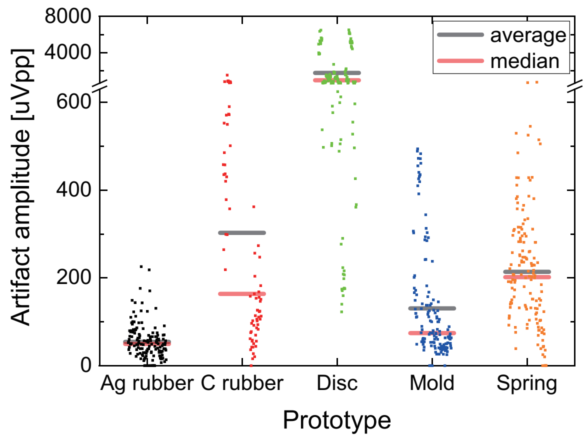

Figure 10. Artifact amplitude introduced by moving jaw. Artifacts with "Ag rubber" are smaller than eye movement in many cases.

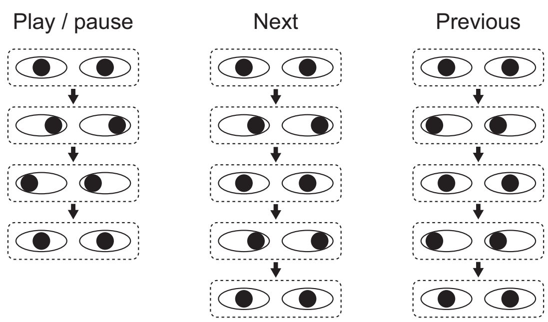

Figure 11. Eye gesture tested in the evaluation. This figure is drawn from viewpoint of the user. When observed from the front, directions are reversed.

because "Ag rubber" provides only one size of eartip that was non-adjustable. Since "C rubber" was confirmed by the prior experiment to be unsuitable for EOG measurement and "Mold" is user specific, the remaining three setups; "Ag rubber", 'Disc", and "Spring" were examined.

Tested application

A simple application by which the user controlled a music player with eye gestures was implemented. It detects a quick EOG change as a saccade and recognizes a sequence of saccades as an eye gesture. The eye gesture commands are; right to left for play/pause, right and right again for next track, and left and left for previous track (see Figure 11). The user can control the player through hands-free operation by moving just the eyes. Other commands, such as volume up were also implemented, but they were not used in the experiment.

Procedure

Subjects used the application while wearing the prototype for about 10 minutes before the evaluation to develop the ability to control the player freely. The subject was asked to wipe his ears with alcohol before inserting the prototype. When the baseline seemed stable or about 5 minutes had elapsed, the evaluation was started. In the evaluation, the display in front of the subject indicated the seconds remaining till the next command and the command to be input was shown every 10 seconds. In the first sequence, the user was allowed to only move the eyes, relax condition, and 30 records (3 commands x 10 trials) were obtained. After that the user was asked to speak the values of the remaining seconds (5, 4, 3, 2, and 1) and one second after he spoke "1" he moved his eyes to match the command, this is the speaking condition and 30 records were similarly obtained. Since the subject received feedback only by the display (the music player was muted), he did not know whether the eye gesture was correctly recognized, which prevented multiple eye gestures for a command and the refinement of gestures during the trials. The sequence of prototype use was changed for the subjects to remove the effect of habituation to eye gesture and the benefits of the electrode examined later.

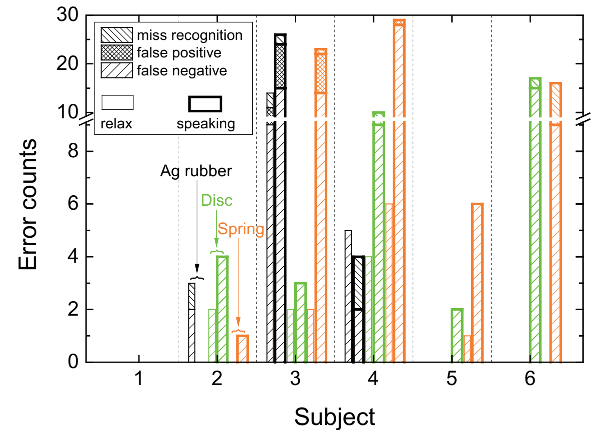

Figure 12. Eye gesture recognition result. Errors were subject dependent. "Spring" offers widest compatibility and "Ag rubber" takes second place.

Recognition results

Three indexes were measured; false negative, false positive, and recognition error. False negative was counted when the system did not recognize that the user had performed an eye gesture. False positive was counted when the system recognized the signal as a command without user's eye movement. Recognition error was counted when the system recognized that a command had been made but identified it wrongly.

The results are shown in Figure 12. One recognition error created by subject 4, which was clearly due to the subject, was eliminated as a result. The errors were found to be strongly dependent on the subject. While subject 1 demonstrated perfect operation, some subjects made over 10 errors while inputting 30 commands. Many errors were false negatives, however false positives and recognition errors were also seen. Focusing on relax condition, "Ag rubber" can be considered as demonstrating the same level of error as the other prototypes; subject 3 created a peculiar result which is discussed later. Though the previous experiment indicates that the baseline stability of "Ag rubber" is low and it was also observed in the signal measured in this experiment, the recognition result is not degraded. Comparing the two conditions, the errors with "Disc" and "Spring" increase in speaking condition compared to relax. It is clearly seen in subject 6 and there is no counterexample. On the other hand, "Ag rubber" does not increase the error while speaking, which means that it offers high tolerance against motion artifacts. This result supports the conclusion that the proposed "Ag rubber" is compatible with different users and offers robustness against motion artifacts.

Comfort

The subjects were asked about the comfort of each prototype after the experiment. Many subjects noted that "Spring" was painful and not acceptable for daily-use earphones. On the other hand, few complaints were reported for "Ag rubber" and "Disc", these are almost same as regular in-ear and intra-concha earphones. The preference between "Ag rubber" or "Disc" was user-dependent.

DISCUSSION

There are several points to be discussed before concluding which electrode setup is suitable for a daily-use earphone-based gesture input interface.

Motion artifact robustness

The experiments show that the proposed "Ag rubber" is robust against motion artifacts, an attribute that is quite attractive for daily-use. Ear shape changes with mouth movement, which changes the contact area and locations of the electrode and results in motion artifacts. The ear canal probably changes less than the pinna, moreover, the eartip presses the canal so physical changes are suppressed. Besides that the whole of the eartip works as an electrode, local changes have little impact on the measured signal. It is same with "Mold" but it is affected more by the shape change compared with "Rubber". With regard to "Disc" and "Spring", they offer only localized point contact between the electrode and the skin so the physical change of the ear directly impacts the measured signal.

Improving baseline stability

The low baseline stability with "Ag rubber" is not a critical barrier to eye gesture recognition. However, high stability is desirable as it brings benefits not only for DC coupled measurement but also AC coupled such as ECG and EMG. The difference between "Ag rubber" and other prototypes which offer high stability is the material; Ag and Ag/AgCl. Ag/AgCl electrode is preferred to Ag in conventional biopotential measurements, because Ag/AgCl offers more stable electrode potential. It is expected that replacing Ag with Ag/AgCl as the filler would yield higher baseline stability.

Enhancing compatibility and comfort

The result with subject 3 seems peculiar compared to the other subjects. The differences are many errors with "Ag rubber" and little degradation in speaking condition with "Disc". Several reasons can be considered. It may seem to indicate a limitation in compatibility, however we do not think so. It is reasonable that many errors occurred with "Ag rubber" because its baseline stability is generally low and it is demonstrably lower in his case. While regular in-ear earphones have several sizes of eartip and support, often three sizes, to assure a comfortable fit to the user's ear, the prototype has only one size. So it can be considered that the size of the eartip did not match his ear and so "Ag rubber" failed to offer proper contact. Providing eartips of different sizes would reduce his error and also expand user compatibility. For the latter point, one possibility is that "Disc" fitted perfectly to his ears and also suppressed the shape change. As other possibility, he could benefited by prior skin preparation, because "Disc" was the third sample in his experiment.

One of the findings is that the filler does not have to be entirely Ag, some regions can use other materials. This means that the hardness of the eartip can be adjusted over a wide range. So not only size but also hardness can be changed to improve comfort. The flexibility offered by the conductive rubber will be effective when implementing other biopotential based applications, for example wrist watch style electrodes. The mixing rate affects not only hardness but also cost and maybe performance. Further research is needed to develop really effective flexible electrodes.

Suitable setup for daily-use

Two experiments were conducted to compare the proposed "Ag rubber" to several other candidates. Four points were confirmed; the baseline stability of the proposal is not so high but it is not a problem for eye gesture recognition, the proposal has high tolerance against motion artifacts, it offers wide user compatibility, and it offers comfort levels matching those of regular earphones. The requirements that remain to be met include cost and durability. Actually, one thin spring of the "Spring" prototype twisted off in the experiments. A thick spring offers high tolerance but it will be even more uncomfortable. The proposal has no such weaknesses. Even if the eartip is broken or degraded due to aging, it is easy and also cheap to replace it. Though the conductive eartip is more expensive to make than the regular eartip, it will be cheaper than the other electrode setups tested. No electrode setup was found to be consistently superior with regard to all requirements and evaluation indexes, and selection should be made after considering the trade-offs. For example, "Spring" would better suit ALS patient or short time experiments in the lab, which involve few motions other than eye movements. Considering many requirements for daily-use and the possibility of improving the performance, we conclude that proposed "Ag rubber" is the most suitable setup for earphone electrodes among the prototypes examined.

Towards daily-usable eye gesture input interface

The preliminary experiments conducted bring us some insights, however they do not address all aspects of an eye gesture input interface for everyday life. For example, the subjects were asked to wipe ears with alcohol before inserting the electrode in the experiment. This was done so as to equalize the test conditions for the electrodes, however wiping with alcohol is not desired in daily-use. To give another example, though there are many factors that can induce artifacts in daily life, only the motion artifact driven by speaking was evaluated.

Moreover, the eye gestures to be recognized as commands were quite simple in the experiment. However, they are not suitable for daily-use, because they are often observed in daily activities with no intention of eye gesture input [4]. They should be carefully re-designed for use in everyday life.

Further research and investigations with more subjects in environments closer to practical use are desired. It is also necessary to explore how to solve or reduce the issues triggered by, for example, daily-variable motion artifacts and EOG change according to illumination level.

CONCLUSION

Several prototypes including the proposed conductive rubber were fabricated to identify the most suitable electrode setup for an earphone-based eye gesture input interface. The basic evaluation confirmed that an eartip electrode made of conductive rubber with Ag filler, "Ag rubber", minimized motion artifacts while achieving adequate performance. A practical evaluation confirmed that its baseline stability is acceptable and that it offers wide user compatibility and comfort. We conclude that the conductive rubber electrode with mixed Ag filler is the most suitable electrode setup for a daily-use earphone-based eye gesture input interface.

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