Simultaneous EEG Recordings with Dry and Wet Electrodes in Motor-Imagery

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Abstract

Robust dry EEG electrodes are arguably the key to making EEG Brain-Computer Interfaces (BCIs) a practical technology. Existing studies on dry EEG electrodes can be characterized by the recording method (stand-alone dry electrodes or simultaneous recording with wet electrodes), the dry electrode technology (e.g. active or passive), the paradigm used for testing (e.g. event-related potentials), and the measure of performance (e.g. comparing dry and wet electrode frequency spectra). In this study, an active-dry electrode prototype is tested, during a motor-imagery task, with EEG-BCI in mind. It is used simultaneously with passive-wet electrodes and assessed using offline classification accuracy. Our results indicate that the two types of electrodes are comparable in their performance but there are improvements to be made, particularly in finding ways to reduce motion-related artifacts.

1 Introduction

Wet electrode preparation presents a major obstacle to widespread, day-to-day use of EEG-BCI, especially for patients with impaired mobility. It is a time-consuming process, due in large part to scrubbing of the scalp to improve signal quality; it can be an unpleasant experience for subjects, especially after frequent sessions that heighten skin-sensitivity; and, over hours of use, it requires regular maintenance as the conductive gel dries and degrades signal quality [1]. Dry electrodes are a promising solution to these problems, potentially reducing set-up times, subject discomfort, and the need for maintenance.

Dry electrode performance is often compared to that of existing wet electrodes. However, for a given experimental paradigm and subject, if dry and wet electrodes are recorded in separate trials, variation between trials can distort electrode comparisons. Simultaneous recording with the two types of electrodes avoids this problem. Comparisons of performance in simultaneous active-dry and wet electrode studies have included visual inspection of spontaneous EEG waveforms [2, 3, 4] or power spectral densities (PSDs) [3, 4], hypothesis testing of evoked potential (EP) properties such as amplitude [3, 5], hypothesis testing of band-power values for an alpha-rhythm concentration task [5], and classification accuracies in EP and alpha-rhythm concentration tasks [5]. Comparisons of performance in simultaneous passive-dry and wet electrode studies have included correlation of electrodes during reactive alpha and motor-imagery tasks [6] and the coherence of electrodes [7]. In general, performance levels of dry electrode systems are found to be comparable to traditional gel-based electrodes. However, the small number of subjects (≤ 12) employed in these studies limits the conclusiveness of findings.

In this article, we present a 20-subject study on motor-imagery (the most frequently used paradigm in BCI-research [8]) in which we record simultaneously with active-dry and passive-wet electrodes, and compare their performance using classification accuracy.

2 Methods

2.1 Experimental Design

Subjects were instructed to perform kinesthetic motor-imagery of the right hand [9]. It was emphasized that they try to feel, rather than visualize, the imagined motion. A computer monitor approximately 1.5 meters away from the seated subjects provided visual prompts to start and stop motor-imagery. The display was black except for a colored square containing a black fixation cross, both centered on the screen. The color of the square represented the two experimental conditions, rest and imagery. For the rest condition trials, the square was gray and subjects were asked to relax and maintain fixation on the cross. For the imagery condition trials, the square was green and subjects were asked to perform motor-imagery. Each trial lasted between 6.25 and 7.25 seconds, selected randomly. The sequence of trials was pseudo-randomized but the number of consecutive rest or imagery trials was limited to 3 so as to avoid subject fatigue during prolonged periods of the same condition. Two runs, each consisting of 30 trials per condition, were recorded for every subject, with a short pause in between. This resulted in a total of 120 trials per subject. Each subject provided informed consent in accordance with guidelines set by the Max Planck Society.

2.2 Hardware Setup

Standard off-the-shelf passive-wet electrodes were used. The active-dry electrodes, Figure 1.A, were designed and manufactured at the Max Planck Institute. They were made to attach to an EEG cap using modified disc-electrode connectors. The connectors were reinforced inside the cap, increasing the area of contact with the head and improving electrode stability. Pressured air, applied to a chamber within the electrodes' housing, is used to protrude an array of 19 gold-plated pins and regulate their contact force. The signal conducted by the pins is then amplified by an op-amp circuit contained within the electrodes.

2.3 Experimental Data & Data Analysis

EEG was recorded using two pairs of electrodes, one wet and one dry, simultaneously. To capture modulation of the sensorimotor-rhythm (SMR) resulting from motor-imagery of the right hand, one electrode pair was positioned at C1 and C5 and the other at Fc3 and Cp3, according to the 10-20 system. The position of each electrode pair was counter-balanced across subjects, i.e., half the subjects had the wet pair positioned at C1-C5 and the dry pair at Fc3-Cp3 and the other half had the dry pair positioned at C1-C5 and the wet pair at Fc3-Cp3. Signals were sampled at 500 Hz using a QuickAmp amplifier (BrainProducts GmbH, Gilching, Germany) with a built-in common-average reference. A wet ground electrode was attached to subjects' right ear lobes. Twenty-three subjects (S1-S23) participated, 9 of whom were female, with a mean age of 28.70 years and a standard deviation of 5.90 years. All subjects were right-handed and none had known neurological disorders. Two subjects were excluded from further analysis since their recordings showed millivolt-scale amplitudes well beyond those of typical EEG. In both cases, hair thickness seemed to prevent the dry electrode pins from contacting the scalp effectively. A third subject was excluded after observing that only 50 Hz mains noise was being measured. The remaining subjects' recordings showed EEG-like amplitudes and typical EEG artifacts associated with muscle movements (e.g. clenching of the jaw) and eye movements.

For each subject, the amplifier's built-in common-average was removed from the data by calculating two bipolar recordings, one between the two wet electrodes and the other the two dry electrodes. A Fast Fourier Transform (FFT) with a Hanning window was applied to the first 6.25 seconds of each trial, per bipolar recording. The log-bandpower, commonly used in EEG-BCI analysis [9], was then averaged across 2 Hz frequency bands, from 7 Hz to 39 Hz. This 16-dimensional feature space (16 log-bandpower values per bipolar recording) was used offline to train two linear ν-Support Vector Machines (ν-SVM) [10], one for each bipolar recording, to dis-

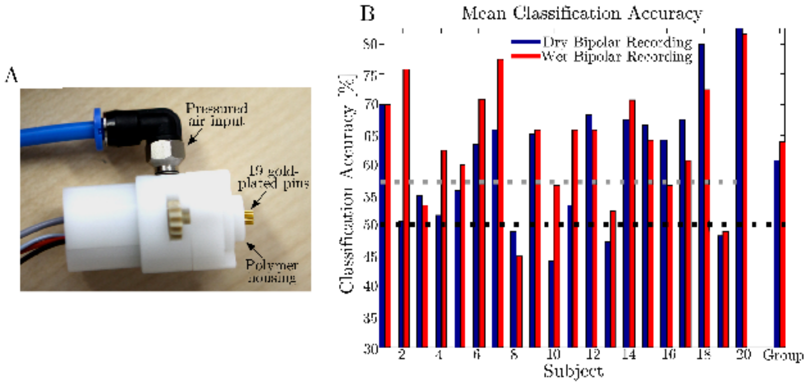

Figure 1: (A) Dry electrode prototype. (B) Mean classification accuracies of the dry and wet bipolar recordings. The dotted black line represents chance-level accuracy (50%). The dotted gray line represents the classification accuracy required to reject the null-hypothesis of chance-level accuracy at α=0.05 (57.50% for individual subjects and 51.67% for the group, not shown).

criminate between trials of the rest and imagery conditions. To avoid over-fitting, ν was selected using 10-fold cross-validation for each of the 10 outer folds.

3 Results

The performances of the active-dry and passive-wet electrodes are presented in Figure 1.B. The group mean classification accuracies of the dry and wet bipolar recordings are 60.83% and 63.88%, respectively. These relatively low means are not surprising given that only one bipolar recording is used for classification in each case [11]. Based on a permutation test at significance level α= 0.05, permuting the bipolar recording label, i.e., wet or dry, of the subject-specific classification results 10,000 times, the mean of classification differences is not large enough to reject the null-hypothesis of equal classification accuracy (p = 0.0610).

4 Discussion

Figure 1.B demonstrates that neither dry nor wet classification accuracies are consistently higher across all subjects. However, there are outliers in the single-subject results that best explain reasons for lower classification accuracies, on average, with the dry bipolar recording. In S2's case, wet classification accuracy is higher than that of the dry by 25%. After examining S2's raw recordings, it was apparent that the second run was dominated by 50 Hz mains noise. Retraining the ν-SVM without the second run, the classification accuracies were identical for both dry and wet at 70%. It is likely that the dry electrode pins lost contact with the subject's scalp between runs. Both dry and wet classification accuracies are low for S13 (47.5% and 52.5%, respectively) and S19 (48.33% and 49.17%, respectively). S13's raw data shows large artifacts at the same points in time for both the dry and wet recordings. It is likely that the dry electrodes, which protrude 3.5cm above the EEG cap, were moving and subsequently shifting the wet electrodes. In S19's raw data, a heart-beat is visible in one dry electrode recording. Such low-frequency, periodic oscillations can be removed by high or band pass filtering. However, the skin-stretch artifacts caused by blood vessels and muscles underneath the scalp may not always display low-frequency periodicity, in which case filtering may be ineffective and classification accuracies are consequently influenced.

It should be noted that some subjects in this study found the electrode pins unpleasant. This brings attention to a trade-off in direct-contact dry electrodes - excessive force may cause the subject discomfort but insufficient force can lead to noisy signals or prevent electrode pins from penetrating thick hair [12].

5 Conclusion

This 20-subject study provides evidence that, for a motor-imagery task during which active-dry and passive-wet electrodes are used simultaneously, the two types of electrodes produce comparable classification accuracies. However, motion, whether that of the dry electrode, cap, or subject, seems to adversely affect classification accuracies. To reduce motion-related artifacts, further research into positioning the dry electrodes on the head (and maintaining their contact with the scalp) is particularly important. In addition, increasing the number of dry electrodes would allow for source separation techniques such as Independent Components Analysis, making it easier to examine physiological artifacts and design improved dry electrodes accordingly. Future designs should also consider the discomfort reported by some subjects by redesigning the pins, adjusting the forces applied to the scalp, or considering pin-free alternatives. The ultimate hope is to make new applications of EEG, such as non-invasive BCI, more viable for day-to-day use.

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