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Determining Comfortable Pressure Ranges for Wearable EEG Headsets

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Abstract. Measuring and interpretation of brain wave signals through electroencephalography (EEG) is an emerging technology. The technique is traditionally applied in a clinical setting with EEG caps and conductive gels to ensure proper contact through a subject's hair, and anticipate inter-subject anthropometric variations. Development of dry electrodes offers the potential to develop wearable EEG headsets. Such devices could induce medical and commercial applications. In this paper, we evaluate a prototype EEG headset that actively places electrodes at standardized positions on the subject's head, where each electrode is applied with equal pressure. The system is designed for use with dry electrodes. Our research delivers a better understanding on the link between general level of comfort and possible useful clear data signals, that can be used in brain computer interfaces (BCI). The present study is confined to the impact of adjustable electrodes pressure on level of user comfort only. Levels of discomfort are assessed in twelve participants, wearing an EEG headset with controllable electrode pressure exerted at 14 locations. Of-the-shelf dry electrodes are used. In a first session, evenly distributed pressure is increased and afterwards decreased in fixed time intervals, going from 10 kPa to 30 kPa and vice versa with steps of 2 kPa. In a second session, a subject specific acceptable pressure level is retrieved from the data of the first session and constantly applied for 30 min. During this intervention, level of discomfort is assessed in a VAS-scale. Additional observation and surveys yields insights on user experience in wearing a pressure exerting EEG headset.

Keywords: Brain computer interface · Electroencephalography
Wearable EEG headset · Pressure · Dry electrodes · Discomfort

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1 Introduction

A brain Computer Interface reads out the subject's brain signals and tune them to control actions performed by a system that is external to the subject's body [1]. Non-invasive BCI is a relative new technology, by which electrical fluctuations are detected onto the subject's head. Fluctuations are typically in a range between 2 and 100 Hz with normal peak-to-peak magnitude between 0.5 and 100 μV [2]. The first EEG assessment dates from 1924, through needles that punctured the upper skin layer, and read-out through a Galvanometer [2]. Since then, signal quality kept being improved using vacuum tubes and transistors. Nowadays, one can get clear signals in a relatively user-friendly and comfortable way. Brain computer interfaces have gained much interest for their potential medical and consumer applications, but current research is mainly confined to lab setting. Main applications in the medical field are monitoring and diagnostics, conducted with classical EEG caps with conductive gel [2, 3]. In order to unlock the full potential that EEG based BCIs offer, wearable EEG headsets should be developed [4]. Preliminary results indicate that a commercial headset can control a robotic arm in four directions, thereby bypassing the neuromuscular system [5]. Such advanced applications of wearable headsets are limited to a proof-of-concept.

An extensive research focus on end user and application is required to accelerate real-live applications [6]. Miniaturization of EEG electrodes, enhanced sensitivity and conductivity, active amplification, electric shielding, wireless data and miniaturization of electronics and improved signal processing and classifiers are all promising technologies that could facilitate such breakthrough. Connection with the scalp and electrodes, adaptability and standardization of electrode positions, comfort and acceptance, ease of use in mounting and un-mounting the headset, are main design drivers in the development of wearable EEG headsets [7]. Gel based electrodes, although they provide proper electrical contact even in the presence of hair, have a low acceptance for the end user to this respect [8]. Sensitive dry electrodes are increasingly offered as an alternative for wearable headsets.

A challenging usability and functional factor in the deployment of dry electrodes is the pressure of the electrodes exerted on the subject's skull [8]. On one hand, this pressure should not be too high, not to induce discomfort or annoyance by the wearer. At the other hand, a sufficiently amount of pressure is required for making stable contact with subjects' head [7]. Also, the presence of hair could be an important factor to take account of in the design of wearable EEG headsets [9] and exerting pressure could be a solution to ensure proper contact of electrodes protruding the hair layer [10, 11]. Increasing electrode pressure evidently increases the chance of electrodes making proper contact with the subject's skin, thus increasing conductivity and thus increasing signal quality. So, the electrode pressure should be not too low, to ensure proper signal quality.

Pressure requirements should be integrated in other requirements for wearable EEG headsets [7]. A particular challenge in the design of EEG head caps is placement of electrodes at pre-defined anatomical locations. These locations are geometrically inferred from four anatomical points: nasion, inion, left pre-auriculair point and right pre-auriculair point (respectively A1 and A2 in Fig. 2, left), along the so called 10–20 system [12]. They should be incorporated in the design of EEG headcaps to ensure accurate, standardized and repeatable EEG recording locations. In clinical applications, these positions are provided through the configuration of the textile cap, and contact is ensured by conductive gel. In the design of wearable headsets, the challenge remains to integrate standardized and accurate positioning with accurate pressure range, bound from above by usability and comfort issues and bound from below by functional requirements.

This pressure range is not yet systematically investigated in scientific literature. The problem is that no research instruments exist that automatically position electrode locations at pre-defined 10–20 locations, independent of the individual user's head size and geometry, at the same time ensures that the same pressure is exerted, uniformly at each particular electrode location, and moreover, that pressure can be controlled to assess subject's discomfort and signal quality.

2 Materials and Methods

Dedicated equipment was developed to acquire correct electrode positioning and controllable pressure, to simulate the behavior of dry electrodes in a wearable headset (patent pending).

This test setting was applied on healthy volunteers in a three phases. Firstly, comfort levels were assessed under subsequently increasing the pressure on the electrodes. Secondly, comfort levels were assessed under subsequently decreasing the pressure on the electrodes. Thirdly, key comfort levels were retrieved from these sequences and the time was assessed that comfort level persisted under corresponding pressure levels.

2.1 Test Equipment

The research and development of the equipment that allows conducting experiments has a long history, with many iterations and the generation of new scientific knowledge.

The first step was a high school design assignment where a group of four students was challenged to design a wearable EEG headset with dry electrodes: easy to mount and clean, comfortable for operator and subject and to be used in a clinical setting. They designed a modular headset, adaptable to multiple purposes in a low cost concept [13], see Fig. 1.

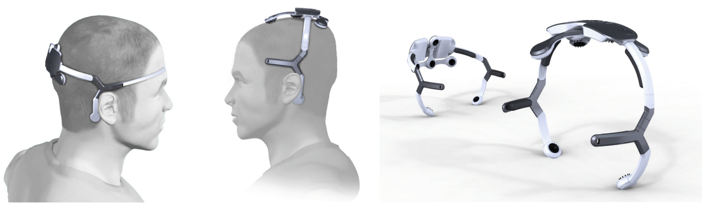

Fig. 1. Modular EEG headset: visually evoked event related potentials can be detected on the back of the subject's skull (left), and cognitive evoked potentials at the top (right). The concept allows for the braces to be configured, thereby using the same components for shells housing electrodes and electronics [13].

Geometry and sizing were based on the British adult population for male and female [14]. Breadth of the headset was adjusted to the breadth of the head at the maximum level above and behind the ears. The maximum circumference above the brow ridges was taken as guideline for head circumference. The bitragion coronal arc measured across the crown of the head (arcwidth) provided the curvature in the frontal plane. As sagittal arc, the length of the occipital-frontal curvature from the external occipital protuberance to the glabella in the sagittal plane was taken (arclength).

The modular concept and design was appreciated through a Red Dot Design award [15], but physical prototyping revealed sub-optimal fit and lack of functionality. Size and shape of the headset were based on available classical anthropometric data of the human head and naive underlying geometrical shapes representing the human head, but the design of wearable products require 3D anthropometric models and methods to link univariate measurements to non-trivial geometrical shapes that accurately represents the human body shape [16].

A shape model of the human skull was constructed from 100 medical images, CT and MRI scans [17], thereby omitting the presence of hair [9]. The model was shown saturated for adding new skull models. Anatomical landmarks were annotated manually, e.g. inion, nasion, glabella, on which anthropometrical measurements can be inferred geometrically, e.g. head length as distance between inion and glabella. Thus, the shape model of the head was enriched with univariate measurements that allows parameterization of the human head shape. Most influencing parameters on global head shapes were retrieved: head length, bitragion width, circumference and arcwidth. Such parameters allows linking product dimensions to head shape to ensure proper fit and function [16, 18].

The enriched shape model of the skull was used to design an EEG headsets at 14 electrode locations (Fig. 2, left) commonly used in of-the-shelve consumer headsets [19]. The electrode variations were mapped with the shape model (Fig. 2, middle) to achieve a one-size fits all prototype (Fig. 2, right). This results in 10–15% improvement in fit and accuracy compared to of-the-shelf available headsets [20].

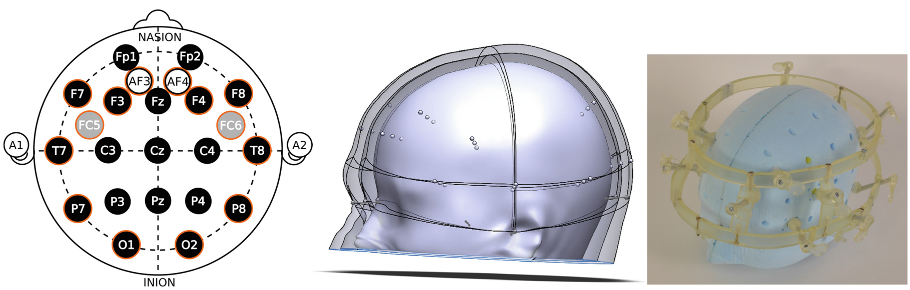

Fig. 2. Adjustable non functional EEG headset. Left: those electrodes at 10–20 locations that are assessed by the design (orange circles). Middle: variation of these locations along the main shape (first principal component), mean head shape and P5 and P95 displayed as ghost surfaces. Right: non functional prototype that anticipates these variations [4].

The test setting in this work is built upon the geometry of this prototype [20]. An additional technology is supplied to ensure automatic electrode positioning at these 14 standardized, pre-defined locations and in which pressure can be controlled in function of e.g. time, signal quality or discomfort. In this work, we present a first pilot study to assess discomfort depending on electrode pressure. The test setting was equipped with dry spikey electrodes from the OpenBCI platform (Florida Research Instruments).

2.2 Subject Assessments

A group of 12 healthy volunteers was enrolled in this study after informed consent. Study was approved by the ethical committee of UA/UZA (16/11/132). Before the experiments, subject completed a small survey on their age, gender, mood and experience with brain computer interfaces.

Pressure is required to ensure proper connection between the electrodes and the scalp. For thicker and more voluminous the hair, more pressure is expected to ensure a good connection between scalp and the electrodes. Therefore, subjects were balanced for amount of hair. A combination of hair thickness and hair volume was assessed to that end, by making a ponytail of maximal length and measuring the circumference of the string. Three categories were distinguished: low hair volume: 5 cm and below, medium hair volume: between 5 cm and 10 cm and high hair volume: 10 cm and up. Each category contained four subjects.

The level of discomfort was measured with a ten point Likert scale, ranging from 1: no discomfort, 5: discomfort, up to 10: very painful.

Tests were conducted in a space with smooth walls where the participant was sitting behind a desk in front of a laptop or handling a smartphone. In each assessment, the test device was initially placed on the subject's head without exerting any pressure. Subjects could control the pressure, ranging from 0 kPa up to 30 kPa. This corresponds to a weight of 600 g on each individual electrode.

2.3 Initiating Pilot

A first pilot was conducted to map bottlenecks and pinpoint a smooth study protocol. While increasing the pressure, a first participant could play on this laptop the puzzle game 'rush hour' online, to simulate a low involvement task. The test started at 0 kPa and every minute, the participant was asked to raise the pressure with 2 kPa. The participant was interested in the game until a pressure level rose above 24 kPa. After this value, she was more focused on the timer than on the game. The last minute, the electrodes were pushing on the test subject with 30 kPa. Then participant had no interest anymore in the game and was waiting for the test to end. In a second part, the participant was exposed to the maximum of 30 kPa and every minute the operator would lower the pressure with 2 kPa.

It was observed that the participant focused on the numbers related to the pressure on the computer and the time on the stopwatch. Being in charge of the test setting stressed the participant.

Both tests were repeated when an operator was in charge of the pressure levels and alerted the participant when altering the pressure. When decreasing the pressure, unpleasantness was instantly noticeable but more bearable than when the pressure was increased. Afterwards, the participant felt better than being in charge of pressure control. Notable, imprints from electrode spikes were more visual than in the first test.

Finally, to pinpoint an optimal duration, the participant was asked to wear the headset for as long as possible under a pressure of 15 kPa. This test was conducted to measure how long the maximum duration of tests could be. The participant could endure this pressure for 15 min. It was estimated that 12 min would be acceptable for participants to spread pressure between 10 kPa to 30 kPa.

2.4 Test Sessions

In the first session, the pressure was gradually increased in 12 min from 10 kPa to 30 kPa. In the second session, the pressure was decreased in the same time and over the same range. In both sessions, the test subject was inquired every minute on the experienced level of discomfort. At any moment, the subjects could press a panic button that elevated the pressure at once.

Between the two sessions, subjects were asked to fill in a short survey on overall satisfaction with the prototype BCI headset.

In the third session, a subject specific pressure was applied for 12 min. The pressure was optimized for each subject, by taking the mean values of the pressures of the first quartiles discomfort. Again, subjects were inquired every minute on the experienced level of discomfort. While the test proceeded, subjects played Tetris on a smartphone, to simulate a task with high involvement. This could correspond to a real world use of wearable EEG headsets.

Tests were conducted by four researchers: two observers, a moderator and a researcher responsible for welcoming the participants and handing out the surveys.

2.5 Research Questions

The setup was used to answer the following research questions.

- Is there a significant difference between the comfort levels of increasing pressure and the comfort levels of decreasing the pressure?
- Is there a significant difference between the comfort levels measured when the pressure is kept constant at subject specific optimized pressure and the comfort levels when the pressure is decreasing or increasing?
- What is the influence on hair volume on the level of discomfort at optimized pressure?
- Does the level of discomfort at optimized pressure remains constant?

Results were statistically analysed using SPSS IBM Statistics. Confidence intervals of 95% were used to define significant differences.

3 Results

3.1 Comfort Levels Under Increasing and Decreasing Pressure

The pressure range where the headset was not inducing discomfort was retrieved from Likert scale levels scoring discomfort between 1 and 5. For each participant, median discomfort score was calculated. A Wilcoxon Signed Ranks Test revealed that mean of median comfort levels in sessions with increasing pressure (A) was significantly lower than in sessions with decreasing pressure (B), respectively 3.5 and 4.9. Two participants had a median of B lower than median of A, eight participants had a median of B higher than median of A and two participants had the same median for A and B.

3.2 Comfort Levels Under Constant and Changing Pressure

Median discomfort level measured when the pressure is kept constant was calculated on the entire time range from 0 tot 12 min. A Wilcoxon Signed Rank Test showed that mean median values were significantly lower when the pressure is kept constant at subject-specific acceptable level than mean median discomfort when the pressure is increasing or decreasing, respectively 2.6, 3.5 and 4.9. Eight participants had lower medians under constant pressure than under increasing pressure, three participants had medians that scored the opposite and one participant had the same median. Two had medians at constant pressure that were higher than their medians under decreasing pressure.

Mean value of subject specific pressure was 12 kPa.

3.3 Influence of Hair Thickness

The hypothesis is that high hair volume results in lower level of discomfort. A Kruskal-Wallis Test was used on the mean level of discomfort on three different hair types. With $p = 0.4$, the null hypothesis was not rejected. So with pressure optimized at subject-specific levels, at first quartile levels of discomfort, no influence of hair could be detected. Further research with a dedicated study design and a sufficiently amount of participants is recommended to pinpoint the effect of hair.

3.4 Fluctuation of Discomfort at Optimized Pressure

An ordinal regression analysis on the acquired data was performed. The null hypothesis that the variation in comfort doesn't differ significantly over time when the same pressure is applied was maintained, with 18% of variance explained by the regression model and a 0.45 goodness of fit (Pearson). So variation in discomfort over time is not significant when constant optimized pressure is applied. However, other tests on longer the time range could yield different results.

4 Discussion and Conclusion

Study was limited to discomfort pain ranging from 1–10, with 1 being marked as 'comfortable', 5 'uncomfortable' and 10 as 'painful'. Most participants marked down '1' as their first reading. So they might see '1' as a baseline, to increase as the pressure went up. Others started at 5, indicating that even the first pressure level wasn't comfortable. Another limitation is that the order of test sessions was not randomized for increasing and decreasing pressure. Subjects were aware of the order in which the tests would be conducted. So there might be a co-founding factor between both test sessions.

Increasing pressure on the participants scalp is - measured by our pain scale – less discomfortable than decreasing pressure on the participants scalp. An evenly applied pressure of 12 kPa through the electrodes on the scalp falls within an acceptable comfort level for most subjects, during 12 min. This corresponds to a weight of 72 g on spike electrodes from openBCI (Florida Research Instruments), exerted at electrode locations used in commercial wearable headsets [19]. Pressure for minimized discomfort could be influenced by the hair thickness of the user but more research is required to pinpoint relation between pressure and signal quality in function of hair type. When the pressure stays within the acceptable range, the comfort level of the user won't change significantly over a time range of 12 min. To make statements about a longer time range, further research is recommended.

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