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Ergonomic design of an EEG headset using 3D anthropometry

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Abstract

Although EEG experiments over the past decades have shown numerous applications for brain-computer interfacing (BCI), there is a need for user-friendly BCI devices that can be used in real-world situations. 3D anthropometry and statistical shape modeling have been shown to improve the fit of devices such as helmets and respirators, and thus they might also be suitable to design BCI headgear that better fits the size and shape variation of the human head. In this paper, a new design method for BCI devices is proposed and evaluated. A one-size-fits-all BCI headset frame is designed on the basis of three digital mannequins derived from a shape model of the human head. To verify the design, the geometric fit, stability and repeatability of the prototype were compared to an EEG cap and a commercial BCI headset in a preliminary experiment. Most design specifications were met, and all the results were found to be similar to those of the commercial headset. Therefore, the suggested design method is a feasible alternative to traditional anthropometric design for BCI headsets and similar headgear.

Keywords: 3D anthropometry, statistical shape model, headgear, EEG, brain-computer interfacing

1. Introduction

1.1. Brain-computer interfacing

Brain activity can be captured by a technique called electroencephalography (EEG), which detects voltage difference between certain points on the human cranium [1]. EEG measurement requires a number of electrodes to make electrical contact with the scalp on certain locations, specified by the international 10-20 system of electrode placement [2], see figure 1 (black circles). Traditionally, this placement is done either manually by an expert or, more commonly, using flexible electrode caps which stretch over the user's head and are fastened beneath the chin. In both cases, electrode placement starts by identifying four anatomical points: the nasion (Na), inion (I) and left and right preauricular points (respectively LPA and RPA) [2], see figure 2. All electrodes are then placed on relative distances between these points. First, a second set of reference points is determined by measuring the surface distance for the curve going from nasion to inion through the left preauricalar curve. The first 10-20-points on this curve are placed at a 10% increment of the measured distance from the start and end points (nasion and inion). Intermediate points are placed at 20% increments of this distance. The procedure is then repeated on the other side of the head for the curve between nasion and inion going through the right preauricular point. Then, the points between nasion and inion on the curve on the plane that divides the head into a left and a right part -the midsagittal plane- are determined in a similar fashion to find the the centerline reference points. Finally, all remaining 10-20-points are

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set by following the same procedure for each coronal curve from the lateral reference points through the centerline reference points. Electrodes are placed at a predetermined subset of these 10-20-points. Later on, alternative electrode placement systems were derived from the 10-20 system to improve the spatial resolution, namely the 10-10 system in which all electrodes are placed at 10% increments and the 10-5 system in which they are placed at 10% and 5% distances instead of 20% and 10% distances. The most commonly used electrodes are Ag/AgCl-electrodes, in combination with conductive gel to bridge the distance (and hair) between the electrode and the user's scalp [1].

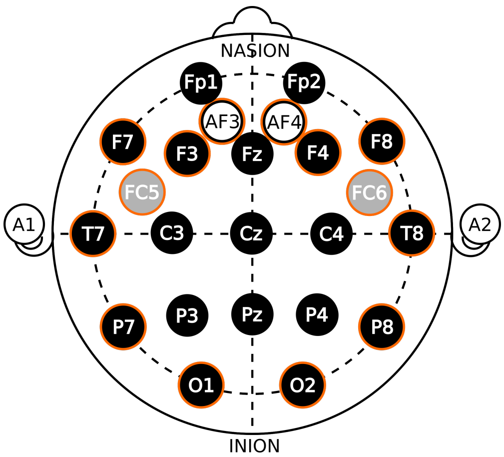


Figure 1: Electrode locations for the 10-20 system (black circles). The electrodes used throughout these work are circled in orange, including locations from the 10-10 (grey circles) and 10-5 (white circles) systems.

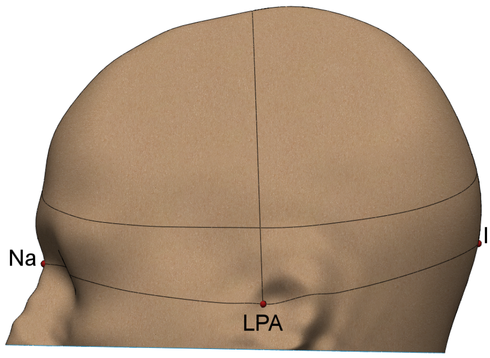


Figure 2: Reference points annotated on the average human head. RPA (not visible) is on the other side off the head, opposite LPA.

EEG research focuses both on understanding human cognition and on applying EEG signals to affect the external world (brain-computer interfacing or BCI). Most of this research is done in medical or academic institutions [3]. While experiments in controlled environments have their advantages, there is also an urgent need to study the brain in real-world situations [4, 5]. Furthermore, there is a large group of potential applications outside of the research lab, such as control of prosthesis, communication without motor function, therapy and gaming [6, 7]. However, a number of problems arises when applying EEG outside of the laboratory. Experts are not always available, electrode caps are complex and time-consuming to put on, conductive gel requires users to wash their hair after each session. Devices that are easier to use and provide more accurate electrode placement would open up more real-world applications for BCI [6, 8, 9, 10].

1.2. BCI headsets

Several companies are targeting the consumer market with the development of low-cost commercial BCI headsets [7]. The most notable ones are the Emotiv Epoc (launched in 2009, see figure 3) and the Neurosky Mindwave (2007). While Neurosky offers a wide range of BCI-related software applications, Emotiv's Epoc has been the most popular device amongst BCI researchers and hobbyists [9]. One reason for this success is that the Epoc has 14 electrode channels, more than any other commercial BCI headset. Apart from that, the headset is wireless, uses saline electrodes instead of gel-based ones and offers access to the raw EEG signals.

Figure 3: Emotiv Epoc BCI headset.

Even though commercial headsets caused a spike in BCI-related research, real-world BCI applications are still rare [9]. Despite all of their advantages, these headsets often do not fit as well as EEG caps [8]. A bad fit causes electrodes to lose skin contact, shift during use and deviate from their target positions. A number of reasons for this can be found in the history of the 10-20 system. First and foremost, human heads vary in size and shape. To date, the only EEG devices that can accommodate both size and shape variation are traditional EEG caps. The Epoc, for example, provides a good fit for different head shapes, but not for different head sizes [8]. Secondly, it was found that the 10-20 system can be used to place over 200 electrodes on the head, if -and only if- they were placed by an expert following a detailed placement procedure [2]. If the procedure is not followed exactly (as with commercial devices), electrode positions tend to vary more widely. This is especially true for the electrodes on the parasagittal and occipital regions of the head, such as P7-8, F3-4 and O1-2 [11, 2], see figure 1 (note: points P7-8 are referred to as T5-6 in [11], as was customary at the time. A modified nomenclature for these electrode positions has been introduced in 2006 [12]). Finally, some anatomical points on the head are difficult to locate by palpation, especially the inion [2]. The most easily identifiable anatomical positions are the nasion, the LPA and the RPA. However, none of the commercial devices use these reference points to mount the headset. Instead, the user is advised to place the reference electrodes on the mastoids, which are the bony areas behind the ears [13]. Because the mastoids have a surface area of several centimeters, it's impossible to precisely and reliably place the headset on the user's head. Electrode positions will thus vary between sessions.

Several papers call for more user-friendly EEG devices that better fit the variation in head shapes, sizes and anatomical points [8]. In order to improve the usability and accuracy, the headset should be designed in a way that brings the electrodes as close as possible to their ideal 10-20 positions and that ensures repeatability between measurement sessions.

1.3. 3D anthropometry and ergonomics

Anthropometry is the field of science that deals with the morphological analysis of the human body [14]. Traditionally, anthropometrists used tools such as calipers and measuring tapes to take limited sets of measurements describing the body shape [15]. Ergonomics deals with the implementation of this knowledge in order to make better fitting products. In ergonomic product design, descriptive statistics (most commonly mean and standard deviation) are performed on a number of anthropometric measurements and a design equation is created to link these measurements to the shape and size of the product [16, 17]. For example, in the design of helmets, the head circumference is often used. A mannequin corresponding to the average circumference is made, and then linearly scaled up or down to correspond to different circumference values. The EN 960 standard prescribes a new design mannequin for every 10 mm increase of decrease in head shape [18].

Just as with electrode placement, for accurate measurement it is important that anthropometrists follow prescribed procedures [19]. When the measurements are performed by non-experts, the variation in measurements made by the same observer on the same subject (intra-observer) is in some cases even higher than the variation between those made by different observers (inter-observer) [20]. Though there are a number of procedures to quantify measurement errors, this is not done in all anthropometric or ergonomic studies [14]. Therefore, not all anthropometric tables correspond to each other, or to the actual body shapes, and products based on some of these tables will not fit the intended population very well.

Another disadvantage of traditional anthropometry is the assumption that several body dimensions vary uniformly, e.g. if the head length increases, the head width is expected to also increase by the same amount. This is not always to case. For example, figure 4 shows the actual human head shape variation as derived from a 3D MRI scan database of a Western population [21]. It appears that head shape does not scale linearly with size: smaller heads are rounder, larger heads are more elongated. This indicates that products designed for different head sizes will also need to have different shapes.

Figure 4: Shape variation for Western heads.

In the last decade, new methods for registering body shapes have become available, the most important of which is 3D scanning [22]. Anthropometrists can now capture the complete shape in a manner of seconds. This has led to the development of 3D anthropometry, in which statistical shape analysis is performed on large collections of 3D scans. Shape modeling reveals valuable information on local and global shape variation and has been demonstrated to lead to improvements in product fit [23]. The benefits of 3D anthropometry have already been discussed for products such as helmets [24] and respirators [25, 26], though few studies verifying the fit of devices or products created using 3D anthropometry have been reported.

It is reasonable to presume that 3D anthropometry will become a valuable asset for the design of BCI headsets. In this paper, the impact of more ergonomic headset design on electrode positioning is discussed. A one-size-fits-all BCI headset is created using a statistical shape model of the human scalp, and the electrode fit is verified with a 3D-printed prototype (section 2). Apart from the deviations of the electrode positions to the ideal 10-20 locations, the stability after controlled and spontaneous movement, and the repeatability (or test-retest reliability [27]) of electrode set-up are also verified. The same measurements are also performed on a commercial BCI headset for comparison (section 3. Finally, the findings are discussed in section 4 and concluded in section 5.

2. Methods

The first part of this chapter, section 2.1, describes the design method for the prototype BCI headset. Section 2.2 contains the methods that were used to verify the prototype in terms of electrode positioning.

2.1. Prototype design

The design specifications for the prototype were as follows: it should only be available in a single size (i.e. one-size-fits-all), it should cover the same electrode locations as Emotiv's Epoc (AF3, AF4, F7, F3, F4, F8, FC5, FC6, T7, T8, P7, P8, O1, O2), fit a Western population, remain as close as possible to their original location during movement (maximum displacement of 5 mm), have an average positioning error of maximum 25 mm (cord length between electrode position and 10-20 location, based on [8]) and should be easy to place on the head by non-experts.

The design was based on a statistical shape model of the human scalp containing 100 North-American individuals, described in a previous paper [21]. In order to determine the shape variation, principal component analysis (PCA) was performed on this dataset. PCA results in an ordered set of "directions" of variation, of which the first principal component (PC) will explain most of the variation, the second PC will explain the second largest part, and so on. The resulting model consists of 9975 vertices, the position of which is represented by 99 principal components in total. In this case, the first PC was found the contain 71,21% of the variation. Three digital mannequins were created by taking the average head surface, the average head surface added with three standard deviations below the average PC weights and with three standard deviations above the average PC weights, representing the average head and the smallest and largest extremes respectively (see [21] for a detailed discussion). The mannequins were then imported in SolidWorks 2014 [28] as templates for the further headset design. The 10-20 system was constructed on the mannequins according to the procedure described in [2]. The heads were aligned according to the Frankfurt plane [18] so the local variation at the anatomical reference points Na, LPA and RPA was minimal. These points were chosen as reference since they are the easiest to identify by non-experts [2, 29]. Once the surfaces were aligned, the variation for the selected electrode positions could be visualized, as in figure 5.

The prototype frame was then designed around these distances and angles. The minimal configuration needed to cover all required points was a combination of two fixed horizontal rings (in transversal plane), connected with supporting struts. The headset's base rings were designed with an offset of 15 mm to the largest mannequin to provide space for electrode parts and hair. Retractable cylindrical struts were created at the base of the headset in order to help the user identify the Na, LPA and RPA points and align the device properly. Sliding electrode mounts were then designed for each electrode according to the specific variation angle. Elastic bands (orthodontic MediMark 10 mm Heavy 4 oz. Elastics) were used in order to keep the electrodes in place on the head. Figure 6 shows the finished prototype, which will be referred to as the "Headset 2" in the remainder of this work.

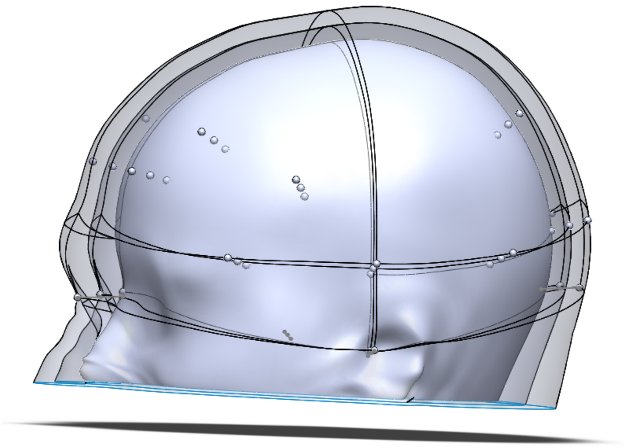


Figure 5: Electrode positions visualized on the smallest, average and largest design mannequin.

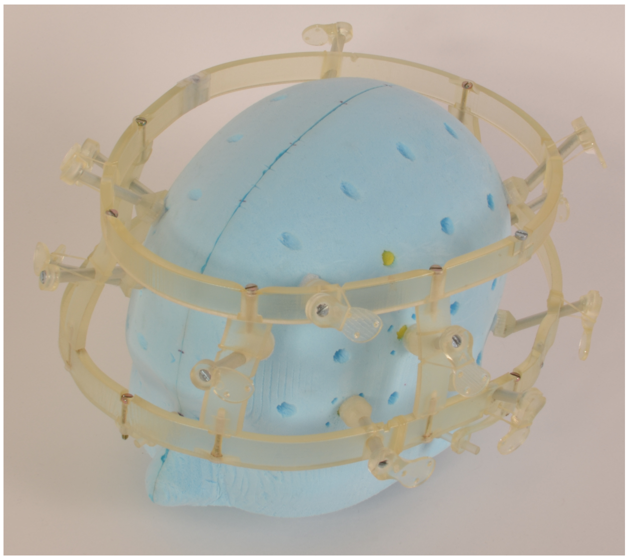


Figure 6: Prototype headset (headset 2) frame.

To place the headset on the user's head, first all of the electrodes should be retracted to the maximal position and fixated there. The headset is then placed on the user's head, aligning the reference struts to the anatomical landmarks described above. Then, the electrodes are released one by one until all of them make contact with the user's head. Finally, the reference struts can optionally be retracted. To remove the headset, the process is reversed.

2.2. Experiment design

A preliminiary experiment to verify the design method was performed by 7 groups of graduate students (1st-year Masters in Product Development, University of Antwerp). The goal of the experiment was to investigate whether the design specifications could be met using the proposed method, and whether the electrode positioning, stability and repeatability of the prototype created using the 3D shape model were comparable to those of a commercial headset. This was tested by comparing the 3D locations for the fourteen electrode positions described in section 2.1 to those of a MedCat EEG cap (reference as "Cap" in the results) and by measuring electrode position deviation after movement and after repeated set-up. The same measurements were also performed on the Emotiv Epoc (referred to as "Headset 1"), which was chosen as a reference for commercial headsets. All 3D locations were digitized using a Microscribe MX digitizer connected to Rhinoceros 4 [30] and saved as text files for further processing.

2.2.1. Sample size

The sample consisted of 13 students (6 male, 7 female), all of which were Caucasian and between the ages of 20-25. None of the subjects had head deformations or a history of head trauma. In each of the 7 groups performing the experiment, one person (designated as operator) was responsible for performing the 3D measurements. The measurements were repeated by 4 different operators for the 6 male subjects and by 3 different operators for the 7 female subjects.

2.2.2. Dependent and independent variables

The independent variables are the EEG devices (Cap, Headset 1, Headset 2). Dependent variables are the locations of the electrodes after each stage in the experiment. From these, the positioning of the electrodes, stability of the headset and repeatability were calculated. The following conditions were tested:

1. FIT – distance of electrode's 3D locations to those of the ideal 10-20 positions
2. CM – deviation of the headset's electrodes from their original positions after controlled movement
3. SM – deviation of the headset's electrodes from their original positions after spontaneous movement
4. REP – average deviation of the headset's electrodes to the 10-20 positions after repeated set-up

The distances for the first three variables were calculated using the formula for euclidean distance between a reference 3D point $\mathbf{v}$ (containing an x, y and z coordinate) and a measurement 3D point $\mathbf{v}'$, as in equation 1. For example, in the case of FIT, $\mathbf{v}$ would be the 3D position of an ideal 10-20 location as determined by the MedCat and $\mathbf{v}'$ would be the 3D position of the same location for the headsets.

$$d(\mathbf{v}, \mathbf{v}') = \sqrt{((v_x - v'_x)^2 + (v_y - v'_y)^2 + (v_z - v'_z)^2)} \quad (1)$$

In the case of REP, the arithmetic mean of the FIT distance between three subsequent headset set-ups was determined as in equation 2, with i being the number of the repetition and d_{FIT} being the average distance between all pairs of corresponding points (electrode locations).

$$\text{REP} = \frac{1}{3}\sum_{i=1}^{3} d_{\text{FIT},i} \quad (2)$$

2.2.3. Equipment used

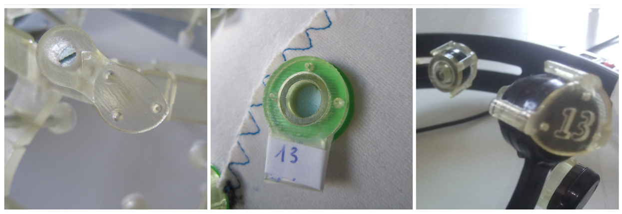
The following equipment was used during the experiment:

- Microscribe MX digitizer
- Desktop computer running Windows XP SP3 and Rhinoceros 4
- Medcat caps 52, 54 and 58 cm (Cap)
- Emotiv's Epoc (Headset 1) (see figure 3)
- Prototype headset (Headset 2) (see figure 6)

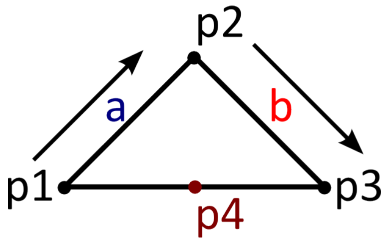
2.2.4. Determining the electrode's 3D coordinates

Placing the tip of the digitizer underneath the electrodes would cause undesirable shifts in the headset's position. Therefore, an alternative method was used to determine the electrode's coordinate positions. A 3D-printed plate was added parallel to the electrode contact surface at the end of the electrode mount, at a distance of 47.5 mm from the electrode. This plate contained three holes at fixed distance and on a concentric alignment (see figure 7). Similarly, custom plates were printed for the Cap (at a distance of 5.5 mm) and for Headset 1 (at 15.5 mm).

The 14 points were measured in the order shown in figure 2. On each electrode plate, three points were digitized by subsequently placing the digitizer tip in the holes in clockwise order, as in figure 7b.



(a) Measuring plate at the end of Headset 2 (left), Cap (middle) and Headset 1 (right) electrode.



(b) Visualization for measurement points on the electrode plate. The points were always measured in clockwise order.

Figure 7: Measuring plates

The middle point between $\mathbf{p}_1$ and $\mathbf{p}_3$ was directly above the electrode. First, equation 3 was used to determine the coordinate for this point. Then, the cross product was used to determine the normal in the direction of the subjects head, as in equation 4. Finally, the midpoint $\mathbf{p}_4$ was moved along this normal for a distance x specific to the headset (5.5 mm for the Cap, 15.5 mm for Headset 1, 47.5 mm for Headset 2) to find the electrode coordinate $\mathbf{p}_e$, see Equation 5.

$$\mathbf{p}_4 = \frac{1}{2}(\mathbf{p}_1 + \mathbf{p}_2) \quad (3)$$

$$\mathbf{n} = \frac{(\mathbf{p}_2 - \mathbf{p}_1) \times (\mathbf{p}_3 - \mathbf{p}_2)}{|(\mathbf{p}_2 - \mathbf{p}_1) \times (\mathbf{p}_3 - \mathbf{p}_2)|} \quad (4)$$

$$\mathbf{p}_e = \mathbf{p}_4 + (x * \mathbf{n}) \quad (5)$$

2.2.5. Experiment

The experiment was divided into two sessions, one for Headset 2 and one for Headset 1. At the start of each session, the subject was asked to take place in front of the custom set-up (see figure 8) and to bite down on a mouthpiece to ensure that their head was in the same position for each measurement.

Figure 8: Experiment setup. The test subject was seated on the red chair, biting down on the white mouth piece to stabilize their head. The box fixating the MicroScribe was positioned such that the experimenter could comfortably move the digitizer's arm around the person's head.

First, the Cap was placed on the user's head to serve as a reference for the ideal electrode positions. The fourteen relevant electrode locations on the cap were digitized using the MicroScribe. Then, Headset 1 was set up on the user's head, using the instructions in the electrode quickstart manual [13]: the reference electrodes were placed on the mastoids and the headset was positioned so that the frontal electrodes were approximately three fingers from the subject's eyebrow. When the device was properly in place, the electrode locations were again digitized (FIT). The subject was then asked to move the head 90 degrees to the left, then up, then down and finally to the right (using markers on the walls for reference). After this, the electrode positions were recorded (CM). The headset was then removed and remounted, and the electrode positions were again digitized. The subject was then asked to play Just Dance on the Nintento Wii for three minutes, in order to examine the stability of the headset during spontaneous movement (as in a real-world scenario). When the game was done, the electrode positions were digitized (SM). Finally, the headset was removed and remounted, and the positions were recorded for the last time (REP). In a second session of the experiment, the above procedure was followed using Headset 2, with the set-up instructions from section 2.1.

3. Results

This section contains the results of the experiment. The distances between all electrodes were calculated using custom PHP- and Python- scripts, and statistics was done in R.

3.1. Verification of design specifications

Table 1 shows the descriptive statistics for the deviation of Headset 2 electrode positions as compared to the Cap.

	Mean	St. dev.	Median	Min.	Max.
FIT	21.97	10.14	20.71	3.63	56.23
CM	8.47	4.85	7.57	0.99	30.93
SM	10.52	7.22	8.91	1.37	68.89
REP	11.28	6.11	9.87	2.06	47.88

Table 1: Descriptive statistics for Headset 2 measurements (in mm). FIT was compared to the Cap, REP was averaged over three headset set-ups for each test subject.

The deviation from the ideal 10-20 electrode positions was 21.97 ± 10.14 mm, which is within the design specification of 25 mm. Surprisingly, the stability did not meet the specifications: the average electrode displacement after movement is larger than 5 mm in both cases (8.47 ± 4.85 mm and 10.52 ± 7.22 mm). After placing the headset on user's heads on three separate occasions, the average electrode displacement was 11.28 ± 6.11 mm.

3.2. Comparison to commercial reference

Table 2 shows the same statistics for Headset 1. A Shapiro-Wilk test revealed that the data is not normally distributed, with p-value 3.87e-33 (<0.05) for FIT, 8.60e-26 (<0.05) for CM, 1.87e-16 (<0.05) for SM and 3.87e-33 (<0.05) for REP. Therefore, the Mann Whitney U-test was used to test for significant differences between the headsets. The distances were compared using the median because, like the Mann Whitney U-test, it is non-parametric and thus not sensitive to outliers. Boxplots of the results for all dependent variables per headset are shown in Figure 9 (data shown is comprised of all observations for all electrode positions for all repetitions for each test subject).

For geometric fit of electrode positions there was a significant median difference of 2.67 mm, p-value 9.39e-5 (<0.05). Controlled movement resulted in a

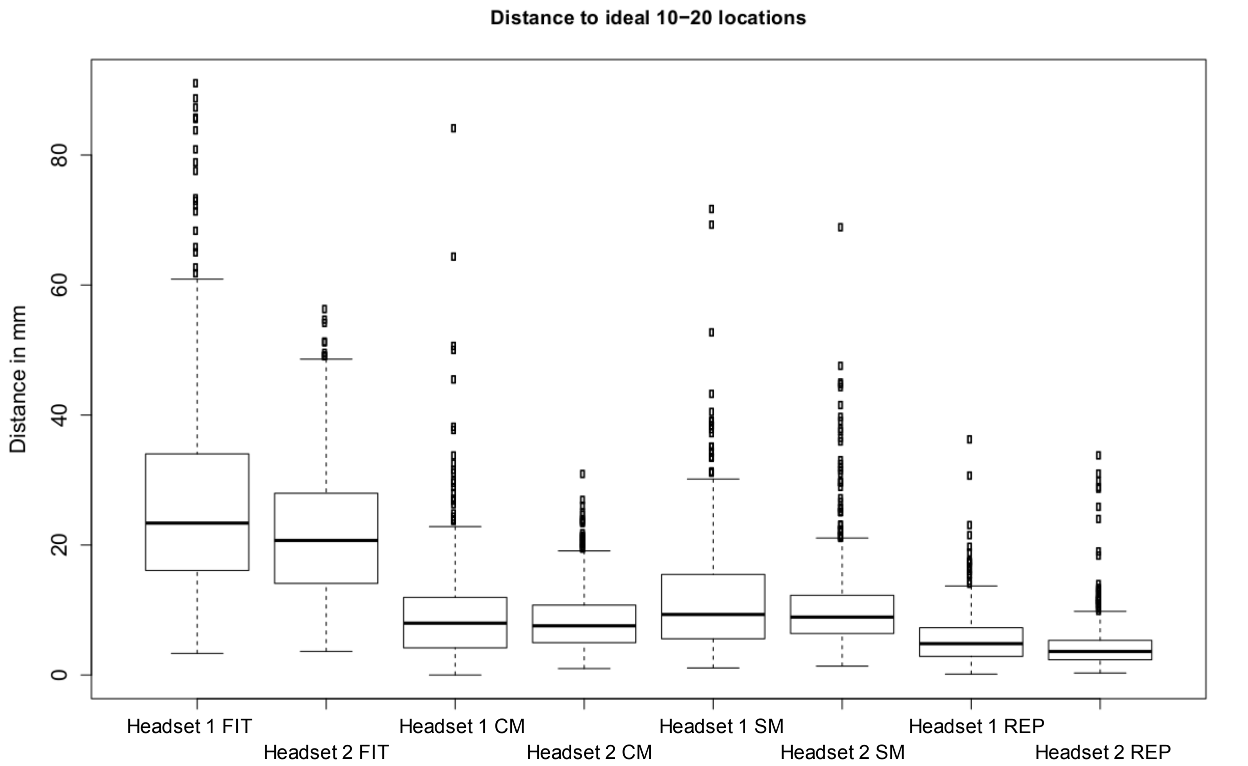


Figure 9: Box plots showing the distances between each headset and the Cap (FIT), the deviation in position after controlled movement (CM) and spontaneous movement (SM), and the average deviation of the electrodes to the 10-20 position after repeated set-up (REP).

	Mean	St. dev.	Median	Min.	Max.
FIT	26.10	15.02	23.37	3.32	91.04
CM	9.63	8.47	7.97	0.00	84.12
SM	13.37	11.88	9.32	1.09	71.69
REP	14.55	11.03	12.17	0.66	99.27

Table 2: Descriptive statistics for Headset 1 measurements (in mm). FIT was compared to the Cap, REP was averaged over three headset set-ups for each test subject.

non-significant difference of 0.40 mm, p-value 0.51 (>0.05), spontaneous movement in a significant difference of 0.41 mm, p-value 0.01 (<0.05). For repeatability there was also significant difference of 2.30 mm, p-value 1.01e-16 (<0.05).

Stability was tested 4 times for 6 male subjects and 3 times for 7 female subjects, giving a total of 45 measurements for controlled movement and 45 for spontaneous movement. Headset 1 fell off 2 out of 45 times for CM and 27 out of 45 times for SM. Headset 2 never fell off.

Finally, the median difference between individual electrode positions can be seen in Figure 10.

4. Discussion

In this chapter, the results are discussed, starting with the implications of 3D anthropometry for the product design process in section 4.1. The following sections all deal with one of the tested aspects: electrode fit (section 4.3), stability (section 4.4) and repeatability (section 4.5). Limitations of the current study and suggestions for future work are found in 4.6.

4.1. 3D anthropometry in product design

3D anthropometry was a considerable asset in the design process. By using the statistical shape model of the scalp, a number of time-consuming steps from traditional anthropometry could be omitted. For example, there was no need to limit the fit to a single measurement such as circumference, or to create

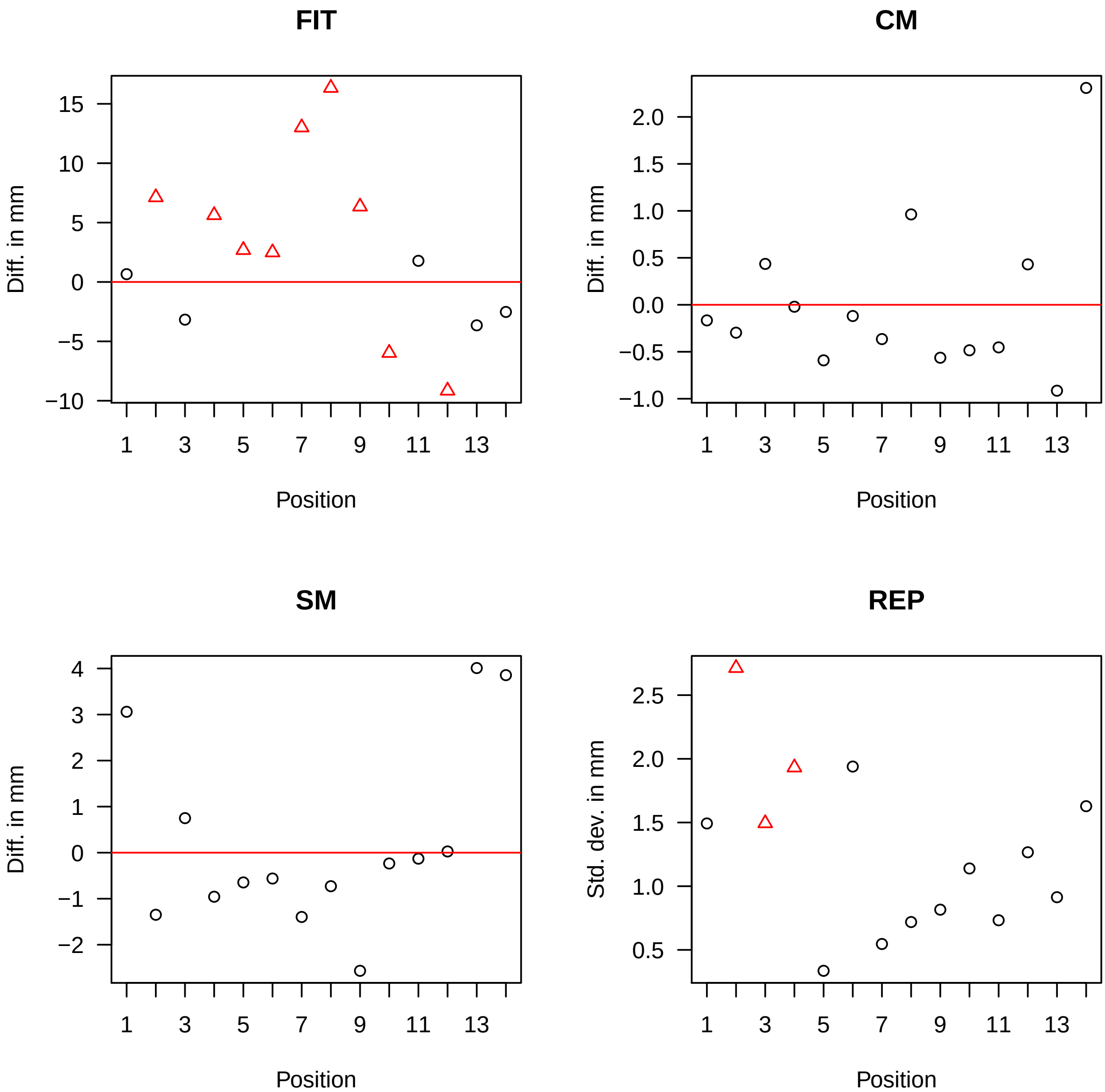


Figure 10: Effect size (median difference between Headset 1 and Headset 2) per electrode position as compared to 10-20 reference (FIT), before and after controlled movement (CM), before and after spontaneous movement (SM) and the average median difference after three repeated set-up measurements (REP). Positive values indicate a better fit for Headset 2, negative values are in favor Headset 1. Triangles (red) represent significant differences.

a design equation in order to link this measurement to a CAD product (as in [16]). Nor was there a need to interpolate the remaining head shape once an appropriate number of mannequins for these measurements were created (as in [18]). Instead, three representative digital mannequins could be created in a matter of seconds using the shape model, and then imported into SolidWorks for immediate CAD design.

Furthermore, 3D anthropometry offers more flexibility in the creation of mannequins. Though the first PC was chosen in this work because it represented the largest part of the variation (section 2.1), shape models contain sufficient information to allow for many other parametrizations. For example, a number of principal components could be combined to cover even more of the shape variation. Alternatively, more intuitive parameters such as circumference or head length could be used in combination with the shape model, as discussed in [21]. This will be explored in future work.

In addition to one-size-fits-all design, a number of other design strategies can be considered, e.g. performing clustering analysis on the shape model to create non-linear sizing systems [17].

There are a lot of opportunities for 3D anthropometry in product design, and these should be explored in further research. Once a number of optimal methods has been established, 3D anthropometry will be invaluable for the design of all products that need to physically fit the human body.

4.2. Choice of variables

To the best of the authors' knowledge, the only variable that has been quantified in previous research is the fit to the 10-20 system, albeit in slightly different ways (e.g. Hairston et. al. used cord length instead of euclidean distance [8]). In this work, a number of new variables have been introduced in order to objectively quantify the stability (CM and SM) and repeatability (REP). Because there was no data available for comparison, these variables were compared to commonly used EEG positioning tolerances (e.g. electrodes within 1-2 cm diameter of the ideal 10-20 locations, as well as to the same measurements for Headset 1. However, since CM, SM and REP are all based on the measure of geometric fit to 10-20 location, they are expected to be valid for future verifications of the ergonomics of EEG and BCI headsets.

4.3. Fit to 10-20 electrode positions

The results relating to geometric fit of the headset were well within the design specifications and are similar to other commercial BCI headsets [8]. Compared to Headset 1, there's even a slight improvement in electrode positioning.

When considering the individual electrode positions, there's an notably high difference in geometric fit for the electrodes at the occipital region of the head (O1 and O2). Interestingly, Headset 1 offers a better geometric fit for locations T8 and F4. It's unclear why this is the case. Since these are the most variable electrode positions, a more detailed study on how to realize an optimal fit for these locations would result in insights with a large impact on the ergonomics of BCI devices.

Whether or not this will result in improved functionality is an open question. In-house experience indicates that because of the low spatial resolution of EEG, electrode locations can vary by 1 or 2 cm without notable effects on the EEG signal. However, to the author's knowledge this has not yet been verified. More research is required to determine exactly how critical the electrode positions are for the signal quality.

Even so, if the location for electrode position O1 in one paper deviates from the O1 position in another paper by 3 cm, can they be considered to compare the same EEG signals? Improved electrode positioning is important for the replication and comparison of experiments. Using 3D anthropometry for design will result in EEG equipment that follows the 10-20 standard and its derivatives more precisely.

4.4. Stability

Neither controlled (CM) nor spontaneous movement (SM) values met the design specifications. It is possible that the specification of 5 mm was too strict and that some displacement is inevitable after movement, although a stronger fixation method should also be considered.

The resulting values are close to those of Headset 1, and no significant differences could be found for individual electrode positions. While there is an overall significant difference for spontaneous movement, it is very small. It was observed that Headset 2 never fell of the user's head, which supports the specifications that it should be easy to use. However, this may be partly due to the fact that the prototype did not yet include electronics and was thus relatively light-weight.

In any case, because the results for stability were still within the general practice for EEG (<15 mm), and since they were comparable to those of the commercial reference, these results should not form an objection for the use of the proposed method.

4.5. Repeatability

Repeatability is important for several reasons. Firstly, a good inter-session fit is crucial is scientific research: more reliable electrode positioning will reduce inter-observer variability as a source of signal variability. Secondly, if the same electrode positions are consistently covered between sessions, the user might not need to recalibrate the BCI device each time it is used, resulting in a better user experience. Finally, repeatability reduces the complexity of the headset. If the electrodes always cover the same locations on the user's head, there is less need for electrode adjustment based on impedance measurements. There's also no longer a need for experts to position the electrodes; the headset can be mounted by the user's family members or caretakers.

While the average electrode displacement after repeated set-up was slightly higher than expected, the prototype shows similar results to the reference headset for most electrode locations, and even a slight improvement in general. This confirms the validity of the proposed method and is within general practice (see section 4.4, *Stability*), though further research should be conducted in order to find how better repeatability can be achieved.

4.6. Limitations of current study

The largest limitation of the current work is the small sample size and high number of outliers in the data. Therefore, no strong conclusions can be drawn from the quantitative data. However, while the sample may not be representative for the general population, the average head circumference of the test subjects was found to be similar to the values reported in other studies, e.g. the MRI dataset used to create the shape model (North American sample, 20-40y) [31] and the DINED dataset (Dutch sample, 20-30y) [32]: 566.9 ± 18.0 mm compared to 564.9 ± 25.7 mm and 562.0 ± 25.0 mm, respectively. Still, the described experiment should be repeated with a representative sample in order to obtain conclusive results.

A second limitation regards the prototype design: Headset 2 was created primarily to verify the electrode positioning of BCI headgear based on 3D anthropometric data. Functionality, usability, aesthetics and user comfort were considered out of scope for this work. However, for a BCI headset to be truly ergonomic, all these aspects will need to be incorporated in the design process.

Even so, the results do indicate that using the proposed design method results in BCI headsets that adhere to current industry standards with regards to electrode positioning and repeatability, while at the same time offering more efficiency, flexibility in region or points of interest, and clear visual feedback to the product developer.

5. Conclusion

3D anthropometric data was used in the design process of a BCI headset. A one-size-fits-all BCI headset frame was based on a statistical shape model of the human scalp and 3D printed. In order to verify the ergonomics of the device, the electrode positions of the printed prototype headset were compared to those of a medical-grade EEG cap, electrode positions were compared before and after movement, and repeatability of the headset set-up was measured.

All of the target specifications were met, with the exception of those related to stability (average displacement after movement lower than 5 mm). The electrode positions deviated from the ideal 10-20 locations by 21.97 ± 10.44 mm on average. The electrodes had shifted by 8.47 ± 4.85 mm after controlled movement and by 10.52 ± 7.22 mm after spontaneous movement. Between-session deviation was 11.28 ± 6.11 on average. These values are all within the deviations accepted in EEG measurement and were found to be similar to those of a commercial reference device.

The results demonstrate that 3D anthropometry is a feasible tool for the design of ergonomic BCI headsets. Alternatively, the proposed method can also be applied to improve the ergonomics of other head-based products such as glasses, helmets and respirators.

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