Design Principles for Mobile Brain-Body Imaging Devices with Optimized Ergonomics

Niell Gorman[1], Antoinette Louw[1], Alex Craik[2,3], Jose Gonzalez[2,3], Jeff Feng[1,2(✉)], and Jose L. Contreras-Vidal[2,3]

[1] College of Architecture and Design, University of Houston, 4800 Calhoun Road, Houston, TX 77204, USA
ffeng@uh.edu
[2] IUCRC BRAIN Center, University of Houston, 4800 Calhoun Road, Houston, TX 77204, USA
[3] Noninvasive Brain-Machine Interface Systems Laboratory, University of Houston, 4800 Calhoun Road, Houston, TX 77204, USA

Abstract. Mobile brain-body imaging (MoBI) technology allows the study of the brain in action and the context of complex natural settings. MoBI devices are wearable devices that typically record the scalp electroencephalogram (EEG) and head motion of the user. MoBI systems have applications in neuroscience, rehabilitation, design, and other applications. Here, we propose design principles for MoBI systems for use in brain-machine interfaces for rehabilitation by individuals with movement disabilities. This design study discusses the validity of the process of utilizing 3D anthropometric data as a basis to design a MoBI headset for an optimized fit and ergonomics. The study also discusses the need for ensuring that EEG sensors keep constant contact with the scalp and face for the best scan quality. Moreover, the need for single-handed correct positioning of the headset is discussed to address disabilities in the older populations and clinical populations with motor impairments.

Keywords: EEG headset · Headset design · Ergonomic design · 3D anthropometry

1 Introduction

With the technology and signal processing advancements in recent years, MoBI systems are transformed into much more ambulatory devices, which opens up a potential for the advancement of the ecological validity of brain imaging research and more practical solutions for in-home medical monitoring and brain-computer interface (BCI) applications [1]. With an increasing interest and demand in applying EEG scan in real-world environments, MoBI systems are developed to record brain dynamics during different tasks in the medical and non-medical fields. Even though there is an uptrend of developing commercial headsets in BCI-related research, consumer-like user-friendly headsets are still rare [6]. Most of the commercially available portable systems are relatively expensive, require proprietary software in function, and lack flexibility or modularity [2]. Ergonomically, headsets are not designed to be truly easy

T. Z. Ahram and C. S. Falcão (Eds.): AHFE 2021, LNNS 275, pp. 1–8, 2021.
https://doi.org/10.1007/978-3-030-80091-8_1

and intuitive to use [3]. They often require trained technicians to help to put on the headset and operate the system. There is a growing need for a low-cost MoBI headset that can be set up with user-friendly ergonomics that is easy to operate and performs a quality scan and data collection consistently [2, 4, 5].

Studies show most headsets on the market often do not fit as well as soft EEG caps [7]. Headsets with a poor fit to the user will likely lose scanning signals due to the unstable sensor-skin contact and shifting position while in use. To date, traditional EEG caps are still the best in terms of accommodating both size and shape variation [2, 12]. Consumers demand such products that closely fit the human body, but the human body differs with a range of variations in size and shape. In the industrial design process, anthropometry data is widely used as a reference for variations between humans and designed products with optimized fit, comfort, functionality, and safety [8]. 3D anthropometric data has been utilized in constructing mannequin head models as a reference in developing the EEG headset [2]. Some one-size-fits-all headset frames are proposed as a valid design direction for EEG headsets with a limited verification in terms of the geometric fit, stability, and repeatability in building the prototype [4, 9]. Several articles indicate a lack of user-friendly MoBI devices that better fit the variation in head shapes, sizes, and anatomical points [7]. Besides, among MoBI headsets on the market, there is little consideration evidenced to emphasize one-hand use design by the user. With such a design criterion on human factors, the solution should extend to a wide range of forms and functions. Hardware design does influence user behavior [10]. Consideration for one-hand use will affect the design in a wide spectrum from overall form, general mechanical movements, sizing, and details in controls.

This paper presents a method and process of developing a MoBI headset based on 3D anthropometry with an emphasis on the ergonomic fit and enhanced usability for one-hand operation. Easy customization for electrodes and sensors in terms of quantity and locations make this headset design possible as a model for varied applications. As a consumer headset design, important factors are considered including overall weight, adjustability, operational precision, wearing comfort, etc. [11]. Good fixation of electrodes is essential for reducing the contact impedance between the electrode and the skin to obtain signals with low noise [12].

2 Design Process

The headset design is guided by two primary criteria. First, the headset is designed to be used by patients at home with only one active hand to operate independently. Without assistance from a technician or caregiver, the patient should be able to put the headset on easily and calibrate sensor locations consistently for testing. Second, the headset is designed with the intent to be a one-size-fits-all device with an optimized range of flex and adjustment in size and shape.

In detailed design, there are some functional challenges to a MoBI headset. The headset needs to ensure on-head dry electrodes go through hair and maintain good contact with the scalp [3]. To achieve a satisfactory scan accuracy, the headset should consistently maintain electrodes' locations matching the ideal 10–20 positions for repeatable results between data collection sessions. Research shows that most users prefer to place the reference electrodes on the mastoids, which are the bony areas behind the ears [4]. Because the mastoids' surface area is about several square centimeters, it is hard to place the electrodes correctly on the mastoid while placing the headset on the user's head.

2.1 Design with 3D Anthropometric Data

Anthropometric data analysis was conducted to determine the size and the range of head size variations. The head size data is based on a 2012 anthropometric survey of US Army personnel (ANSUR) (Fig. 1). Measurements of the smallest (1st percentile female) to largest (99th percentile male) head sizes are selected to provide referencing perimeters for the design of headset sizing, shape, and the range of adjustment.

Fig. 1. Head breadth, circumference, and length based on 2012 U.S. Army survey personnel anthropometric data.

In our design process, the head circumference, breadth, and length data are calculated based on an approximate range of 5^{th} percentile female to 95^{th} percentile male. A mannequin corresponding to the 5^{th} percentile female is built and then scaled up to correspond to different circumference values up to 95^{th} percentile male (Fig. 2). Head breadth refers to the headband minimum and maximum widths. 5^{th} percentile female is 5.45 in. 95^{th} percentile male is 6.53 in. The difference is about 1.08 in. as the referenced range of adjustment. Head circumference refers to the headset minimum and maximum circumferences. The 5^{th} percentile female is 20.60 in. whereas the 95^{th} percentile male is 24.10 in. The difference is about 3.5 in., which will serve as the referenced range of adjustment for the headset's inner circumference. Head length refers to the headset minimum and maximum lengths. The 5^{th} percentile female is 6.79 in. and the 95^{th} percentile male is 8.41 in. The difference is about 1.62 in., which will serve as the referenced range of adjustment for the headset length. In product design ergonomics, real-world data collection normally presents a range of deviation. Some anthropometric measurements will be put in a design equation to establish an accurate conversion to the shape and size of the product [15, 16]. Traditional anthropometry calculation is based on a uniform variation on several body dimensions. For instance, if the head length increases, the head breadth is expected to also increase by the same amount. Some studies show that this is not always to case [2, 14]. Our study confirmed that, in some cases, the i.e. head breadth doesn't grow in the same way as the head length.

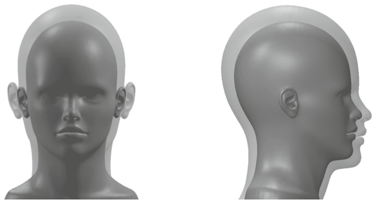

Fig. 2. 5th percentile female head is overlapped with 95th percentile male head as the reference.

The headset design starts with the electrode mapping. The specific application dictates the amount and locations of electrodes with a reference to the international 10–10 system provided by the American Clinical Neurophysiology Society guidelines (Fig. 3). In this design, the headset needs to provide 5 dry EEG electrodes on top of the head at the FC3, FC1, FCz, FC2 & FC4 positions shown in blue. These dry electrodes will need to go through users' different hairstyles to reach the scalp and maintain a constant steady contact during use. Additionally, this headset needs to equip up to 6 dry skin sensors on the front face as shown. These dry skin sensors need to be adjustable in terms of location and orientation to fit varied face profiles and contours maintaining constant and steady contact.

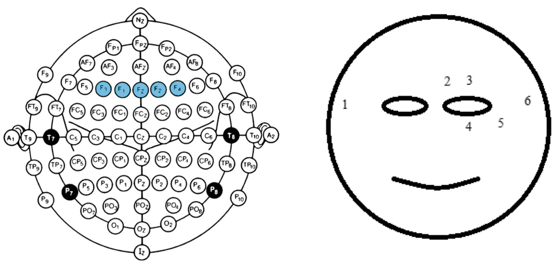

Fig. 3. Mapped electrodes on a modified combinatorial nomenclature for the 10–10 system [13].

To fit a wide range of users' heads, the headset design should allow a 3-degree adjustment in sizing (Fig. 4). There are different ways to achieve the range of adjustments. The electrode mapping and the functional operation are the principal determining factors in the headset structure design. Based on the particular mapping and needs, the presented design utilizes two length-adjustable bands to hold most electrodes and achieve 3-degree adjustments in sizing. One band is over the head at the leaning forward angle from the perpendicular plane to match the top 5 electrodes. This band is extendable for 1.2 in. on each side on a sliding track. Another band is wrapping around the forehead with an extendable range of 0.75 in. on each side on a sliding track. The third main component is the electronic housing at the back of the head. It is connected to the hub from both sides with extendable arms on a sliding track.

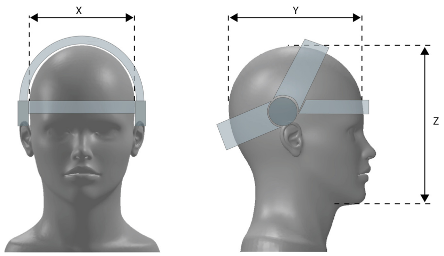

Fig. 4. Headset structure design with the 3-degree sizing adjustment.

3D printing is an effective way to prototype and produce such a device at a low volume. Among printing plastic materials, medical-grade thermoplastic polyurethane (TPU) stands out with its flexible conforming property and durability. Medical-grade TPUs are thoroughly examined by scientists in the context of biological interactions. The FDA approves many medical devices that are based on TPU polymer [17]. The presented design is built with a combination of rigid PLA and flexible TPU. The overhead band is printed in TPU, which is flexible while holding its overall form, enabling the band to comply with most head sizes and shapes.

2.2 Dry Electrode and Skin Sensor

For any electrode placed over the top of the user's hair, it is common to experience unstable and noisy scan signals due to an interrupting contact between the electrode and the head scalp [3]. The challenge is to keep the dry electrode penetrating through varied hair layers to reach and maintain steady contact with the scalp. In the electrode bracket design, a flexible up-and-down movement should be considered to accommodate the regional changing shape. A micro-movement at the tip of the electrode will be necessary to enable the electrode to go through the hair. For instance, a rotational shift may help to push the hair away from the path instead of compressing in between the electrode and the scalp.

For some BCI applications, it is crucial to the reliable collection of EEG to include face sensors, as these sensors provide a measurement of suspected noise, which allows for effective removal of noise. Most EEG skin sensors need a sticky gel medium to contact the skin for a steady constant contact. In this application, it's not desirable because it would be difficult for the stroke subject to apply gel correctly. A dry skin sensor is selected for this application. Without the sticky gel medium to keep the sensor to the skin, it is a challenge to maintain constant contact. Casting silicone elastomer is a good choice to build the skin sensor holders because of its malleable and skin-friendly property. Due to the wide difference in face profiles, the skin sensor holder needs to be customizable to each individual. To achieve a satisfactory contact, a steel wire or aluminum band is embedded in the part so that the holder's arm is bendable to conform to the individual's face while holding its form (Fig. 5).

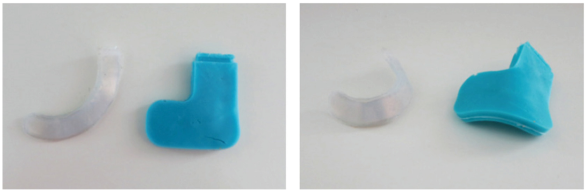

Fig. 5. The molded silicone extension parts are form holding.

2.3 Fabrication

The prototype is fabricated through 3D printing in several parts and assembled with a minimum of 4 fasteners. PLA plastic filament is used to build the rigid structure as well as the electrode bracket. TPU filament is used for the overhead band and forehead band with its compliable property (Fig. 6).

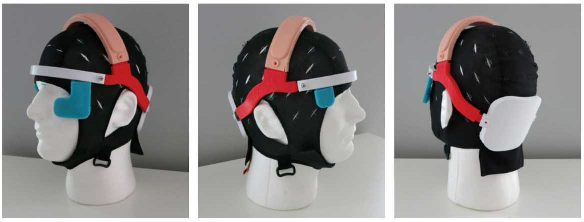

Fig. 6. The prototype on a mannequin head for form and sensor positioning evaluation.

3 Design Assessment

At the early stage of development, as an initial assessment to guide the design, the prototype was evaluated by team members with a reference of varied head sizes, shapes, and hair types. The focuses of the evaluation are size adjustment and fit, one-handed use, scan quality of electrode and skin sensor, and head comfort during extended wearing.

Users followed the procedures of use as the design intent. First, the headset was adjusted by a researcher to fit the user's head properly. The headset fasteners were tightened to fix the size. Then, the user was asked to put on the headset, position the eye sensors and reference electrodes, and take off the headset. Participants were instructed to use only one hand to complete all the tasks (Fig. 7).

Fig. 7. Internal prototype assessment on sizing and sensor fitting.

Key learnings of the initial assessment are highlighted as follows:

- The overhead band was easy to put on and take off with one hand.
- The skin sensor mechanism was easy to adjust and stick to the face naturally.
- The bracket enabled dry electrodes to maintain constant and steady contact with the scalp.
- The forehead band was limited in terms of conforming to the participants' foreheads and causes high-pressure areas along two sides.

Design modifications and prototyping were conducted based on initial responses. To eliminate the pressure points and enhance the usability of a one-hand operation, the forehead band was modified with an open profile in TPU. The band maintains a more flexible structure that conforms to the user's forehead without causing any high-pressure area. Skin sensor brackets were reshaped to ensure a steady contact with comfort. The finalized design is optimized in the overall weight, adjusting deviation, dry electrode and skin sensor brackets, and the comfort for extended use. The modified headset can be easily put on and taken off by users with one hand.

4 Discussion and Future Work

The design process based on an anthropometry dataset is valid and effective in generating the overall size and form for a MoBI headset, but a good headset design demands substantial effort in the detailed development. While there are different ways of sizing, the focus should be on developing a mechanism that matches the electrode mapping and best fits the targeted userbase. In this headset design, one-hand use is another unique requirement for ease of operation. Since the shape and size of the head vary considerably, a flexible and adaptive sensor mount is a good general design approach. With self-adaptive mechanisms and pliable materials, the dry electrode bracket and skin sensor holder designs meet the functional requirement in the initial evaluation with relatively clear scan results.

On the other side, more improvement is needed in the sliding tracks for the overhead band and the electronic housing at the back for ease of adjustment with clear tactile feedback. The skin sensor holder can be improved in making a better contact for a longer time.

Although the headset is designed for a particular application with designated sensor specifications, the headset can be easily adjusted to adapt to other BCI applications. The design has the potential to be an open-sourced BCI hardware to support other research and consumer practices.

References

1. Brunner, C., et al.: BNCI Horizon 2020: towards a roadmap for the BCI community Brain Comput. Interfaces **2**(1), 1–10 (2015)
2. Verwulgen, S., et al.: A new data structure and workflow for using 3D anthropometry in the design of wearable products Int. J. Ind. Ergon. **64**, 108–117 (2018)

3. Kawana, T., Yoshida, Y., Kudo, Y., Iwatani, C., Miki, N.: Design and characterization of an EEG-hat for reliable EEG measurements. Micromachines **11**(7), 635 (2020)
4. Lacko, D., et al.: Ergonomic design of an EEG headset using 3D anthropometry Appl. Ergon. **58**, 128–136 (2017)
5. Feng, T., Kuhn, D., Ball, K., Kerick, S., McDowell, K.: Evaluation of a prototype low-cost, modular, wireless electroencephalography (EEG) headset design for widespread application. US Army Research Laboratory (2016)
6. Ahn, M., Lee, M., Choi, J., Jun, S.: A review of brain-computer interface games and an opinion survey from researchers, developers and users. Sensors **14**(8), 14601–14633 (2014)
7. Hairston, D., et al.: Usability of four commercially-oriented EEG systems. J. Neural Eng. **11**, 046018 (2014)
8. Pheasant, S., Haslegrave, C.M.: Bodyspace: Anthropometry, Ergonomics and the Design of Work. CRC Press, Boca Raton (2005)
9. Ellena, T., Subic, A., Mustafa, H., Pang, T.Y.: The Helmet Fit Index–an intelligent tool for fit assessment and design customization. Appl. Ergon. **55**, 194–207 (2016)
10. Karlson, A.K., Bederson, B.B., Contreras-Vidal, J.L.: Understanding single-handed mobile device interaction (2006)
11. Yates, D.C., Rodriguez-Villegas, E.: A key power trade-off in wireless EEG headset design. In: Proceedings of the 3rd International IEEE EMBS Conference on Neural Engineering Kohala Coast, Hawaii, USA, 2–5 May 2007
12. Li, G., Wang, S., Duan, Y.Y.: Towards gel-free electrodes: a systematic study of electrode-skin impedance. Sens. Actuators B Chem. **241**, 1244–1255 (2017)
13. Jurcak, V., Tsuzuki, D., Dan, I.: 10/20, 10/10, and 10/5 systems revisited: their validity as relative head-surface-based positioning systems. NeuroImage **34**(4), 1600–1611 (2007). ISSN 1053-8119
14. Lacko, D., et al.: Evaluation of an anthropometric shape model of the human scalp. Appl. Ergon. **48**, 70–85 (2015)
15. Chang, J., Jung, K., Hwang, J., Kang, Y., Lee, S., Freivalds, A.: Determination of bicycle handle diameters considering hand anthropometric data and user satisfaction. In: Proceedings of the Human Factors and Ergonomics Society Annual Meeting (2010)
16. Luximon, A., Zhang, Y., Luximon, Y., Xiao, M.: Sizing and grading for wearable products. Comput. Aided Des. **44**(1), 77–84 (2012)
17. Haryńska, A., Kucinska-Lipka, J., Sulowska, A., Gubanska, I., Kostrzewa, M., Janik, H.: Medical-grade PCL based polyurethane system for FDM 3D printing—characterization and fabrication. Materials **12**(6), 887 (2019)