Faith Ociti, Bradley Schussel, and Nelson Zhang

BME-7

Professor Timko

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Project Proposal:

Designing a Modular Headset for Non-invasive Optical Imaging of the Human Brain

Abstract

It is important to ascertain which individual regions in the brain are responsible for which specific functions. A current, non-invasive optical method to map the activity of the brain is through the use of optical fibers to detect changes in flux of hemoglobin in the brain. In this method, near-infrared light is transmitted through both the scalp and skull into the brain while hemoglobin absorbs the majority of light at these wavelengths [5]. Furthermore, perfusion of hemoglobin and changes in oxygenation are associated with brain activity [6].

The objective of this project is to design a headset that facilitates the placement of optical fibers on all parts of the scalp to facilitate the gathering of brain activity data. We will achieve this by ensuring that the headset is adjustable in fit, keeps the fibers in a conformation that facilitates acceptable data and allows the placement of fiber clusters on all parts of the head. This headset will be in the form of either a soft or hard helmet. This helmet will be attached to a mesh that is designed to facilitate the placement of optical fiber clusters on the head. Possible constraints of this device include the ability to properly fit all head sizes, the presence of hair (which can obstruct data collection) and the effects of the subject's motion, which must be minimized in order to optimize the device's signal acquisition.

Introduction

The brain is a highly complex organ that is mired in mystery. There is currently data on what parts of the brain are responsible for associated actions and characteristics. For example, it is known that the frontal lobe is primarily responsible for characteristics such as personality, emotions, judgement, intelligence whereas the parietal lobe is associated with language, memory, hearing, and organization [2]. However, though the general functions of the parts are known, the relationship between neuronal, hemodynamic, and oxygenation changes that are associated with particular actions still remain a mystery in the field of neuroscience. In recent years, there has been innovation in technology and the formation of optical techniques that allow for the active monitoring of the brain. Moreover, the brain can now be monitored when performing particular actions thereby allowing for the specific mapping of specific areas of the brain and their given function.

A current non-invasive optical method to monitor the activity of the brain is through the use of optical fibers to detect changes in flux of hemoglobin in the brain. It has been established that near-infrared light gets transmitted through both the scalp and skull into the brain [5]. It was also established by earlier research that hemoglobin is the main absorber of near-infrared light in the brain and its light absorption properties are dependent on the oxygen saturation of hemoglobin [5]. As such, these near-infrared signals can be used to monitor changes in hemoglobin perfusion and oxygenation through the tissues of the brain which in turn allows for the mapping of brain activity and associated physiological responses [5,6].

The use of optical fibers is key in this method of measuring brain signals. The propagation of light within optical fibers is governed by geometrical optics laws. The optical signals to be measured with this device are described by diffusion theory and photon migration in highly scattering media. General engineering design approaches will be used, including consideration of practical constraints, testing, and iterative improvements.

Though brain activity data can be gathered using this near- infrared techniques, in practice, it is hard to conduct in a holistic fashion. This is because current optical measurement devices are designed in such a way to only gather data on specific parts of the head- not the whole head. Furthermore, optical fibers must be securely fastened to the scalp in a way that minimizes interference from hair.

In this design process, the main focus would be designing an optical headset that can facilitate the placement of optical fiber holders on all parts of the head. This requires that the headset can be used on a variety of shapes/ sizes of heads and that the headset remains relatively comfortable for extended amounts of time. If this objective is complete, the next objective would be to devise a way to minimize the interference in the data and images collected due to the presence of hair.

Elements of Engineering Design

Over the course of this project, we shall design and prototype an optical headset that extends the functionality of a similar headset prototyped in Professor Fantini's laboratory. The current iteration of the optical headset design can only gather data from a part of the frontal lobe due to the physical constraints of the headset. With this new iteration, we aim to expand the scope of non-invasive brain imaging with diffuse optical techniques currently performed in Professor Fantini's lab by facilitating placement of optical fibers on all parts of the head.

The optical data gathered is contingent on both the proximity of the fibers to one another along with the arrangement of said fibers in space. Although an increase in the distance between two fibers increases the depth of optical penetration into tissue, the increased distance also considerably reduce the optical signal. This next iteration of the helmet will need to ensure that the pre-established dimensions and conformations of fibers are maintained. The optical headset to be designed will consist of modular components for flexibility of placement on the head area to be covered.

In terms of allowing the device to read signals from more parts of the brain, hair is a distinctive constraint. The fibers need to be in as close contact to the skin as possible, and this is difficult to do on parts of the head that are covered by hair. We must ensure that any plans for the placement of our fibers takes this obstacle into consideration. Depending on how well the helmet is able to secure the optical fibers to the head and get proper data, designs for the type of headset will be further explored (e.g. soft versus hard helmet designs). It may be that there is too much signal reduction introduced by hair regardless of fiber proximity to the scalp. If this is so, we will consider options to physically displace hair from underneath each optical fiber.

The main milestone would be to build optical headset modules that can be integrated to allow for the collection of good quality optical data on the human head without causing any discomfort to the subject. This requires a comfortable and relatively lightweight design.

There are a number of commercial instruments and laboratory devices that include optical headsets for functional optical imaging of the brain. However, the modular approach proposed here, and the specific features of the individual headset modules, are unique.

Aims

Aim 1: Constructing a headset that facilitates placement of optical fibres on all parts of the head.

The goal of the design, improvement and production of this headset can be divided into two specific aims with associated design requirements. Firstly, the optical headset itself must be designed in such a fashion that it facilitates placement of optical fibers along with their accompanying holders in a predetermined cluster of two or four fibers on all parts of the head. This optical headset must then be comfortable to wear during the entire duration of data acquisition which can occur over a period up to several hours. The patient's comfort must be minimally compromised by our design, where a happy medium between the effectiveness of the measurement and the accommodation of the patient is reached. This comfort is important as it ensures patient compliance with the data acquisition.

Aim 2: Increasing the quality of data collected due to the introduction of hair interference between the optical sensor and the scalp.

Secondly, only if the first aim is completed, the next specific aim would be to increase the quality of data gathered by the optical fibers. This will be done by reducing the signal degradation introduced by hair that obstructs the fiber during data acquisition. Hair on the head is often a roadblock when it comes to measuring brain signals. Concepts of how to achieve this will be considered only after aim one is completed, but could include the use of small, long optical fibers that can go between hair clusters, as well as small LED lights attached to the sensors that allow us to indicate where on the head the sensor will land and how we must adjust the hair to accommodate this placement.

Experimental Design & Methods

Construction of Headset Mesh

To accomplish the construction of the optical headset, we first need to create the "mesh" – a lattice structure to hold the optical fibres in place. This mesh needs to be flexible enough such that it can assume the shape of the headset in the final stages of headset construction.

The mesh used in the initial prototype used for the forehead region was constructed using two strips of 0.02-inch thick Acrylonitrile Butadiene Styrene (ABS) with holes 5/8 inches in diameter punched along the strip. The two strips were then placed together to form 2 x 8 matrix to place the optical fibres in. We propose a design that produces the same spacing between the optical fibre holders that uses less material to improve flexibility. Instead of having two strips, we shall have one sheet to minimise extra material. This design will be more of a frame to hold the optical fibres therefore the mesh must be made of a strong material capable of handling the weight of the optical fibres.

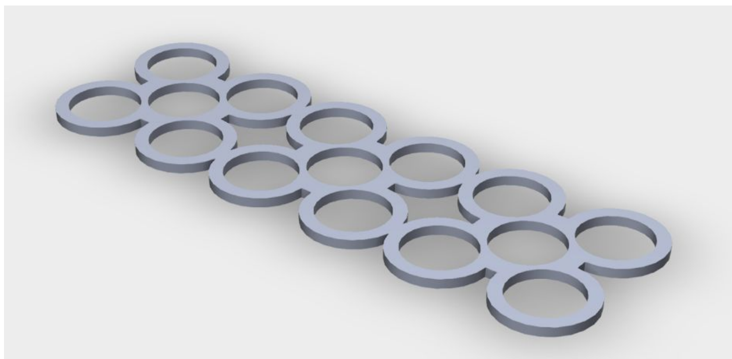

Figure 1: This image demonstrates the frame-like mesh design we are aiming to accomplish. All material not needed to support the conformation of the optical headset will be discarded to increase mesh flexibility. Moreover, the frame will be optimised so it is thick enough as to not tear/fail under the weight of the optical sensors.

As such, we shall use 0.02 inches thick Ultra-High Molecular Weight (UHMW) polyethylene to construct the mesh. This material is optimal as it is a tough plastic with high wear resistance [7]. The mesh will undergo a lot of torsion as it needs to be folded into the ellipsoidal shape of the head. Furthermore, because we are trying to minimise the amount of material used, the material needs to be strong enough to hold the optical holders with only a few millimetres of material.

We shall also construct the mesh using 0.02-inch thick ABS sheets as this was used in the original prototype and has similar properties to the UHMW polyethylene. This material, however, is more rigid and could therefore handle the weight of the optical fibres better than the polyethylene.

Head-Locking Mechanism

One challenge with the headset design is variable head sizes and our design must accommodate for that. We propose a soft cap design where we attach the mesh to the soft cap and have a Velcro attachment to secure everything in place. Among ideas we shall explore:

1. A silicone or latex cap similar to a swim cap - This design is ideal because it has a tight fit to the head and would help eliminate some of the noise introduced by the hair because it allows the sensors to be in close proximity to the scalp.
2. A cloth cap with a velcro attachment - This design is more comfortable for longer periods of time, is easier to put on and the adjustable velcro will be able to secure everything in place. This design, however lacks the optical fibre proximity that the silicone cap forces.

Determination of Design Feasibility

To measure the effectiveness of the headset design we shall first measure the signal on the forehead region as there is a working prototype for this region. This experiment will ensure the signal quality is maintained sans the interference of hair. After it is confirmed that the new design maintains the quality of the signal, we shall begin to collect signal on the motor cortex region of the cranium. We expect at this stage of the experiment that there will be significantly less signal as compared to the forehead region. Even so, we anticipate that there will be some signal picked up.

Expected Outcomes

We expect that the mesh constructed out of UHMW polyethylene to be able to fulfil the needs of the optical headset design. ABS will most likely fulfil the design needs as well, but it may be harder to construct a more complicated ellipsoidal shape with a stiffer material. Moreover, we anticipate that the soft cap design is sufficient to obtain good results.

Potential Problems and Alternative Strategies

During the construction of the mesh, we may find that the UHMW polyethylene or the ABS may not be handle the combination of conforming to the head shape while carrying the weight of the sensors. Although this possibility is slim due to the nature of the material, if the ABS fails, we could tweak the mesh design such that it allows for millimetres more material to give the mesh more girth. The ABS is more rigid and therefore less likely to maintain its strength when contorted. If the UHMW polyethylene fails, we could explore the idea of stacking two sheets on top of each other. Although this limits is flexibility, the material would still be flexible enough to conform to the head shape. If neither material produces optimal results, we will then transition to 3D printing nylon mesh sheets.

Risk Assessment

It is imperative that throughout the entire design process, regardless of the task that is currently being completed, consistent and factually accurate communication is practiced between members of the design team, graduate students, and PI. Failure to do so would naturally lead to confusion and inefficiency. As such, regular end of the week group meetings for the whole lab will be conducted so that information is conveyed in a consistent and transparent manner.

Secondly, it is important to establish and adhere to a timeline of deliverables. Failure to do so may lead to inadequate deliverables along with general tardiness in the development process. To address this, a timeline of deliverables is shown below which outlines the steps and time it takes to complete them. The timeline was made in the form of a Gantt Chart that represents each individual task with a blue bar that shows its span in the timeline. We will refer to this timeline to keep ourselves organized and to ensure that each step is being completed efficiently and each deliverable is as effective as possible.

Thirdly, it is important to parallelize the development process and have contingency plans for each element of our design. If one part of the device fails later in the development process, it would be good to have “backup” designs that could have feasibly worked beforehand so that the transition would be seamless. It is also important to keep the PI and graduate students updated when something goes wrong so they can assist us in coming up with other solutions and planning out the best route of action.

Milestones and Deliverables

The first milestone will be to redesign the connections that hold the optical clusters together. The current version of these connections is inefficient both to manufacture and ergonomically speaking because holes must be punched by hand and that the final product lacks overall flexibility. To solve this, a laser-cut or 3D-printed “mesh” will be designed in solidworks and manufactured to interface with the optical fiber holders and form said cluster.

The second milestone will be to find the optimal “helmet” that can facilitate the placement of optical fibers along with fitting the largest number of head shapes and types. The two main types of helmets would fall into the soft and hard categories. The soft helmets considered so far have been made from cloth or silicon while the hard helmets considered were based off of existing devices such as various sports helmets. The deliverable for this milestone will be a type of helmet that is easily adjustable, fits on most head sizes and works well with our mesh (more on this interface in the next paragraph).

The third milestone will be to find an optimal way to align the mesh onto the cap so that it can stay in place while holding the fibers on the head in a secure way. As such, we will be revisiting and revising the design of our mesh in order to find an alignment that allows us to maximize the adjustability of the cap as well as the amount of sensor clusters that can be accommodated. The deliverable will then be the completed prototype of the optical helmet that can map parts of the head that could not previously be obtained by the design presented to us at the start of our project.

The final milestone will be to fix smaller issues in the prototype. It is unlikely that the first prototype will be very comfortable to wear for prolonged periods of time. At least, it will likely not be as comfortable as desired. As such, we will experiment with sensor cluster designs and types of interfaces until all design requirements specified in the aims have been addressed. The deliverable will then be the completed optical helmet that ideally covers the entire head and allows for mapping of all parts of the brain simultaneously.

CITATIONS

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APPENDIX
Timeline - Gantt Chart