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The NIRS Cap: Key Part of Emerging Wearable Brain-Device Interfaces

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Chapter 1

The NIRS Cap: Key Part of Emerging Wearable Brain-Device Interfaces

Amal Kassab and Mohamad Sawan

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Abstract

Nowadays, near-infrared spectroscopy (NIRS) fills a niche in medical imaging due to various reasons including non-invasiveness and portability. The special characteristics of NIRS imaging make it suitable to handle topics that were only approachable using electroencephalography (EEG) such as imaging infants and children; or studying the human brain activity during actions, like walking and drawing that require a certain amount of freedom that non-portable devices such as magnetic resonance imaging (MRI) cannot permit. This chapter discusses the unique advantages of NIRS as a functional imaging method and the main obstacles that still prevent this technology from becoming a prominent medical imaging tool. In particular, in this chapter we focus on the design of the brain-device interface: the NIRS cap and its important role in the imaging process.

Keywords: NIRS cap design, fNIRS, NIRI, medical imaging accessories, portable brain imaging, optode holder

1. Introduction

Near infrared spectroscopy (NIRS) has been gaining momentum due to its unique advantages that makes it an indispensable tool in medical research. By successfully resolving certain issues of portability and data filtration, NIRS is expected to find a wide application not only in medicine but also in the gaming industry as well as any thought controlled electronic devices due to its relatively inexpensive, portable and non-invasive nature. From a medical standpoint, the advantages of NIRS imaging, or functional NIRS (fNIRS), are quite distinct. Much like electroencephalography (EEG), its portability and non-invasiveness make it a natural choice for imaging young children and infants [1]; however, while EEG signals are inherently noisy, non-linear and rely on electrical signal variations on the scalp [2], NIRS offers 1–2 cm depth resolution that is

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capable of capturing cortical activation [3]. Additionally, NIRS offers higher temporal resolution than traditional immobile imaging devices such as functional magnetic resonance imaging (fMRI) and positron emission tomography (PET), which allows the detection of transient cortical events [4]. Undoubtedly, present imaging techniques in general are bound to offer higher temporal and spatial resolution as their design develops over time, but what makes NIRS imaging an interesting contender is the combination of the previously mentioned factors which allows it to be a suitable device for long-term cortical activity monitoring. NIRS promises a device that can be used anywhere, inside or outside of a lab or hospital setting and that can register cortical activation throughout different activities with varying degrees of freedom without particular concern towards the subject's age group or physical condition which can have important real-life applications today [5–8]. Nevertheless, for NIRS to achieve its full potential the topic of its interface is yet to be properly addressed and designed.

The application of NIRS imaging relies on two primary factors: the first factor is the relative transparency of human tissue to near infra-red (NIR) light, which penetrates the skin, subcutaneous fat, skull and brain [9]. The second factor is the high attenuation of NIR light due to haemoglobin oxygenation levels [3]. More specifically, the term 'optical window' is used to define the range between 650 and 1350 nm where light absorption coefficients of water, melanin in addition to oxy and deoxy haemoglobin, are lowest. This allows a certain amount of light to penetrate biological tissue, where it is scattered and eventually diffused allowing for a limited amount of tissue penetration to occur. NIR imaging relies on light absorption coefficient values of key biological components, such as water, oxy and deoxy haemoglobin to measure changes in their concentration over time. For example, as shown in **Figure 1**, the absorption coefficients of oxy and deoxy haemoglobin intersect at around 805 nm allowing for the use of two distinct NIR wavelengths within the optical window to measure the changes in each of these elements [10–12].

Pigmented compounds such as chromophores of skin and hair melanin are also a high source of NIR attenuation; however, these factors are easily corrected by adjusting light intensity since their value over the period of imaging is constant [13]. The behaviour of NIR light inside tissue is also relevant, as the main mechanism of NIR light propagation is scattering, and while a part of NIR light is attenuated as it is absorbed by chromophores, the remaining scattered photons resurface back a certain distance away from the light source allowing the detection and measurement of light attenuation over time.

Since NIRS allows the measurement of oxy and deoxy haemoglobin changes over time, it is considered an indirect method of measuring brain activity based on the neurovascular coupling phenomenon that relates neural activation with vascular response. Neurovascular coupling refers to the increase in oxy-haemoglobin (HbO) and simultaneous decrease in deoxy-haemoglobin (HbR) when spatially clustered 'cortical columns' that share the same functional properties are stimulated. This cluster formation is what makes brain oxygenation levels detectable using optical imaging [14, 15].

NIRS can also provide non-haemoglobin-based measurements, by recording data from several wavelengths simultaneously, in order to detect tissue chromophores, including cytochrome oxidase the marker of metabolic demands [16]. While some studies suggest the use of

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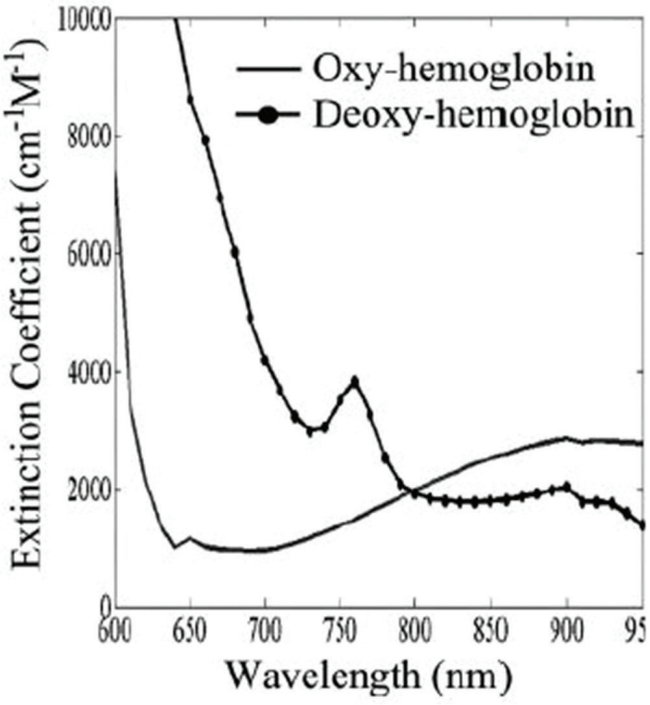


Figure 1. Light absorption spectrum of oxy and deoxy-haemoglobin, the span between 650 and 950 nm is called the 'optical window' due to the relatively low absorption factors in tissue [3].

NIRS in the detection of cell swelling as a result of neuronal firing in order to directly detect neuronal activity; however, these signals are 0.01% smaller than hemodynamic activity making it a less reliable method for detection [17–19].

Overall, although the special characteristics of NIR light were first published by Jobsis in 1977 [9], yet the first 10-channel NIRS imaging system was only introduced in 1995 and actual interest in this technique was only seriously considered with the advent of multi-channel wearable and wireless devices in 2009 [20]; since then NIRS has been used extensively in brain imaging research which is reflected in the number of publications that cover its development, use and various applications today. Nevertheless, NIRS has low reliability still in single subjects, which makes it unsuitable for clinical applications and restricts its use in large group medical research [21–24].

2. fNIRS instrumentation

Any NIRS device can be divided into three major components: (1) a brain device interface that includes optodes and the cap stabilizing them, (2) a control module that collects, sorts registered data and provides the various illumination schemes in addition to data transfer to the (3) user interface and main software responsible for analysing data using signal processing algorithms.

These three branches will be discussed briefly; however, emphasis will be on the interface and the essential role it plays on the imaging process.

2.1. The brain-device interface

The term 'optode' refers to both the NIR light emitter and detector that ideally create a fixed and predetermined illumination scheme within the cerebral cortex. The source, or light emitter, shines light directly into the scalp, this light is scattered by head tissue causing it to deflect in all directions and only a small fraction of this light (approximately one out of 10^9 photons) resurfaces back to the scalp some distance away from the entry position [3]. This NIR light distribution was simulated by Okada and Delpy, their study showed the light-scattering pattern within the scalp, skull and cerebrospinal fluid in addition to the sensitivity of each source-detector pair to this scattering, which creates a banana-like shape within the scalp with two narrow ends at the source-detector locations [25]. Light attenuation can be calculated based on the Beer-Lambert law that links the ratio of incident and reflected intensities to the absorption and diffusion phenomenon [9]. On the other hand, the distance where the NIR light resurfaces back differs from one subject to another based on age, curvature of the scalp and head size and it generally ranges from 3 to 4 cm; therefore, an ideally placed light detector at that exit position can capture it. The change in the amount of detected light overtime is used as an indicator of the absorption variation of NIR light due to cortical activation.

Based on this light emitter-detector coupling, also called 'channel', it is clear that unlike other non-invasive brain imaging techniques, such as EEG, the integrity of a NIRS signal relies on the assumption that the cortical illumination and detection scheme is ideal. This assumption entails that the relative position of the detector/emitter couple is constant, and that the detector, emitter operational conditions are constant throughout the imaging session. However, this is often not the case, and so far, it has been a very difficult condition to maintain, particularly for the type of experimental requirements that fNIRS is designed to meet such as imaging freely moving subjects over extended periods of time.

Most successful fNIRS imaging experiments are commonly conducted inside a lab, where the subject sits still on a chair and is refrained from talking, smiling or moving their head. With the advent of better signal filtration, successful use of fNIRS was also registered in rehabilitation centres with walking patients, or even cycling [5, 26, 27]; however, constrains on facial expression and subtle head movements still apply, because while certain movement artefacts such walking and running and obvious head movements are easier to isolate and/or filter out, facial expressions are far more difficult to detect. Small facial muscular fluctuations or hair resistance to NIRS optodes that are unnoticeable to outside observers can cause the entire optode holder to slide or cause slight optode inclinations. Such inclinations that fluctuate over the imaging period can cause light scattering outside the scalp, poor light detection or displacement of surrounding hair in front of optodes resulting in false attenuation values that cannot be accounted for using common artefact detection methods. Therefore, subjects with dark and voluminous hair are typically the hardest to image as any displacement of hair in front of the optodes can jeopardize the integrity of the results while voluminous hair adds resistance and counter pressure against the optode holders.

As mentioned previously, optical penetration is usually 1–2 cm, which is typically half the source-detector distance. Such penetration depth translates to 5–10 mm of outer brain tissue penetration after subtracting the thickness of the skin, subcutaneous fat and skull (which vary from one person to another and with age), this allows the detection of the outermost cortex activation [3, 10]. Most NIRS devices rely on two light wavelengths simultaneously to measure both oxy and deoxy haemoglobin changes [28–30], while three or four wavelengths might be used in some cases in order to either extract changes in other species, such as water and lipids [31, 32], or to couple with time resolved methods for additional parameters such as blood flow and absolute tissue saturation [19].

There are various types of NIR light sources, the two most commonly used emitters today are laser diodes and light-emitting diodes (LEDs). Laser diodes provide a technical advantage over LEDs as they have higher light intensity and smaller optode size, which allows for better hair penetration and scalp contact. However, they have higher energy consumption and cost, thus their use is not suitable for portable devices outside a lab environment. LEDs require simpler circuitry; they generate a light spectrum of about 30 nm and are the natural choice so far for portable fNIRS systems [19].

As for light detectors, the most common choice is avalanche photodiodes (APDs) that translate the amount of detected photons into current and have low power consumption with the capacity to increase the detected light intensity. In addition, APDs are fast with more than 100 MHz speed and have a high sensitivity with the dynamic range of approximately 60 dB. Some devices rely on silicon photodiodes, however, these have a medium speed and lower sensitivity but a higher dynamic range with approximately 100 dB [19]. Modern microfabrication techniques are aiming at the creation of smaller LED and APD designs with enhanced capability, which is essential to the development of next generation portable fNIRS devices.

Finally, when it comes to optode holders, there are two major types of optode stabilizing methods, the cap (a soft headwear) that covers the entire head, with prefixed locations for optodes, much like an EEG cap. However, in NIRS caps, the optodes are not prefixed on the cap in order to allow for hair manipulation and tossing to take place prior to optodes installation. The other common types of optode holders are the rigid patches that cover a certain cranial zone. The term 'rigid' refers to the material used for stabilizing the optodes, since although they are made of silicon which allows it to bend slightly to fit the head shape at a given location, the distance between the optodes is fixed as the material itself does not stretch, unlike the cap, thus the distance between the optodes is fixed throughout the imaging session giving the patches a clear advantage over the caps. Both designs are prone for sliding, however, requiring additional restrains to keep them in place, such as attachments under the chin or to a belt that goes under the armpits and over the chest.

2.2. The electronic control module

The electronic control volume is directly connected to the optodes and therefore is the portable part of the fNIRS device in addition to the interface. This component is responsible for the illumination scheme in addition to data gathering and transmitting (in portable devices).

Lighting strategies in fNIRS aim to reduce power consumption and heating of the scalp in addition to differentiating between various light emitting sources, which is essential to distinguish between the different channels when there are multiple light emitters within the range of a single detector. Therefore, the control module employs a certain method for multiplexing and/or modulating of light sources.

However, the most significant aspect of the control module is its illumination technique. There are three major types of illumination schemes used today which are shown in **Figure 2**. The most common type is continuous wave (CW) which measures simply the backscattered light intensity attenuation. The second type is the frequency domain (FD), which uses intensity-modulated light in order to measure both attenuation and phase delay of returning light. The third technique is the time domain (TD), which relies on short pulses of light as an illumination source and detects the shape of the pulse after propagation through the tissue; this technique provides information about spatial specificity in addition to tissue absorption and scattering [33].

The CW scheme is relatively simple and cost effective as it relies on establishing a baseline, or a zero state, and then compares oxy and deoxy absorption changes to this initial value during a certain test or a task. However, only FD and TD methods can provide absolute characterization of tissue properties including the distinction between absorption and scattering in the tissue [20]. Nevertheless, a more complex scheme is generally associated with lower time resolution and is more susceptible to noise and movement artefacts, since determining the

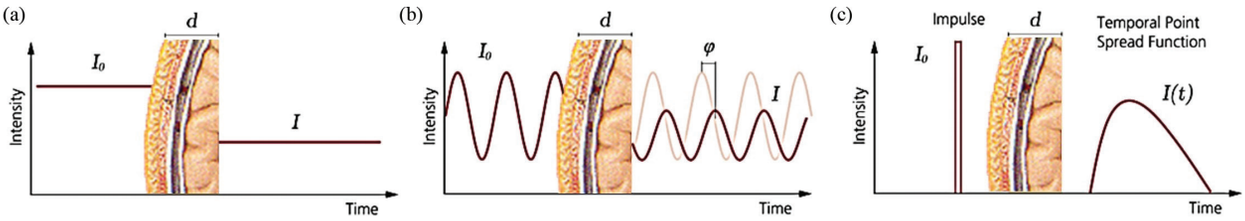


Figure 2. The three type of fNIRS illumination techniques: (a) continuous wave, (b) frequency domain and (c) time domain (TD).

Main characteristics	Continuous wave	Frequency domain	Time domain
Sampling rate (Hz)	≤100	≤50	≤10
Discrimination between cerebral and extra-cerebral tissue	Not possible	Feasible	Feasible
Measuring HbR, HbO	Only changes	Absolute value	Absolute value
Measuring scattering, absorption coefficient and pathlength	No	Yes	Yes
Measuring tissue HbO saturation (%)	No	Yes	Yes

Table 1. The main differences between the three different illumination types in fNIRS (adopted from Ref. [20]).

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time of flight is effected with geometrical and contact changes. The major differences between the three techniques are summarized in **Table 1**.

It is important to keep in mind that as fNIRS fills a special niche for portable imaging systems, the most important qualifications in general are those related to power consumption and size, which explains why most fNIRS devices adopt the simplest illumination technique. In addition, present application of fNIRS does not require tissue characterization as it is more concerned with changes in blood oxygenation rather than absolute absorption values [3]. However, both of these aspects might change as fNIRS reliability is increased and the technology used in FD and TD systems becomes more compact and power efficient.

2.3. Data analysis and user interface

This is where data from each illumination channel are gathered in order to be filtered, quantified and presented in a user friendly fashion. It is also where certain controls over the system in general are provided from the end user as actions and input variables. The fNIRS software package is usually provided on a computer or even a tablet with a Bluetooth connection to the control module.

There are many algorithms and software dedicated to optical imaging and signal quantification based on how light behaves in tissue. The two most widely used theoretical models are the differential pathlength factor (DPF) and the diffusion approximation. Both assume that tissue is homogeneous, however, the diffusion approximation method assumes that scattering is larger than absorption; therefore, each type of tissue has a specific geometry (infinite, semi-infinite, slab or two-layered) [34, 35]. Still, since the two models rely on quantification over a given path, interpersonal differences such as the thickness of scalp, skull and cerebral spinal fluid in addition to hair and skin melanin concentrations are bound to create biases in spatial localization of brain activity particularly with TD and FD methods, but they are less significant in CW methods [25, 36, 37].

This chapter will not cover all the various aspects related to the proper functionality of this component, it will only concentrate on aspects related to noise attenuation and filtration for their obvious relation with the signal quality obtained that is provided by the device interface and is affected by the cap design.

In general, noise sources can be either instrumental, experimental or physiological. Instrumental and experimental artefacts refer to experimental errors including movement artefacts and device malfunction and have to be dealt with prior to data analysis. Physiological errors on the other hand are due to certain changes in the physiology of the subject that affect but are not part of the intended experiment. These are usually treated with filters after the conversion of raw signals to haemoglobin units either using algorithms that compensate for pulse-related artefacts or by using additional NIRS channels that measure extra-cortical hemodynamic variations [3, 10–12, 38]. Instrumental errors have to be dealt with prior to any testing, since they can easily overpower the measured signals. Whereas movement artefacts should be approached by carefully controlling the experimental environment whenever possible. However, since absolute control over the entirety of the experiment is not likely, not to mention that the nature of the experiment itself might produce movement artefact, such as walking or cycling, special algorithms have been developed to filter out these errors using additional data collecting methods, such as a camera [39] or an accelerometer [38, 40].

Nevertheless, to date there are no methods that can provide any information regarding optode-scalp contact 'quality' to ensure that the received data reflect that of an ideal illumination condition throughout the imaging session.

3. fNIRS caps: objectives and challenges

Clearly, the primary objective of the NIRS cap is to stabilize the optodes, making sure that they are in constant contact with the scalp throughout the imaging period. However, in practice, there are other concerns that affect the proper functionality of the NIRS cap and its future use, namely: the installation process and subject comfort.

The effect of optode stability on fNIRS signal quality was not quantified until recently, when the work presented by Yücel et al. was published in 2013 and 2014 [41, 42]. In these studies, the authors glued fibre optic optodes on the scalp using collodion, which is normally employed with EEG electrodes to monitor epilepsy patients. Using this method, the authors reported 90% reduction in signal change due to movement artefacts, a signal-to-noise (SNR) increase by sixfold and threefold at 690 and 830 nm wavelengths, respectively, and a statistically lower change in both oxy and deoxy haemoglobin during movement artefacts. In spite of the fact that their optode stabilizing methodology may not be practical for short-term and off-hospital settings. Nevertheless, this study provides an objective assessment of the effect of interface stability on the fNIRS signal, especially with moving subjects.

Nevertheless, the task of stabilizing the optode using a mechanical device is quite elusive due to several reasons:

1. Current optode stabilization techniques rely on pressure; however, pressure is also a major source of discomfort. Thus, the more stable the optode, the more discomfort it is bound to create for patients. Such conditions might be tolerable for short-term monitoring periods of 10–20 minutes; however, as the imaging session becomes longer these stabilizing techniques may not be acceptable. Presently, there are no studies identifying the comfort pressure threshold on the scalp, although such studies were done for other anatomical parts of the body [43]. Additionally, pressure values necessary to stabilize the optode are also unspecified yet. Preliminary results indicate that comfort pressure values on the scalp are not uniform, as the forehead and the back of the head, particularly the area behind the ears tend to be more sensitive than other areas on the scalp. More importantly, the difference between the pressure needed to provide optode stability (approximately 30–45 Pa) versus the comfort pressure margins on the head (50–60 Pa) is very small [44], therefore, designing an optode holder that relies solely on pressure is quite a challenging task. It is important to mention at this stage that both the comfort pressure as well as the pressure values necessary to stabilize the optode are tentative preliminary results and that such claims can only be established once a study on a large number of participants is conducted. In general, the results obtained from the preliminary study are in accordance with lab observations as fNIRS results tend to be better with less comfortable and higher pressure inducing headwear.

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2. Since the importance of having a tight headwear at all cranial positions has been well clarified, one of the major obstacles in designing an ideal fNIRS cap is presented in head shape variations from one subject to another. Such variations can even be present within the same subject as differences between the right and left side of the cranium might exist. These often cause uncomfortable high pressure areas versus 'pressure gaps' where the optode fails to provide the necessary force to maintain scalp contact or prevent surrounding hair from covering the optode. While imaging companies try to compensate for general head shape variations by providing three (or more) headwear sizes (small, medium and large); even introducing different designs for certain markets in order to compensate for head shape differences between several ethnicities [45]. However, interpersonal head shape variations cannot be accounted for and simple caps often cannot meet the basic requirement of providing a perfect fit for all subjects. Partial head covering patches may present a reasonable solution in cases where imaging the entire head is not required, as their size allows for a certain degree of manipulation over the required imaged zone. However, such patches are prone to slippage and require extra attachments to keep them in place.
3. The third factor in assessing an optimal cap design is the difficulty associated with its installation. While fNIRS cap installation is considered a cumbersome task that necessitates an expert technician, it is important to keep in mind the anticipated goals of a portable brain imaging system, including its role as a brain-device interface with applications spanning from gaming to medical devices. Therefore, unassisted single person installation is the ultimate goal for future fNIRS applications, albeit it is far from becoming reality with present designs.

Today, the installation of the fNIRS cap can be a long process that starts with taking general head measurements to identify important reference locations based on the 10/20 system. This is followed by the placement of the patch or cap and documenting the distance of the optodes from this (these) reference points, then rigorous clearing of hair at various optode locations is performed, and finally the optodes are placed. This process may take up to one hour based on the cranial area covered and the type as well as the amount of hair present. Therefore, attempts at creating easier installation of optode holders invariably address easier hair tossing or clearing methods, since this is generally the most time-consuming part of the process. Apart from providing certain clearances around the imaged zoned to easily toss the hair (particularly when using the patches) the only solution so far seems to be in creating smaller optodes that would infiltrate hair to ensure optimal scalp contact in addition to increasing localized optode pressure by an in-house spring. These solutions assume that optode size can eventually decrease to a point where it can become comparable to hair strands. However, this is far from the actual optode design available presently.

Based on these observations, it is clear that traditional fNIRS caps cannot meet the demanding requirements of portable fNIRS-based imaging. But before proceeding to possible future solutions, the next section will focus on fNIRS cap designs that were developed so far in the literature and whether possible solutions can be based on these proposals.

4. The design of the optode holder: an overview

The design of the fNIRS cap has not received much attention in research or in the literature. This was due mostly to the fact that the fNIRS device is purely an electronic one, thus it elicited the focus of electrical and optical engineers and physicians while the optode stabilizing method itself, a mechanical device, was mostly dealt with as an accessory. The NIRS cap and the installation process were mentioned in 2009 by Huppert et al. for the first time, where the author voiced the importance of stabilizing the optodes and its effect on reducing experimental errors. The authors suggested more anchoring methods to attach the head band to the body in order to reduce the effect of the weight of the optodes on motion instability. They were also the first to mention the important dilemma of subject comfort during imaging due to the additional restrains [3].

The design proposed by Huppert et al. is shown in **Figure 3**, and it portrays the stretchable cap that is used to stabilize a polymer patch which acts as an optode holder. Thus, the cap provides both a rigid spacing for the optodes and a flexible material to hold the patch in place, with additional Velcro attachments to stabilize the optodes and their wiring. The authors specify that even more rigorous attachments are needed for moving subjects. The design was made for in-lab fNIRS measurements; therefore, the stability it provided with moving subject was not demonstrated.

Apart from this example, other attempts to create a head band for the prefrontal area were also introduced in 2009, where no complications due to hair interference can be found and the stability of the head band can be controlled by simply increasing the amount of pressure by changing the size of the head band. One such design is presented by Atsumori et al. [46]. While similar designs may be useful for gaming applications, in addition to few medical and research studies that focus on the prefrontal cortex, however, the bulky

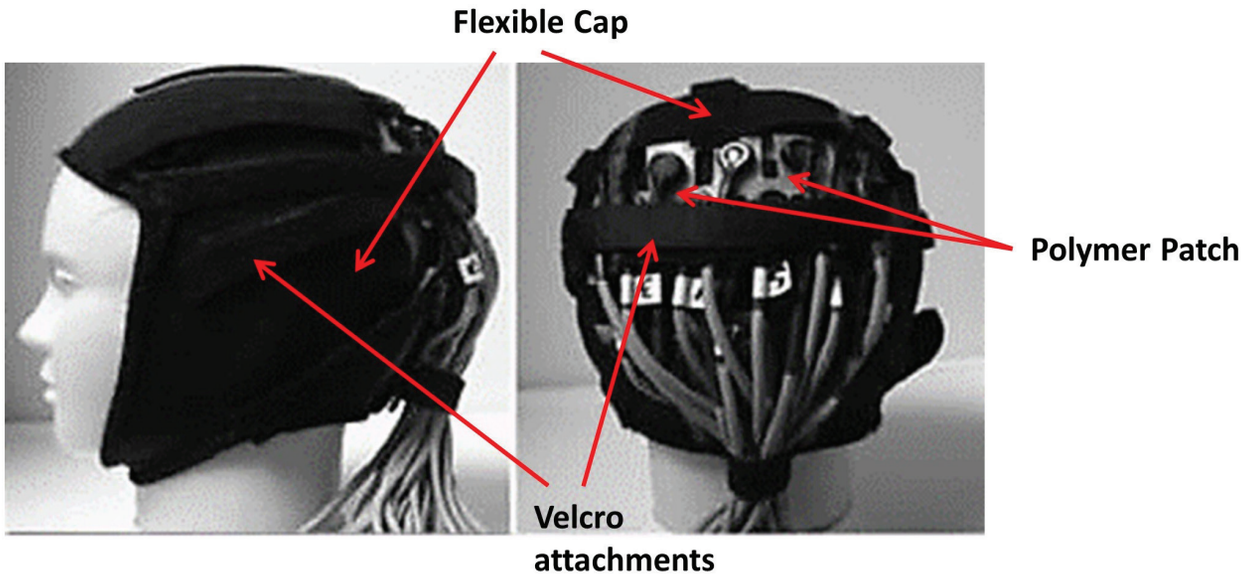


Figure 3. Stretchable cap design that holds a flexible polymer patch and stabilizes it with Velcro attachments [3].

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design represents additional mass that would contribute to movement artefacts, also the fact that it relies solely on pressure to ensure stability makes its use restricted to short-term applications.

Another study for an fNIRS cap was presented by Kiguchi et al. in 2012 [47], using a cap that was made of a black rubber. This might be considered the earliest study dedicated to the fNIRS cap for 'haired' regions including the design of the optodes. The optodes in the helmet like cap are fixed on the inside, as an integral part of the helmet that cannot be accessed or manipulated by the end user. Instead the authors chose to stabilize the optodes surrounding hair by rubber teeth. These teeth aim also to reduce the discomfort presented by optode localized pressure that was induced by a spring. Although this study is dedicated for portable fNIRS devices, however, it does not mention neither the installation process nor present a comparative demonstration of the stability it provided to the optodes versus other cap designs. Nevertheless, the bulky design does not present a practical solution against weight-induced movement artefacts, additionally, holding the hair in place does not guard against slippage or blocking the NIR light by hair in front of the optode.

Regardless of the success of the design proposed by Kiguchi et al. the idea of using a glass rod to reduce optode-scalp contact area which results in less optode resistance by surrounding hair has been adopted in the first open-air fNIRS study published by Piper et al. in 2014. This study also provides the first comparative look at the effect of movement artefacts on signal integrity. The imaging quality was tested under three different conditions that varied between indoor sitting on a stationary bike, indoor pedalling on a stationary bike and outdoor bicycle riding [26]. The fNIRS cap used in this study is the regular EEG-inspired elastic cap that has been available in the market for sometime. However, innovation lies within the minimization of optode size that is further reduced by the use of a 3 mm in diameter glass rod to guide the light into and from the scalp, in addition to reducing the weight of the connecting optode wires. Although this improved design has allowed the implementation of fNIRS imaging outdoors, still movement artefacts affected the fNIRS signal visibly as demonstrated by the study. As rejected channels per person were only 5% for someone sitting on a stationary bike, but this value increases to 7.5% during indoor pedalling and reaches 35% for outdoor cycling [26]. Obviously, a different approach for designing optode holders is warranted.

A comprehensive study on the design of an optimal fNIRS cap was provided by the work of the Imaginc group, in order to explore several design ideas that targets the issue of patient comfort and signal stability [11, 12, 44, 48]. Their study showcased several concepts ranging from padded fNIRS caps/helmets that were geared towards patient comfort, to Velcro patches that provide a none flexible alternative to stretchable caps with an option of adding strands or adjusting for size based on the subject's head shape; in addition to stretchable elastic bands that provide extra space for hair tossing and ventilation, as shown in **Figure 4**. The study concluded that designs that focused on patient comfort as a primary goal failed completely in providing the necessary grip for optode stability. While designs that focused on optode stabilizing based on applied pressure were relatively successful and their success was a function of the amount of pressure it provided on the participant's scalp.

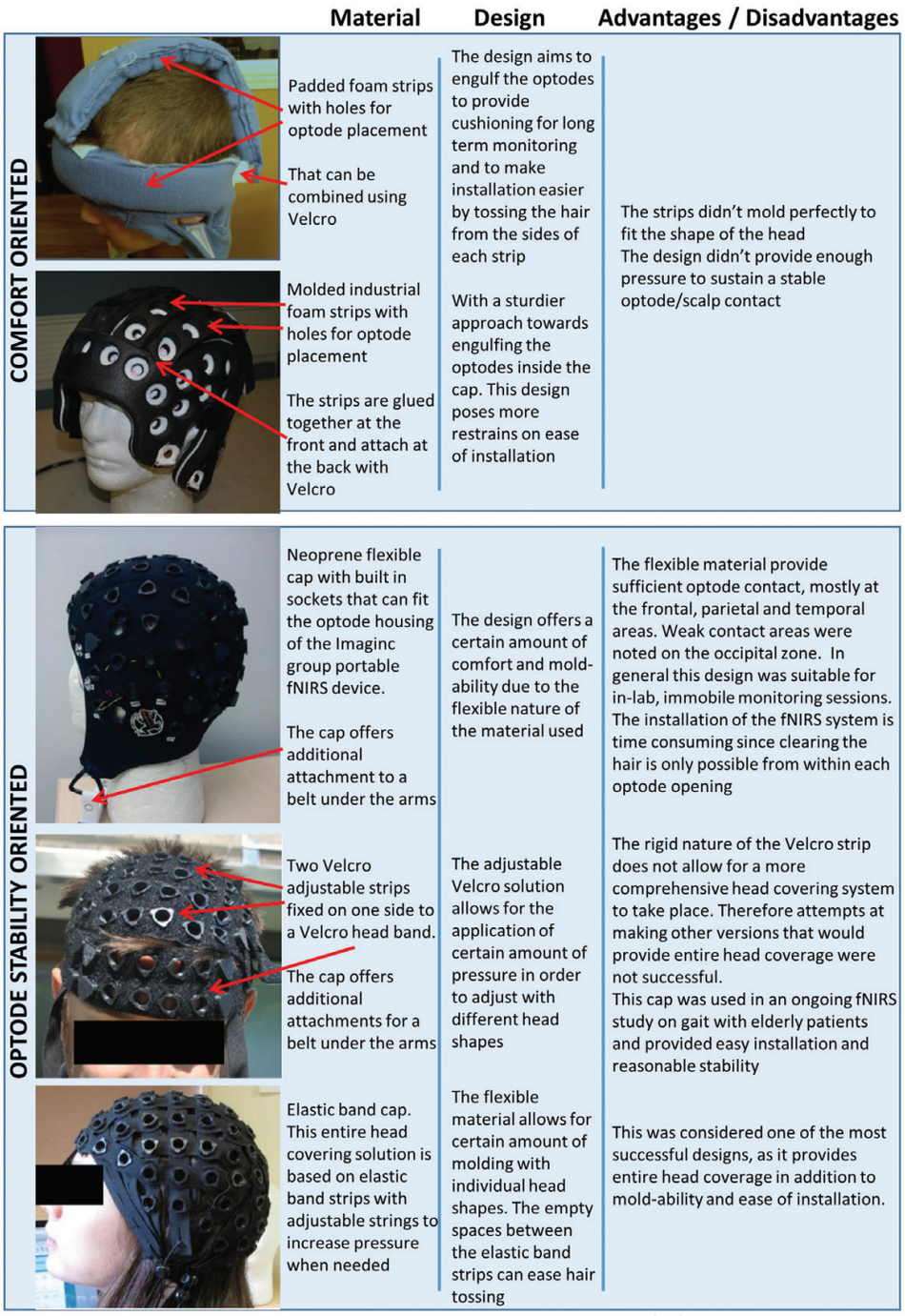


Figure 4. Different headwear designs for optode holders, comfortable versus stable cap designs.

The direct correlation between pressure and signal stability regardless of cap design was clearly demonstrated in a comparative experiment between different cap models that were developed by the Imaginc group. The most successful models that were tested included the Velcro cap, the elastic band cap and the neoprene cap. Movement artefacts were recorded while the subject was sitting motionless, as a baseline, then while moving the head backwards, forwards and sideways followed by a period of walking. The results obtained are

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shown in **Figure 5**, that also note the number of rejected channels in each case. Surprisingly, in spite of previous results that have restrained the use of the neoprene cap to stationary in-lab testing, while the Velcro and elastic band caps were more successful with freely moving subjects, the neoprene cap presented surprising noise artefact reduction, even while moving the head. This was due to the fact that the cap was too tight and visibly uncomfortable for the user, which is a clear indication of the inverse relation between optode stability and comfort. On the other hand, the effect of head movement on motion artefacts was much larger than walking, even without using motion filtration methods.

This led the team to explore other methods to stabilize the optodes that do not rely entirely on localized pressure. These proposals will be reviewed in the following section.

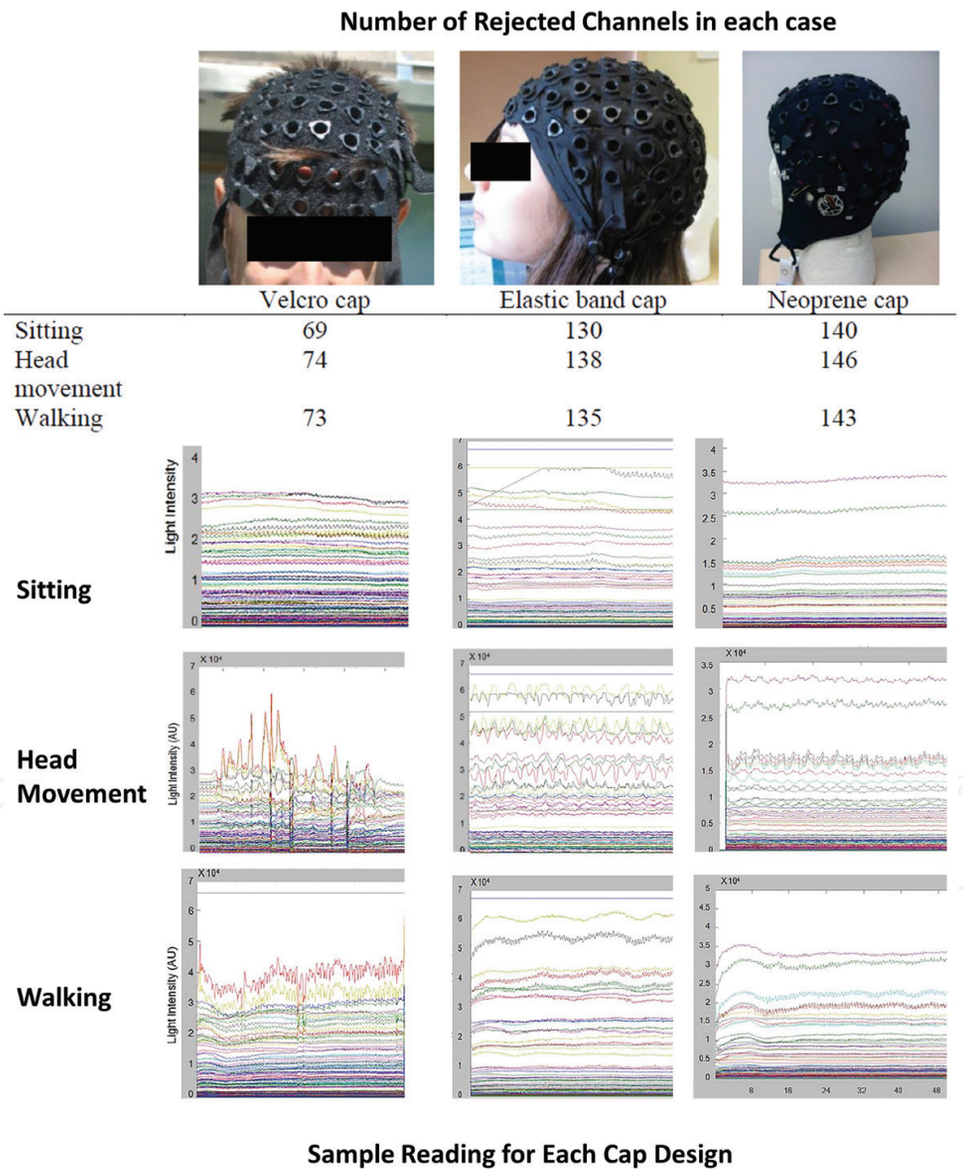


Figure 5. Comparative look at the various cap designs and motion artefacts under different conditions: sitting, head movements and walking.

5. Gripping the head: the future of fNIRS caps

Previous studies conducted in the field of fNIRS cap design lead to an obvious conclusion, relying on pressure alone as a means of stabilizing the optode is not a good strategy when it comes to imaging applications. Conversely, the science of providing a perfect grip for any object is not a new one particularly in the field of robotics. Indeed, robotic arms that are being developed for several applications ranging from the industrial to the medical have already crossed several milestones in achieving gripping capabilities against slippage in addition to handling sensitive objects with speed and accuracy. In reviewing the vast literature published in this field, it is possible to find a couple of comparable solutions that can provide the required amount of grip, mould-ability with individual head shapes and ensuring patient comfort at the same time [48].

While handling sensitive objects, a firm grip is often associated with engulfing the gripped item in order to create a distributed pressure force instead of localized ones; additionally, engulfing the gripped object creates friction, which is the horizontal force that prevents slippage [47]. The more surface area of the object is covered the better hold the gripper provides with improved protection against slippage. Technologies such as the 'universal gripper', for example, can firmly hold a raw egg without breaking it. While on the other end, sensor-equipped artificial hands provide a perfect grip using accurate feedback of the amount of force applied on each point. The difference between these two technologies is vast, as the universal gripper is an extremely simple solution that relies on moulding the gripper to fit around the object, by the use of a simple grain-filled elastic bag and a vacuum pump [49]. On the other hand, the sensor-equipped gripper requires numerous actuators, a processor and sensors to perform properly [50].

Since the quality of the grip is as important as the force that is required to provide it. The two previous methods can translate into pneumatic solutions that are promising for fNIRS imaging. The sensor-based system although costly offers an important additional feedback input that has been thus far lacking in present fNIRS systems, the quality of contact: or in other words, the amount of pressure at each optode location. Thus, defining the optimal optode pressure becomes an important factor in such systems and can help filter out signals when optode pressure values are below a certain threshold. Such a system can have the inflatable cap structure proposed in **Figure 6**. The two-layered air tight cap should be made of two different polymer types, with a more elastic one at the interior in order to allow for maximum moulding and expansion on the inside of the cap rather than the outside. Additionally, the interior of the cap should be lined with pressure sensors that provide feedback to a microcontroller. Based on the return signal, the microcontroller changes the state of the valves (either open or close) in order to inflate the air pockets. It also controls the air pump that inflates the balloons and turns it off once all the valves are closed. Dividing the cap into several air pockets is also an important part of the design, since interpersonal variations in certain cranial zones are less than in other areas.

The inflatable pockets can help also provide optode cushioning, which not only increases its stability but also allows for overnight use of the fNIRS imaging system.

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However, this solution presents technological challenges, such as the fabrication of sensors, micro-valves, miniaturized pump and controller. In addition to ensuring that the power consumption of the added electronic components is minimal and that the cap's weight is low.

The second pneumatic solution, on the other hand, requires a vacuum pump that is not necessarily integrated in the cap itself, and it can be considerably less challenging from a technological point of view. One example of a vacuum fNIRS cap that is an adaptation from the universal gripper concept is presented in **Figure 7**. As shown, the cap can be a regular fNIRS headwear that is lined with small grain-filled balloons, or it can be made of an air tight polymer that covers the entire head also filled with small grains (the examples shown are filled with coffee or small foam grains). No embedded electronic components are necessary or required for this solution, instead, the cap can be firmly placed on the participant's head, then

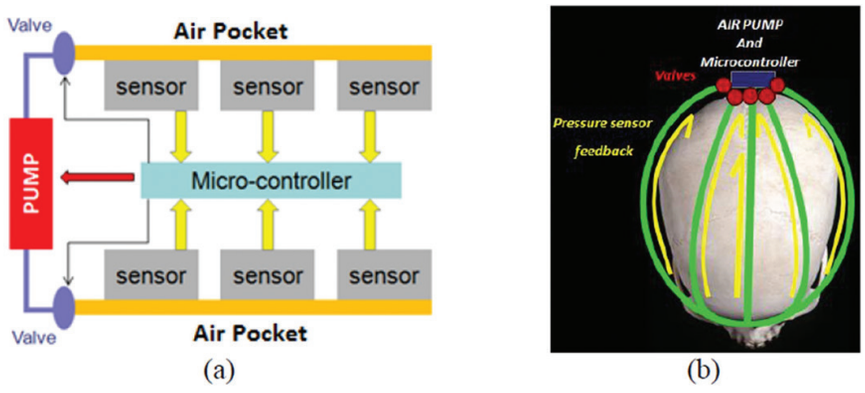


Figure 6. Inflatable pneumatic cap design: a) a schematic representation of the various inflatable cap components b) a top view showing the location of the various components on the head. The cap is divided to several air pockets that are lined up with pressure sensors, once the return signal from all pressure sensors at a given air pocket are above a certain value, the microcontroller closes the valve of that air pocket, and once all air pockets valves are closed the pump is turned off too [44].

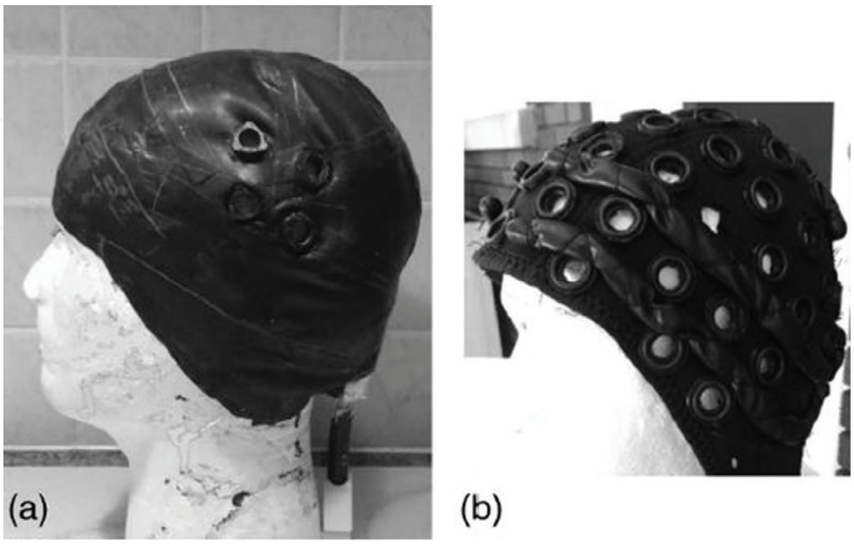


Figure 7. Vacuum fNIRS cap design (a) an airtight latex cap covering the entire head and filled with granular foam balls, (b) a regular fNIRS cap lined with tube balloons filled with coffee grains [44].

the vacuum pump is used to 'mould' the cap and jam the grainy material in order to create a tight grip on the head. Once this is achieved, hair can be tossed securely and the optodes can be placed in their designated sockets. The cap firmly holds the head until the imaging session is over then air is allowed back into the cap thus loosening its grip.

With such gripping methods, the cap is expected to be worn without the need for additional attachments connecting the cap to a belt under the arms or to the chin. However, without an actual demonstration of the stability of these designs, such expectations remain speculative. Preliminary results from the vacuum cap design indicate that the complete head wear provides a tighter grip than the balloon-lined design due to the increase in the gripped surface area.

So far, the topic of future fNIRS caps focused on user's comfort and optode stability. However, cap installation is an important part of anticipated fNIRS imaging applications, not to mention its present day relevance for medical research considering the time and effort it requires from experts in the field of imaging. This has been generally due to the assumption that once smaller optodes were designed, the need for hair clearing would diminish; therefore, no mechanical methods would be necessary to clear the hair and ensure optode/scalp contact. Additionally, as optode holders generally provide a very small space (0.7–1.2 mm in diameter) to place the optodes, this complicates the design of a mechanical hair tossing device to operate in. Consequently, designing a hair clearing optode holder can be a very expensive endeavour. So far, the best caps or optode holders from installation point of view were considered the ones that provided a clearing around the optode location to help with the hair tossing process. Therefore, small polymer patches or the elastic band cap in addition to the adjustable Velcro strips cap in **Figure 4** are preferable to other complete head covering models. Still, the installation process even with the help of adjustable patches or additional spaces around the optode requires the help of an expert technician, as the only advantage they provide thus far is that of reduced installation time.

Although the topic of the importance of a hair clearing optode holder is debatable given its complexity, clearing and holding the hair in place can potentially help in stabilizing the optode holder itself. Therefore, the basic concepts for such a device will be mentioned here for future references. As shown in **Figure 8**, hair tossing can be performed using either a double hair tossing pins, a single hair tossing pin or multiple pins directing hair from the middle of the opening outwards. Such mechanisms can be added to the socket, which is the locking mechanism used to place the optode on the cap. Integrating a hair clearing mechanism that can be activated by simply placing the optode inside the opening can potentially allow for single user installation, without the need for an expert technician.

Applying these clearing techniques on hair is faced with certain complications, such as hair directionality; therefore, for a socket that has two pins, parting the hair from the middle cannot be helpful at locations where hair direction is not parallel to the pins. This is even more complicated with one pin parting designs, therefore 'adjusting' methods for

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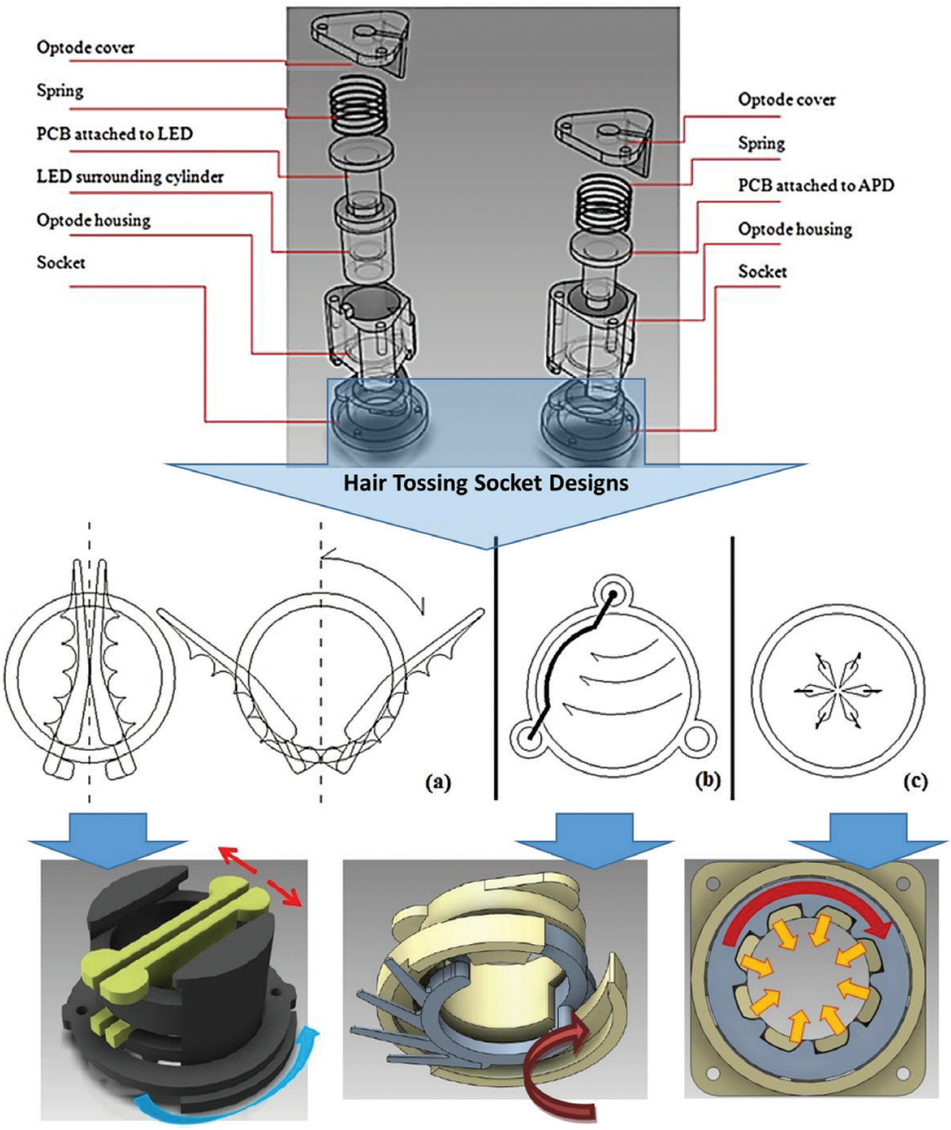


Figure 8. The various components of the optode housing and how it connects to the socket that is attached to the cap, a spring located inside the optode housing provides an additional pressure to maintain optode/scale contact. Hair clearing can be achieved via the development of socket designs that can play a dual role, by adding a hair clearing mechanism to it. Possible hair parting methods are: (a) dual parting pins, (b) single parting pin and (c) multiple parting [48].

pin directionality are necessary, such as designing a pin that can be placed in any of three placement combinations. Ideally, parting the hair from the middle is the best method, as it eliminates all difficulties associated with the other two methods. From a practical standpoint, the size of such pins would be in the millimetre range (maximum a centimetre); therefore, any concept needs to be tested on various levels, mechanical design, machining and implantation in order for it to be viable. Preliminary results obtained from the study presented by Kassab [48] shows that a collet-based pin concept that parts the hair from the middle by a simple twist of the optode holder can provide an interesting solution

for single user applications. Such a design can be very simple to use, would not require knowledge about hair directionality and is not affected by a hair type. More importantly, it can potentially lock the hair around the optode holder thus providing additional cap stabilizing mechanism.

6. Conclusion

The aim of this chapter is to demonstrate the importance of fNIRS caps or optode holders as an interface, and how the imaging signal and ergo the future use of fNIRS can be affected by its efficiency and performance. The major challenges of an efficient imaging cap were articulated as well as present available models and possible future solutions. In general, the field of fNIRS imaging has not been generous when it comes to studies aimed at the interface itself, albeit designing an ideal imaging cap can potentially be a major factor in solidifying the marketability of fNIRS imaging as an inexpensive medical device by increasing its reliability and creating a user friendly and practical system.

In preparing this study on fNIRS caps, it was obvious that several areas were in need of proper documentation, including basic definitions or guidelines, such as the pressure values for optode stability versus pressure values for patient comfort on the head. Such design parameters are important for any tight headwear and medical device designs. On the other hand, while there are numerous studies on movement artefact algorithms and how to filter out or control them, studies on optode inclination and detachment as a movement artefact associated with facial expressions or head movement, and how it affects the imaged signal is not yet approached. With long-term imaging, issues pertaining to the effect of sweat and heat on the imaged signal is also an important one, and when considering freely moving subjects, pressure fluctuation with motion, or the dynamic pressure, on the head and how it correlates with motion artefacts can also present an important feedback defining sources of error and isolating factors that have affected the reliability of fNIRS imaging for the past couple of decades.

Finally, when it comes to testing the efficiency of fNIRS cap designs, there are no protocols or standards that define its proper use and limitations. For example, some patches can be very practical with motionless subjects for finger tap testing or visual stimulation; however, they might fail with freely moving subjects. Therefore, establishing a proper testing mechanism for fNIRS caps can also aid workers and end users in understanding the limitations of each device and thus avoid possible errors in application.

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Nomenclature

APD	Avalanche photodiodes
CW	Continuous wave
DPF	Differential path length factor
EEG	Electroencephalography
FD	Frequency domain
fNIRS	Functional near infrared spectroscopy
HbO	Oxyhaemoglobin
HbR	Deoxyhaemoglobin
LED	Light-emitting diodes
MRI	Magnetic resonance imaging
NIR	Near infrared
NIRS	Near infrared spectroscopy
PET	Positron emission tomography
SNR	Signal-to-noise ratio
TD	Time domain

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