Augmented Reality Display with Hands-free Control for Surgical Procedure Enhancement

An Electromyographic-based approach

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Abstract

The constant evolution of surgical interventions in medicine has saved countless lives and improved overall patient health. However, the increasing complexity of variables and information in the operating room has created challenges for surgical teams, potentially impacting intervention outcomes. Particularly in high-risk procedures like cardiac surgeries, preventable errors often result from teamwork or system constraints. Improving the access, visualization, and integration of information in the operating room is a crucial challenge to enhance the flow of surgery and minimize disruptions that can impact patient safety. In this dissertation, an EMG-based hands-free Augmented Reality (AR) system is proposed to assist the surgeon and auxiliary team during surgery, in visualizing patient information on demand, in real-time. The system is composed by a head-mounted Augmented Reality see-through headset, which displays relevant clinical information about the patient being intervened (e.g., vital signals, previous medical imaging). The displayed information is controlled by the user, through specific forehead movements, captured by facial electromyography. Studies were carried out to assess optimal EMG acquisition and processing, as well as different electrode models were evaluated. A mobile application, *ARSurgery*, was developed as the interface for the AR system, including the algorithm responsible for detecting and classifying facial muscle inputs. The developed system was tested with two groups of subjects, including surgeon doctors, obtaining a very satisfactory performance, with mean precision and recall rates of 0,951 and 0,988, respectively.
Keywords: Augmented Reality, Surface Electromyography, Onset Detection, Operating Room, Signal Processing, Hands-free Control

1. Introduction

1.1. Problem Description and Motivation

The constant evolution of medicine, particularly in surgical interventions, has significantly improved patient health and saved lives. However, technological advances have led to a complex and information-intensive surgical environment. The Operating Room (OR) involves collaboration among various experts and personnel, each with specific responsibilities. Accessing and managing pre-operative and real-time physiological data is crucial during surgery, but this complex information flow can disrupt the surgical process, leading to technical errors and unfavorable outcomes [11]. Higher-risk procedures, like cardiac surgeries, have a higher incidence of preventable adverse events (12% compared to 3%) [12, 10]. One of the challenges is the static nature of information access in the OR, with scattered monitors and displays requiring active information seeking by the surgical team. These interruptions, Flow Disruptions (FDs), can cause distractions and errors. Therefore, it is crucial to find ways to minimize these preventable errors by improving information access and integration in the OR. The physical layout of the OR impacts the surgical process and needs optimization for efficient and safe interaction between medical team, equipment, and patients. However, current ergonomics in the OR are suboptimal, leading to layout-related FDs, which not only affect patient outcomes but also increase surgery duration and costs. Access to information in the OR contributes to interruptions, communication difficulties, and layout obstacles. The need to check external computers and monitors can disrupt the surgery flow and affect the surgeon's focus. This work aims to tackle information-related FDs and explore alternative ways to access information, particularly using hands-free control through facial expressions (fEMG) and augmented reality (AR).

1.2. Research Goals
Based on the previous findings, the research aims to develop a novel system using AR headsets and hands-free electromyography (EMG) control to minimize attention-related FDs and improve surgical procedures. The research questions addressed are (1) How can information access in the OR, currently displayed on static monitors, be facilitated? (2) How can surgeons interact with the information while their hands are occupied and limited in space for additional devices? (3) How can this interaction be performed safely without compromising sterility?

The proposed solution presents clinical information in the surgeon's line of sight, enables navigation through content with minimal FDs, and allows control through forehead gestures detected by sEMG sensors. The project also aims to identify efficient control gestures and evaluate the system performance through an experimental protocol in a simulated environment.

1.3. Achievements
The project successfully accomplished various tasks, including developing a mobile application for information visualization - **ARSurgery**, an interactive algorithm for sEMG-based control, and an experimental protocol for facial sEMG data acquisition and analysis. The mobile app was integrated with a biomedical data acquisition platform for vital signs monitoring. A hands-free EMG-controlled AR system prototype was built, compatible with surgical apparatus. Two groups of subjects, including regular individuals and surgeon doctors, participated in the validation and performance evaluation of the prototype. Requirements and constraints were gathered through interviews with surgeon doctors to guide the solution's design.

2. Related Work

2.1. Augmented Reality
Augmented Reality (AR) was created to simplify users' life, and refers to the integration of digital information - in the form of text, graphics, audio and other virtual enhancements - with the user's environment, in real time. AR technologies therefore include all systems that enhance the real world by superimposing computer-generated information on top of it. With the recent advances in display and optical technologies, together with the continuously evolving digital processors, AR technologies have been emerging and increasingly applied to different industries, such as health care, education, engineering design, manufacturing, retail and entertainment [13].

Particularly in the medical field, AR technologies have offered a new approach for treating patients, explaining complex medical situations to patients and their relatives, educating and training medical professionals, and also for planning surgeries [6].

The main difference between AR and the other commonly used technology, VR (Virtual Reality), is that, while VR completely immerses the user in a synthetic world, abstracting him from the real one, AR technology augments the sense of reality by superimposing virtual objects in the user's live view [4]. This is the main feature that makes AR the most adequate technology to use upon this project, since it is of utmost importance that the surgeon's senses, especially the vision, are not obstructed nor compromised during surgery.

2.2. Hands-free Control Modes
For the proper functioning and control of a technological device, its user must be able to communicate and interact with it, giving his input to the machine. This interaction, designated by Human-Machine Interaction (HMI), requires a user interface, that can include different input devices and modes.

However, there are instances in which using the hands for technology control is not the best or most efficient option, particularly when the operator's hands must remain engaged in their primary task. Additionally, individuals with physical impairments may encounter difficulties using hand-dependent control mechanisms. Hence, in recent years there has been an emphasis on the development of alternatives that are hands-free, i.e., input modalities that don't depend on using the hands [3]. In this section the main hands-free input modalities will be briefly discussed, as well as some of their advantages and disadvantages.

Speech-based Control
Speech-based control utilizes machine learning to convert user speech into text or discrete outputs, enabling the identification of specific commands for corresponding actions. This mechanism is efficient for navigating menus or performing direct control tasks, as isolated or connected words suffice as inputs. Visual feedback, such as icon highlighting, confirms successful voice command recognition.

Conversely, continuous speech recognition is more suitable for filling out information fields and reporting forms. In these cases, the recognized speech should be displayed to provide feedback on the intended action. Challenges persist with voice control systems, including background noise interference in high-noise environments like operating rooms. Placing the microphone near the user's mouth mitigates this but introduces hardware complications. Designing the input vocabulary is another challenge, requiring simplicity and specificity to avoid complexity and interference from parallel dialogues.

Due to these constraints, this hands-free user interface has limitations in controlling the developed Augmented Reality system in this project.

Eye-based Control

Eye-tracking control technology utilizes devices that track eye movement and position in real time. This type of interface is particularly useful when the user is focused on a display, as the gaze direction serves as a real-time pointer, replacing traditional input devices like the computer mouse. It is especially beneficial for individuals with motor disabilities, such as Amyotrophic Lateral Sclerosis (ALS), who face challenges using standard controllers to interact with technology due to severe motor impairment.

Various methods are used to track eye movements. Video-based tracking uses image processing to detect eye features and map their position. However, this method has constraints regarding computing power, lighting conditions, and the need for head-mounted cameras. Another approach involves using special contact lenses equipped with eye-tracking technology, which offers fewer constraints but is more invasive. Another method, called Electrooculography (EOG), measures the electrical potential of the eye muscles to infer movement. While EOG-based eye-tracking is straightforward and suitable for executing simple commands, it requires the placement of electrodes near the eye, which can be uncomfortable for the user and may disrupt other surgical equipment's functionality. Considering the project's requirements, the EOG-based eye-tracking method is not suitable due to the discomfort it may cause for surgeons and potential interference with surgical apparatus like magnifying glasses.

2.3. Electromyography

Electromyography (EMG) measures electrical muscle activity using electrodes placed directly on muscles or the skin above them (surface EMG). In the context of pathology, it helps diagnose neuromuscular diseases, motor problems, nerve injuries, and conditions like ALS. EMG is also used in applications such as prosthetics control, grasp recognition, exoskeletons, and human-computer interaction.

Muscle Physiology

Skeletal muscle electrical activity is produced from two states of the muscle - at rest, with each cell having an electric potential of $\approx$ –80 mV, and during contraction, when an electric potential is generated in its Motor Unit (MU). MUs represent the anatomical and functional element of the neuromuscular system, and designate each group of muscle fibers and corresponding motor neuron. These electric potential differences arise when a motor neuron activates a neuromuscular junction, generating intracellular action potentials in muscle fibers. The combined action potentials of all muscle fibers form a motor unit action potential (MUAP), which is captured by the EMG electrode as a linear summation of multiple MUAP trains. The most commonly analyzed parameters of the MUAP are its amplitude, duration, phase, turn and baseline.

3. Methodology

Building upon the description of the existing solutions, and motivated by the lack of suitable hands-free control methods for AR headsets in the context of OR, as characterized in Section 2, this section aims to detail how the proposed solution was developed and implemented. Figure 1 outlines the main components of the proposed approach.

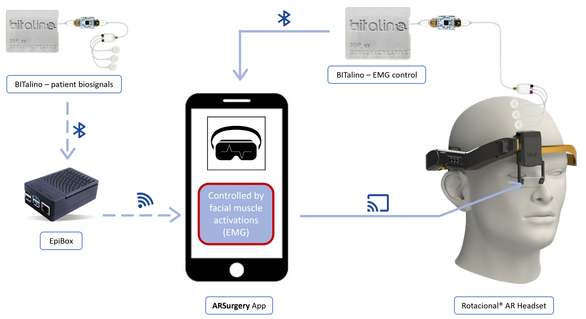


Figure 1: Augmented Reality System main components: Augmented Reality head-mounted display; BITalino for EMG control of the headset, with connected sEMG electrodes; ARSurgery mobile application. Optional components for direct acquisition of patient's biosignals: EpiBOX interface; BITalino connected to the patient.

The developed AR system is composed by different components that interact with each other:

- An optical see-through AR Headset with hands-free control, which should be placed and adjusted on the user's head;
- A mobile application - ARSurgery - whose screen is mirrored on the AR headset display in real-time, i.e., the content being displayed for the user is the application itself;
- A BITalino with an EMG sensor using three electrodes (bipolar montage and reference electrode), to collect data from which the commands used to interact with the ARSurgery app will be detected [2];
- The mobile application also allows to connect a second BITalino measuring biosignals directly from the patient, if desirable. This connection is made through a Raspberry Pi device, configured for that purpose (EpiBOX). EpiBOX connects to the patient's BITalino and

ARSurgery via Bluetooth and WiFi technologies, respectively.

The system and the choices made its development will be further explained in the next sections.

3.1. Requirements and Hardware Restrictions

The system was designed having in mind two main aspects: on the one hand, the characteristics and features that were found to be key for its appropriate functioning, and, on the other hand, the design requirements and restrictions existing within the OR and surgery context. Different aspects and features were considered due to the specific context of application, namely: (1) The Augmented Reality headset requirements, to be able to integrate it in a surgical environment without disrupting the surgery's flow; (2) The type of sEMG electrodes being used to capture the control signals from the user; and (3) The facial triggering signals chosen as input for the HCI.

AR Headset Requirements

The AR headset used in surgery should be see-through for an unobstructed view. It should be easy to put on and remove, lightweight, and adjustable for comfort and to prevent fatigue. Furthermore, is crucial that the headset is compatible with the surgical apparatus, such as clothing, mask, magnifying glasses, and surgical headlamp. The headset must not interfere with these devices on the surgeon's forehead. An integrated camera in the headset is desirable for additional system features and functionalities, which will be discussed in Section 7.

Different AR headset models were analysed, and for the prototype it was decided to use the ViP-display (version A1) AR Headset manufactured by ROTACIONAL[1]. This model was selected since it is completely see-through, fully compatible with the use of eyeglasses, adjustable to different users' head anatomy, and also has adjustable brightness / contrast, which allows to adapt to various light environments. ViP-display's main specifications are presented in Table 1.

sEMG Electrode Model

Dry electrodes were chosen for this system instead of gelled self-adhesive electrodes, considering their practicality, ease of application, and lower maintenance requirements. While gelled electrodes typically provide better EMG signal quality, studies support the satisfactory signal quality obtained by dry Ag/AgCl electrodes. The electrodes were connected to a BITalino EMG sensor [2] using a 3-lead UC-E6 cable.

[1] Available at `https://rotacional.com/vipdisplay/`.
[2] Available at `https://www.pluxbiosignals.com`

Table 1: Summary of the ViP-display AR headset main specifications

ViP-display AR headset main specifications		
Display	Resolution	1920×1080p (FullHD)
	Color Depth	RGB 16 Million colours
	Contrast Ratio	>10 000:1 (color)
	Maximum Luminance	100 to 500 Cd/m2
	FOV (diagonal)	30º
	Eye Relief	Adjustable
Luminance Control	Brightness adjustment	Indoor and Outdoor
	Contrast adjustment	Indoor and Outdoor
Connection	Communication	Wi-Fi
	Power Supply	Built-in (1 work shift autonomy)
Measurements	Dimensions	185×44×228 mm (w × h × l)
	Weight	111 g

Two different models of dry Ag/AgCl electrodes were tested and compared in the developed prototype, with one model being more elevated (Er) and the other more proximal (Ef) to the skin. Standard gelled self-adhesive electrodes (Eg) were also tested for comparison as the reference. The different electrodes are illustrated in the Table 2. Results for these comparison tests will be presented and discussed throughout Section 5.2.

Table 2: Illustration of the electrodes used in the signals' acquisitions and summary of their main characteristics

Electrode denomination	Illustration	Sensor material	Conductive gel	Diameter
Raised profile - Er		Ag/AgCl	No	11 mm
Flat profile - Ef		Ag/AgCl coated polymer	No	10 mm
Gelled - Eg		Ag/AgCl coated polymer	Yes	24 mm

Facial Expressions Chosen as Input for the HCI

When selecting movements for input in the AR headset, hands-free control and minimal interference with primary tasks were prioritized. Facial commands using EMG signals were chosen as a result. Common facial movements in HCI applications typically require electrodes on the lower half of the face, but selecting movements involving the upper face allows for electrode placement in that region, conveniently integrated into the AR headset headband. Thus, three potential commands were selected: single-eye winking (W), brief eyebrows' raising (BER), and extended eyebrows' raising (EER). Periodic blinking, a natural human behavior, was also included for analysis to study its impact on EMG signals and interaction with the AR system.

Electrode Placement on the Face

Electrode placement was also chosen considering the usability requirements for this system. To minimize its impact in the surgeon's primary tasks, and due to the limited space available in the surgeon's head (as described in Section 3.1) it was determined to integrate the electrodes in the AR headset itself, within the headband, between the two *frontalis* muscles, and above the *procerus* muscle.

Bipolar montages benefit from placing the electrodes adjacent to each other along the muscle direction, with a reference electrode further away in an electrically neutral tissue. However, for HCI applications, the usability approach is to place the EMG electrodes horizontally, with the reference electrode slightly above, which allows distinguishing between muscle rest and activation in the temporal domain.

Figure 2: Surgeon doctor using the developed system, together with the potential surgical apparatus necessary during surgery

3.2. Application Structure and Displayed Pages

The mobile application, named **ARSurgery**, developed as the interface for the AR display, was built assuming two phases: a (1) setup phase, and (2) the display phase itself, which is hands-free. The setup phase, leads the user in connecting the different devices to the app (via Bluetooth and WiFi), and allows the user to calibrate the app in order to optimize the EMG commands recognition. It is worth mentioning that the auxiliary devices (BITalino and EpiBOX) should be switched on beforehand, and be ready to allow connections. Additionally, the smartphone where the app is running must have Bluetooth and WiFi enabled. After the devices are connected and the app is conveniently calibrated, the user can proceed to control the displayed information on the app, and consequently, on their AR headset display, in real-time. The hands-free controlling mode allows the user to switch between the different pages of the app, each one containing relevant clinical information about the patient being intervened. The prototype features two pages: Biosignals Viewer and Monitor Viewer. The Biosignals Viewer displays the patient's acquired biosignals through a connected BITalino, while the Monitor Viewer continuously presents the view from the phone's camera. This feature can be used to emulate one of the OR monitors chosen by the surgeon. Users can switch between these pages and also access a dark page for hands-free switch-off of the AR display.

Figure 3: ARSurgery displayed pages. At the top, from left to right: Home page; Calibration Page; Patient's Biosignals Viewer page. At the bottom, Camera Viewer page.

4. Implementation

This Chapter outlines the implementation of the prototype, providing an overview of the choices made throughout its development and detailing the technical aspects of the implementation process. Furthermore, it describes how the different components of the methodology were validated and explains the evaluation of the system's performance.

4.1. BITalino and EpiBOX Integration

To acquire the EMG signal for the app control, a wireless interface is needed to collect and send the data in real-time. Due to its usability and wireless capabilities, a *BITalino (r)evolution Board BLE* [3] was chosen to collect the signal arising from the EMG electrodes. This assembled board has all the needed electronics for biosignal acquisition, and can connect via Bluetooth Low Energy (BLE) to the smartphone, with ARSurgery running.

Furthermore, BITalino can record a variety of biosignals additionally to the EMG, including Electrocardiography, Electroencephalography (EEG) and Electrodermal Activity (EDA). Hence, a second BITalino device can be used to record biosignals of the patient being intervened, and present them directly on the surgeon's AR headset. Since most smartphones do not allow pairing two Bluetooth devices simultaneously, the optional BITalino to record patient's biosignals was connected to ARSurgery via Wi-Fi. An adaptation of *EpiBOX* [5] was used as the interface between this second

[3] Available at `https://www.pluxbiosignals.com/products/bitalino-revolution-board-kit-ble-bt`.

BITalino and ARSurgery. EpiBOX platform allows the long-term acquisition of biosignals, using a *Raspberry Pi* as the recording unit (EpiBOX Core), coupled with a Python software (PyEpiBOX) responsible for the data communication, acquisition configuration, and storage. EpiBOX was adapted for this project, to incorporate the visualization of the data coming from the BITalino directly in ARSurgery.

4.2. Final Prototype Application description

(b)

Figure 4: ARSurgery displayed pages, with sequential guidance for the setup phase.

In the setup phase (Figure 4a), the user connects the system devices to the app by pressing the top left and right buttons (③). The homepage offers two start modes - with or without measuring patient's biosignals (① or ②). After connecting the BITalino devices, the user calibrates the forehead EMG sensor by pressing the calibration buttons (⑤) and following on-screen instructions. For the "Gather Stats" button, this consists in remaining still for 7 seconds while the app retrieves features from the rest EMG signal (indicated in Figure 4a - ⑦). For the "Gather Test Trial", it consists in performing three separate eyebrows' raising movements, one of the system's input commands. The calibration page displays the real-time EMG signals (⑥) for visual feedback. Finally, the user can press "Start EMG control" (⑧) to control the app hands-free.

The user can use the facial commands to navigate between the three different screens described in Section 3.2. The Monitor viewer, in addition to display the OR chosen screen in real-time, also allows to photograph and/or record said screen, allowing to keep track of the patient's health state during surgery, and for subsequent teaching purposes.

ARSurgery supports both portrait and landscape modes, providing the flexibility for users to explore the app in their preferred orientation. When mirrored on the AR headset, the app can be fully utilized in landscape mode, optimizing the screen's usable area. Lastly, the app was safeguarded with a blocking/notification system to ensure users follow the desired order and complete all necessary steps. For instance, if the user attempts to connect the BITalino EMG without enabling Bluetooth, the app displays a warning message. During the gathering of EMG signal characteristics, the app notifies the user with popups indicating the progress, such as "Gathering rest stats" and "Stats completed!".

The connection between the smartphone running ARSurgery and the AR headset is established using screen mirroring, a wireless feature available on most smartphones. This allows real-time presentation of ARSurgery on the headset, using default applications like Smart View for Android or AirPlay for iOS, or third-party options like Chrome Cast. Screen mirroring offers a user-friendly, practical, and wireless interface, making it well-suited for this system.

Signal processing and onset detector

The system requires a lightweight onset detector to process the EMG signal and differentiate muscle activations from silent periods. The detector, implemented on a mobile app, must operate in real-time with low latency. To improve the EMG signal quality, real-time preprocessing and filtering were performed, and experimental tests were conducted to compare different filters. Based on the results, further presented and detailed in Section 5.2, a Weighted Moving Average (WMA) filter with a 100-point window size was chosen for real-time signal processing.

Methodology validation

An experimental study was conducted to evaluate the system's performance and the effectiveness of the hands-free control mechanism. The study consisted of two tests: one focusing on measuring the app's response to user movements without the AR headset, and another to assess the overall performance with the integrated electrodes on the headset. For the first test, the participants interacted with the electrodes and app using a headband, built for that purpose, while in the second test, they wore the AR headset with the electrodes attached.

In both tests, the participants were asked to use the ARSurgery app following a defined protocol, with a set of at least two trials, each composed by a specific sequence of the forehead movements described above – brief eyebrow raises (BER) and extended eyebrow raises (EER). The protocol was designed to let the user run across all pages.

Additionally, the surgeons were surveyed to assess the system's suitability and usability, given their primary interest in the project. The results from the tests and survey are presented in Section 5.2.

5. Results

5.1. Characterization and optimization of the EMG signal and hardware

A primary experimental study was conducted to ascertain which electrode type should be used in the signal acquisition, as well as to define the most suitable pipeline to process the signal, including which type of digital filter to use. Three participants took part in this study. The acquisition of the electromyographic signals was carried out following an experimental protocol composed by four different facial gestures - brief (BER) and extended (EER) ($\approx$ 3 seconds) eyebrows' raising, single-eye winking (W), and eye-blinking (EB). The first three gestures were tested as potential inputs for controlling the augmented reality headset, while eye-blinking was included to assess false positives. The sequence of facial gestures for each trial is shown in Figure 5.

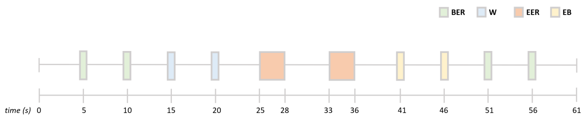


Figure 5: Illustration of the experimental protocol for the acquisition of the electromyographic signals. BER = Brief Eyebrow Raise; W = Single-eye wink; EER = Extended ($\approx$ 3 seconds) Eyebrow Raise; EB = Eye-Blink.

5.2. Electromyographic signal pre-processing

A set of pre-processing steps was performed before analyzing the acquired EMG signals. Firstly, the values sampled from the EMG sensor's channel were converted to their physiological unit of measurement, mV, according to the transfer function represented in Equation (1)

$$signal_{EMG}(mV) = \frac{(\frac{ADC}{2^n} - \frac{1}{2}) * VCC}{G_{EMG}} * 1000 \quad (1)$$

Then, the time series was centered around 0 mV by subtracting the baseline average, and a full wave rectification was performed. Finally, to precisely identify the regions corresponding to muscle activation, the onset and offset of each movement were manually annotated using the SignalBit software [1, 9]. These steps are illustrated in Figure 6.

Electromyographic signal quality

Tests were conducted to determine the optimal type and positioning of electrodes for measuring surface electromyographic (sEMG) signals on the forehead. The acquired signals are affected by

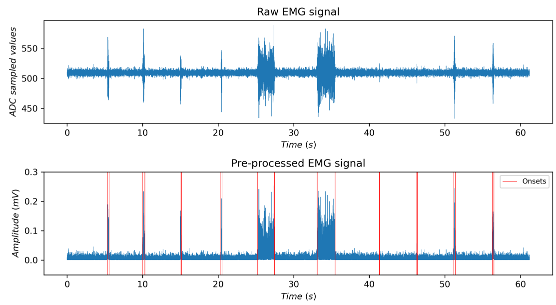


Figure 6: Illustration of the EMG signal before and after the pre-processing: conversion to mV units, subtraction of the baseline mean and full wave rectification

noise, reducing their quality and Signal to Noise Ratio (SNR). Metrics such as mean, standard deviation, maximum amplitude, and signal integral were computed for both the baseline and muscle activation time frames to assess signal quality. SNR was also calculated for the entire signal, according to Equation (2). The metrics computed for each region are presented in Table 3.

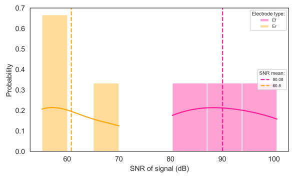
$$SNR(dB) = 20 \times log_{10} \frac{Power(activation)}{Power(baseline)} \quad (2)$$

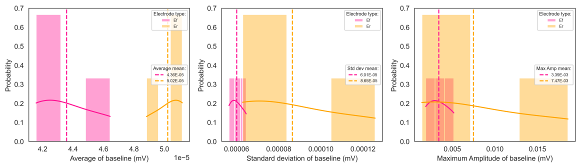
Table 3: Metrics computed from the signal, depending on the signal's region

Signal Region	Metrics Calculated				
	Mean (μ)	Standard deviation (σ)	Maximum amplitude	Integral of region ($\int$)	SNR (dB)
Baseline	X	X	X		
Activation region	X	X	X	X	
Total signal					X

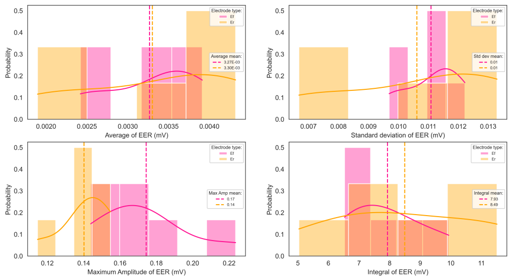
Electrode model selection

The two types of non-gelled Ag/AgCl electrodes presented in Table 2 were compared. Metrics for the signal's baseline and for each onset region (BER, W, and EER) were computed according to Table 3. The results were aggregated in histograms to compare the two electrode models (Ef in pink and Er in yellow). The histograms include probability density estimation curves and vertical lines indicating the mean result of each metric. Relative frequency was used to normalize the data and consider the imbalance in the number of trials acquired with each electrode type. The histograms were divided based on two criteria: (1) number of subjects included and (2) signal filtering. Initially, metrics were calculated for all subjects combined. Then, the trials were split by subject to examine inter-subject variability and identify outliers. The metrics were computed for both the raw signal and after applying an adaptive filter called "adaptive filter error," which calculates the difference between the original signal and the signal filtered using adaptive Least Mean Square (LMS) filtering. For abridgement purposes, the results presented are when considering only 1 subject, and after filtering the signals.





(b) Baseline average, SD and max. amplitude



(c) EEB average, SD, maximum amplitude and integral

Figure 7: Statistical comparison between EMG test trials obtained with Ag/AgCl dry electrodes - raised profile (Er - yellow), and flat profile (Ef - pink).

From the analysis of the histograms and corresponding statistics, several conclusions can be drawn. The Ef electrodes exhibit higher SNR values compared to Er electrodes, resulting in an SNR increase of 32,50% for the Ef model. Additionally, the Ef electrodes demonstrate lower average and standard deviation values for the baseline, indicating better myoelectric silence representation. The mean and standard deviation of the signals show reductions of approximately 15.14% / 43.93%. Regarding the specific facial movement being studied (Extended Eyebrows' raising - EER), the Ef electrodes show higher mean, maximum amplitude, integral, and standard deviation values before filtering. However, after filtering, the difference between Er and Ef electrodes is eliminated. Based on these results, the Ef Ag/AgCl dry electrodes, which are closer to the skin, were chosen to integrate the Augmented Reality system.

Filtering of the acquired signal

To enhance the acquired signals, the next step involved studying the application of digital filters. The focus was on reducing noise captured by the electrodes and improving the signal's SNR, as the goal was to detect electromyographic onsets and offsets. Filters that attenuate specific frequency components were considered, with a preference for temporal features. The selected filters were chosen based on their computational complexity, taking into account the real-time signal processing requirements on a mobile operating system (Android/iOS). Both IIR and FIR filters were tested.

The filters' performance in enhancing the EMG signal was evaluated using an onset detection algorithm based on Hodges and Bui's approach (1996) [8]. This algorithm, available in the BioSPPy Python toolbox [4], takes the filtered EMG signal, a rest period segment, sampling rate, detection threshold, and detection window size as inputs. The detector's performance was assessed by analyzing Precision-Recall curves, which illustrate the trade-off between recall (true positive rate) and precision (positive predictive value).

In this specific context, the variables were defined based on several steps. Muscle activation segments were annotated for each EMG signal acquisition using the SignalBit software as the ground truth. The detections made by the detector were classified as TP or FP based on their temporal alignment with the real onsets, allowing for a certain time tolerance. If a detection coincided with a real onset within the tolerance, it was considered a TP; otherwise, it was classified as a FP. In cases where multiple detections occurred near the real onset, the closest one was considered a TP, while the others were classified as FP. False Negatives (FN) were defined as instances where the detector failed to detect muscle activity. The tolerance was calculated based on the average latency between the real onsets and the obtained detections, with a maximum latency of 150 samples (150 ms) considered acceptable for the intended application.

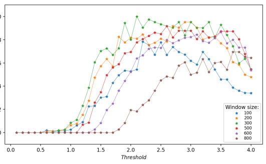
The Precision and Recall graphs were obtained, and results for 2^{nd} order Butterworth and SMA are shown in Figure 8.

Based on the Precision and Recall curves obtained for the different filters, the Moving Average filters consistently yielded higher precision and recall values across different detection thresholds and window sizes. Particularly, SMA (w=10) curves are more stable with respect to the threshold used, turning the detector more robust. For that reason, it was decided to use a Moving Average filter to process the input EMG signal being acquired from the user.

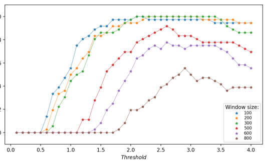
Onset detector implementation

The analysis was based on the detector proposed by Hodges and Bui and computed in the BioSPPy toolbox. The detector implemented in the AR-Surgery Mobile application has slight differences

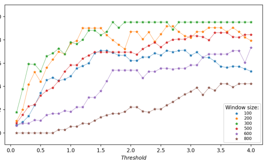
[4] Available at `https://github.com/PIA-Group/BioSPPy/blob/master/biosppy/signals/emg.py`.



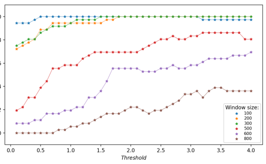
(a) Precision - 2^{nd} order Butt.



(b) Recall - 2^{nd} order Butt.



(c) Precision - SMA (W = 10)



(d) Recall - SMA (W = 10)

Figure 8: Precision and Recall curves obtained while applying to the input EMG signal: (a, b) Butterworth 2^{nd} order filter with cut-off frequencies of 20Hz and 450Hz; (c,d) Simple Moving Average filter with window size = 10 samples.

due to contextual constraints and real-time usage. The EMG electrodes used are not fixed to the skin but on the head-mounted AR display, leading to variability in acquired signals. To adapt to this, the implemented detector uses a dynamic threshold based on a test trial where the user performs 3 BER movements. The test trial is pre-processed, rectified, and smoothed with a Weighted Moving Average of 100 samples. The baseline average and standard deviation are calculated, and a test function is computed following Equation (3). The threshold is defined as 1 σ above the test function average [8], as illustrated in Figure 9.

$$testfunction(x) = \frac{1}{\sigma_{baseline}} * (x - \mu_{baseline}) \quad (3)$$

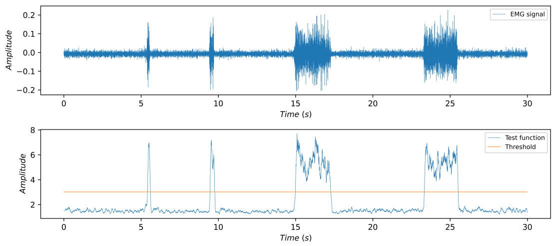


Figure 9: Illustration of an EMG signal segment and its resulting test function, as well as the corresponding computed threshold.

AR system prototype validation

As described in Section 4.2, two different tests were performed to validate both the onset detector and the EMG-controlled AR headmounted display as a system, following the protocol defined in Figure 10.

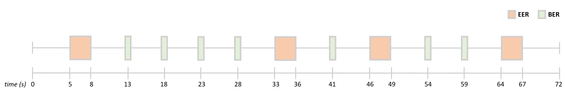
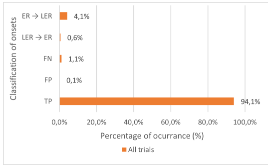
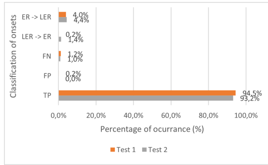


Figure 10: Illustration of the movements' sequence followed by the participants for both Test 1 and Test 2. Sequence composed by alternated BER and EER ≈ 3 s.

The results of the experimental tests are presented in Figure 11.



(a) All trials



(b) Test type

Figure 11: Results of the experimental tests' performance metrics - TP, FP and FN rates, EER mismatch Rate (EER -> BER) and BER mismatch Rate (BER -> EER). Focus on the comparison between: test type (Test 1 vs Test 2)

The experimental tests yielded satisfactory results overall, with a TP rate of 94.1% and an FP rate of 0.1%. The FN rate was 1.1%, which is sufficiently low. Regarding the distinction between brief and extended eyebrow raises, the algorithm had a higher tendency to perceive brief raises as extended raises. Varying the threshold for this distinction affected the results, with a higher threshold resulting in more extended raises being perceived as brief raises. The threshold was adjusted to 1000 milliseconds based on participant feedback, providing satisfactory results.

The results showed slightly more optimistic results for Test 1 (sEMG sensors and app only) than Test 2 (AR system with integrated sEMG sensors), with Test 1 having a 1,3% higher TP rate and a summed 1,6% lower rate of mismatches. This is to be expected since the AR headset may slightly hamper the correct positioning of the electrodes on the forehead.

6. Study with the interest group (surgeon doctors)

Additionally, it was asked for surgeon group to answer a survey regarding the developed system's usability. This survey consisted in two parts. The first, adapted from the System Usability Scale (SUS) [7], which is commonly used to assess the usability of new technology systems, and the second part with questions specifically regarding the proposed solution, developed for the surgery context. The mean score of 82.5 points obtained by the surgeons' group on the SUS questionnaire corresponds to a percentile rank of 90-95%, indicating a highly satisfactory reception of the designed prototype in terms of usability and user-friendliness.

The feedback from the surgeon doctors on the second part of the questionnaire was very positive, with constructive suggestions for possible applications of the prototype in surgery scenarios. They highlighted the importance of presenting preoperative imaging and real-time intraoperative imaging, such as fluorescence cholangiography, on the AR display. They also suggested screen casting monitors displaying image intensifiers to enhance focus and reduce the need to look away during surgery.

7. Conclusion & Future Work

The increasing complexity of variables and information in the operating room presents challenges that can impact surgical outcomes. Currently, the information flow during surgery is mainly static, with scattered monitors and displays, requiring surgeons and the auxiliary team to actively seek information. Enhancing access, visualization, and integration of information is crucial to improve surgical flow and minimize disruptions that may compromise patient safety.

To address this, the use of head-mounted displays for surgeon doctors and auxiliary team members to access relevant patient information is a viable solution, provided it is user-friendly and does not interfere with the surgery flow. Additionally, the display should be ergonomic and not physically obstruct the use of surgical apparatus such as masks, magnifying glasses, or surgical headlamps.

A hands-free Augmented Reality headset controlled through forehead movements using electromyography (EMG) was developed, considering the requirements and constraints. Hardware selection was based on experimental tests. The solution was tested and evaluated by two groups, including two surgeon doctors. The control mechanism showed promising accuracy. Feedback from the surgeon doctors, through interviews, questionnaires, and usage feedback, indicated a highly positive reception of the prototype in terms of usability and user-friendliness. The feedback also provided valuable insights into potential applications in various surgical contexts.

For future developments, the system can be enhanced by incorporating a wider range of input movements, increasing navigation and selection options, as well as enabling the display of different contents on the headset screen. Additionally, connecting the monitors in the operating room to ARSurgery via Wi-Fi instead of using the smartphone's camera would improve screen casting quality and allow for seamless switching between multiple monitors.

To simplify the setup phase, it would be beneficial to allow ARSurgery to save calibration parameters for each user. However, this would require more stable positioning of the electrodes on the user's forehead or the development of a more robust algorithm for processing the acquired EMG signal.

Finally, implementing data protection mechanisms, such as individual user profiles with password protection, would enhance the solution's security and privacy measures.

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