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Developing an EOG-Based Communication Interface for Quadriplegic Patients: Signal Processing and Algorithm Design

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Abstract

Electrooculography is considered one of the significant electrophysiological signals. These signals carry data on eye movements, which can be employed in a human-computer interface (HCI) as a control signal. This project focuses on creating a text and voice-based interpreter for quadriplegic patients using electrooculography (EOG) signals. EOG is a technique that measures the electrical activity of the eye muscles responsible for eye movements and can be used to track changes in eye location to reveal information about human eye activities. The EOG signal is commonly used in human-computer interface (HCI) systems as an alternative input for patients suffering from quadriplegia, ALS, and locked-in syndrome. The BioAmp EXG Pill Sensor is used to acquire EOG signals of left and right eye movement, as well as up and down eye movement. The signals are processed using an ESP32 microcontroller and Arduino IDE, and an algorithm is created to analyze the observed ranges and generate text and voice-based outputs. The system's accuracy was tested by asking 10 healthy participants to perform each of the four types of motions ten times, and the results showed an overall accuracy of 81.04%. The system involves detecting EOG signals using sensors that are placed around the patient's eyes, and the text-based output is displayed on an LCD screen, while the voice-based output is played on an MP3 player see Figure 5. The output is then displayed on an application enabling communication with the patient remotely, potentially improving the quality of care and increasing the patient's sense of security. Future developments could include increasing the degrees of motion and addition of an eye-blink sensor for a more convenient user experience. This project provides a valuable solution for quadriplegic patients, enabling them to communicate effectively and empowering them with a sense of independence. However, further research and testing are needed to fully evaluate the efficacy of the system on actual quadriplegic patients.

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1 Introduction and Background

For people all over the world, language is a gift that enables them to communicate their thoughts, ideas, and opinions and is a driving force in building a friendly environment. However, this communication becomes a difficult task for people suffering from quadriplegia, a condition in which a patient is conscious but cannot move or communicate verbally due to complete paralysis of all voluntary muscles in the body except for eye movements and blinking. This restricts patients from communicating. As technology advanced, developers developed software and hardware mechanisms to curb this dependency and bridge the gap between the two communities. Eye movements can be used as alternative inputs for human-computer interface (HCI) systems such as virtual or augmented reality systems as well as new communication ways for patients suffering from quadriplegia. Quadriplegia, often referred to as tetraplegia, is a pattern of paralysis that can afflict a person from the neck down and causes them to be unable to control or move their muscles on purpose. It may impair your capacity to move particular body parts as well as some of your body's automatic processes that keep you alive, depending on how and why it occurs [1].

Many research projects are currently looking into ways to help the elderly and disabled communicate effectively with machines or computers. Various interface types have been proposed depending on the users' capabilities, including; Speech recognition based on both voice [2], Surface electromyography [3], lip movement control system [4], infrared and ultrasonic non-contact head controllers [5], multifunction myoelectric control system (MMCS) [6], brain-computer interface (BCI) [7].

However, due to the limitations of each interface, such as speech recognition and vision-based head gesture's poor classification performance in outdoor and noisy settings, infrared and ultrasonic non-contact head controller's low classification performance, or MMCS and BCI's issue with noise [11], the electrooculography (EOG) signal is one of the parameters of communication. Amyotrophic lateral sclerosis patients will find this interface to be very helpful (ALS). Patients with ALS may lose their ability to talk verbally and use their hands, but they typically have some ability to move their eyes, which serves as their final means of communication [8].

The eyes and associated movements are a crucial component employed to convey wants, emotions in humans. The ability to detect eye movements can be a substitute for spoken language for those with severe difficulties. There have recently been more chances for research in this field. For instance, eye motions for using and managing appliances were once more observed [9]. Wheelchairs with EOG control receive the greatest attention.

From our literature review, there are several studies are there using EOG signals. Studies have been done on processing the signals obtained from electrodes positioned around the eyes, understanding the function of the eyes, and other topics including using EOG signals to examine sleep [10]. There is also research on new signal classification techniques [11]. Popular studies attempt to improve the quality of life for patients with mobility-impairing illnesses (such paralysis and ALS) by assisting them with daily chores using EOG signals [12]. The invasive scleral search coil (SSC) technique inserts a coil into the eye's lens [13]. This technique is employed for clinical observations with a view to diagnosis. The coil that is attached to the eye experiences voltage when this coil of wire is moved through a magnetic field. This generates a signal that is inversely correlated with the position of the eye. EOG can be used to simulate the ocular motor system and detect eye movements using a variety of ways. The support vector machine [14], multiple feature classification [15], the Kalman filter [16], peak detection deterministic finite automata [17], saccadic eye movement quantification [18], pattern recognition [19], and spectrum analysis [20] are a few of them. Significant efforts have also been undertaken to 8 lessen and eventually eradicate the issues with drift, blink, overshoot, ripple, and jitter [21] that are related to ocular tracking in EOG.

Another field of study that makes extensive use of EOG data is human-computer interface. This study shows that even people with limited mobility can easily execute eye movements to operate computers, browse the internet, and accomplish other tasks. [22] propose an HCI that relies on eye movement to handle numerous apps (such home automation software and communication aids) for people with motor paralysis and speech impairment. [23] presents an EOG signal processing hardware system with three stages: command output, pattern recognition, and signal conditioning. As an expansion to the previous one, a GUI is given in [24] but it is designed to play games with an eye-controlling orientation. Researchers have long developed a graphical user interface (GUI) with a virtual keyboard for message composition and a module to request particular requirements.

Utilizing electrooculograms to produce effective HCIs has been the subject of recent research and developing new electrode configurations to create wearable EOG recording devices, like headphone-style gaze detectors [16], wearable EOG goggles [25], or lightweight head caps [26].

Although, multiple researches have been done as well as many devices have been developed to record eye movement using EOG but none of them were able to build an easy mode of communication between patients and their environment. The novel aspect of this work is that eye movements are used to facilitate the patient rather than using letters to construct a whole phrase through a graphical user interface (GUI). Additionally, it will support oral communication as well as written communication, allowing voice synthesizer to read entered text aloud.

Electrooculography (EOG) is one of the useful electro-physiological signals that can track changes in eye locations and reveal information about human eye activities is the EOG signal. The "cornea-retinal potential (CRP)"—which is produced by the potential difference between the cornea and the ocular fundus—is what causes it. The retina, which corresponds to the front of the eye and contains a significant number of electrically active nerves, can be compared to a constant electrical dipole with a positive pole at the cornea and a negative pole at the retina. As a result, the potential difference between the electrodes positioned close to the eyes will vary anytime there is an upward or downward eye movement or a left to right eye movement. These modifications are used to track eye-ball movement as shown in the Figure 1.

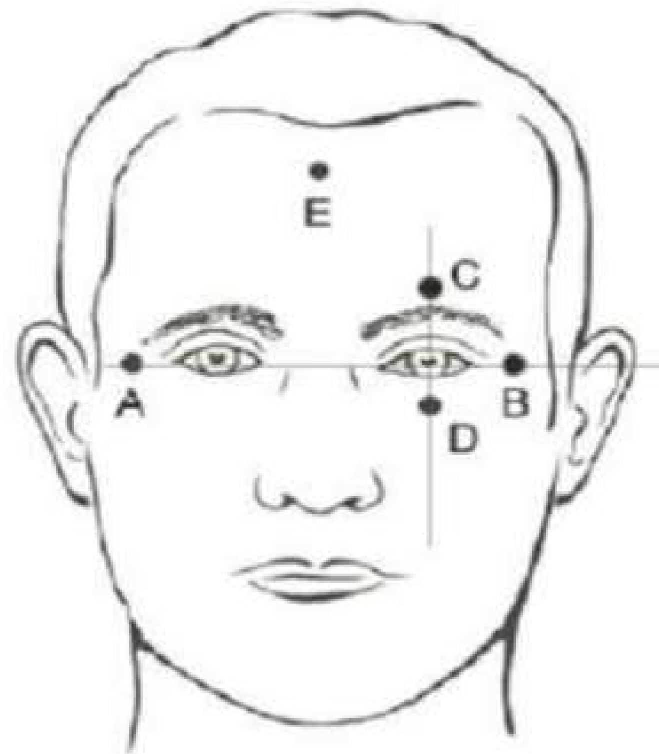

Figure 1. Medical electrode location EOG. [27]

The EOG signal may seem like an excellent candidate for an eye movement classification system due to its relatively high signal-to-noise ratio (SNR) in comparison to other electrophysiological signals, its amplitudes range between 15 and 200 V, and a linear relationship between its amplitude and eye movement angle, as shown in the Figure 2 [28, 29].

2 Methodology

ESP32 microcontroller is used to design the project. It is responsible to acquire the analog data from the BioAmp EXG pill and interprets to generate the data. It is done by programmatically by using Arduino IDE. BioAmp EXG pill is wired to the microcontroller. It is a non-invasive method to acquire EOG signals from a subject's eye movement to measure the corneo-retinal electrical potential [30]. BioAmp EXG Pill acquires the EOG signal and sends it to the Analog pin of the ESP32

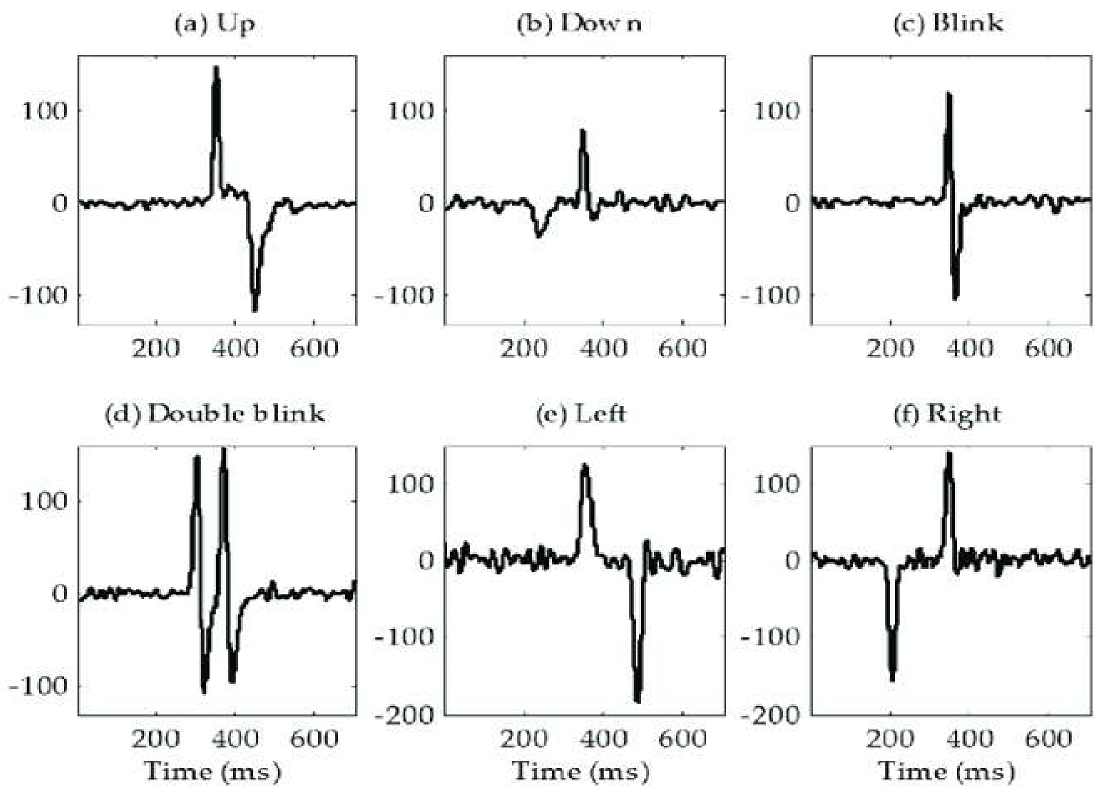

Figure 2. Forehead EOG signal patterns after signal processing. (a) Up (long blink); (b) Down; (c) Blink; (d) Double blink; (e) Left and (f) Right. [29]

for manipulation. To measure the eye movements, electrodes are placed to the right and left of the eyes or on the up and down the eye for right and left or up and down movement respectively. These electrodes pick up electrical signals generated by the eye muscles and convert them into electrical signals, which are then processed by an ESP32 microcontroller using the Arduino IDE, see Figure 3 .

The LCD is programmed using if conditions. So, when the particular movement is initialized and the "if" condition is satisfied then the LCD will display the respective command. If the person is looking left and once the range values are detected and processed through the EXG Pill and the MCU, the respected command 'Call the Doctor" will be shown on the LCD. RGB is equipped with the board for the indication purposes. It gives off different hues on the detection of different movements.

DFplayer mini is used as an mp3 device for the audio output. It is used with an additional speaker to get the audio sound and for the better understanding of the output. It has a slot for a SD card to store the audio which is to play be played.

2.1 Calibration

Ranges of eye movement potential vary from person to person. When the eye moves from the center position towards any placed electrodes then that electrode will take this as a positive side of the retina and the negative side of the retina will be facing the opposite electrode. That's how a potential difference exists between the otherwise standing corneo-retinal potential. The observed potential serves as the measured values of eye movements. With no specific range, the ranges fluctuate depending on how fast or in which direction the subject is moving their eyeball. Therefore, it is decided to set the specific ranges for every movement which will be used. It is done by taking minimum and maximum values from the raw data of left, right, up, and down eye movements by examining and executing

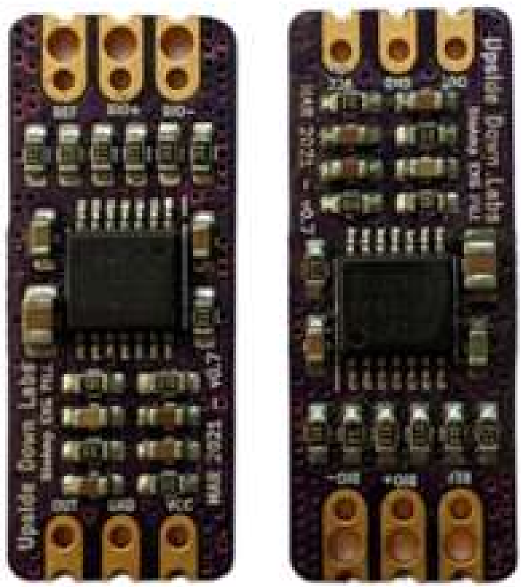

Figure 3. EXG Explorer Pack [30]

the same movements with respect to resting potential until the specific ranges for the mentioned eye movements are not determined. Following are the ranges for four-degree eye movements taken from the serial monitor. The scaling helped to create a dataset. It is common knowledge that eye ranges differ from person to person due to their gaze direction and their associated aging factor. However, these values mostly will be within the scale regardless of whoever uses the prototype.

Table 1. Ranges of Eye Movements

Movement	**Range**	
Up	4500-5300	
Down	> 6400	
Right	< 1940 Left	> 3800

3 Working

Arduino IDE is an open-source platform that is used to sketch the whole code for the discussed prototype. The goal is to develop a program for easy communication of devices through the ESP32 to the server and

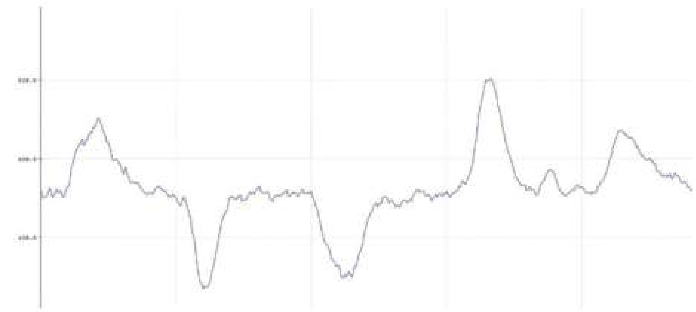

Figure 4. EOG signal recorded from EXG Pill Sensor on serial plotter

Figure 5. DFMini Mp3 Player [31]

vice versa. To receive and transmit the data from peripheral devices different libraries have been installed which were not built-in in the IDE. Four eye movements are being used i.e., Right, Left, Up, and Down. Four conditions are given with a set range for every movement to generate the output commands accordingly. Additionally, a push button is equipped and programmed for the mere purpose of ON/OFF the prototype. Once the sketching and wiring is done the algorithm is fed to the ESP32 by connecting it to the laptop and also to give power to the board via micro USB. It is a looped program based on if/else commands, see the Figure 6.

The first step after uploading the sketch is to read raw values of the acquired EOG from EXG Pill with the help of the electrodes placed around the eye and compare to the value of set ranges that are given in the code to get the matched value for the given movement. After the calibration is done, the given eye movement value goes through every if condition to match the desired value of the given movement. Once the acquired EOG range is detected and interpreted correctly, the specific command or text message given to that condition will be displayed on the 16x2 LCD in real-time along with the RGD LED indicator lighting the set color assigned to it. Additionally, an MP3 player is interfaced with the ESP32, allowing voice-based output to be played through a speaker or headphones for better understanding, all the process is shown in the Figure 7. The output is then sent to the remote monitoring app , see figure 8, and displayed on the screen of the application.

For instance, if the subject moves the eye to the left, the signal generated because of potential difference will be acquired by the EXG Pill with electrodes. It is then fed to the ESP32 to interpret the analog data and match it with the given ranges. Once it is matched the text message assigned to the movement such that “Call the Doctor” will be displayed on the LCD with the RGB indicating “Red” hue and the displayed command will then be voiced out at the same time along with the same command notifying on the remote monitoring app to complete the process. However, if it doesn’t find any match then the no display or indication will initiate until the next movement will be given or acquired.

4 Results and Discussions

To achieve the aims, EOG signals are collected using one sensor for left and right movements and one for up and down movement. In this study condition loops are used to give specific messages on specific range values of EOG signals, which were fed into an ESP32 microcontroller for post-processing.

We recruited 10 healthy participants to participate in our proof-of-concept study. Each participant is fitted with BioAmp EXG Pill sensors and electrodes to record their EOG signals, see Figure 4. The study procedure is explained to the participants and obtained their written informed consent.

```
include library

{
  int EOG= AnalogPin //store reading from EOG signal
  const int lcd pins= DigitalPins //output on LCD
  const int MP3 pins= AnalogPins //output on MP3

  //Initializing eye movements
  right= Range1
  left= Range2
  up= Range3
  down= Range4

  //if block for individual messages
  if (EOG in Range1){
    lcd.lrint("string message1")
    music.play(audio file1)
  }

  else if (EOG in Range2){
    lcd.lrint("string message2")
    music.play(audio file2)
  }

  else if (EOG in Range3){
    lcd.lrint("string message3")
    music.play(audio file3)
  }

  else if (EOG in Range4){
    lcd.lrint("string message4")
    music play(audio file4)
  }
  else{ //if eye movement out of given range
    break
  }
}
```

Figure 6. Algorithm to Program the Prototype

The findings indicate that EOG signals to control text and voice commands is a viable option for quadriplegic patients, with an overall accuracy of 90%. However, since the system is not tested on actual quadriplegic patients, it is unclear how well the system would perform in real-world situations.

During the experimental procedure, eye movement ranges are captured through the BioAmp EXG Pill sensors and electrodes, and the corresponding output is displayed on the LCD screen. The output, which is also simultaneously played at the speaker, confirmed the message being conveyed. This integration of eye movement pictures and output display is allowed for a comprehensive understanding of the

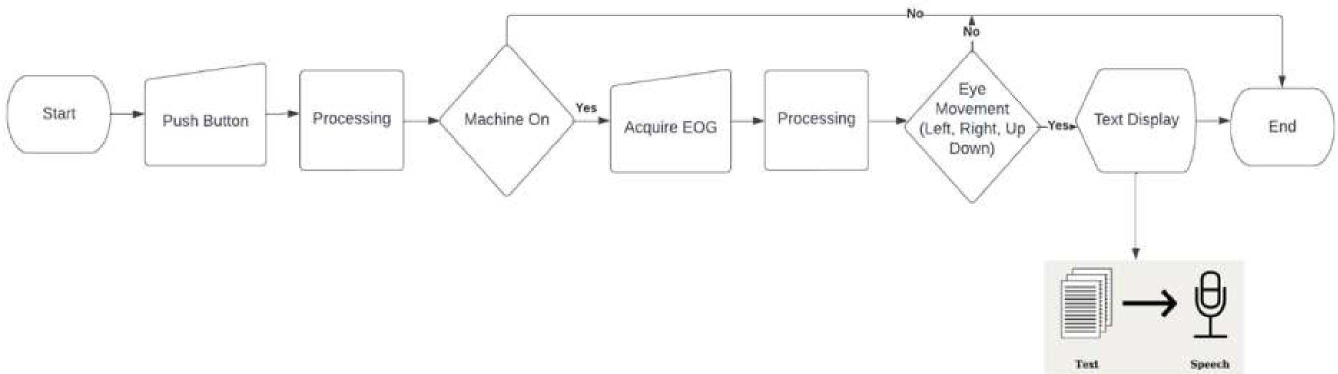

Figure 7. System Flowchart

patient's intended message and ensured that the system is responsive to the patient's needs.

Table 2. Overview of the text and voice commands generated by the ESP32 microcontroller

Movement	Command
Up	Looking up
Down	Looking down
Right	Looking right
Left	Looking left

To validate the accuracy of the system, each participant is asked to perform each of the four types of motions ten times. For each motion command, the range of EOG signal values generated by the participant and the corresponding text and voice command generated by the ESP32 microcontroller are recorded.

Table 3. Error rate

S.no	Eye Movement	No. of Errors
1	Up	11
2	Down	15
3	Right	8
4	Left	13

The range values of the EOG signals are analyzed to determine the accuracy of the text and voice commands generated by the ESP32 microcontroller. Specifically, the true positive (TP), false positive (FP), true negative (TN), and false negative (FN) rates are calculated for each motion command. A true positive is defined as the system correctly recognizing the intended motion command, a false positive as the system generating an incorrect motion command, a true negative as the system correctly recognizing the absence of a motion command, and a false negative as the system failing to recognize an intended motion command.

Based on the analysis, it is found that out of the 400 samples, there are 281 true positives (TP) representing the number of times the system correctly identified and interpreted the eye movements of the patients, resulting in accurate text and voice commands. 53 true negatives (TN) represent the number of times the system correctly identifies the absence of eye movements and does not interpret any commands. 20 false positives (FP) represents the number of times the system incorrectly identified eye movements when there were none, resulting in inaccurate text and voice commands. and 46 false negatives (FN) represent the number of times the system failed to identify eye movements when they were present, resulting in missed opportunities for patients to give text and voice commands.

Table 4. Confusion matrix to evaluate accuracy

	Actual Positive	Actual Negative
Predicted Positive	281 (TP)	20 (FP)
Predicted Negative	46 (FN)	53 (TN)

By analyzing the confusion matrix, various performance metrics can be calculated for the model, such as accuracy, precision, recall, and F1 score.

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN}, \quad (1)$$

$$Precision = \frac{TP}{TP + FP}, \quad (2)$$

$$Recall = \frac{TP}{TP + FN}, \quad (3)$$

$$F1Score = \frac{2 \times Precision \times Recall}{Precision + Recall}, \quad (4)$$

Accuracy is the proportion of correct predictions over the total number of predictions. At the same time, precision and recall are the proportion of true positives over the total number of positive predictions and true positives over the total number of actual positives, respectively. The F1 score is the harmonic mean of precision and recall, and it provides a single value to assess the model's performance. Based on these values, an accuracy rate of 81.04%, a precision rate of 93.33%, a recall rate of 85.95%, and an F1 score of 89.42% were achieved. However, it is worth noting that the system did produce a relatively high number of false positives, which could be an area for improvement in future iterations of the technology. Additionally, the relatively high 42 number of false negatives suggests that further refinement may be necessary to ensure accurate identification of eye movements in all patients.

5 Conclusion and Recommendations

Quadriplegia is a condition that affects the ability to move the limbs due to injury or disease affecting the spinal cord. This condition can result in a communication barrier, as patients are unable to communicate their needs or express themselves effectively. In this project, EOG signals are used to create a text and voice-based interpreter for quadriplegic patients. EOG stands for electrooculography, which is a technique used to measure the electrical potential between the cornea and retina of the eye. The EOG signals are generated by eye movements, and these signals can be used to control a computer-based system that generates text and voice-based outputs. This system provides a non-invasive and cost-effective method of communication for quadriplegic patients. The text and voice-based interpreter created in this project can be customized according to the specific needs of the patient. The system currently has four degrees of motion, which allows the patient to move their eyes up, down, left, and right. This range of motion is sufficient to generate a variety of text and voice-based outputs, providing the patient with a means of communication. However, there is potential for further development, such as the inclusion of additional degrees of motion, which would allow the patient to communicate more nuanced messages. The addition of an eye-blink sensor could allow the patient to turn the system on and off, providing a more seamless and convenient user experience. This would require additional sensors and modifications to the signal processing algorithms, but it could provide a valuable feature for patients who have limited mobility or who find it difficult to operate the system manually.

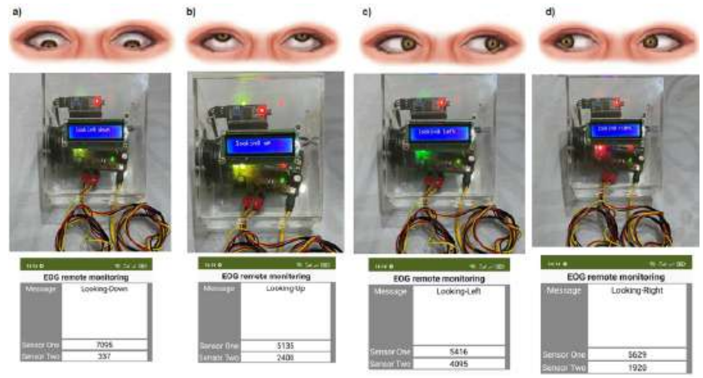

Figure 8. Eye movements and their corresponding outputs on the device and on the remote monitoring application

Author Contributions

Rania Ashraf: Conceptualization, Methodology, Software **Fahad Shamim**: Reviewing and Editing **Sarmad Shams**: Supervision.: **Murk Saleem**: Validation. **Roz Nisha**: Data curation, Writing- Original draft preparation

Compliance with Ethical Standards

It is declare that all authors don't have any conflict of interest. It is also declare that this article does not contain any studies with human participants or animals performed by any of the authors. Furthermore, informed consent was obtained from all individual participants included in the study.

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