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Portable decision support for diagnosis of Traumatic Brain Injury

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Abstract

Early detection and diagnosis of Traumatic Brain Injury (TBI) could reduce significantly the death rate and improve the quality of life of the people affected if emergency services are equipped with tools for TBI diagnosis at the place of the accident. This problem is addressed here by proposing a portable decision support system called EmerEEG, which is based on Quantitative Electroencephalography (qEEG). The contributions of the paper are the proposed system concept, architecture and decision support for TBI diagnosis. By the virtue of its easily operable mobile system, the proposed solution for emergency TBI diagnosis provides valuable decision support at a very early stage after an accident, thereby enabling a short response time in critical situations and better prospects for the people affected.

Keywords: Clinical Decision Support, Diagnosis; Electroencephalography (EEG); Portable Medical System; Traumatic Brain Injury (TBI).

1. Introduction

Traumatic brain injury (TBI) is brain dysfunction, which may have physical, cognitive, social, emotional, and behavioral effects[1]. It is caused by an external force, which traumatically damages the brain as a result of a fall, car accident, violence, contact sports, recreational activities or explosion blast. Symptoms are dependent on the severity of the brain injury, which can be mild, moderate, or severe. The symptoms associated with mild TBI include reduced concentration, decreased information processing capacity, behavioral or mood changes, as well as headache, vomiting, nausea, difficulty balancing, blurred vision and changes in sleep patterns[2,3,4]. Despite the recent advances in the diagnosis and treatment of TBI, which have led to decreased death rates and improved outcome, the number of people suffering from TBI continues to rise. For example, the total combined rate for TBI-related emergency department visits, hospitalizations, and deaths have increased from 521.0 in 2001 to 823.7 per 100,000 US citizens in 2010[5]. Similarly, in Europe, the TBI statistics based on twenty three European reports from 1980 to 2003 show average

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mortality rate of around 15 per 100,000 people[6]. The total economic burden caused by TBI in Europe is estimated at 33 billion Euros annually[7].

Early detection and diagnosis of primary brain injury can reduce significantly the death rate and improve the quality of life of the people affected by TBI. Primary brain injury occurs during the initial insult at the moment of trauma and is often followed by secondary brain injury, which could lead to irreversible outcomes. Therefore, there is a need for portable, accessible and reliable medical devices, which can be deployed quickly by emergency services at the place of injury. Quantitative Electroencephalography (qEEG) is a sensitive diagnostic method of brain injury after mild head injury, and has shown over 80% accuracy in discriminating between normal and traumatic brain-injured subjects[2,3,4]. However, its use is currently limited to clinical environments.

This paper addresses the above problem by proposing a portable decision support system based on EEG technology for early diagnosis of TBI at the point of need. A system capable of providing a medical diagnosis at the place of the accident has to be highly mobile and provide an automatic diagnosis along with remote medical advice from experts. Moreover, anyone from the emergency services with minimal training must be able to operate it using a simple and intuitive interface.

The remainder of the paper is organized as follows. Related diagnostic techniques, portable devices, and decision support systems are reviewed in section 2. Section 3 discusses an emergency scenario, outlines the technical requirements and describes the concept of the developed system called EmerEEG. Section 4 details the system architecture. Section 6 presents the decision support provided by the system. Section 7 describes the evaluation of the system in terms of the communication and decision support. Finally, section 8 summarizes the paper and highlights future work.

2. Literature review

Portable medical devices have become prevalent in the health care environment, thanks to advances in electronic systems integration and wireless communication. Bluetooth and Wi-Fi wireless technologies have been used in the development of health monitoring systems[8] and in particular in systems involving EEG data acquisition and processing[9]. Internet and especially mobile network architectures play an increasing role in the development of real-time monitoring systems that enable emergency telemedicine support[10,11,12]. Those systems are usually composed of two main parts connected over the network. On one side, a small unit enables the interaction with the patient and data acquisition. On the other side, a remote doctor's workstation enables real time monitoring. These systems also take advantage of small but powerful devices such as smartphones, laptops or micro-pc, i.e. small units including embedded processors with increased processing power, storage and wireless communication capabilities.

A clinical decision support system is defined as any computer program designed to help a healthcare professional make a clinical decision[13]. It includes tools for information management, tools for focusing the operator's attention on important elements, and tools for providing patient-specific recommendations. Decision-support systems are characterized along five dimensions: the system's intended function, the mode by which advice is offered, the consultation style, the underlying decision-making process, and the factors related to human-computer interaction. Decision support has to be carefully considered in the case of mobile medical system with integrated telemedicine capabilities, because the end-user might not be a medical expert and thus have the appropriate knowledge and training to provide a diagnosis.

The decision-making process can be supported by methods such as numerical analysis, Bayesian modelling, decision analysis, artificial neural networks, and artificial intelligence. Some of these methods have been used in the processing of EEG data for the detection of epileptic seizure[14], the discrimination of children with controlled epilepsy[15,16,17], the classification of EEG signals[18,19], or the incorporation of expert advice in automated systems[19].

3. System concept

3.1. Emergency scenario

The emergency scenario is used to define the main requirements and evaluate the proposed system. The scenario involves an emergency requiring intervention by a paramedic team who use the proposed system to obtain an early diagnosis of TBI. Fig. 1 illustrates the emergency scenario reenacted on a sports pitch. A young male adult is found unconscious after being hit on the head during a violent sport game. A paramedic team comes onto the pitch in order to secure the player and perform a first assessment of the injury. The patient is placed in a stabilized position. He is first visually inspected to seek evidence of injuries. The following preliminary conclusion is made based on the preliminary observations: the potential head and neck injuries indicate a severe injury. Stabilization, assessment, and care of the head and neck should be prioritized.

After this initial clinical assessment, the paramedics decide to assess the level of the suspected TBI using the proposed system. A paramedic deploys the portable EmerEEG system which is ready to use and can be activated via a secure interface. The system is composed of a head device equipped with electrodes for recording EEG data. The device is placed onto the patient's head and the automatic montage of the electrodes onto the patient's head is enabled by a positioning system, which is patented by one of the authors of the paper[20]. Once the montage is completed, the paramedic enters some information about the patient including the patient age and gender, as well as GCS result. The EEG recording can then be started.

The paramedic is not expected to be qualified at assessing TBI from EEG data, so algorithms automatically process the acquired data and provide an indicative diagnosis. The result of the analysis is then displayed on the screen to inform the operator about the injury. Finally, the paramedic contacts a specialist to obtain approval and advice. A medical expert, located at a remote telemedicine center, can access and view the data through a secure channel to the user interface, and provide expert clinical assessment and advice on the case.

Fig. 1. Emergency scenario reenacted by students.

3.2. User requirements and system specification

The scenario has identified strong needs for portability, communication capabilities, and embedded computational power. Use on the field will require that the operators be able to easily transport the system and deploy it as fast as possible. Delivery of an early diagnosis of TBI needs a portable instrumentation and communication system for EEG data recording and management. Sufficient mobile processing power is required for fast processing of EEG data, as well as long distance wireless communication methods for remote support from specialists. In addition, user interfaces are needed to operate the portable system and obtain decision support. Other requirements, such as data security, have also been taken into account but are not detailed in this article.

3.3. Elements and interactions in the system

The system is composed of several inter-connected elements[21] (Fig. 2). The portable sub-system, to be used in the field, consists of an acquisition device, a communication device, a processing device, which also displays the user interface. These are respectively the head device, the portable server, and the control unit shown in Fig. 2. The acquisition device is a portable helmet, which integrates the EEG electrodes with the necessary electronics, and enables fast automatic positioning. It has been developed as part of this project. However, it is not in the scope of this paper.

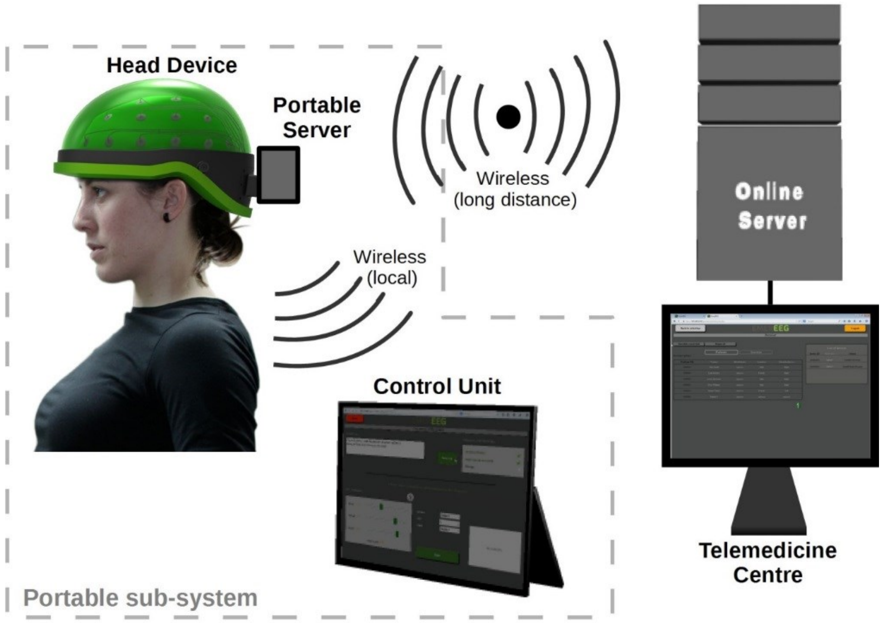


Fig. 2. System concept[21].

The communication device is a compact ARM-based computer (Odroid U3[22]) running a server version of the operating system Linux. This type of device is selected because it provides good performance characteristics along with low power consumption, all in a small and lightweight single board package. This portable server is integrated with the head device; both are battery powered.

The local wireless connection enables data transfer to the control unit using the portable server as central communication hub. It is a personal computer with a touchscreen, running the Windows operating system. This device is selected for its computational power, portability and convertible capability. It can hence be used as a computer or tablet. The selected product, a Getac V110[23], integrates an Intel Core i7-4600U processor[24]. On the one hand, the control unit provides access to a web-based graphical user interface. It enables the operator to control the system, input patient information, and display the automatic diagnosis, as well as obtain telemedicine support from specialists. Because it is web-based, the interface is made accessible from any device that has a web browser, through a secure connection with the web server located on the communication device. On the other hand, the choice of using a Windows operating system for this device is made to enable the development of the processing and diagnosis algorithms using Matlab and the EEGLAB toolbox[25]. Moreover, most of the existing software for EEG data analysis runs on Windows, which can be particularly useful if the system is deployed in a hospital environment.

The integration of long distance wireless communication resolves the requirement for mobility and enables real-time online data transfer as well as telemedicine support. The complete system is therefore composed of portable sub-systems that connect to an online server. The telemedicine center is equipped with a second specifically designed web-based user interface that gives specialists the tools to access and review recorded data, and provide diagnosis approval and advice for real-time emergency cases.

4. System architecture

4.1. Communications Protocols

The development of the architecture has been focused on defining a coherent way to exchange data in order to match the communication requirements of this multi-device and multi-platform system.

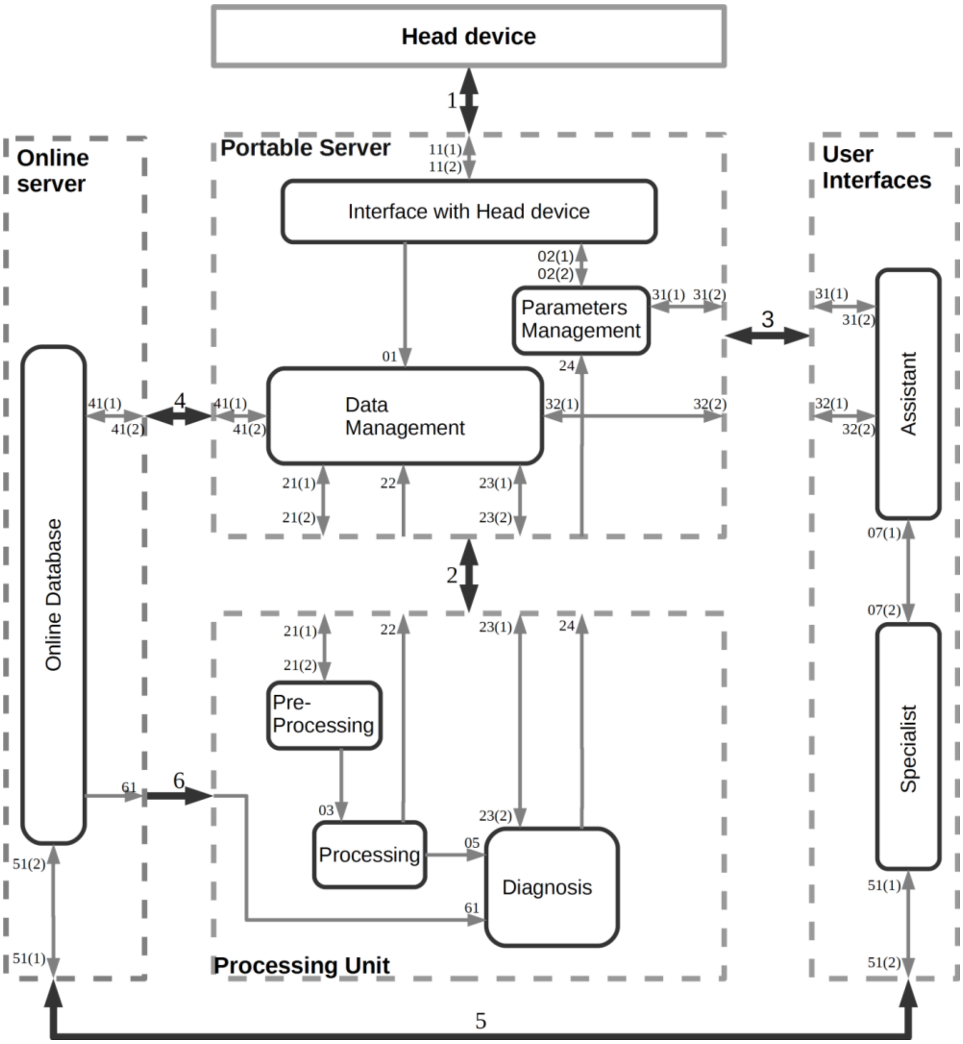


Fig. 3 Functional architecture of the system.

As shown in Fig. 3, five entities are considered in this structure: the head device, the portable server, the processing unit, the two user interfaces, and the online server. The portable server is the communication entity and the computer integrates the processing and the user interface entities. Functional elements are also considered and spread out across the entities, following their type. The portable server undertakes the communication functions, including the interface with the head device and the management of parameters and data. The processing unit processes EEG data and computes the diagnosis.

Six main links represent the connections between the five entities in Fig.3. Each has different functions and corresponds to different technologies, so the communication means and protocols also differ depending on the entities involved.

Link 1 is the wire connection between the portable server and the head device. Both of these entities are portable and the portable server is small and lightweight; therefore, connecting them and carrying them together is not physically difficult. The safety of the connection is an important point, especially because the head device is controlled from the software running on the portable server. Watchdog procedures have therefore been developed to prevent unwanted actions resulting from disconnections.

The maximum data transfer rate would not exceed 512 kB/s, considering that the system employs 32 EEG channels at 4 kHz each. This transfer speed is achievable with a standard universal serial bus (USB2.0). The communication protocol for this link, and especially for the transfer of EEG data, has been inspired by an existing protocol from one of the partner companies, and based on the IEEE single precision floating-point standard[26].

The flexibility of the portable sub-system is made possible by building local wireless communication for links 2, between the portable server, and the processing device, and 3, which connects the portable server with the user interfaces. The communication device acts as a standard Wi-Fi router for a local area network (LAN). Each device from the portable sub-system has a unique internet protocol (IP) address. The web-interfaces are hence accessed (Link 3) by entering the IP address of the portable server. Data are transferred for processing via link 2 by virtue of a network data share method and synchronization tools, which enables compression and encryption of the data during the transfer.

Links 4 and 6 are possible as a result of recent breakthroughs in long distance communication technologies and great improvement in transfer rates. Data can be sent to and received from the internet via a dedicated online server with a static IP address. Data is stored in a database located on this online server and is accessible through a user interface provided for the specialist via link 5, which is a standard broadband connection. The local and online databases are symmetrical, which simplifies the synchronization.

In remote locations, the control unit can be used as a processing unit for in-field diagnosis processing. This makes possible to obtain results, even in areas with poor wireless network connection. In a clinical situation, the online server is used as a processing unit in order to reduce the required computational power of the control unit and hence reduce its size and price; in this case a simple tablet or smartphone could be used instead.

4.2. Data Management

Nine functional elements have been defined, in accordance with the system requirements, for control, communication, data management, processing, and telemedicine. The links in Fig. 3 show how information is shared within the system. The first digit of the sub-links (in grey) refers to the corresponding main link (in black). The first digit 0 indicates an internal link and the last digit in brackets indicates the direction, considering a two-way communication.

The portable server has three main functions: management of data, management of the control parameters, and interfacing with the head device. All controls 11(1) and measurements 11(2) to and from the head device, go through the interface with the head device. Controls are received through the interface of the assistant 31(1). Parameters are adjusted by the parameters management unit and transmitted via the interface with the head device 02(1). Status parameters and feedback from the head device are collected 02(2) and displayed onto the interface of the assistant 31(2). Data, including EEG data acquired by the head device, are transferred to the data management unit through 01. They are formatted following existing standards, such as EDF for EEG data, and stored in the memory of the portable server. In addition, any patient information input by the assistant is stored in the database 32(1).

Data is sent to the processing unit via link 2 in order to obtain an automatic diagnosis. Processed data and results are then sent back to the portable server. Data is synchronized between the online server and the portable server. New data acquired by the portable subsystem is sent over to the online database 41(1). Specialist input, as well as additional information about the patient, are synchronized back 41(2), and displayed on the interface for the assistant 32(2). The interface for the specialist provides the medical experts with access via 51(1) to the data stored in the online database for review and decision making. Their approval on the diagnosis is then returned 51(2). Communication between the specialist and the assistant is possible via 07(1) and 07(2), although all data in the current implementation go through the online database.

5. Decision support

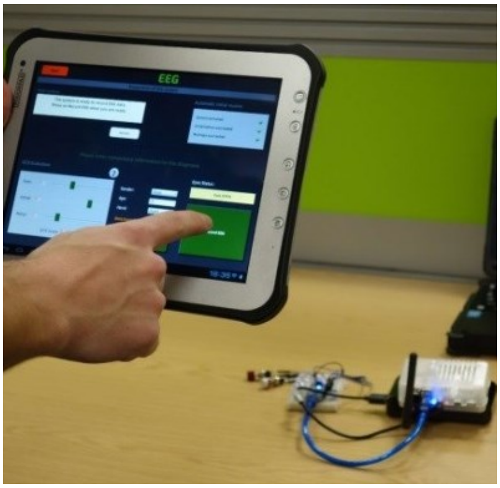
5.1. Database and model

The user interacts with the EmerEEG system by accessing, inputting, and controlling data from a database through the user interface. This data is originally hosted and managed by the portable server and also synchronized with the online server. The local and online databases are symmetrical and store metadata generated by the system. This metadata provides precise identification and description of the data collected during a particular session. Each session corresponds to a single accident. The database is structured around four main tables, each with their own unique identification number (ID): patients, devices, operators, and events. A unique ID for the session is generated with the creation of a new entry in the event table. This session ID is then used to link all data related to the session through metadata about the files. This provides a structured way of organizing and sorting out information. It also enables fast access to the database by avoiding space-consuming data to be stored directly in the database.

One important function of the proposed decision support is to provide a diagnosis of the patient's condition. The pre-diagnosis and diagnosis tables of the database contain information from the clinical assessment made by the assistant, the results of the automatic diagnosis, as well as the final diagnosis approved by the specialist. Related files including raw EEG recordings, artifacts free recordings – artifacts include eye movements, heart beats, muscle activity, etc. – and other files including processed EEG data are also stored. This enables possible further retrieval and analysis by the specialist.

5.2. Graphical User Interface

The system (Fig. 4) is in standby until the operator activates it. The preparation phases are important for the quality of the recording. The assistant activates the system and prepares the head device for installation on the patient's head. The interface guides the operator through the initialization and montage steps, and provides real-time recording and visualization.



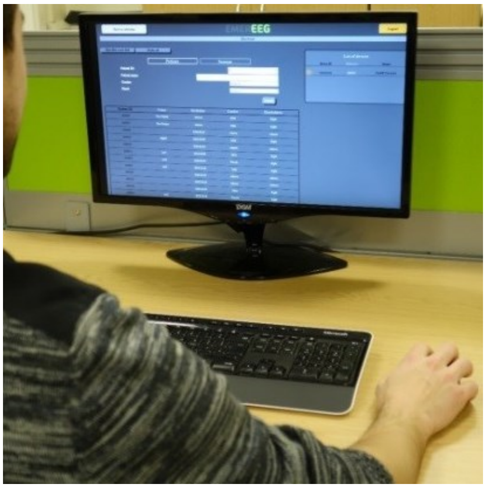


Fig. 4. Left: An assistant controlling the portable sub-system. The head device here is simulated with a micro-controller. Right: A specialist in the telemedicine center using the specialized interface.

The acquisition of the EEG starts when the montage is completed (i.e., when all EEG electrodes are correctly positioned and in contact with the head) and all compulsory information is collected. This includes the GCS result, patient age, gender, and handedness. The user can add additional optional information about the patient, such as his/her name, if known, clinical data (e.g. blood pressure, glucose level, or alcohol level), as well as information about the accident (e.g. location, and description of the circumstances). The result of the automatic diagnosis is then displayed in a very comprehensive manner: TBI or No TBI.

The specialist in the telemedicine center has access to specialized visualization and analysis tools, as shown in Fig. 9. All activations of the portable sub-system(s) are notified in real time. The specialist can review the data and provide expertise including diagnosis approval as well as advice to the assistant in the field. Simple online visualization tools for EEG and qEEG data have been developed, but data is also available in standard formats (e.g. EDF+ for EEG data) and can therefore be analyzed using existing software. A decision on the patient's condition is made on the basis of all recorded data, the expertise of the specialist and the results of the automatic diagnosis. The decision is delivered to the operator in the field through the user interface, along with advice on how to proceed with the patient.

6. Evaluation

This section evaluates the developed system in terms of its main requirements including mobility, reliability, simplicity, efficiency, and provision of remote support. The section highlights first the evaluation of the EEG processing and TBI diagnosis. This is followed by the evaluation of the system communication, control, and decision support.

The purpose of evaluating the control and communication part of the system is to test the developed structure and software, but also obtain precise feedback and test data from professionals using the system. The system was tested under conditions close to real-life application. As only the control and communication part was tested in this experiment, the head device and the processing unit functions were simulated to eliminate external factors. Ten participants from all partners within the project consortium contributed to this experiment. The partners located in three European countries, Germany, Norway and UK, had access to the prototype through a remote computer connection. Thus, the developed interfaces were remotely accessible, and the only limitation was that the participants did not have access to the tablet and did not interact with the assistant interface through a touch screen.

Table I. Evaluation tasks performed. (The tasks with * are optional or not explicitly requested)

	Assistant point of view		Specialist point of view
1	Activating the system	14	Going to session tab
2	Initializing the system	15	* Searching by date and patient age
3	Performing the montage	16	* Looking for patient/session directly
4	* Verifying electrodes impedance and position	17	Accessing the correct session
5	Inputting compulsory information	18	* Displaying EEG data
6	* Changing eyes status to closed	19	* Displaying channel Fc1
7	Starting EEG acquisition	20	Visualizing the result of the diagnosis
8	* Changing eyes status to open while recording	21	Inputting the specialist diagnosis
9	* Visualizing analysis steps completion		
10	Inputting additional information		
11	Accessing the diagnosis		
12	Contacting a specialist		
13	Going to Standby mode		

The participants had previous knowledge of the project aims and system's concept but they had never used the system before the experiment. The participants were first asked to operate the system as an assistant and then take the role of a specialist. Precise instructions and guidance were provided to allow successful completion of the tasks as described in the emergency scenario. All sessions were recorded and the sequences of actions performed by the participants were analyzed. The tasks are shown in Table I. The time taken to complete a task was recorded, as well as whether the task was successfully completed or not. The average completion time from all evaluation tasks is shown in Fig. 5 and Fig. 6.

The system performed well during all tests. The developed structure for control and communication worked as expected and was found reliable. The users could control the system without delays and access the data in real time.

The physical interaction with the interface was seamless.

Fig. 5 shows the relatively low reaction time regarding the actions to be done, considering that the participants were seeing the two interfaces for the first time. All tasks requiring a control action were performed as requested, and in a relatively quick manner, with results normally below 20 seconds to find the right control, understand it, and make the action. All tasks explicitly asked were fully performed and a high percentage of the optional/implicit tasks were performed as well.

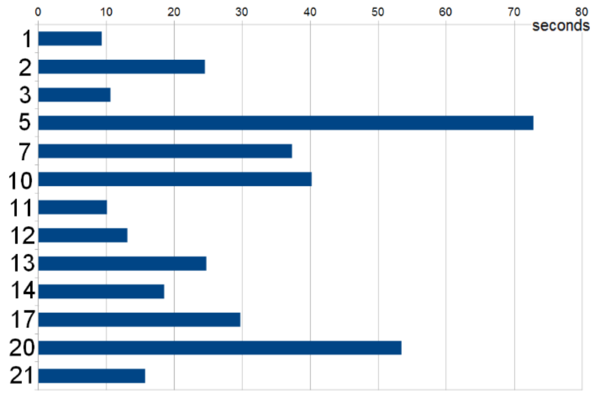


Fig. 5. Task completion of the main tasks (average time, s).

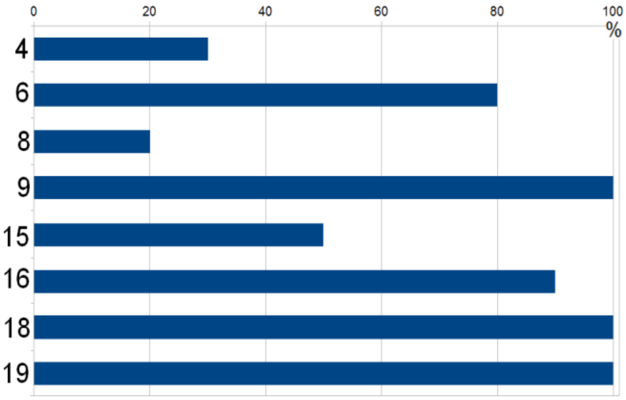


Fig. 6. Task completion of participants who the optional tasks (% of have completed them).

The task instructing the participants to start the acquisition took longer because they consciously made sure all preparations were correct before pressing the button. In particular, participants verified the correct input of compulsory information, which was the longest step, and 80% of them checked the eye status. However, only 30% of them verified the data from the montage, because this item was hidden when the montage is successful.

The experiment highlighted the weaknesses and strengths of the developed process and user interfaces. Some features in the interface required improvement to provide more intuitive use. Small hesitations on some controls revealed the need for more clarity or explanation of these elements, but the overall process was very well understood and followed by all participants. The simple and condensed display of the diagnosis result was appreciated, and the participants spent, on average, under 15s to understand the diagnosis and contact the specialist.

7. Conclusion

This paper proposes a portable system for early diagnosis of TBI in emergency situations. The system has been specifically developed in response to real and specific needs: fast and reliable assessment of possible brain injury at the scene of an accident. The system operator is provided with an assessment of the possible patient's traumatic brain injury, and decision support including visualization and a communication channel with a specialist.

The systematic evaluation demonstrates that the coherent control and communication architecture, along with two multi-platform graphical user interfaces, enable the easy operation of the mobile system and provision of remote support. The evaluation of the proposed system has shown it to be fast and reliable, with a good generalization performance of the model. The result of the automatic diagnosis, coupled to a decision support system, provides the assistant with an effective basis for the early application of an adapted treatment in an emergency situation.

Currently, the data stream from the head device is simulated with previously recorded data. The actual testing with humans is beyond the scope of this project. Future work includes integration of the head device with the portable system and clinical evaluations once medical approval is obtained.

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