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Dedicated to the memory of Academician Andrei Ţugulea

DEEP UNDERSTANDING OF AUGMENTED FEEDBACK AND ASSOCIATED CORTICAL ACTIVATIONS, FOR EFFICIENT VIRTUAL REALITY BASED NEUROMOTOR REHABILITATION

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This paper presents the state in which the TRAVEE (Virtual Therapist with augmented feedback for neuromotor rehabilitation) project has ended, what it has achieved, why it should be pursued, as well as outline a few of the main directions in which the research started by TRAVEE must be continued. For this purpose, the paper begins by presenting information on the necessity of using technology in medicine, with a focus on medical rehabilitation. A state of the art regarding the use of technology in medical rehabilitation is then provided, especially concerning use of EEG data in assessing the rehabilitation session results. We then present – briefly – the architecture of the TRAVEE system, with its virtual reality module, that uses multimodal input data to provide augmented feedback through various output channels (visual, haptic, robotic, functional electrical stimulation – FES). In the following sections, the paper discusses the observations that were made during the in-vivo testing sessions of the described system, as well as during the clinical trial to which it was subjected. Based on these observations, the directions in which the research must continue are outlined: the study of the effects of various rehabilitation session augmentation level in terms of cortical activation through electroencephalography (EEG), the study of the effects of augmentation on spasticity, the influence of the virtual environment (VE) on EEG data, as well as a comparison between visual and mechanical augmentation. The paper also proposes methods for each study path. It is very important that the results of TRAVEE are further studied and understood as it only scratched the surface of a very sensitive domain and it set the foundation for a high-quality research with potential great outcomes.

1. INTRODUCTION

The TRAVEE project was implemented as a PNCD-II (National Project for Research and Development - PNCD) project between 2014–2017 and it set the foundation for a high-quality research process, by bringing together doctors and engineers with the purpose of developing a state of the art rehabilitation system with novel, complex, promising ideas.

The TRAVEE system created a VE in which the patient was immersed for the rehabilitation session. While immersed in the VE (through the aid of a head mounted display) he was presented with a Virtual therapist, an avatar exemplifying the movement he had to perform, and he tried to execute the same movement in real life. The system acquires multimodal data: optical tracking, brain computer interface (BCI), electromyography (EMG), to analyze it before providing the patient with an augmented feedback. The augmented feedback was either visual, haptic, motor (robotic glove) or through functional electrical stimulation.

The purpose of the augmented feedback was to potentially stimulate the cortical reorganization process, by closing the feedback loop: the patient sends the command and perceives the effect – magnified if otherwise difficult to observe. The idea behind the visual augmentation used in TRAVEE is pending for patent with the title “System, method and computer program for augmenting human movements based on automated decisions”.

The TRAVEE system was tested in-vivo in 2016 [1, 2] and during a clinical trial in 2017. The tests and clinical trial were conducted with the collaboration of the medical partners at the National Institute of Rehabilitation, Physical Medicine and Balneoclimatology (INRMFB) in Bucharest. The results of the in-vivo tests were presented in past work [1, 2] and they revealed that the tested TRAVEE prototype can be used in a medical settlement without significant discomfort for the patients, and that is was easily accepted by them as a rehabilitation tool. The tests also revealed some immersion flaws in the prototype, that were resolved in order to obtain the final prototype of the system, that was successfully tested during a qualitative clinical trial in April-May 2017.

During the clinical trial several changes were observed in the abilities of the patients, that still need to be further explained.

In this paper we present the achievements of the TRAVEE project, the point at which it ended, what it has achieved, why its research should be pursued - as it has set a foundation for high quality research that still has to be made – and presents several directions that must be considered in the continued research.

2. PROBLEM STATEMENT

As the cortical motor homunculus shows in a visual manner, a great part of the cortex is dedicated to controlling movements of the hand. This means that any conditions that affect the integrity of the cortex have a great chance of influencing negatively the cortex dedicated to the motor activity in the upper limb, thus leading to disability in the arm or hand.

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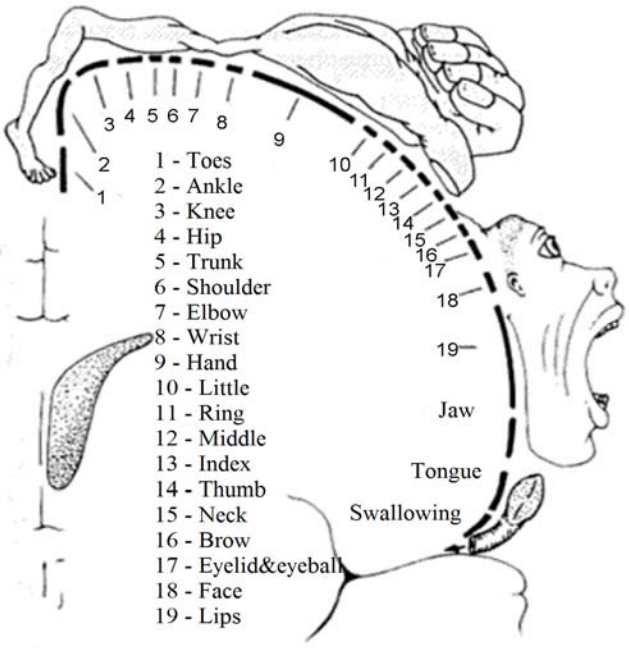

Fig. 1–The motor cortex homunculus 0.

Technology can have a significant impact in medical sciences, from providing the doctors with tools to organize their work, helping in taking decisions, analyzing visual imagery, to assisting them in supervising the medical processes, supporting rehabilitation

One such field is that of rehabilitation after brain damage, as proved by numerous research analyzing the field [4, 5]. Studies 0 show the importance of rehabilitation and the importance that the process is adapted to the current stage of the patient: early stages 0 and later stages of rehabilitation are treated differently and both need to be implemented correctly for a better chance at recovery 0. The rehabilitation process takes many forms, depending on the disability suffered by the patient.

An automated solution that would help the patient perform the rehabilitation session correctly, with increased concentration levels, motivation for performing the movements accurately, and with an exact progress assessment would greatly benefit the rehabilitation process and it could provide essential information to the therapist by analyzing the patient's session while allowing them to also supervise or visualize information about the session remotely or later.

Low cost solutions that enhance a rehabilitation session could stimulate the patient to execute the session, thus improving the condition and quality of life of the patients, and having an impact in society by helping them re-integrate more successfully.

For these ideas to become reality it is essential that assistive systems are developed and enhanced in order to overcome their potential downfalls 0, all while implementing original, high-potential ideas, such as the ones in the TRAVEE project. Apart from being implemented, they must also be well understood, and their effect quantified and evaluated in search for an important medical relevance.

3. STATE OF THE ART OVERVIEW

There have been other attempts at studying the effects of augmentation of movement for rehabilitation purposes, as observed in a survey of such studies presented in 0. In 0 an experiment was conducted to study the possible treatment of chronic pain based on the idea that the brain responds to what it perceives and that it can be different than reality – thus they successfully helped reduce phantom limb pain in tested patients with more than 60 % by improving their tactile acuity – teaching the brain to sense fine differences between stimuli on the arm lead to improvements in perceived pain in the missing limb.

There are systems developed to help rehabilitation of speech impairments 0, and systems that acquire various data, that could be used in rehabilitation support technologies 0.

In 0 and 0 also the perception was changed by placing a mirror between the arms of the patient so that he can perceive the missing limb as being present, also leading to better control of phantom limb pain.

An experiment in 2012 0 determined that patients that used augmented reality in rehabilitation that amplified a small movement into thinking it was better than it really was lead to improvements on the Fugl-Meyer disability evaluation scale.

Also, in 0 the authors concluded that displaying a movement to be much wider in amplitude than it really was helped the patients re-learn the action through corrections in the perceived visual feedback.

In 0, the authors evaluated the detected EEG signals for subjects immersed in either 2D or 3D Virtual Environments, concluding that 3D ones require more cortical resources during tasks performed in the virtual world, thus possibly having a greater potential for rehabilitation purposes.

A system used visual representations of EEG signals to study the possibility of stimulating the user creativity 0. There is active research in studying the usage of EEG data in assess the working memory load by using various classifiers and two different EEG devices, a professional and a low cost one 0, as well as attempts at determining the emotional state of a user based on EEG signals 0 or even controlling a hand orthosis 0.

In their Mindwalker Project, ANT neuro 0 used EEG signals to control an exoskeleton for lower limb rehabilitation. Their eego sports system 0 uses EEG and EMG input as well as tracking information to study the posture and gait of the user.

Bartur *et. al.* 0 created a marker for attention evaluation, based on EEG, named brain engagement index (BEI) and found – throught the performed experiments – an association between the difficulty of the rehabilitation exercise and the values of this marker, as well as preliminary evidence that the higher the values of the BEI, the better the temporary induced functional change resulted from the session.

In 0 the authors succeeded in detecting intention of movement from EEG signals, to allow patient to control either a VR avatar or a robotic rehabilitation device. In 0 EEG patterns were detected that could determine with an accuracy of over 75 % whether a movement was a fast or slow. Such patterns are expected to be revealed by the continuation of the research started by TRAVEE system, as we will be able to compare and observe differences between the proposed scenarios to be studied - in order to better understand if there are any specific EEG signals and – if so – where do they come from.

The presented works suggest that it is possible to detect various patterns in EEG data and to associate them with emotions or intentions, which we desire to obtain in our study. The proposed research tries to analyze and understand the changes in activation of the cortex as detected by EEG devices during various rehabilitation session scenarios.

4. TRAVEE

As presented in 0, the TRAVEE system implemented the described functionalities by implementing the architecture presented in Fig. 2.

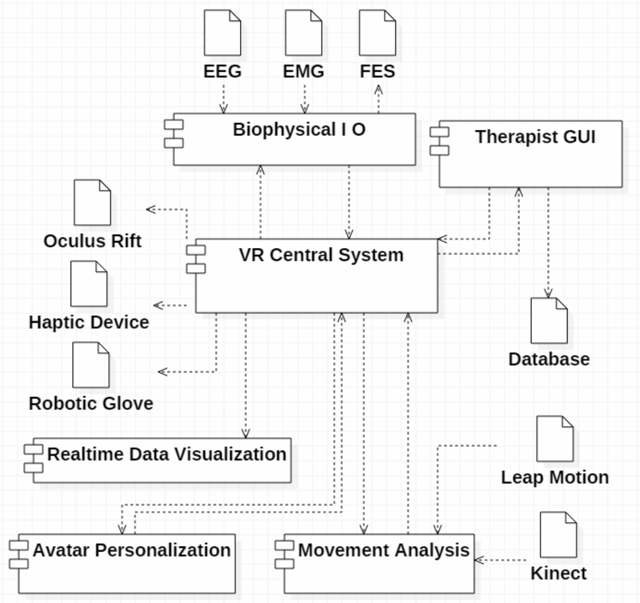

Fig. 2 –TRAVEE system architecture 0.

The architecture was described in detail in 0. The main components in the diagram are:

– The biophysical I/O component that oversees acquiring data from EEG and EMG devices and controls the FES device.

– The therapist GUI allows the doctors to configure the sessions and patients available in the system. More details regarding the TRAVEE GUI were published in 0.

– The VR central system is the core module of the TRAVEE system, implements the server of the system that coordinates the main logic of the application.

– The realtime data visualization module displays EEG and EMG data variations synthetically, as graphs.

The Avatar Personalization module allows the therapist to alter several characteristics of the patient avatar in order to help the patient be immersed in the VE.

– The movement analysis component is responsible for evaluating the degree of execution of each exercise at each moment of time. For each movement we chose one or several angles of interest. At each frame obtained by the tracking devices, consisting of the pose of the patient at that given time, the angles of interest for the currently executed movement are analyzed. Based on this analysis, the system calculates a score representing the degree of execution.

4.1. VR CENTRAL SYSTEM

The core VR module of the TRAVEE system was implemented at the University Politehnica of Bucharest. It is a highly configurable subsystem, that in its various configurations uses hybrid data: optical movement tracking information, BCI, EMG taken in real time from the patient, to assess his or her progress and to provide the augmented feedback when necessary.

Various configurations were implemented. With optical tracking devices (Leap Motion and Kinect)0, we detected the patient’s movements, analyzed them, and then provided an augmented feedback. The technologies were chosen after a thorough study of the state of the art 0 to be affordable, and were evaluated, out of the available low-cost options, to be able to track the TRAVEE movements as well as possible 0.

The augmented feedback was provided to the patient using either visual augmentation, haptics, functional electrical stimulation or robotic assistance.

For configuring the rehabilitation sessions (exercises, durations, devices used, etc.), patient database, visual charts etc., the Virtual Reality module communicates with a Graphical User Interface module dedicated to the doctors, developed by OSF Global Services S.R.L. company in Bucharest, through TCP (Transmission Control Protocol) sockets.

For acquisition of BCI and EMG data, as well as for FES control, the Virtual Reality module communicates also through TCP sockets to another module, the Data Acquisition and Control module, developed by the team at the “Gheorghe Asachi” Technical University in Iasi.

4.2. AUGMENTED FEEDBACK

The augmentation of the feedback provided by TRAVEE was either visual (improving the patient’s movement – based on the analyzed pose, it altered the body pose data obtained by the optical trackers into a more complete pose of the current movement before applying it to the virtual avatar of the patient), haptic (by controlling vibration motors placed on the hand or arm, to inform that progress was detected), or robotic (by assisting the patient in performing the movement if the system detected lack of activity in the hand or that the patient was stuck while performing the movement – based on a configurable algorithm of motion analysis). The robotic glove device used is part of the IHRG (Intelligent Haptic Robotic Glove) project of prof. Nirvana Popescu 0.

The configurability of the system makes it useful in various stages of the rehabilitation process. As the rehabilitation after a disabling event is made in a proximal to distal manner, beginning with re-learning movements of the joints.

4.3. VISUALLY AUGMENTED FEEDBACK

The visual augmentation is an original idea implemented by TRAVEE that is pending for patent with the title “System, method and computer program for augmenting human movements based on automated decisions”, as by our research in existing local and international patent databases, we have not identified a similar implementation of a movement augmentation that is determined and calculated automatically by a technological system.

The augmentation in TRAVEE is implemented based on the evaluated score for the current movement, as described above. Each movement has two associated parameters: the maximum degree of augmentation, the maximum score (threshold) up to which the movement will be augmented.

The visual augmentation of a movement is made by analyzing the score for the current pose detected by the tracking devices. If the score is smaller than the defined threshold for that movement, the current pose will be enhanced before being applied to the patient avatar, in order for the patient to observe a better quality pose than the real one, as long as the movement has a score lower than the threshold (which is equivalent with being executed with a small amplitude).

An example of augmentation is presented in the image below, for the arm Anteduction-Retroduction movement.

Fig. 3 – Example of augmentation for the arm anteduction-retroduction movement. on the left the un-augmented pose, on the right the improved anteduction.

The continuity of the movement is ensured by using a variation function for the augmentation factor that provides continuous values around the threshold. This fact is important for the naturality of the movements observed by the patient: the movement observed in the VE must be continuous, and sudden movements given by abrupt variations around the threshold – when switching from augmented to un-augmented and vice-versa - would greatly affect the immersion and the identification of the patient with the virtual patient avatar.

5. THE EVALUATION OF THE TESTS RESULTS

The TRAVEE project also included several testing sessions. In 2016 took place two in-vivo testing sessions that validated the prototype as it was implemented at that time [1, 2]. Based on these testing sessions, we continued to improve the system and prepared for the clinical trials in April-May 2017.

During the clinical trials, the virtual reality module was tested on 21 patients, with various degrees of disability. The results of the clinical trials were promising, some patients reducing the number of seconds per repetition of several exercises, or improving the execution of some movements, but as the clinical trial only lasted 4 weeks it was hard to find a consistent and definite result.

Also presented in [1, 2], the conclusions of the in-vivo tests were obtained through questionnaire forms that the patients were asked to fill in. Based on these forms, the patients reported low levels of discomfort, tiredness or anxiety, which we found to show a good acceptance of the system regarding the convenience of using its devices. Although the immersion was rated with a good evaluation, it appeared that some of the patients noticed that their movements were enhanced. These observations lead to the improvement of the system by the end of the project, and must be still taken into consideration when further developing the system.

5.1. TESTING OBSERVATIONS

The TRAVEE project has ended soon after the clinical trials, therefore there are still observations made during the tests that are left unanswered as well as ideas and functions that could enhance the performances of such a system. These observations are listed below and detailed in the following chapters.

5.1.1. AUGMENTED *VS.* CLASSICAL REHABILITATION SESSION

One of the most important such problems is that the processes that take place in the brain of the patient during an augmented session (with any of the specified methods or with combinations thereof) are not fully understood.

Optimizing and understanding the effect of augmentation on the rehabilitation process is therefore a main aim of the proposed research.

The cerebral mechanisms that lead to some of the observed improvements during the tests with TRAVEE need to be observed and analyzed. These processes could be studied using an electroencephalography (EEG) device that could observe the areas of the brain that are activated by each type of session, the sequence and periods in which they are activated and any such patterns that could lead to a better understanding.

5.1.2. AUGMENTATION LEVELS

The continuation of the research must also consider using various augmentation levels, to study the influence of a higher or lower degree of augmentation to the activations of the brain areas.

5.1.3. UTILITY FOR SPASTICITY

Another problem to be studied, that was not covered by TRAVEE is the utility of augmenting the extension movement for patients with spasticity.

Spasticity is a condition where, because of the interrupted communication between the muscles and brain that follows a stroke or another condition that affects the brain, certain muscles in the arms or legs are contracted uncontrollably. As a result of long term contractions of the muscles the life of the sufferer is strongly affected, causing disability in areas of daily living as well as painful spasms 0.

It could be a possibility of improving this condition by using the augmented feedback in a manner that presents the patient with a posture where the affected muscle is less contracted. The effect of the altered feedback may support cortical reorganization in the direction of relaxing the muscle because of the perceived posture.

It is important to determine whether the perception of a better posture for them would help in their rehabilitation efforts or could help reduce spasticity. If this would be a possibility, the effect would be extremely useful, as currently the most common treatments are exercises, movement, medication or surgery.

5.1.4. VIRTUAL ENVIRONMENT INFLUENCE

Also, the continuation of the research must study the influence the virtual environment in which the patient is immersed has on the session evolution and performance. Only one rehabilitation environment was tested, that presented a simple empty scene with the avatar of the patient and that of the therapist.

It is possible that the virtual environment in which the session takes place can influence the progress or at least the attentiveness or the overall mental attitude of the patient. We believe that, apart from studying the cortical activation we could also benefit from recording heart rates, as to observe if the patterns are affected by the change in environment.

5.1.5. VISUAL VS. MECHANICAL AUGMENTATION EFFECT

A comparation between visual augmentation and augmentation using the robotic glove that helps the patient perform the movement, for it to be displayed as detected by the optical trackers in the Virtual Environment is also necessary to determine whether the actual mechanical act has an influence on the cortical level.

5.2. PROPOSED APPROACH

The EEG data will be obtained using at first an affordable solution, the emotiv epoc 0, that provides 14 channels of EEG data. This device is available at the Politehnica University of Bucharest. If possible, more complex EEG acquisition solutions will be used, if they become available to obtain data that is as accurate as possible, and that could possibly reveal valuable information.

All the data in the TRAVEE system is recorded in a recording file, and it was analyzed by another program made specifically to evaluate automatically for each session the number of repetitions of the movement and the average score. This was used for centralizing the results of the clinical tests in TRAVEE.

This recording tool will be updated to include more detailed multimodal information. The recorded information will be analyzed – automatically – to detect and observe patterns that can be associated to either of the tested session conditions, and to detect any changes that take place during the rehabilitation sessions.

5.2.1. AUGMENTED VS. CLASSICAL REHABILITATION SESSION

For the comparison between augmented and classical rehabilitation, the same subjects will perform the same sessions with augmentation and with the augmentation disabled. A greater number of sessions will be needed to ensure that the data is relevant, preferably with the same subjects for a longer period.

The recorded information will be analyzed to search for patterns in cortical areas activity during each type of session.

5.2.2. AUGMENTATION LEVELS

These will be configurable in the solution. The same session will be tested with various degrees of augmentation to search for each patient to acquire relevant data.

We will create a solution that will allow configuration of multiple augmentation levels and patients will be asked to perform rehabilitation sessions with each of the defined levels. Their EEG activity will be recorded during each of these sessions and we will analyze them to observe differences in cortical activation patterns between sessions with various augmentation levels and the patient evolution in terms of rehabilitation progress.

5.2.3. UTILITY FOR SPASTICITY

This will also be tested similarly, but by using a configuration that will specify whether the augmentation of the movement is made on the flexion or on the extension of the hand/fingers. The degree of augmentation against spasticity will also be defined to be configurable – multiple pre-defined levels – in order to also study the importance of the degree of augmentation and the optimal values for various situations. In this manner, we will be able to test whether there are differences when a patient executes the exercises in the VE with augmentation against spasticity or without augmentation. The differences will be analyzed as possible differences in the cortical activations as well as a verification of the evolution of the given scores, in time, as we hope that the spasticity will improve over time

The augmentation of the extension movement will be implemented similar to the one for the flexion, by presenting the patient with a movement that is more extended than the one detected by the tracking devices.

For patients affected by spasticity, we will also test the system with extension augmentation, as described. We will analyze if – over time – the spasticity changes in intensity and the degree to which it is affected.

5.2.4. VIRTUAL ENVIRONMENT INFLUENCE

This idea will be implemented by creating several rehabilitation environments to be tested and evaluated. It is possible that a virtual environment can create changes in the results of a session and this is a theory we wish to evaluate.

For the implementation of the configurations for these tests, we will design several VE, each representing a different scenario. At least, a medical facility environment and an at-home style environment will be tested – but we wish to include as many scenarios as possible.

The scenarios should also be studied from a heart-rate point of view, meaning we should follow the differences in possible signals of distress or relaxations in patients in various VEs, as well as observe the evolutions in these variations during successive rehabilitation sessions.

The differences will be studied as variations in cortical activation patterns, as well as variations in the evolutions of the patients when using each VE.

5.2.5. VISUAL *VS*. MECHANICAL AUGMENTATION EFFECT

A comparison between the visual augmentation and the robotic augmentation will be tested by comparing results obtained during many rehabilitation sessions with each augmentation type.

For the mechanical augmentation we will use at first the same robotic glove that was used within TRAVEE. This solution may also be enhanced during the research if novel ideas are identified. During the TRAVEE testing sessions the robotic glove was tested very briefly. These tests will be extensive, to observe the influence the robotic augmentation has on the evolution of the patient, in terms of motion and control rehabilitation as well as influences on the spasticity in the hand.

For the comparison between visual and robotic augmentation, we will analyze the EEG data obtained during sessions with the glove and with the visual augmentation to detect variations and possible patterns that could lead to theories regarding the differences between the two.

6. CONCLUSIONS

The research that is planned according to this paper wishes to be a continuation of the efforts made during the development and testing of the TRAVEE system. With the continued research we wish to define very clearly what are the effects TRAVEE can obtain in a longer, quantitative study, what are the mechanisms behind these effects, what would be its greatest potential in rehabilitation and how it could be achieved.

For these purposes we established the directions the research must continue in, as well as defined several possible analysis methods for the quantification of the effects of the system, some based on the analysis of EEG data, some on automated analysis of the tracking data obtained, some based on additional input in the system, such as heart rate.

The understanding of the aspects studied by this research will strongly advance the state of the art in Virtual Reality neuromotor rehabilitation and will lead to treatments with maximum efficiency and priceless social impact.

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