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The TRAVEE System for a Multimodal Neuromotor Rehabilitation

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ABSTRACT As more and more people are left disabled by stroke each year, it is of vital importance to progress in the research of new ways to improve their condition and to ensure that they maintain their independence as much as possible in everyday life. A step in this direction of research was taken with TRAVEE, a system dedicated to neuromotor rehabilitation after stroke. To reach this goal, the TRAVEE has benefited from several innovative ideas and technologies—virtual reality, brain–computer interfaces, functional electrical stimulation, robotics, haptics, multimodal feedback, and a novel idea in information and communications technology systems for rehabilitation—visual augmentation as a form of feedback to the patient. Through visual augmentation, the TRAVEE immerses the patient in a virtual environment where his movements are rendered as being better than in the real world, and in this way diminishing his disability. We believe that this process—that is pending for patent—will greatly impact the recovery process after stroke, by providing more motivating sessions, while supporting the cortical reorganization process. This paper presents an overview of the TRAVEE system, the perspectives that supported it, details regarding its development, as well as the results of the clinical tests that were performed with the system.

INDEX TERMS Multimodal feedback, neuromotor rehabilitation, virtual reality, visual augmentation.

I. INTRODUCTION

According to the World Health Report [1], stroke affects 15 million annually. Out of them, a third die and a third are left with permanent disability.

According to the Heart Disease and Stroke Statistics 2018 [2] provided by the American Heart Association, stroke is a leading cause of disability in the United States. Approximately 90 million Americans are estimated to be living with a cardiovascular disease (CVD) or an aftereffect of stroke. Increasing the quality of life of those affected by stroke can therefore have a significant impact worldwide.

The TRAVEE system is the result of a national research project, undergone between 2014-2017. It is a neuromotor rehabilitation system for the upper limb, that took the first steps toward developing a low-cost solution that could be used on a large scale in the rehabilitation process.

The system combined multiple technologies (VR, BCI, FES, a robotic hand assistant device and haptic feedback), as well as complex ideas such as virtual therapist (VT), visual augmentation and multimodal feedback to develop a low cost, highly customizable rehabilitation solution. The resulting system has multiple functioning modes, a graphical user interface (GUI) dedicated to a non-technical healthcare practitioner and a database for storing the information regarding the patients.

One of the purposes of this project was to validate two ideas: the visual augmentation process in VR (transmitting to the patient an improved visual representation of his actual movements) and the eficacity of the virtual therapist, a virtual avatar that executes the movements that the patient must try to reproduce during his rehabilitation session.

TRAVEE was tested in iterations. The initial prototype was tested during two in-vivo testing sessions, in a medical settlement, in order to validate the technical solution. After refining the initial prototype into the final one, a clinical trial

took place, in the same medical settlement, to qualitatively assess the final result of the project.

This paper presents the medical prerogatives that were used and supported the ideas of the TRAVEE project, the overview of the system functionality and its architecture as well as several technical implementation details. The article will also provide the results of the preliminary in-vivo tests and the clinical trial, along with their interpretations, conclusions and future development perspectives.

II. MEDICAL BACKGROUND AND PERSPECTIVES

A. STROKE AND REHABILITATION

Stroke is the main cause of adult disability; approximately 60% of survivors remain with dysfunctional sequelae, especially at the upper limb.

Rehabilitation therapy allows people with disabilities and activity limitations to gain and maintain optimal physical, intellectual, psychological and / or social functioning. It includes a broad and heterogeneous range of activities, therapeutic interventions and methodologies, in addition to standard medical care.

Over the past 15 years, significant scientific evidence has emerged that argue that intense and repeated training can influence the reorganization of the brain through the acquisition / revival of motor regimes. The learning of motor engram is done through internal processes associated with practice and experience, which leads to changes in the ability to move.

B. NEUROLOGIC PERSPECTIVES ON VISUAL AUGMENTATION

Neuroplasticity is the ability of the brain to undergo functional changes in the short term and also to undergo structural changes in the long-term to adapt to changes in the living environment, central or peripheral injuries, aging phenomena. Brain reorganization is the main mechanism for achieving neuroplasticity. The stimulation of brain reorganization is done by: enriching the environment, stimulating attention, social interactions, tactile stimulation, motor re-learning, direct brain stimulation.

The cortical reorganization for restoring the movement of the hand affected by stroke is done on three ways, which are not excluding one another:

1. Bilateral cortical activation, with significant recruitment of nerve networks in the unaffected hemisphere.

2. Increasing recruitment in secondary cortical areas in the affected hemisphere.

3. Recruiting nerve paths around the infarcted area.

A potential role in reorganization is the use of feedback (augmented or not) as a way to stimulate the reward mechanism underlying the learning process. The use of imagination or visual representations of movement is called motor imagery. According to an extensive study in the field of motor imagery in rehabilitation [3] there is at least theoretical and experimental proofs on healthy subjects for the support of this idea.

A study regarding the possibility of 'fooling' the brain into believing that the perceived improved feedback is the result of the motor action of the body was published in [4]. This paper presented the presence of techniques for fooling the brain in rehabilitation purposes starting from 1996 with Virtual Reality Box and Mirror Therapy [5], [6], both using mirrors to reflect the movements of the healthy hand in upper limb amputees to simulate the presence of the missing limb, in order to successfully alleviate or treat phantom pain, to Functional Electrical Stimulation consisting in application of electric currents on the missing limb also in the purpose of relieving phantom pain.

Other experiments also presented in this survey [4] include the use of Augmented Reality (AR) to amplify a small movement in order to trick the brain into thinking it was a wider, more ample one in the TheraMem system [7]. This system was tested on five patients and observed a high degree of motivation during the sessions with the system.

Another system that implements this idea is a Virtual Reality (VR) for ''corrective learning'' where small movements of the disabled arm generate full range movements in the VR to help the patient re-learn the given action by correcting the perceived feedback [8]. The system referred by [8] is called VirHab [9] and it augments movements by using image processing of video streams to replace the image of the disabilitated arm with a recording of a movement of the healthy one when an input device is actioned - a small ranged movement determines the visualization of a full range one. A similar system is presented in [10] and the presented study showed improvements in the involved patients on several disability scales that were maintained even after three months after the sessions with the system.

As there are previous researches that tested the feasibility of stimulating cortical plasticity by fooling the brain by providing virtual improved feedback, TRAVEE introduced the augmented feedback - tracking the body of the patient and displaying on the patient avatar in the virtual environment a slightly improved version of the detected movements, combined with multimodal feedback.

III. OVERVIEW OF PREVIOUS ICT REHABILITATION SOLUTIONS

Starting from a survey that was presented at the 8th International Conference on Speech Technology and Human-Computer Dialogue [11], we evaluated the existing literature regarding ICT systems for neuromotor rehabilitation. We observed two tendencies in the development of these kind of systems. Either the experiments used a unique technology, developed exclusively for the study, or they involved the use of commercially available solutions, in the aim of developing a more accessible system.

In the category of systems dedicated exclusively to rehabilitation, several experiments were presented, and will be mentioned in the following. The Rutgers Arm system [12] includes a forearm support that slides on a surface, to assist the patient in performing the movements necessary in

a pick-and-place game that exercises the ability of following a given trajectory or a treasure-hunt game that tests arm endurance. The system also tested a game designed to exercise grasping gestures. The two subjects participating in the experiments with the system showed improvements in motor abilities and pinch and shoulder strength. The follower of the Rutgers Arm system is the Bright Arm [13] where the training table was completed with a rubber pear for monitoring the grasp strength in the palm, two infrared cameras placed above the head of the patient for movement tracking, a display and a computer connected to a remote medical server. Five games were available in this version of the system, and it was tested with 5 participants that – after the experiment – improved their shoulder strength, grasp strength, shoulder and elbow flexion and extension capabilities.

Another system that enhances the rehabilitation sessions using dedicated ICT is the ImAble [14], with its three configurations, all dedicated to rehabilitation using virtual games. The Able-B supports the disabled hand against gravity and moves it with the support of the healthy one. It uses a webcam to track the movements of the disabled hand by detecting a colored patch placed on it. The Able-M contains a sliding device to which the hand is strapped while sliding on a table and controlling a mouse for finger strength training. The Able-X consists of a lightweight handlebar that can be rotated in transversal and sagittal plane to control the movements of a pointer on screen. These systems are integrated with various games for static or dynamic target hitting. The three configurations (Able-B, Able-M and Able-X) were tested with five, three and 14 subjects respectively and in all cases improvements on the Fugl-Meyer scale were observed.

One of the systems that use commercially available solutions for rehabilitation is the Gertner Tele-Motion Rehabilitation System [15] that uses the Kinect to detect the movements of the patient. The patient performs certain rehabilitation movements that are translated to actions in specially designed video games. This system was tested on 18 subjects, 9 in the test group and 9 in the control group. Greater improvements were detected in the test group post-sessions, but a larger test is required for a definite result. The ioTracker is another system that uses Kinect to track the body movements of the patient as a form of input.

Other commercially available devices used in ICT systems for rehabilitation is the Wii. It was used for vestibular rehabilitation [16] in which over 50% of the 17 participants improved their balances indexes after the sessions.

Several studies [17], [18] used head mounted displays to immerse patients in virtual environments, with positive results on experiments with several patients, in the improvement of conditions such as memory and attention deficits: in [17] two patients were involved in ten sessions each with the system and in [18] the patients were evaluated using scales for attention deficit before and after using the system that immersed them in real-life scenarios, such as finding paths to certain destinations or memorizing information from the virtual world. The results showed improvements on both the Wechesler Memory Scale and on the Toulouse-Pieron scale.

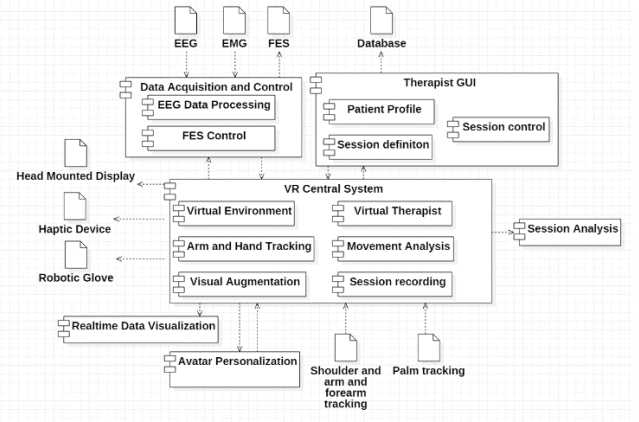


FIGURE 1. TRAVEE architecture overview.

The studied literature presents experiments in various fields of rehabilitation using ICT systems and most of them seem to have a positive influence on the rehabilitation procedures. TRAVEE is a complex system that combines several of the ideas that are already present in the existing literature with novel ideas, such as the visual augmentation, virtual therapist and multimodal feedback, using various technologies that are commercially available (Kinect, Leap Motion, Oculus Rift) or devices that are designed especially for the system (robotic glove, haptic device) as the system wants to evolve towards a low-cost solution. Several of the used technologies (for EEG, FES and EMG) are at the moment not low cost, but the desired evolution of the system is to replace them with accessible solutions at a satisfactory quality.

IV. TRAVEE NEUROMOTOR REHABILITATION SYSTEM - FUNCTIONALITY, ARCHITECTURE AND IMPLEMENTATION DETAILS

The system implements many original ideas, some original by themselves, others original in the context they were used. These are: the virtual therapist, that exemplifies the correct movement to the patient; the multimodal input, consisting of body tracking, EEG and EMG; multimodal feedback to the patient and visual augmentation of the patient's actions (an idea that is pending for patent).

The system integrates a variety of functioning modes in a modular architecture, presented in the image below.

The main components of the TRAVEE system are: the VR Central System, the Data Acquisition and Control component, the Therapist GUI, the Movement Analysis component, the Realtime Data Visualization component and the Avatar Personalization module. The rehabilitation sessions are recorded by the VR Central System. The resulted recordings are analysed using a standalone application, the Session Analysis component.

A. BIOPHYSICAL INPUTS

The system accepts input data from different devices, depending on the functioning mode: body tracking, body tracking + brain activity monitoring, detection of muscle activation in the limb. To stimulate the patient, the system generates many types of feedback: visual (true or augmented) through immersion in a virtual environment (VE), FES (Functional Electrical Stimulation), vibrations (haptic) and robotics.

B. BODY TRACKING

The tracking of the patient body is made using optical tracking devices: Kinect and Leap Motion. These devices are used to obtain information regarding the positions, rotations and scales of the main joints in the arm, forearm and palm of the user.

C. BCI

In the traditional therapy, the patients are asked to try to execute a certain movement with their impaired limb while they are imaging that movement. The goal is to perform a corresponding motor imagery (MI) task in order to produce a correct neural activation. The visual feedback of that action is obtained by using rope and pulley, if possible, a FES device to stimulate the corresponding muscles or a robotic device. In all cases the patient or the therapist are pulling the rope, trigger the FES or robotic device while the patients are imaging that movement. The problem is that for the patients it is very difficult to ''see'' that their impaired limb is moving because they are imaging so and not just because they or someone else is pulling the rope or pushing the button. This is the reason for which the causal loop cannot be closed and the recovery is blocked. On the other hand, the therapists don't have a real feedback from patients and they must rely on patients that they are really imagining that movement and carry on with the therapy. In reality, most of the patients, after a short time, lose concentration, they are getting bored, they start to think at something else like personal problems or even fall asleep. TRAVEE uses the BCI technology to determine if the patient is correctly performing the MI task. That can be used to trigger the FES, the robotic device or to update the patient avatar in the VE and to receive a corresponding feedback. Also, the therapist can have a feedback regarding the patient's mental activity and guide him in order to sustain and/or maximize this activity.

D. EMG

In case of the patients with residual motor potential or for those that start to have some minor muscle activity or to gain a small control over their limb due recovering therapy, electromyography (EMG) can be used as an alternative to detect the patient intention to make a movement. This is done by acquiring the EMG signal(s) and compare their amplitude(s) with a threshold. If it exceeds the threshold the patient intention is detected and can be used as a trigger signal for devices that guide/helps the patient to perform that movement and/or to update the patient avatar in VR.

FIGURE 2. Capture from the VE of the TRAVEE system.

E. FEEDBACK MODALITIES

1) VISUAL FEEDBACK (AUGMENTED OR DIRECT) THROUGH IMMERSION IN A VIRTUAL ENVIRONMENT (VE)

The visual feedback provided to the patient is obtained by immersing him or her in a VE where the patient sees the Virtual Therapist (VT) - an avatar that executes the current movement that the patient must try to perform, as well as an avatar of the patient (virtual representation of his or her body). The patient's avatar performs the movements of the patient either exactly as they are detected by the body tracking devices, either augmented - to be closer to the Virtual Therapist movements - before being applied to the patient's avatar.

2) VIBRATIONS (HAPTIC)

This feedback form consists in applying vibrations to certain key points on the hand or arm of the patient to inform him or her that the movement was sufficiently executed. The used haptic device was custom made for TRAVEE and it consists of vibrating motors attached to electrodes that are placed on the skin. The device is controlled by the system with commands that start and stop the application of vibrations.

3) LIGHTWEIGHT ROBOTICS

Robotics are an important feedback path and are represented by a glove actuated by five motors that support the extension of the fingers and hand. The device tested in the clinical setting was developed specifically for TRAVEE and includes five medium servo motors attached to a glove, controlled by an Arduino Mega 2560 development board.

4) FES

The functional electrical stimulation (FES) is a technique often used for recovering neuromotor functions in

neuromuscular disabilities due to a central nervous system lesion. By artificially inducing a pulse train in muscle nerves, contractions of the respective muscles can be obtained in proportion to certain parameters of the stimulation signal. Thus, by modifying the stimulation signal parameters, intense muscle contractions can be induced to produce functional movements. The main requirement for electrical stimulation to produce the contraction of the target muscle is that both the muscle and the nerve that connects it with the spine must be intact. In the TRAVEE project FES is used to help the patient to perform the desired movement and/or to maintain the muscular tonus, reduce the spasticity, maintain the limb joints. A side effect of working with FES is that the electrical impulse is travelling back to the brain via the nerve. This is seen as a benefit because the brain is bombarded with information and it is forced to reorganize in order to process it.

F. THE VR CENTRAL SYSTEM

This is the central communication point and also the system server. The VR Central System is responsible with the VE (using the Oculus Rift device) in which the patient is immersed and the main logic of the application. Based on the session configuration and on the available input data it decides what kind of augmentation or feedback should be applied and controls the augmentation and feedback modalities. It directly controls the haptic device and the robotic glove. The VR Central System is also in charge with logging relevant information regarding the current session, such as the postures of the patient obtained from the body tracking devices, as well as data acquired from EEG and EMG devices.

1) VIRTUAL ENVIRONMENT

The Virtual Reality environment was implemented using the Unity game engine version 5.3.4. It contains an avatar for the therapist (VT) and an avatar for the patient. In the VE, the patient sees the representation of their own body, the virtual patient avatar, from a first-person point of view, in order to better identify with the movements of this avatar, in a sitting position, with the VT also in a seated position in front of the patient's avatar, as in the capture below.

The immersion is achieved through a Head Mounted Display, Oculus Rift.

2) VIRTUAL THERAPIST

The VT is an avatar placed in front of the patient avatar, that exemplifies the movements that the patient needs to try to reproduce in the real world. The VT avatar was made using the Adobe Fuse CC software that allows creating humanoid characters. The patient avatars were made using the open source Make Human software.

3) SESSION RECORDING

The session recording functionality is integrated with the VR Central System, and it consists of a mechanism that stores all the relevant information for each session in a .session file:: avatar poses obtained from the body tracking devices, data synthesized from the EMG and EEG devices, exercise codes.

Having this information is enough to be able to use the session analysis component and simulate the entire rehabilitation session, by performing the same analysis on the logged data as in real time during the session. The session recorder is started automatically when a new session is created.

4) MOVEMENT ANALYSIS

This component is coupled with the VR Central System. It analyses the patient posture using the data from the optical tracking devices. Each movement is evaluated based on several predefined parameters and classified by a score, representing the degree of correct execution of the current movement. Decisions regarding body tracking based augmentation and feedback are taken by the VR Central System according to this score.

5) BODY TRACKING

The tracking of the arm and hand were made using the Kinect and Leap Motion devices. Both of them were necessary, as the Leap Motion tracks the forearm, the joints of the palm, and the phalanges of each finger, while the Kinect device tracks - among others - the joint of the shoulder and the elbow. Each movement defined in the TRAVEE system is tracked by one of these devices.

The movements implemented by TRAVEE and their classification as either being tracked by Kinect or Leap Motion is presented below.

Movements tracked by Kinect: Forearm flexion-extension, Arm adduction-abduction, Arm anteduction-retroduction, Shoulder raise.

Movements tracked by Leap Motion: Palm flexion-extension, Finger flexion-extension, Thumb opposition, Forearm pronation-supination.

More details regarding the implementation of the hand tracking with the two devices are presented in [19].

6) VISUAL AUGMENTATION

During the rehabilitation session execution, the data from the input devices – tracking devices, BCI, EMG – is analysed by the VR Central System and, depending on the functioning mode, the movement is visually augmented.

The visual augmentation of a movement based on tracking data within the TRAVEE system is the process through which, during the execution of a certain movement in a rehabilitation session, the movement detected by the tracking devices is improved before being applied to the virtual avatar of the patient. This means that the patient tries to execute correctly the current movement in the session – exemplified by the therapist avatar – and the movement the patient observed on the patient avatar will be a slightly improved version of the real movement, as detected by the tracking devices.

The visual augmentation of the movement based on movement tracking data uses the score calculated for the movement and a previously set threshold.

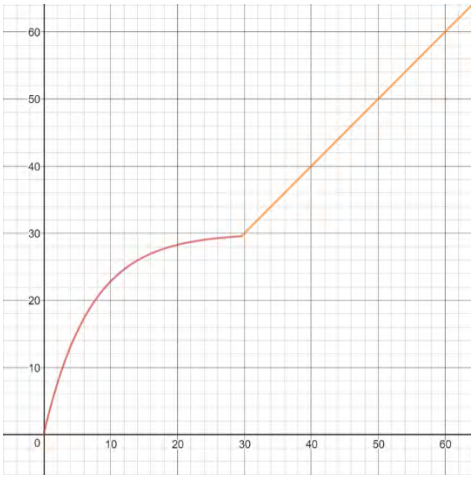


FIGURE 3. Graphical representation for augmentation function with threshold value 30.

The movement is augmented if the score is below the

$$\begin{cases} threshold \times (1 - e^{-\frac{x}{7}}), & x \leq threshold \times (1 - e^{-\frac{x}{7}}) \\ x, & x > threshold \times (1 - e^{-\frac{x}{7}}) \end{cases}$$

threshold with a factor. Several formulas of augmentation were tested, but the one we believe represents the envisioned visual augmentation of the TRAVEE system has the following form:

A graphical representation of this function, for a threshold value equal to 30 is presented in Fig. 3.

The augmentation algorithm is the following:

1) Evaluate the degree to which a movement was performed, based on the current body tracking data: for each movement we identified a joint or a set of joints that are most relevant and used them to calculate a degree of execution, referred to as score. The score is represented by a number, which is calculated differently for each movement, as it can represent a relevant angle or a distance between two bones or joints of the hand.
2) If the score is beneath the threshold for the currently executed movement, augment the relevant angles and distances of the movement according to the augmentation.
3) If the score is above the threshold, display on the patient avatar the pose obtained from the body tracking devices, without any alterations.

The process of visual augmentation based on body tracking is pending for a patent with the title: ''System, method and computer program for augmenting human movements''.

The joints used for the movements are presented in Fig. 4 and Fig. 5. As the system knows what the current exercise is, for each pose, it evaluates the current relevant angle or distance. This value is considered to be the score for the movement. Each type of movement has a predefined threshold.

The joints evaluated for each movement are presented in Figures 4 and 5.

FIGURE 4. The angles considered for evaluating the movement score for Forearm Flexion-Extension (top-left), Thumb Opposition(top-right), Arm Adduction-Abduction (bottom-left), Arm Anteduction-Retroduction (bottom-right).

FIGURE 5. The angles considered for evaluating the Palm flexion-extension (top-left), Forearm pronation-suppination (top-right), Finger flexion-extension (bottom-left) and Shoulder raise movements (bottom-right).

1) Forearm Flexion-Extension: the elbow joint was considered the most relevant. Therefore, the given score was the angle between the forearm and the arm. The maximum augmentation angle, up to which the movement was augmented, was set to 45 degrees.
2) Thumb Opposition: the angle between the direction of the first phalange of the thumb and the axis between

the base of the thumb and the base of the pinky fingers is considered the relevant angle. The maximum augmentation angle, up to which the movement was augmented, was set to 60 degrees.

3) Arm Adduction-Abduction: the angle between the direction of the arm and the direction of the spine is considered the relevant angle. The maximum augmentation angle, up to which the movement was augmented, was set to 60 degrees.
4) Arm Anteduction-Retroduction: the angle between the direction of the arm and the direction of the spine is considered the relevant angle. The maximum augmentation angle, up to which the movement was augmented, was set to 60 degrees.
5) Palm flexion-extension: the angle between the direction of the hand and the direction of the forearm is considered the relevant. The maximum augmentation angle, up to which the movement was augmented, was set to 45 degrees.
6) Forearm pronation-supination: the local Euler roll rotation angle of the forearm relative to the arm is considered the relevant. The maximum augmentation angle, up to which the movement was augmented, was set to 30 degrees.
7) Finger flexion-extension: all the angles between the phalanges of the fingers were analysed. The minimum angle between either two phalanges was chosen as the score for the movement. The maximum augmentation angle, up to which the movement was augmented, was set to 60 degrees.
8) Shoulder raise: this movement was more complicated to analyze as it did not have a relevant angle between two joints, so it was evaluated based on the distance between the position of the base of the neck and the position of the shoulder. The maximum distance up to which the augmentation was performed was defined at 0.6 units. The augmentation for this movement consisted in changing the position of the shoulder joint on the vertical axis with the calculated augmentation distance.

G. THE DATA ACQUISITION AND CONTROL COMPONENT

This component acquires several types of data from the patient, EEG and EMG and controls the FES.

1) EEG DATA PROCESSING

In the recent years, a series of scientific publications demonstrated that BCI (brain computer interface) and more precisely the ones based on motor imagery (MI) can stimulate the mirror neurons and induce neuroplasticity [20]–[22]. These evidences support the inclusion of BCI as an important tool for post-stroke recovery therapy to enhance the motor rehabilitation outcome. During the exercises where MI-based BCI is used, the patient is asked to imagine the movement of his hands in a random order. Motor imagery is a skill that must be learned by the patient during the so called ''training phase''. MI can be measured (real-time processing and classification of the EEG) and used to provide neurofeedback. The neurofeedback must be similar to the real motor activity that patient is asked to imagine [23]. The visual representation of the neurofeedback through the popular bar feedback (bFB) [24] or virtual reality (VR) [25] it is a very important component of the learning process because it actively involves the patient (meaning the patient's brain) in the task.

The MI based BCI assume that the exercises are performed with both hands. The method used to discriminate between the two imaginary tasks is Common Spatial Patterns (CSP). The method is based on the simultaneous diagonalization of two covariance matrices. Thus, the method allows to construct a new time series that maximizes the variance of the samples of a task, while minimizing the variance of samples of the other task. The matrices contains a set of spatial patterns, subject dependent, which provides information about the activity of a specific cortical area corresponding to imaging the movement of one of the hands. Given one projection matrix W, the decomposition of EEG signal for one trial X can be projected as:

$$Z = WX \tag{1}$$

where W^{-1} are sets of CSP models and are time-invariant EEG sources distributions [26]. After interpolation these CSP can be displayed as topographic maps [27].

Fig. 6 shows a set of CSP models for EEG recordings during MI for left and right hand which correspond to the firsts and respectively the lasts column of W^{-1}. The topographic distribution of these components correspond to expected contralateral activities of the sensorimotor rhythms induced by imagination of the movement. Another advantage of this method is that is not necessary the variances computation for the all n series. Müller-Gerking demonstrate that the optimal number of CSP models used to create a feature vectors is four, only first and last two rows of W [27]. The variance is calculated using a sliding window of T according to (2)

$$VAR_p = \sum_{t=1}^{T} (Z_{p(t)})^2 \tag{2}$$

where:

p – is the number of CSP filters ($p = 4$)

T – is the time window for which the variance is calculated ($T = 1.5$s)

To obtain the feature vectors the values are normalized and log (3)

$$f_p = log_{10}(\frac{VAR_p}{\sum_{p=1}^{4} VAR_p}) \tag{3}$$

In order to categorize a movement to be right or left hand a LDA (linear discriminant analysis) classifier is used based on the classification of the four feature vectors. The result of the LDA classifier is used as visual feedback for the patient, Fig.7.

The EEG signals where acquired using a g.USBamp 16 channels biosignal amplifier device from g.tec medical

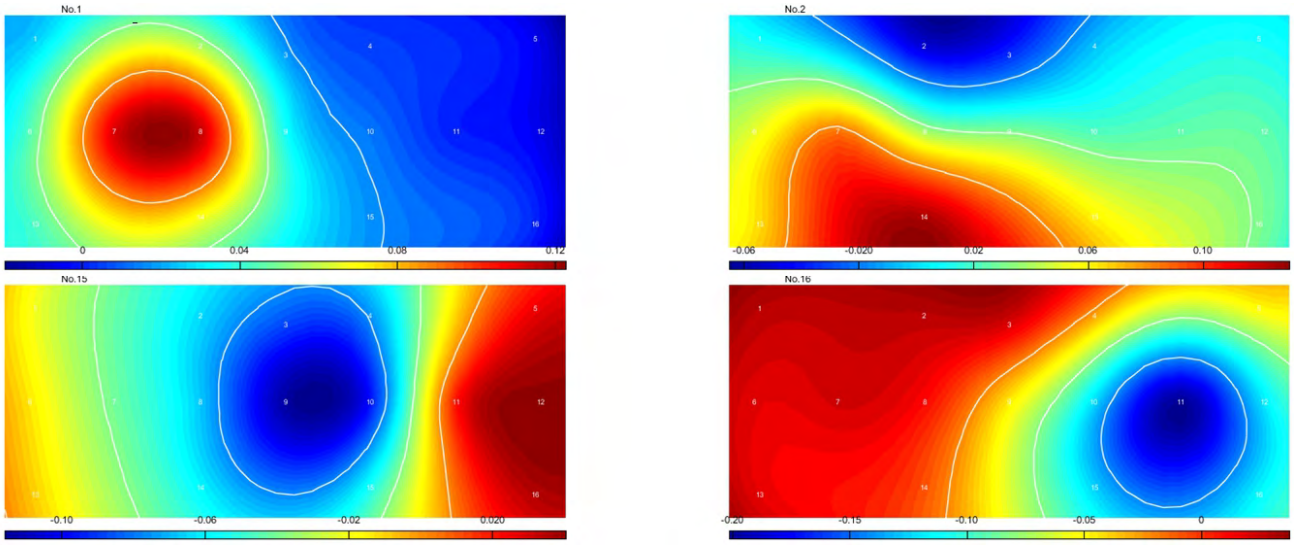


FIGURE 6. CSP over 16 channels for one of the patients during MI (left column – right hand, right column – left hand).

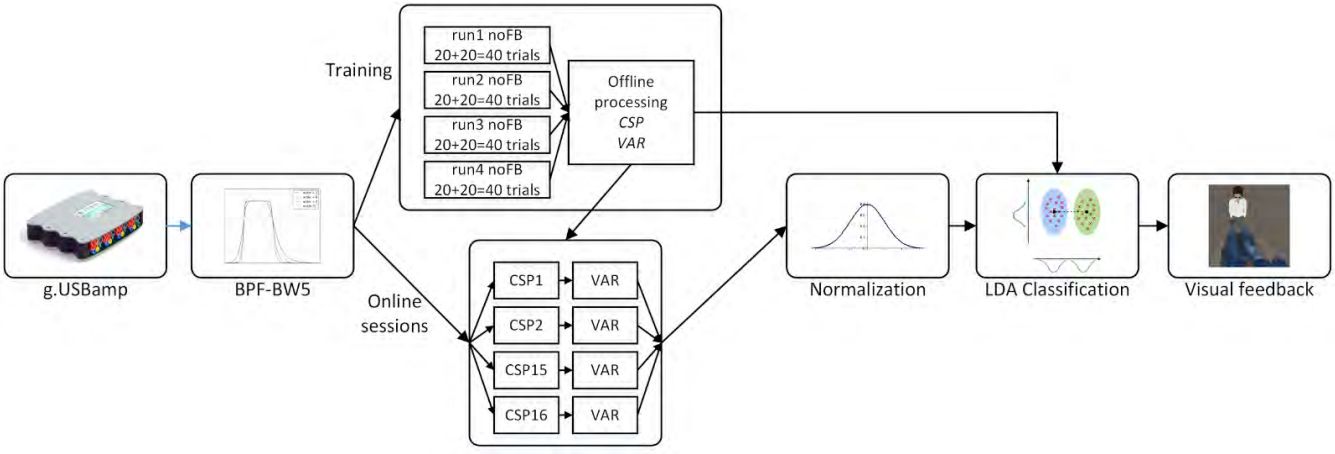


FIGURE 7. Workflow of BCI signal processing for visual feedback control.

engineering GmbH [28]. The electrodes are positioned on the EEG cap according to 10-20 International System in order to cover the sensorimotor areas of the brain, Fig. 8.

Before starting the recovery exercises there is a training session during which the patient must learn to imagine the movement. The session consists of 4 runs of 40 trials of hands movements, 20 for one hand and 20 for the other hand, in a randomized order without feedback. Each trial consists of 8 seconds of EEG recordings. At second 2, the patient hears a beep that informs him about the upcoming cue and at second 3 the cue (left or right) is presented, this representing the moment when the patient has to start imagining the movement. The feedback phase starts at second 4.25 and lasts till second 8. During the feedback phase, the patient has to imagine the movement of the hand dictated by the cue.

The training data recorded during the calibration phase is used to calculate the classifier that will be used for providing the feedback during the next phase.

After an online session, an error rate is calculated by comparing the cue presented to the patient with the classified movement at every sample time. For a number of N trials, the error rate is calculated as:

$$Err = \left(1 - \frac{Tcc}{N}\right) \cdot 100 \tag{4}$$

where Tcc is the number of correctly classified trials. The mean error rate and the minimal error are calculated during the feedback phase. Figure 9a presents the LDA classifier output for an online session. The dotted lines represent the output for each trial (blue for right and green for left) and the solid lines represent the averaged classification output for each class. Figure 9b presents as example the error rate for an online session, and the minimal error rate is marked with a red circle.

The system configuration using BCI to detect the patient intention to move is shown in fig. 10. The LDA output is

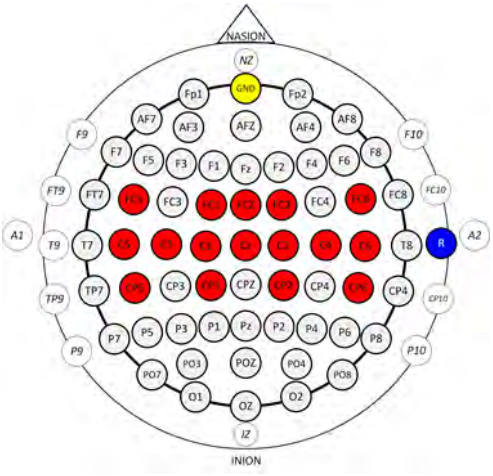
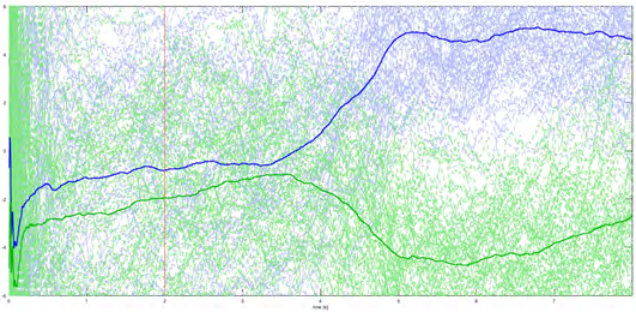
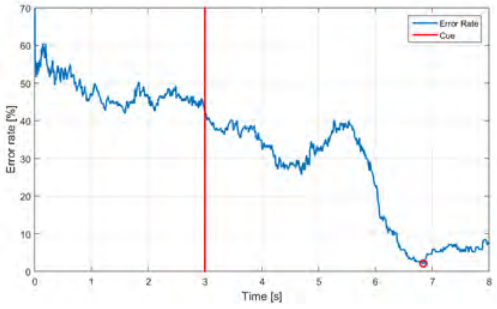


FIGURE 8. Position of the EEG electrodes according to 10-20 International System.



(a)



(b)

FIGURE 9. LDA classification output (using g.BSanalyze provided by g.tec medical engineering GmbH) and error rate.

used by the processing and control unit (PCU) to trigger the devices (robotic glove, robotic arm etc.) which helps the patients to perform the desired movement. At the same time it provides the patient with visual feedback he needs.

2) FES CONTROL

The FES is used in TRAVEE system to help the patient to perform the desired movement and as a technique to recover neuromotor functions by artificially inducing a pulse train in muscle nerves. Contractions of the respective muscles

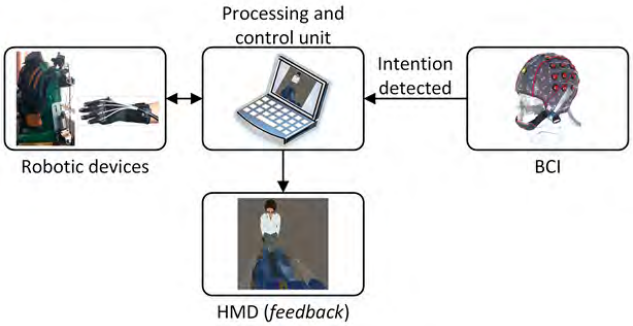


FIGURE 10. TRAVEE system configuration using BCI to detect the patient intention to move.

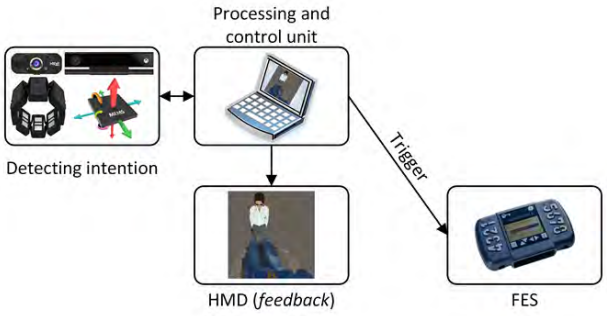


FIGURE 11. TRAVEE system configuration using BCI to detect the patient intention to move.

can be obtained in proportion to certain parameters of the stimulation signal. Thus, by modifying the stimulation signal parameters (timings for impulse rising, front and falling and current intensity), intense muscle contractions can be induced to produce functional movements. Because the muscle contraction is directly dependent by muscle tonus, skin resistance and electrode position, the FES parameters must be adjusted for every patient every time is used. The system configuration in which the FES device is used to help the patient to perform the desired movement is shown in fig. 11. This time the user intention is detected by using one of following devices: kinect, video + aruco markers, mio armband, IMU sensor etc.

The most used configuration is BCI - FES with additional robotic devices if needed (depends on the rehabilitation exercise). The patient must be able to seat without discomfort in a normal chair or wheelchair for 30 – 60 minutes, with his hands laid on the seat armrest. The exercise, for example flexion and extension of the hand fig. 11, is executed by the patient with his impaired hand but also with his healthy hand, one at a time. For this reason the FES electrodes are mounted on both hands over the finger extensors muscles (two channels).

The system configurations in which the BCI and FES devices are used are shown in fig 13.

In the first configuration, (Fig. 13 a), the BCI system component automatically triggers the FES component when it detects the patient intention to move and notifies the PCU.

FIGURE 12. Flexion and extension of the hand.

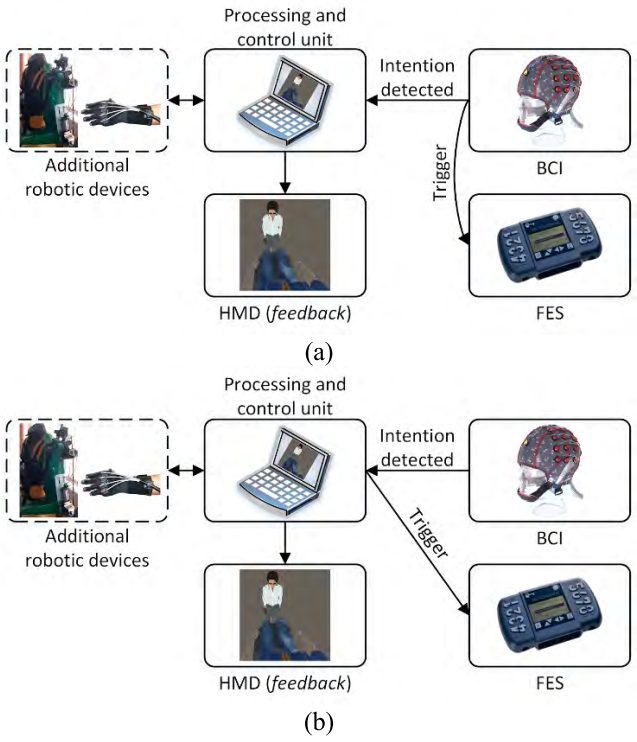


FIGURE 13. BCI - FES system configuration: a) BCI triggers FES & notifies PCU; b) BCI notifies PCU, PCU triggers FES.

In the second configuration, (Fig. 13 b), the BCI component only notifies the PCU about the patient intention and the PCU takes the decision to trigger the FES component. Fig. 14 shows a patient using the TRAVEE system configured as in Fig. 13. a.

H. THE THERAPIST GUI

This is the interface dedicated to the medical practitioner, which enables defining the patient profile (containing information regarding the patient, such as gender, age, weight, height, etc.), session configuring (exercises, durations, devices used) and analyzing statistics regarding the history of the sessions executions for the current patient. More details regarding the Therapist GUI are presented in past works [29]. This component is also integrated with a database that stores the patient and sessions information.

1) PATIENT PROFILE

The doctors are provided tools - in their dedicated user interface - to retain certain information regarding the patients that use the TRAVEE system for rehabilitation. The patient

FIGURE 14. Patient using the TRAVEE system.

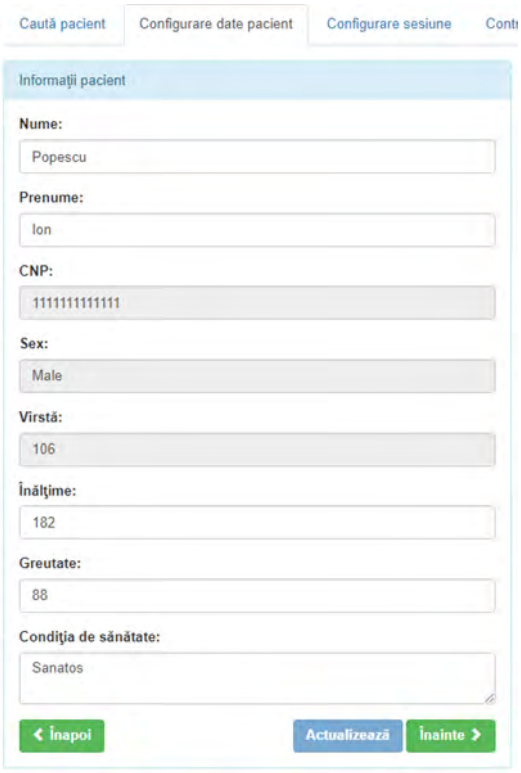


FIGURE 15. The patient profile configuration form.

profiles are defined by filling out a form with the following information: surname, name, personal identification number (PIN), gender, age, height, weight, health condition. This information is stored in a database and can be retrieved for further sessions.

2) SESSION DEFINITION

The doctor also has a view dedicated to the configuration of the rehabilitation session. In this view the doctor can select the exercises to be included in the rehabilitation session, their

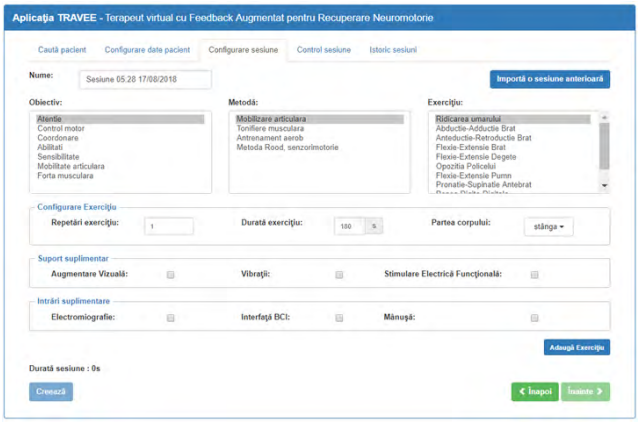


FIGURE 16. The session definition form.

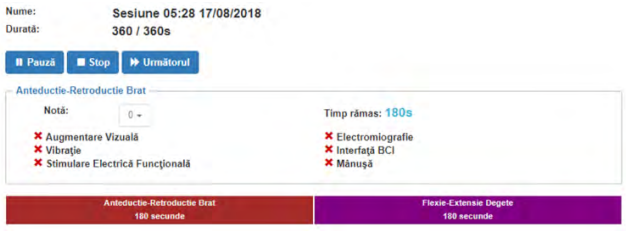


FIGURE 17. The session control tools.

durations and the devices used for each one. The doctor also has the option to filter the available exercises based on their objective and the methods they are part of.

3) SESSION CONTROL

The session control view that is also a component in the interface dedicated to the doctors, allows the supervisor of the rehabilitation session to start, stop and pause the session. After the time chosen for an exercise has passed, the supervisor is asked to fill in a grade, evaluating the performances of the patient in the real world, based on the visual observations of the movement, as perceived by the supervisor.

4) SESSION ANALYSIS

The session analysis tool can analyze automatically many session recording files and extract synthetic data, so that the therapist can gather information without visually inspecting all the sessions.

This tool is a Unity application with a scene containing only the patient avatar, on which the recorded poses are played successively. As it was developed to automatically process many files without operator intervention, it allows the user to select a folder containing as many session recording files as necessary. It then automatically opens the session files one by one, and analyzes the poses in the file with the same algorithm described in the Visual augmentation of movements subchapter to determine the score for each pose. Using the variation of the scores and the other information in the files, the analysis tool calculates the following data:

TABLE 1. Augmentation and feedback pathways allowed for various input modalities.

	Visual augmentation	FES	Vibrations	Robotics
Body tracking	Augment	Yes	Yes	Yes
BCI	Fool	Yes	Yes	Yes
EMG	Fool	Yes	Yes	No

1) The execution times for each session
2) For each execution of an exercise in a session:

- The number of repetitions, as perceived by the system through the variations of the calculated scores for the tracked poses sequences. Each time the score changes the variation direction (was decreasing and is determined to be increasing, or if it was increasing and it is now considered to be decreasing), the algorithm records a change in the variation direction. Two successive changes in the variation direction is interpreted as a repetition.
- The average score for all the poses detected for the execution of a given exercise

The results of an analysis process is a file containing, for each recorded session: the total duration of the session and for each exercise in the session, the average score and the number of repetitions - as perceived by the Session Recording Analysis application.

5) THE REALTIME DATA VISUALIZATION COMPONENT

This component displays graphical representations of the EEG and EMG acquired data, to inform the doctor of their variations in time.

I. THE AVATAR PERSONALIZATION COMPONENT

This component allows the medical practitioner to change several characteristics of the virtual representation of the patient (gender, age, weight, hair and skin colour, clothes and hairstyle) in order to increase the immersion of the patient in the VE.

J. MODULAR AND INTEGRATIVE APPROACH

Using the dedicated graphical user interface, the doctor can define, for each rehabilitation session, a series of exercises and their durations, as well as the input devices to be used during the exercises and the feedback modalities.

Not all combinations of input modalities and feedback pathways implemented by TRAVEE make sense to be used together, therefore a set of allowed combinations was defined. These combinations are presented in Table 1 and are discussed below.

The Table 1 presents, for each input device, the available feedback modalities. The configurations that can be selected by the healthcare practitioner are limited by the conditions

presented in this table but the doctor is not obliged to select all the available feedback devices for the session.

For the body tracking input as well as for the BCI one, any feedback can be implemented and used. For the EMG input, robotics would not be necessary, as the values of the electrical activations in the muscles will not be necessarily relevant if the muscles are actuated by the glove.

Depending on the selected inputs and feedbacks, the system behaviour changes. Therefore, several distinct functioning modes were defined. Out of these, the most significant ones are:

- Visual augmentation based on body tracking

During the session, the changes in the pose of the patient are analysed, and for each detected pose, the movement is slightly improved before being applied on the avatar in the VE, so that the patient perceives a better movement than he or she actually performed.

- Haptic feedback based on body tracking

For each pose detected by the optical tracking devices, the movement is analysed and when it is evaluated to be better than an established threshold, vibrations are applied on certain points on the hand of the patient. Therefore, the haptic feedback tells the patient when he or she has performed a good execution of the movement.

- BCI and FES

This functioning mode has a training phase in which the patient learns how to imagine the movement and the system computes an LDA classifier with a corresponding classification error. If the error rate is higher than 20% the training phase is repeated. If the error rate is lower than 20% the system can be switched to online mode where it can detect whether the patient is imagining the correct movement (with a certain degree of accuracy) or not and correspondingly activates FES for the respective hand. Therefore, the patient sees the feedback of what he is imaging.

- BCI and visual augmentation

This functioning mode is similar to the previous one, with the difference that instead of actually moving the patient hand through FES, the patient is immersed in the VE and the imagined movement is executed by the patient avatar in the VR.

- Robotic hand controlled mode based on body tracking

In this functioning mode, the position of the patient body as detected by the tracking devices is continuously evaluated. When the system detects that the patient cannot complete the movement, it activates the robotic glove for support, to help the patient perform the current exercise completely and correctly. Another function of this mode is that if no movement is detected in the patient hand, the robotic glove will start automatically to perform the whole movement, as the system will assume that the patient has no control of his hand muscles.

V. IN-VIVO TESTS AND CLINICAL TRIAL

The testing of the TRAVEE system took place in two stages. Initially, at the end of 2016, the initial prototype of TRAVEE was validated through two in-vivo testing sessions. Based on the observations made in these two tests the system was refined, to obtain the final prototype that was used during a clinical trial in May-June 2017.

For the tests to take place, permission was granted from the ethical council of the Neurological Recovery clinic of the National Institute of Recovery, Physical Medicine and Balneoclimatology (INRMFB) in Bucharest.

A. PRELIMINARY IN-VIVO TESTS

1) OBJECTIVES

The preliminary in-vivo tests were designed to test the initial prototype of the TRAVEE system, in order to determine whether it could successfully be applied to patients with neuromotor disabilities, what were the aspects that could make it easier to be used in a clinical settlement, and to test several functioning modes.

Two in-vivo testing sessions took place, in November and December 2016, respectively.

2) TECHNICAL DESCRIPTION

The first in-vivo tests evaluated the system for the Forearm flexion-extension, Arm anteduction-retroduction, Palm flexion-extension, Fingers flexion-extension. The second in-vivo test evaluated the system with the Forearm flexion-extension and Palm flexion-extension movements.

The hardware used in the first in-vivo testing session was: a computer running the TRAVEE VR Central System, Oculus Rift for immersion in the VE, BCI and FES. The second set of in-vivo tests used a computer running the VR Central System, Oculus Rift for immersion in the VE and the haptic feedback device.

The TRAVEE components that were tested during the preliminary in-vivo tests: the VR Central System, the Data Acquisition and Control and the Movement Analysis component.

The tested functioning modes: visual augmentation based on body tracking, visual augmentation based on BCI, FES controlled by BCI and haptic mode based on body tracking.

3) CLINICAL SETUP

Each in-vivo testing session took place in one day, at the Neurological Recovery clinic of the National Institute of Recovery, Physical Medicine and Balneoclimatology (INRMFB) in Bucharest.

Patients, as well as their families, have been informed about the device created in this research project. The Information Form was handed in, the questions and the unclear things were answered. Those who have accepted to participate in the test have signed the Informed Consent, in the presence of the medical team members and their families.

The patients selected by the doctors had various degrees of disability, ranging from patients with no motor control to patients who only had a slight tremor in their hand. All the patients had suffered a disability of their hand as a result

of stroke. In the first in-vivo tests one patient tested the system with BCI and FES, and three patients tested only the VR Central System component with visual augmentation. In the second in-vivo testing session, three patients tested the VR Central System.

In the first in-vivo testing session, one patient executed a session containing the Palm flexion-extension movement with the BCI controlled FES augmentation, and three patients used the TRAVEE system in sessions with Palm flexion-extension and Forearm flexion-extension movements.

In the second in-vivo testing session, three patients tested the TRAVEE system for the Forearm flexion-extension and Palm flexion-extension movements with visual augmentation based on body tracking. One patient also tested the haptic feedback device.

4) INTERPRETATION OF THE RESULTS

The results of the in-vivo testing sessions were presented in previous works, for the first session [30] and the second session [31].

The results of the in-vivo tests were mainly technical conclusions regarding the usability of the TRAVEE system as well as possible improvements that could be brought upon the solution to prepare it for the clinical trial.

The participants to the in-vivo tests were asked to fill in questionnaires regarding their experience with TRAVEE, based upon which several conclusions were drawn.

1. During the test, what was the perceived level of tiredness?
2. During the tests did you feel dizziness?
3. During the tests did you feel nauseous?
4. During the tests did you feel any anxiety or fear?
5. The image perceived on the virtual glasses/monitor was clear?
6. Did you feel physical discomfort due to the system components?
7. Did you feel pain due to the FES/haptical stimulation?
8. How real did the avatar movements seem to you?
9. How well do you identify your movements to those of the avatar?
10. Did you feel that the movements of the avatar were different than yours (greater)?
11. Are the indications of the virtual therapist useful for the exercise execution?
12. How useful do you find such a rehabilitation system?

B. CLINICAL TRIAL

The effort necessary for the experiments associated with an extensive clinical trial are tremendous, therefore our goal was not to include in the tests a large number of patients, but to prove the validity of our system and the ideas that support it, and its use in a clinical environment. This decision was taken also because the system is still a prototype, not a final product, therefore we treated each patient participating in our trial as an individual test case, not necessarily aiming for statistical evidence as we believe it is still very early for such results.

TABLE 2. Questionnaire responses of the patients for the two in-vivo testing sessions [30], [31].

Q	#1	#2	#3	#4	#5	#6	#7	Avg.
1	5	3	3	1	1	1	3	2.43
2	1	1	4	4	1	1	1	1.86
3	1	1	1	1	1	1	1	1.00
4	1	1	1	3	1	1	1	1.29
5	4	3	4	3	3	5	5	3.86
6	1	1	2	1	1	2	1	1.29
7	1				1	1	1	1.00
8	3	1	1	5	5	4	4	3.29
9	4	3	2	5	4	4	2	3.43
10		2	2	1	1	5	4	2.50
11		3	3	5	5	3	2	3.50
12		4	4	1	4	5	1	3.17

1) OBJECTIVES AND APPROACH

The clinical trial took place between 28th April 2017 and 19th May 2017, at the National Institute for Rehabilitation, Physical Medicine and Balneoclimatology (INRMFB) in Bucharest. The tested configurations were chosen based on the degree of disability of each patient and included BCI, FES, VR and robotic glove.

From a clinical point of view, this study is an experimental acute one of a number of cases in which we followed, for each subject, the persistent therapeutic response in patients with stroke sequelae in the upper limb after post experiment and the possible occurrence of side effects.

The secondary goals were:

- Establish with maximum possible accuracy the clinical and functional profile of the patient after stroke that can benefit from a clinical and functional treatment with the TRAVEE system
- Determining the factors that restrict the application of the method
- Weaknesses of the device and corrective ways
- A qualitative assessment of the final prototype of the TRAVEE computerized system and to track the effects of TRAVEE during the development of the program.

From a technical point of view, the results of the clinical trial were measured in the evolutions of the scores given by the system to each rehabilitation exercise, as processed from the recording file. As neither of the patients has taken part in more than six rehabilitation sessions with TRAVEE and

many only participated to one or two sessions, the results were mostly specific to a qualitative clinical trial and not to a quantitative one. The system has been improved from the testing sessions, by refining the existing functionalities, as well as adding several new functioning modes as well as the recording function, described previously.

During the clinical trial, the TRAVEE system contained all the designed components: VR Central System, Data Acquisition and Control, Therapist GUI, 3D animations of the VT, tracking of the patient body movements, session recording, session analysis.

2) CLINICAL SETUP

30 patients with stroke were included in the study, 21 of them benefited from the complete experiment with the TRAVEE device.10 patients were tested for the response to BCI therapy, 2 patients were included in the mixed experiment, TRAVEE plus BCI, and one patient was included in the experiment with additional stimulation with FES and vibration stimulation.

For all the patients included in study the stroke was less than 12 months.

The general clinical profile of the patient included in the study was: conscious, temporal-space-oriented, cardio-respiratory balanced, no digestive or renal accusation, with central post-stroke motor neuron syndrome.

It is essential that passive mobilization applications that are made analytically and / or globally by the therapist to restore / revive the neural circuits defining the correct parameters of the movement: amplitude, direction, speed before TRAVEE training

The lot of patients had the following demographic characteristics:

- 15% women and 85% men
- ages between 43 and 79 years;
  The followed clinical parameters were:
- motor control
- spasticity, reflexes, other signs of hypertonia
- muscle strength
- vicious postures (joint, type, degree)
- synkinesis of the upper limb (type, description)
- coordination problems
- superficial and deep sensitivity
- articular mobility degree
- CRPS I complications, glenohumeral subluxation, thalamic pain

3) FUNCTIONAL EVALUATION

For functional evaluation assessed the degree of general dysfunctionality of an upper limb; to all patients this was in the range 2-5.

On the scale of functional independence regarding self-care and locomotion activity, the situation ranged from modify independence to 75% dependency (the Functional Independence Measurement scale).

Other scales used:

- Deficit scale: Manual Muscle Testing (MMT) for Muscle Strength Assessment, Ashworth Scale Assessment Scale, Mini Mental State Examination (MMSE) for cognitive status assessment, reflex score, fatigue scale
- Disability:
  - Action Research ARM Test (ARAT)
  - Box and Blocks Test
  - Motor Assessment Scale (MAS)
  - Rivermead Motor Assessment

4) INCLUSION CRITERIA

- Stable neurological status
- Conscious state
- Significant persistent neurologic motor deficit
- Functional disability at the level of at least two of the following: mobility, self-care capacity, communication, sphincterian control, swallowing
- Cognitive functions well preserved to allow learning
- Ability to communicate well enough to allow collaboration
- Physical exercise tolerance sufficient to perform the active program
- Achievable therapeutic goals

5) EXCLUSION CRITERIA

- Central motor neuron syndrome older than 6 months
- Spasticity > Ashworth Grade 2
- Instability of central neurological lesions; Progressive motor deficit
- Cardiac unstable or other co-morbidities requiring emergency medical care
- Intercurrent infections, other comorbidities that contraindicate inclusion in a medical recovery program
- Complete lack of proximal motor control at the level of the upper limb
- Uncontrolled psychiatric disorders
- Uncontrolled seizures
- Significant cognitive impairment with MMSE <18
- Bilateral marked deafness or hearing loss
- Amputations, ankyloses or severe limitations of joint mobility at the level of the upper limb, caused by diseases prior to neurological disease
- Multiple/ repeated central neurological lesions
- Co-existence of a peripheral neurological deficit at the level of the upper limb
- Absence of consent (informed consent) of the patient or family

6) RESULTS

a: TECHNICAL RESULTS. EVALUATIONS BASED ON THE AUTOMATED ANALYSIS MADE BY THE SYSTEM

The sessions that were performed with the VR Central System were recorded and then were analysed using the previously described Session Analysis application.

A total of 21 patients tested the TRAVEE system with visual augmentation. The recordings of the sessions were analysed and the most relevant ones are summarized below. The number of repetitions was determined automatically, based on the number of changes in the direction of variation of the calculated score for each movement.

Because each movement has different parameters used in its evaluation, the scores assigned to different movements cannot be compared. Also, the average scores for each patient are individual, based on his/her abilities in the exercised hand. A greater score indicates a larger amplitude of movement, therefore a possibly more complete execution.

Another important observation is that the performed clinical test evaluated more patients for a small number of sessions, to assess the usability of the system in various scenarios and various degrees of disability. For the results to be medically relevant, a more extensive clinical test would have been appropriate, with the same patients exercising for several sessions each day, for at least several weeks.

Out of the 21 patients that tested the TRAVEE system during the clinical trial, we selected for presentation in this paper those that had at least three rehabilitation sessions with the system.

i) Patient RV2

This patient had the most remarkable evolution with the TRAVEE system. Before the first session, the patient had a very strong tremor in the arm, that did not allow him to execute accurate and controlled movements. As soon as the Oculus and tracking devices were installed, the patient was immersed in the virtual environment, the session started and he was asked to repeat the movements shown by the virtual therapist; the tremor almost disappeared, being reduced greatly. The progress – as we were reported – was maintained outside of the virtual environment. Although we cannot determine exactly the reason for this improvement and we cannot necessarily connect it to the system, it is a coincidence that definitely requires further research.

Evolution of the Forearm Flexion-Extension movement

TABLE 3. Exercises executed with TRAVEE by Patient RV2.

Date	Exercise	Secs	Reps	Avg
04.05	Forearm Flexion-Extension	200	17	65.85
04.05	Forearm Flexion-Extension	180	18	62.65
08.05	Forearm Flexion-Extension	200	26	59.91
08.05	Forearm Flexion-Extension	200	24	67.14
09.05	Forearm Flexion-Extension	200	26	59.92
10.05	Forearm Flexion-Extension	200	40	33.91
10.05	Forearm Flexion-Extension	200	17	24.4
11.05	Forearm Flexion-Extension	200	41	40.86
12.05	Forearm Flexion-Extension	200	26	65.97
12.05	Forearm Flexion-Extension	180	29	62.99

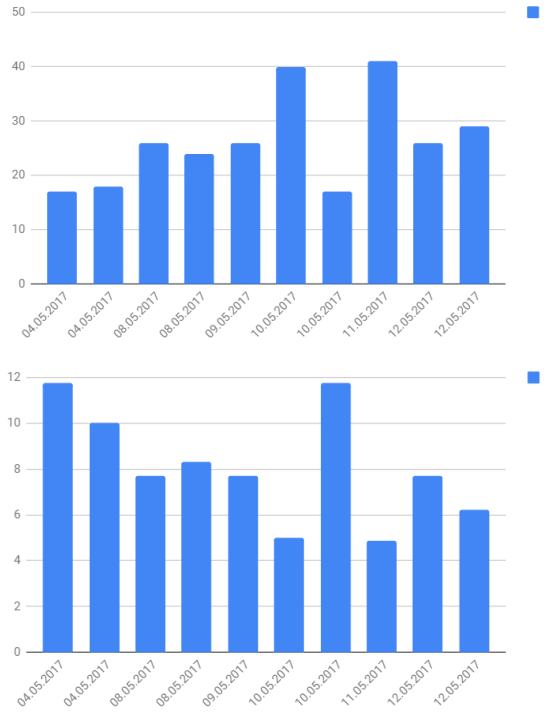


FIGURE 18. Average scores evolution (top) and average seconds/repetition evolution (bottom).

ii) Patient RV5

This patient came to the sessions regularly, was receptive to the idea of the system, had a positive attitude and a good evolution. For each session the patient had two repetitions of the Forearm Flexion-Extension, each of 180 or 200 seconds, during which, each time, performed approximately 20 repetitions, as evaluated by the system. The average scores did not vary significantly during the trial period, more sessions would have been required for statistical relevant information regarding the progress of the patient.

iii) Patient RV13

For this patient we observed an ascending trend for the average scores given by the system for the two movements executed for each of the three rehabilitation sessions in which the patient took part. At the same time, the number of repetitions detected by the system decreased. This observation could mean a more qualitative execution of the movements, at a slower pace, with better motion control.

The evolution of the Forearm Flexion-Extension movement is presented below.

TABLE 4. Exercises executed with TRAVEE by Patient RV5.

Date	Exercise	Secs	Reps	Avg
09.05	Forearm Flexion-Extension	200	19	92.64
09.05	Forearm Flexion-Extension	200	23	89.28
11.05	Forearm Flexion-Extension	200	44	79.77
11.05	Forearm Flexion-Extension	200	26	74.1
12.05	Forearm Flexion-Extension	200	25	84.12
12.05	Forearm Flexion-Extension	180	23	83.74
19.05	Forearm Flexion-Extension	220	26	76.15
19.05	Forearm Flexion-Extension	200	27	87.83

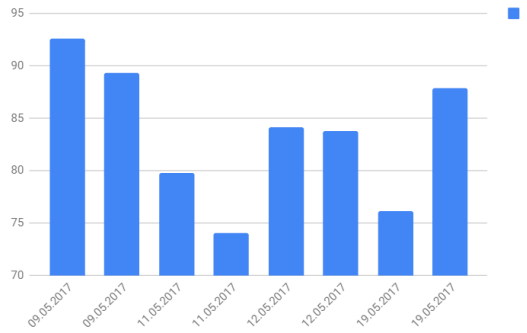


FIGURE 19. Average scores evolution (top) and average seconds/repetition evolution (bottom).

TABLE 5. Exercises executed with TRAVEE by Patient RV13.

Date	Exercise	Secs	Reps	Avg
09.05	Forearm Flexion-Extension	200	42	68.95
09.05	Palm Flexion-Extension	200	56	20.16
11.05	Forearm Flexion-Extension	200	30	75.38
11.05	Palm Flexion-Extension	180	47	27.57
19.05	Forearm Flexion-Extension	200	34	75.69
19.05	Palm Flexion-Extension	220	33	30.05

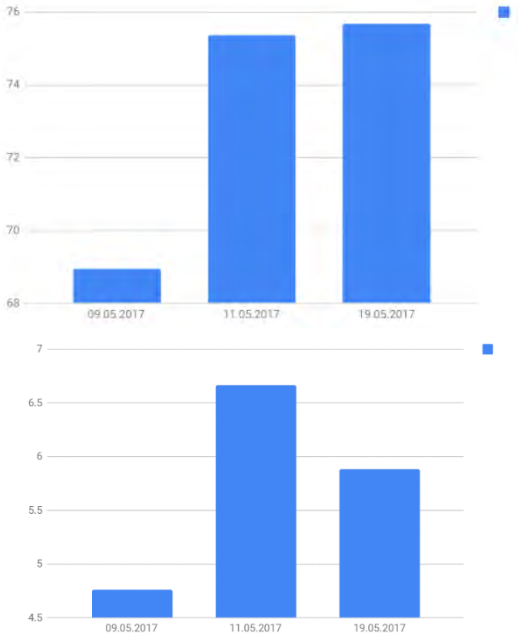


FIGURE 20. Forearm Flexion-Extension: Average scores evolution (top) and average seconds/repetition evolution (bottom).

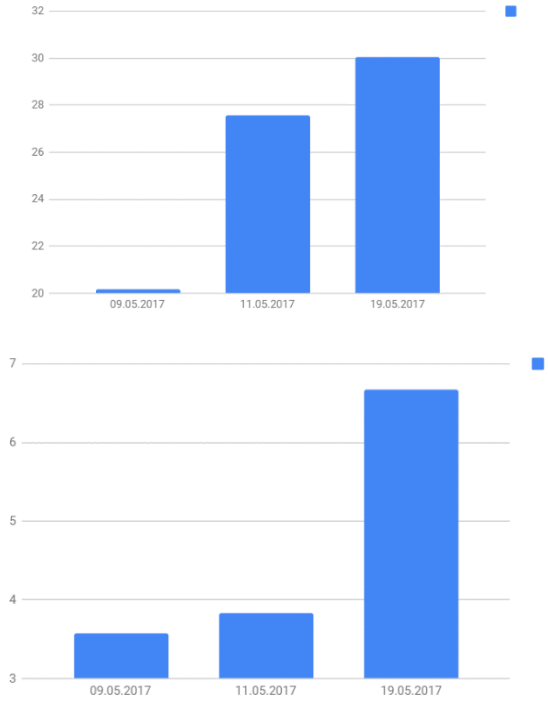


FIGURE 21. Palm Flexion-Extension: Average scores evolution (top) and average seconds/repetition evolution (bottom).

iv) Patient RV15

The patient also took part in several rehabilitation sessions with the system. Slight improvements were observed between the sessions regarding the number of repetitions detected by the system as well as the average scores.

v) Patient RV21

This patient took part in three rehabilitation sessions with the system. For all the three types of exercises there was a reduction in the average execution time, as perceived by the system.

TABLE 6. Exercises executed with TRAVEE by Patient RV15.

Date	Exercise	Secs	Reps	Avg
04.05	Fingers Flexion-Extension	200	32	17.86
04.05	Palm Flexion-Extension	180	10	31.82
04.05	Forearm Pronation-Supination	180	18	125.78
04.05	Forearm Flexion-Extension	180	35	71.5
05.05	Fingers Flexion-Extension	180	40	22.05
27.04	Fingers Flexion-Extension	310	80	18.29
27.04	Palm Flexion-Extension	300	37	35.42
28.04	Forearm Flexion-Extension	300	57	79.7

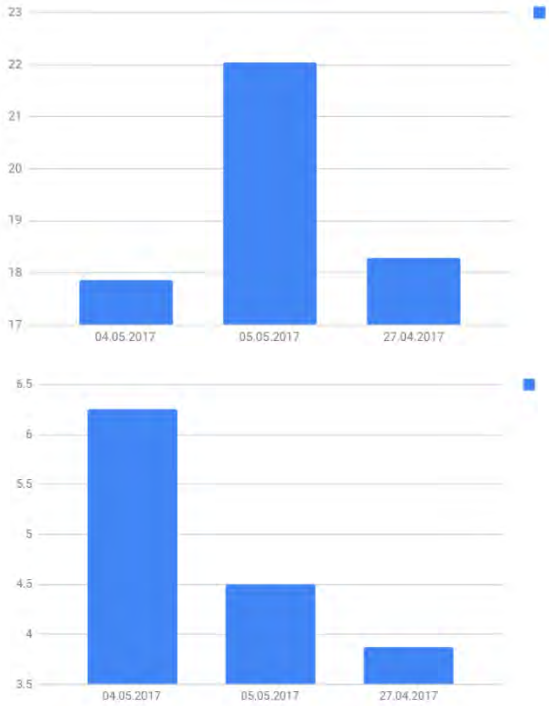


FIGURE 22. Fingers Flexion-Extension: Average scores evolution (top) and average seconds/repetition evolution (bottom).

b: CLINICAL RESULTS/SCORES

We underline that this clinical trial is an initial, acute-type experiment through its design team managed to adjust the TRAVEE program and bring it into its current form. This study will be followed by research to track the effectiveness and efficacy of TRAVEE in patients with stroke sequelae and to transpose the project into real life. The experiments aimed the adaption of the patients, their ability to learn, the ability to integrate TRAVEE into a complex, comprehensible medical poststroke recovery program.

TABLE 7. Exercises executed with TRAVEE by Patient RV21.

Date	Exercise	Secs	Reps	Avg
19.05	Forearm Flexion-Extension	200	29	101.75
19.05	Palm Flexion-Extension	200	43	26.97
19.05	Fingers Flexion-Extension	200	31	28.14
19.05	Fingers Flexion-Extension	120	31	29.13
22.05	Palm Flexion-Extension	200	22	21.28
22.05	Fingers Flexion-Extension	200	55	28.18
22.05	Palm Flexion-Extension	180	61	21.57
22.05	Forearm Flexion-Extension	200	36	96.17
25.05	Fingers Flexion-Extension	200	62	21.98
25.05	Palm Flexion-Extension	200	61	21.57
25.05	Forearm Flexion-Extension	200	36	96.17

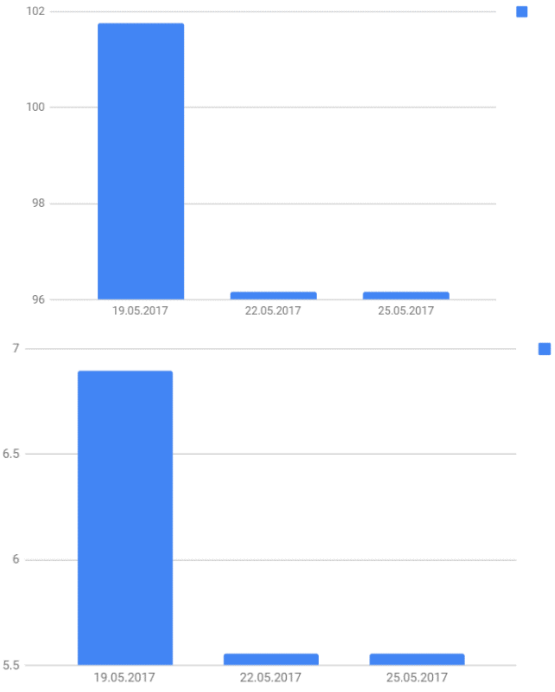


FIGURE 23. Forearm Flexion-Extension: Average scores evolution (top) and average seconds/repetition evolution (bottom).

From the point of view of the outcome of the acute experiment in each patient, this study led to increased motor control in the upper limb, especially proximal and intermediate, in 80% of patients. A statistically significant increase cannot be defined, but the evolution trend is positive. The lack of a positive response was seen in one of the patients with a low MMSE score (19, 20) and in 3 of the patients with

TABLE 8. Questionnaire answers.

Pat.	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
1	2	2			3	4	1	2	3	2	2	3
2	2				3	3	2	3	3	3	3	3
3	3	2	1	1	3	4	1	2	3	2	4	3
4	3	2			3	3	1	2	2	4	2	2
5	4	2	1	1	3	3		2	3	4	2	2
6	4	2	1	2	3	4	1	1	2	4	2	2
7	2	2			3	4	1	2	2	2	2	3
8	3	2	1		3	3		2	3	2		3
8	4	3	2	3	3	4	3	2	3	4	3	3
10	2				3	4	1	2	2	4	2	3
11	2				4	3		3	3	2	4	3
12	4	3	2	3	4	4	3	2	2	3	2	2
13	2				4	3		3	3	2	3	3
14	4	1			3	3	2	3	3	1	3	2
15	4	2	1		2	3	3	3	3	2	3	2
16	2	2		1	4	3	1	3	3	2	3	2
17	4	2	1	1	2	3	1	2	3	2	3	3
18	2				3	3		2	3	3	2	2
19	4	1			3	3		3	2	2	2	2
20	2	2			3	1		3	3	2	2	3
21	4				3	4		3	3	2	3	3
Avg	3.00	2.00	1.25	1.71	3.10	3.29	1.62	2.38	2.71	2.57	2.60	2.57

MAS 2 measured on the MMT scale. The other patients with MAS 2 had a positive response after associating additional stimuli (BCI, Vibration, FES).

There were no serious adverse effects. As a common side effect present in all patients, we underline the fatigue that occurred more rapidly in those with higher cognitive impairment, with grade 2 spasticity and those with low muscular strength; the presence of abnormal movement patterns increased fatigue

Interpretation of results

Using the TRAVEE device for medical recovery of the upper limb function:

1. Allows improvement of motor control at the upper limb for patient after stroke, especially at the proximal and intermediate levels

2. This device is ideal to be use for patients with muscle strength 4 (MMT) patient, less than 2 Ashworth grade spasticity, with no abnormal movement patterns without severe cognitive impairment. Age and cardio-vascular associated pathology do not appear to negatively influence the patient's response to acute experimentation.

3. No serious adverse effects were seen. As a side effect we've identified fatigue. Patients also accused: dizziness, pain, feeling discomfort, but of low intensity, not interfering with the experiment. Just fatigue has the main cause of stopping the experiment.

4. Adding additional stimuli: functional electrical stimulation, vibrational stimulation, cerebral brain-computer brain stimulation seem to increase the positive effect on motor control in patients with lower muscular strength, even in plegical ones.

5. Validation of the method requires a prospective, double-blind, controlled clinical trial in batches of patients sufficiently large to have statistical power.

c: QUESTIONNAIRES

The patients that participated in the clinical trial received a questionnaire containing 12 questions. Each question had five answer options, on a scale from 1 to 5. The questions and the answers given by the patients are presented below.

Q1. During the training sessions, what was the perceived level of tiredness?

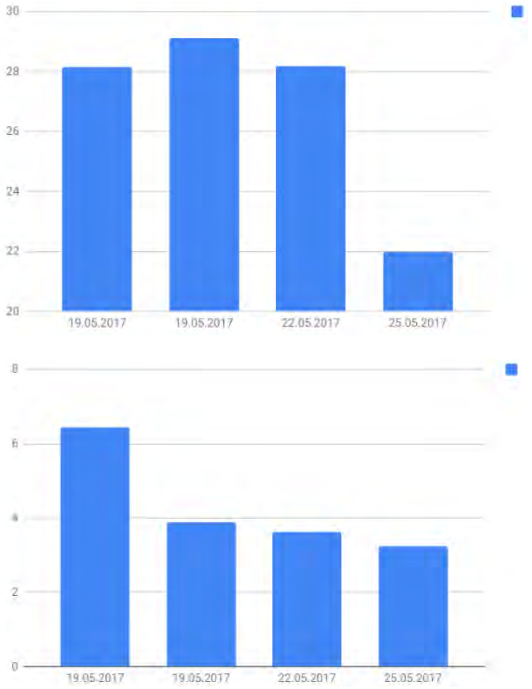


FIGURE 24. Fingers Flexion-Extension: Average scores evolution (top) and average seconds/repetition evolution (bottom).

Q2. During the training sessions, did you feel dizziness? If so, how intense?

Q3. During the training sessions, did you feel nauseous? If so, how intense?

Q4. During the training sessions, did you feel any anxiety or fear? If so, how intense?

Q5. During the training sessions, how clear was the image perceived on the virtual glasses/monitor?

Q6. During the training sessions, did you feel physical discomfort due to the system components? If so, how intense?

Q7. During the training sessions, did you feel pain? If so, how intense?

Q8. During the training sessions, how real did the avatar movements seem to you?

Q9. During the training sessions, how well did you identify your movements to those of the avatar?

Q10. During the training sessions, did you feel that the movements of the avatar were different than yours (greater)? If so, how much different?

Q11. During the training sessions, were the indications of the virtual therapist useful for the exercise execution? If so, how useful?

Q12. Do you consider that the training sessions with this system were useful for your rehabilitation? If so, how useful?

The responses received from the 21 patients are presented in the following table.

VI. CONCLUSIONS AND PERSPECTIVES

The current paper presents the vision implemented by the TRAVEE system, the medical background and perspectives upon which it was designed, as well as technical details regarding its implementation. TRAVEE is a system dedicated to medical neuromotor rehabilitation of the upper limbs that combines multiple technologies: VR, BCI, FES, robotics and haptics, with novel ideas, such as augmented feedback through natural movement augmentation and multimodal feedback. It was designed to support rehabilitation at several levels of disability - providing various degrees of support, from complete movement (through FES and robotics) to support for completing a movement either motor (robotic) or virtual (visual augmentation). The system was tested in a medical setting, during development in two in-vivo sessions, as well as after the final prototype was implemented, through a clinical trial. The paper presents the results of all the testing sessions, that correspond to those of a qualitative evaluation.The results we observed during the clinical trial show that the visual augmentation through VR has a great potential in rehabilitation, that must be further developed and researched.

The perspectives of future development of the system are vast and heterogenous. The main desired evolution for the system is the migration towards a low-cost solution. Providing an accessible system was one of the main targets of TRAVEE and - partially - it has succeeded. The areas in which we believe there is room for improvement are related to the EEG device which may be substituted by a low-cost solution (such as Emotiv Epoc [https://www.emotiv.com/epoc/]). This direction could assist TRAVEE to evolve into a commercially available product, with a wide applicability in the rehabilitation process. This commercial version could be based mainly on the VR component, arm and hand tracking and light robotics, with aspects of gamification. This solution could also be enhanced in clinical settings with the EMG and FES components.

Other possible paths of evolution for our research aim a better understanding of the effects that visual augmentation and multimodal feedback have upon the rehabilitation processes and on the cortical reorganization process. Another direction is to study whether the visual augmentation affects spasticity that appears in patients suffering after-effects of stroke, to test various environments and their influence on the sessions and study evolutions with various visual augmentation degrees and a proper comparison between classical rehabilitation sessions and the ones enhanced through visual augmentation and multimodal feedback.

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