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TEZĂ DE DOCTORAT

A system for Neuromotor Rehabilitation using Virtual Reality

Sistem pentru reabilitarea neuromotorie folosind realitatea virtuală

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1 Introduction

1.1 Motivation

As medicine evolves, more solutions are found for various diseases. From vaccines that prevent disease, to new treatments and surgeries, the medical world is finding new ways of prolonging the lives of the human population.

According to the annual statistic of the American Heart Association (AHA)[1], every 40 seconds a person in the United States of America suffers a stroke, and every 4 minutes someone dies as a result of it. Moreover, stroke is the leading cause of disability in adults in the Unites States[1].

Worldwide, according to a statistic of the World Health Organization (WHO)[2], approximately 15 million persons suffer a stroke each year, out of which approximately 5 million lose their lives, while other 5 million remain with permanent disability.

Such statistics show the frequency of stroke and the need for urgent prevention measures, to decrease the death rates as well as the need for improvements in the rehabilitation of those affected because of stroke.

Technology can potentially assist the rehabilitation of physically disabled patients, and one very promising field in that aspect is Virtual Reality (VR). According to Burdea and Coiffet [1], Virtual Reality can be defined as a realistic-looking environment simulated through computer graphics, with which the user can interact in real-time. The use of such environments could enhance the rehabilitation sessions by presenting the users with scenarios in which they are motivated to perform various movements by being immersed in potential real-life situations in which they must act. This could increase motivation by providing a certain feedback as a result of the movement, could use other technologies to evaluate the progress of the patient and could also represent an assistive tool for the medical practitioner in charge of the session.

This research was part of an extensive national project, TRAVEE (Virtual Therapist with Augmented Feedback for Neuromotor Recovery) that implemented a state-of-the art system dedicated to assisting the neuromotor rehabilitation process. The system creates a Virtual Environment (VE) - in which the patients are immersed - and tracks multimodal data: the movements of the patient, Electroencephalography (EEG) data, Electromyography (EMG). The system then analyzes the multimodal data and, based on this analysis, provides multimodal feedback: visual (visually augmented feedback), haptic (through vibrating motors), robotic (using a robotic glove), or electric - through Functional Electrical Stimulation (FES). This thesis presents my contributions to the TRAVEE project, focused around the functionalities of the Virtual Reality Central System component - the central server of the application - responsible with the main logic of the system and controlling the visual, robotic and haptic augmentation, as well as implementation of several functioning modes, specific for various types of input data and feedback methods. The research also included in-vivo and clinical testing of the implemented components. The testing results gave us a feedback of the patients involved and also a qualitative measure of the system efficiency.

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[1] Heart Disease and Stroke Statistics—2017 Update A Report From the American Heart Association. Referinte\Heart_Disease_and_Stroke_Statistics-2017_Update_A_.pdf
[2] The world health report 2002 - Reducing Risks, Promoting Healthy Life. http://www.who.int/whr/2002/en/. Last Accessed June 2017.

Goals of the research

This research presents the contributions brought to the development and testing of a novel system dedicated to Virtual Reality enhanced rehabilitation after stroke. The goals of the research were to contribute to the implementation of several modules, mainly the Virtual Reality Central System that had multiple attributions: creating the VE in which the patients are immersed and are guided by the Virtual Therapist (VT), serving as the server of the system, that intermediates the communication between all the components while also implementing the main logic of the application and multiple functioning modes – depending on the used input and outputted feedback. The main original idea of TRAVEE – to which I also contributed in implementing – was that of visually augmented feedback. This is currently pending for patent under the title "System, method and computer program for augmenting human movements".

The implementation phases took place according to the project schedule. After the implementation of the initial prototype, that already contained several main functions (the VE with the Virtual Therapist, the main server communicating with all the major components, visual and haptic augmentation, based on either body tracking data as well as a functioning mode for EEG input-based function) the system was tested during two in-vivo testing sessions. These sessions, apart from obtaining a feedback from the patients were also used to validate the solution as being usable in a medical rehabilitation scenario, and to discover any downfalls that had to be remediated. Based on the observations made during these in-vivo testing sessions, the system was further developed to obtain the final prototype of the system, containing all the functioning modes proposed by the project. The final prototype was tested during a qualitative clinical trial before the end of the project. The purpose of the clinical trial was to further validate several functioning modes of the system, while also obtaining feedback from the patients and the doctors.

All the goals of the research were fulfilled, the system was delivered according to the schedule and it successfully passed all the testing phases. The results of the testing phases were a promising feedback received from the patients and led to the discovery of several further research directions that must be studied as they could potentially have a significant impact in the evolution of the VR-based rehabilitation field.

1.2 The author's scientific publications in connection with the thesis

Papers published in conference proceedings
1. *O-M. Ferche, A. Moldoveanu, F. Moldoveanu, V. Asavei, A. Voinea, I. Negoi*, Challenges and Issues for Successfully Applying Virtual Reality in Medical rehabilitation. Proceedings of the International Scientific Conference on eLearning and Software for Education (eLSE), Bucharest, April 2015, vol. 1, pg. 494-501. WOS:000384469000073
2. *A.Voinea, A. Moldoveanu, F. Moldoveanu, O. Ferche*, ICT Supported Learning for Neuromotor Rehabilitation - Achievements, Issues and Trends, eLSE International Scientific Conference on eLearning and Software for Education, April 2015, vol. 1, pg. 594-601. WOS:000384469000086
3. *O. Ferche, A. Moldoveanu, D. Cinteza, C. Toader, F. Moldoveanu, A. Voinea, C. Taslitchi*, From Neuromotor Command to Feedback: a Survey of Techniques for Rehabilitation through Altered Perception, EHB International Conference on e-Health and Bioengineering, November 2015. WOS:00038039790010
4. *A.Voinea, A. Moldoveanu, F. Moldoveanu, O. Ferche*, Motion Detection and Rendering for Upper Limb Post-Stroke Rehabilitation, Proceedings of the 5th IEEE International Conference on E-Health and Bioengineering - EHB 2015, pg. 811-814. Iasi, Nov. 2015, Print ISBN:978-1-4673-7544-3, WOS:000380397900124.

5. *O. Ferche, A. Moldoveanu, M. Dascalu, C-N. Bodea, R. Lupu, D. Irimia, F. Moldoveanu*. The TRAVEE neuromotor rehabilitation system: In-vivo testing. ZINC, Zooming Innovation in Consumer Electronics International Conference, vol. 1, pg. 30-33, 2017. ISBN: 978-1-5386-0865-4. WOS:000392785700165

6. *O. Ferche, A. Moldoveanu, F. Moldoveanu*. The TRAVEE system for neuromotor recovery: Architecture and implementation. EHB E-Health and Bioengineering Conference, pg. 575-578, 2017. ISBN: 978-1-5386-0358-1. (IEEE) DOI: 10.1109/ZINC.2017.7968655.

7. *RG. Lupu, P. Herghelegiu, N. Botezatu, A. Moldoveanu, O. Ferche, C. Ilie, AM. Levinta.* Virtual Reality System for Stroke Recovery for Upper Limbs Using ArUco Markers. 21st International Conference On System Theory, Control And Computing (ICSTCC), vol. 1, pg. 548-552, Sinaia, Romania, 2017. (IEEE) DOI: 10.1109/ICSTCC.2017.8107092, WOS:000427419900090

Unpublished papers presented at conferences

1. *O. Ferche, A. Moldoveanu, F. Moldoveanu*, Brain Computer Interfaces for Neuromotor Recovery –Achievements, Issues, Trends. WPA 2015 Bucharest International Congress. June 2015

2. *O. Ferche, A. Moldoveanu, F. Moldoveanu, V. Asavei,* A Survey of Motion Tracking in Automated Neuromotor Rehabilitation after Stroke. WPA 2015 Bucharest International Congress. June 2015.

3. *O. Ferche, A. Moldoveanu, F. Moldoveanu*, An up to date survey of assistive technologies for neuro-motor rehabilitation using Virtual Reality. SpeD International Conference Speech Technology and Human-Computer Dialogue, October 2015.

Papers published in journals

1. *O-M. Ferche, A. Moldoveanu, F. Moldoveanu, M-I. Dascalu, R-G. Lupu, C-N. Bodea*. Deep Understanding of Augmented Feedback and Associated Cortical Activations, For Efficient Virtual Reality Based Neuromotor Rehabilitation, Revue roumain des sciences techniques, Série Électrotechnique et Énergétique, 2018, issue 2, pg. 233-239. (Impact Factor = 1.114) WOS:000428622400006

2. *O. Ferche, A. Moldoveanu, F. Moldoveanu*, Evaluating Lightweight Optical Hand Tracking for Virtual Reality Rehabilitation, Revista Română de Interacţiune Om-Calculator, 2016, vol. 9, no. 2, pg. 85-102. DOI: 10.5171/2017.155350

3. *C.A. Boiangiu, M. Zaharescu, O. Ferche, A. Danescu*, Automatic Correction of OCR Results Using Similarity Detection for Words and Fonts, International Journal of Applied Mathematics and Informatics. 2016, vol. 10, pg. 10-18.

Books

A. Moldoveanu, F. Moldoveanu, M-I. Dascălu, A. Ioniţă, O-M. Ferche, V. Asavei, A. Morar, UML Practic, Matrix Rom, 2014.

A. Moldoveanu, F. Moldoveanu, O. Balan, O-M. Ferche, TRAVEE - Raportare la Stadiul Actual al Domeniului. Abordare si Obiective Generale. Chapter in TRAVEE - studiu de caz - initierea unei cercetari ICT in recuperarea neuromotorie, volum colectiv editat de Alin Moldoveanu, Printech, 2014.

Prizes and awards

Distinguished Paper. *O. Ferche, A. Moldoveanu, M. Dascalu, C-N. Bodea, R. Lupu, D. Irimia, F. Moldoveanu*. The TRAVEE neuromotor rehabilitation system: In-vivo testing. ZINC Zooming Innovation in Consumer Electronics International Conference, 2017.

Annual BCI award 2018 nomination. Neuromotor Recovery based on BCI, FES, Virtual Reality and Augmented feedback for upper limbs. Robert Gabriel Lupu, Florina Ungureanu, Oana Ferche, Alin Moldoveanu. Awarded by BCI Award Foundation, Stanford University.

Research projects
TRAVEE – Virtual Therapist through Augmented Feedback for Neuromotor Recovery. National project, PN-II, ID. 1/2014(PN-II-PT-PCCA-2013-4-1580), 2014 – 2017

1.3 Thesis structure

The thesis is composed of 11 chapters. It begins with a first chapter presenting the motivation for my work during the doctoral studies as well as the resulting scientific publications. The second chapter briefly presents some details regarding the biology of cerebrovascular accidents and the hypotheses regarding cortical reorganization that support the potential of the ideas behind the thesis. Chapter 3 presents a survey regarding the use of Virtual Reality technology in the rehabilitation processes and the issues that may arise from it. Chapter 4 contains a survey of existing work in the field of rehabilitation through altering the perception of the patient. Chapter 5 analyzes existing rehabilitation solutions developed with various commercially available technologies. The thesis continues with a brief presentation of the TRAVEE project in Chapter 6, containing overviews of the functionality available for the patient and the therapist, the description of the rehabilitation movements included by TRAVEE as well as an overview of the system architecture. Chapter 7 presents my contributions to the TRAVEE system regarding the evaluation of available technologies for motion tracking and brain computer interfaces. Chapter 8 contains a presentation of my contributions to the implementation of the TRAVEE functionality. In chapter 9 I describe the results of the two in-vivo testing sessions with the initial prototype of the TRAVEE system, while chapter 10 presents the results obtained from the clinical trial with the final prototype.

2 Stroke

According to information available on the *National Stroke Association* page[3], stroke is a disease of a region of the brain that appears as a result of an interruption of the blood stream towards it. Blood is responsible – among others – with transporting the oxygen necessary for cellular life towards the tissues in the body. If a region of the brain is deprived of the blood flow for a certain amount of time, the neurons in the respective region die, and with them, disappears – partially or totally – the set of abilities controlled by that region.

Depending on the cause that lead to the interruption in the brain blood flow to the affected brain area, stroke can be *hemorrhagic*, *ischemic* or *transient*.

The hemorrhagic stroke is caused by an aneurysm in the blood vessels in the brain (an abnormal dilation of a weakened area of the wall of a blood vessel[4]. This type of stroke, although less common, is usually fatal[3].

In the case of an ischemic stroke, the impairment of the region in the brain is caused by a blockage in the blood vessel caused by a clot that interrupts the normal blood flow[3].

There is also the transient stroke, in which the blood flow is only temporarily interrupted, that manifests itself with the same symptoms as stroke, but they disappear after maximum 24 hours after apparition[3].

According to the World Stroke Organization, each year 15 million people suffer a stroke worldwide[5]; in every 1000 newborn children, 2.1 are estimated to suffer from cerebral palsy [41] and only in the United Stated, in 2010, approximately 2.5 million emergency department visits, hospitalizations or deaths were associated with traumatic brain injuries[6]. This leads to an increased number of patients which require that alternatives are found to the classical rehabilitation procedures, to support the activity of the medical staff and to accelerate the rehabilitation process.

Medicine has found ways of prolonging the lives of these patients, but in most cases, they suffer a permanent motor disability as a direct cause of the accident or disease. This imposes a great burden on the patients, caretakers, medical professionals and society. The motor rehabilitation process is a long-term commitment for all those involved, as it requires many repetitions of the same exercise and long periods of time. During this process, the medical staff may be overwhelmed, and the patients may lose focus or motivation.

One promising solution for these issues seems to be using Virtual Reality for neuromotor rehabilitation. Presenting the rehabilitation process as a task-oriented activity in a virtual environment will stimulate the attention of the patients, providing rewards to motivate them and also may ease the process for the rehabilitation specialists, by recording precise data regarding the session in order for them to analyze it at an ulterior time.

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[3] National Stroke Association. Hope after stroke. „Understand stroke." http://www.stroke.org/understand-stroke/what-stroke. Last Accessed June 2017.

[4] Spitalul Monza. Anevrismul cerebral. https://www.spitalulmonza.ro/afectiune/anevrismul-cerebral/. Last Accessed June 2017.

[5] World Stroke Organization - World Stroke Campaign. http://www.world-stroke.org/advocacy/ world-stroke-campaign. Last accessed July 2017.

[6] CDC Injury Center Traumatic Brain Injury & Concussion: Get the Facts. https://www.cdc.gov/ traumaticbraininjury/get_the_facts.html. Last accessed July 2017.

2.1 Risk factors for stroke

The 2002 World Health Report[2] is one of the greatest projects in which the WHO was involved and evaluates worldwide data to identify the amount of disease, disability and death as well as the associated risk factors and to identify ways to reduce them effectively. In this report[2], risk is defined as "a probability of an adverse outcome, or a factor that raises that probability". The risk factors are diverse, and the report excludes those related to bacterial and viral infections, antimicrobial resistance, etc. as it focuses on a selection that are often the causes for major diseases. Apart from risk factors, the report also considers several *protective factors* that are considered to increase resistance to disease, promote healing and minimize or delay disability. It is stated that these factors must also be considered in a risk assessment process. Such protective factors are fruit and vegetable intake and physical activity.

Out of the risk factors, several are connected to stroke, as can be observed in the following table:

Risk factor	Theoretical minimum exposure	Measured adverse outcomes of exposure
Blood pressure	115; SD 11 mmHg	Stroke, ischaemic heart disease, hypertensive disease, other cardiac disease
Cholesterol	3.8; SD 1 mmol/l (147 SD 39 mg/dl)	Stroke, ischaemic heart disease
Overweight	21; SD 1 kg/m²	Stroke, ischaemic heart disease, diabetes, osteoarthritis, endometrial cancer, postmenopausal breast cancer.
Low fruit and vegetable intake	600; SD 50 g intake per day for adults	Stroke, ischaemic heart disease, colorectal cancer, gastric cancer, lung cancer, oesophageal cancer
Physical inactivity	All taking at least 2.5 hours per week of moderate exercise or 1 hour per week of vigorous exercise	Stroke, ischaemic heart disease, breast cancer, colon cancer, diabetes

Fig. 2-1 Selected major risks to health - outcome of exposure includes stroke[2]

These risk factors are very common in today's world: according to WHO[7] in 2008 around 40% of adults aged 25 and above suffered of raised blood pressure, the highest in the Africa region, with 46%, and lowest in the region of the Americas, with 35%.

The prevalence of raised cholesterol was estimated in 2008 at 37% of the males and 40% of the female population[8] while in 2016 approximately 39% of the world population aged 18 and over were overweight (Body Mass Index – BMI $\geq$ 25), with 13% of the population being obese (BMI $\geq$ 30)[9].

This information shows that the risk factors for stroke are very common in today's world and therefore measures must be taken to prevent stroke and – until then - to minimize its consequences.

2.2 The human brain

In an image representing the motor cortex homunculus (a graphical representation of the human brain surface with the associated controlled body parts drawn at a smaller or larger scale approximating the proportion of the cortex surface that controls it), such as the one below, it is easy to observe that a significant area of the cortex is dedicated to the motor control of the hand and fingers. This fact could mean that a condition that affects the cortical integrity may – with a sensible probability – also affect these regions, thus impairing the movements of the hand or arm.

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[7] WHO | Raised blood pressure. http://www.who.int/gho/ncd/risk_factors/blood_pressure_prevalence_text/en/. Last accessed March 2018.

[8] WHO | Raised cholesterol. http://www.who.int/gho/ncd/risk_factors/cholesterol_text/en/. Last accessed March 2018.

[9] WHO | Obesity and overweight. http://www.who.int/mediacentre/factsheets/fs311/en/. Last accessed March 2018.
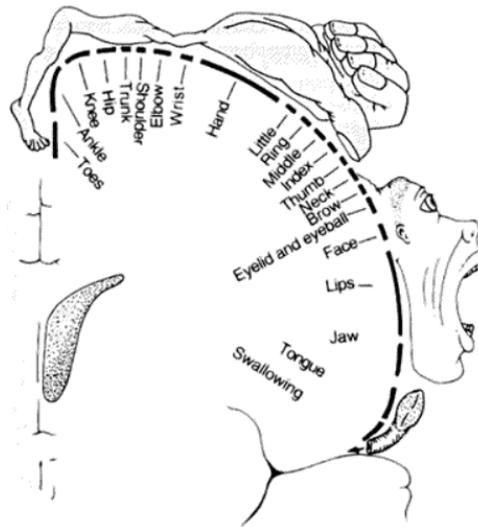
Fig. 2-2 The motor cortex homunculus [10]

2.3 Cortical reorganization

Studies such as the one made by Schaechter et. al. [2] reveal the possibility of rehabilitation of patients that have lost the abilities associated to a certain area of the brain due to disease, through a process named *cortical reorganization*. This process is using the plasticity of the cortex and represents the possibility that new neural paths are built in order for the regions of the brain that are adjacent to the affected one to overtake its attributions, basically the patient re-learning the lost abilities.

For re-learning lost abilities, there were studies that revealed the potential of Virtual Reality to support this process by creating realistic visualizations to simulate lost abilities. A study regarding this subject was published in [3] and studied the available literature regarding the role played by fooling the brain through additional visual and motor feedback in the process of creating alternative neural pathways in rehabilitation.

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[10] Neurobiology. http://neuronbiology.synthasite.com/brain-structure.php. Last accessed February 2018.

3 Virtual Reality in Rehabilitation

Virtual Reality is a technology that has been available since the late '80 [5] and currently its application domains cover a wide range, such as:

- Aviation (pilot training in virtual environments)
- Education (simulations that create a feeling of "being-there" for students and educators of various fields in order to train for future real-life situations)
- Archaeology (creating replicas of existing work)
- Medicine, where VR proves to add promising value to various activities, from surgical training to rehabilitation and experiments.

Physical rehabilitation is a branch of medicine that is dedicated to helping the patient re-learn behaviors and gestures that were lost because of an accident or disease. This often proves to be an overwhelming task for the patient and for the clinician. Many repetitions of the same movement may be necessary until it is re-learned and can be executed independently. This is one of the many reasons why technology and particularly Virtual Reality could be a major help in assisting the medical rehabilitation sessions: a VR environment could present the patients with an example of the correct movement that they have to execute, as well as create an interesting environment that would motivate them to continue the session without getting psychically tired or lose focus. A virtual environment is also flexible, and it could be adapted to various deficiencies and personal preferences of the patients, allowing them to rehearse actions in a safe environment, thus providing less anxiety and enhancing their autonomy in real life situations [6].

Several relatively recent studies have shown that VR-enhanced rehabilitation sessions could potentially be more efficient than non-immersive ones [5]. Together with telemedicine (providing medical assistance from distance through technology), VR has the potential to deliver therapy services to patients in rural settings or therapy at home [4] for patients that would otherwise not be able to access these services. A comprehensive study of VR worlds is the one made by Moldoveanu et. al. [7].

Although VR seems to be an enormous potential to the rehabilitation process, VR technology developers need to consider the potential issues that can arise from implementing technology for a medical field especially where disabled people are the targeted users.

Virtual Reality can create limitless scenarios using dedicated software and hardware for information transfer from the user towards the system and from the system towards the user. The system output can be transmitted using various stimuli: visual, auditory, haptic, vestibular or olfactory [8].

Visual information is usually presented using a Head Mounted Display (HMD), a device consisting of two small displays positioned in front of each eye within special helmet or goggles. Such displays are

Oculus Rift[11], a virtual reality headset with low latency head tracking and stereoscopic view, Google Glass, a lightweight head mounted display[12], HTC Vive[13] or the Fifth Dimension Technologies HMD[14].

Auditory system response engaging the user in the virtual world can be transmitted either through dedicated headsets or using audio devices integrated to the head mounted displays (such as the Oculus Rift). Binaural audio is a technology dating back to the 1800s that records sounds exactly as the human ears would perceive it, thus it is able to recreate the sound so that the listener were actually involved in the scene where the recording was made[15].

More complex Virtual Reality systems also provide haptic feedback that enables its users to experience tactile sensations therefore recreating the sense of touch through vibrations or forces. The physical sensation of resistance integrated into VR instruments is called force feedback[16]. In medicine such systems that reproduce resistance are especially useful in training for surgeries, as well as in remote procedures. In rehabilitation, force feedback could prove to be very useful, as it could provide feedback to a patient undergoing treatment by simulating the presence of solid objects in the VE to sustain reproducing daily activities. Force feedback is transmitted with the aid of haptic gloves and exoskeletons (lightweight robotics, taking the shape of human body parts to perform or assist movements) - that are mostly not affordable on a large scale - or through a joystick or steering wheel.

The enhancement of the virtual world with olfactory feedback, whose potential has not been yet thoroughly investigated is possible, but still rarely implemented [8].

As described by Weiss et. al. [8], the number of applications of VR in rehabilitation continues to grow due to various advantages it provides over traditional practices:

- Can simulate an environment that would otherwise be dangerous. Examples of such applications are: training patients with neglect to safely cross the street, or to assess the driving capabilities of patients following brain injury.
- Allows control over provided stimuli and environmental adaptations to the performance of the patient
- Allows quantification of performance and could lead to standardization of treatment protocols, as presented in an application that assesses the cognitive function using a virtual kitchen, presented in [9] or in one that quantifies the hand functions such as range of motion of fingers after stroke [10].

3.1 Related works

The survey presented in this chapter was disseminated – although remained unpublished – in:

O. Ferche, A. Moldoveanu, F. Moldoveanu, An up to date survey of assistive technologies for neuro-motor rehabilitation using Virtual Reality. SpeD International Conference Speech Technology and Human-Computer Dialogue, October 2015. (unpublished).

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[11] Oculus Rift | Oculus. https://www.oculus.com/rift/.
[12] Google Glass Explorer Edition. https://developers.google.com/glass/.
[13] VIVE™ | Discover Virtual Reality Beyond Imagination. https://www.vive.com/eu/
[14] 5DT | Training Simulators and Virtual Reality. http://www.5dt.com/
[15] Binaural audio is returning from obscurity to make virtual reality more awesome – Polygon. http://www.polygon.com/2015/2/12/8028379/binaural-3d-audio-virtual-reality-oculus-rift-project-morpheus. Last accessed July 2017.
[16] Medical Dictionary. http://medical-dictionary.thefreedictionary.com/

The purpose of this subchapter is to assess the state-of-the-art in using Virtual Reality for rehabilitation with focus on works published in the past years, in order to ensure the novelty of the presented data.

In general, the existing research regarding VR-enhanced rehabilitation seems to be focused either on developing a proof-of-concept system with original one-of-a-kind hardware or on using existing technology in order to obtain a solution that is accessible not only to hospitals and rehabilitation facilities, but also for at-home rehabilitation. The at-home rehabilitation solution has become more of an option once low-cost VR equipment (such as the Wii Fit[17], Microsoft Kinect[18], Oculus Rift[11], etc.) has become available in recent years.

Virtual Reality is gaining more and more applications in the medical motor rehabilitation field, due to its great advantages, such as: stimulating movement and cerebral activity, increasing attention levels and the ability to simulate various environments that enhance the rehabilitation sessions by increasing motivation or allowing the patient to feel comfortable in a familiar environment rather than that of a medical facility [42], and the hypothesis of cortical reorganization.

One of the main ideas that supports the advantages of using Virtual Reality in rehabilitation is cortical recovery or reorganization, such as discussed by Schaechter et. al. [2]. This is evidence that after a certain area of the cortex was disabled as a result of an accident, it is possible for new neural links to be constructed in order for nearby cortical regions to overtake the functions of the lost tissue. In order for this process to take place, the patient needs to re-learn the lost capabilities.

VR could help in such processes, as it can simulate disabled capacities thus reminding of the lost abilities by creating the associated immersive sensations through supplemental feedback.

3.1.1 VR-enhanced sessions vs. Classical rehabilitation

An experiment that evaluated the efficiency of VR-enhanced rehabilitation sessions compared to that of classical rehabilitation is described by Turolla et. al. [44]. This experiment [44] documented the results obtained using Reinforced Feedback in the Virtual Environment (RFVE) therapy combined with Upper Limb Conventional (UCL) ones over double UCL traditional techniques. 263 patients received both methods of treatment while 113 received double the UCL number of sessions. Out of these patients, 129 were included in the program less than 3 months after stroke, 148 between 3 months and a year after their accident, and the remaining 99 were admitted more thanone year after stroke. The patients were also divided by their proficiency on the Fugl-Meyer Upper Extremity scale into three categories: mild (over 40), moderate (21-39) and severe (<20).

The rehabilitation therapy in this experiment[44] consisted of 40 total hours, divided in sessions of daily therapy (5 days per week for 4 weeks). The therapy of the RFVE group consisted of one hour of traditional UCL session and one VR enhanced session, while the UCL group had two hours of UCL therapy.

The VR therapy system used by Turolla et. al. [44] was VRRS (Virtual Reality Rehabilitation System - Khymeia Group, Noventa Padovana, Italy), consisting of a computing workstation connected to a Polhemus Liberty 3D motion-tracking system and for the display of the virtual scenarios, a high resolution LCD projector. The RFVE therapy required the patients to interact with the virtual environment by performing certain movements while holding a real object in their hands and being monitored by a motion tracking system. One of the exercises required the patient to repeat a movement performed as an example by the therapist: the therapist executed the movement of placing a glass on a shelf in the virtual environment by moving a glass with an attached receiver for position monitoring. The movement performed by the therapist was recorded and displayed in the virtual environment as a

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[17] Nintendo WiiFit. http://wiifit.com/. Last accessed July 2017.
[18] Microsoft Kinect. http://www.xbox.com/en-US/xbox-one/accessories/kinect. Last accessed July 2017.

line that the patient needed to follow when trying to repeat the exercise. The therapist adapted the difficulty of the task (by complicating the required movement, adding obstacles, etc.) for each patient and was able to increase it once the patient progressed.

The classic therapy was based on the Bobath principles [45] and the exercises included: flexion-extensions of the shoulder, abduction-adduction, rotations and finger flexions.

The outcomes of the experiment were evaluated using the Fugl-Meyer Upper Extremity (F-M UE) scale [46] and the Functional Independence Measure [47] and found an increase with 10% for RFVE therapy on F-M UE scale, compared to 4% in UCL and an increased improvement with 5-7% on FIM scale for RFVE compared to UCL. The only difference between the test and the control group were related to the number of included individuals (70% in RFVE compared to 30%) and the fact that the RFVE group was – on average – 4 years younger.

3.1.2 Dedicated systems

Here we enlist the systems encountered in our research that do not use commonly available hardware solutions but solutions dedicated to rehabilitation systems.

Rutgers Arm II

The experiment described by Burdea et. al. [48] uses the Rutgers Arm II and studies the possibility of simultaneous motor, cognitive and emotional rehabilitation by using virtual environments. Two subjects suffering from severe traumatic brain injury (TBI) exercised their upper limb by means of playing an engaging virtual game using the Rutgers Arm II.

The Rutgers Arm II [49] is a virtual reality rehabilitation system consisting of a low-friction forearm support that slides on a table that tilts four ways with 0-30 degrees, a visual tracking system guided by LEDs placed on the corners of the table, on the forearm support and on the opposite shoulder for compensatory movement detection, a multicore PC and a display. Games developed for this system use Java 3D and include a "pick-and-place" game that requires users to move objects following a given trajectory, or a "treasure-hunt" game that tests arm endurance. Trials with a chronic post-stroke subject showed difficulty increases substantially with table tilt angles.

The patients involved in the experiment described by Burdea et. al [48] both have mild depression symptoms and impaired attention capabilities. The training sessions had various durations and difficulties, included dual-tasks and rewarded increase in performance. Evaluation was made prior to the experiment as well as post experiment and a 6 week follow up and included emotional and attention capabilities evaluation as well as motor functions of Fugl-Meyer scale and Activities of Daily Living assessment.

The tilt of the Rutgers table was used to support grasp actions. Five games were used during the sessions, out of which a card matching game ("Card island") was used to train short-term and visual memory while "Tower of Hanoi" game – which required subjects to move disks from one pole to another using a third one as an intermediate – exercised the participant's arm movement and grasp functions. Evaluation of the performance in these games included the number of mistakes made and the duration until the completion of the task.

Participant 1 showed an increase in shoulder and pinch strength post sessions, and a small improvement of the motor abilities. Hand speed increased by 25% and reported to not have any more difficulties with the 7 out of the 20 ADL reported as being difficult pre-training.

Participant 2 maintained the pre-sessions level of depression but remarked an increase in auditory attention levels while the simple visual attention increased as a result of the sessions but suffered a small decrease until follow up. The motor abilities increased: 100% in shoulder strength and 200% increase

in grasp strength, as well as a 3 point improvement of Fugl-Meyer score, and a 30% increase in writing speed.

Bright Arm

Rabin et. al. [50] present an experiment that evaluates the results that can be obtained using the BrightArm system for the upper limb rehabilitation of elderly patients post stroke. The BrightArm system is the follower of the Rutgers Arm II (one improvement being that it does not require table rotation in order to exercise the opposite arm) and is formed of a table actuated by motors with a computer-controlled arm support, two digital cameras with infrared (IR) sensors, a display and a multicore PC, games specially designed for rehabilitation and a server. In order to use the system, the patients place their hand on the arm support and grasp a rubber pear whose air pressure is monitored and transmitted wirelessly to the PC. The position of the hand is monitored with the aid of two diodes placed on the arm support. Table tilting produces different degrees of difficulty.

The games available for the BrightArm are similar to the ones on the Rutgers Arm II: Pick-and-place, Breakout 3D, Treasure Hunt, Card Island and Towers of Hanoi 3D. Pick-and-place requires the user to grab an object in the virtual world and to place it on a specific location following a given trajectory. Breakout 3D is a version of the original game but the user needs to perform a grasp movement in order for the ball to bounce off the platform. In Treasure hunt the user acts by moving a shovel to dig out several treasures. The shovel cannot be moved unless a grasp gesture is maintained. Card Island is targeted to short memory exercise and grasp movements while the Tower of Hanoi game exercises grasping and logic. Each game produces rewarding feedback for progress.

The experiments described by Rabin et. al. [50] included 5 participants between ages of 62 to 81 who had suffered a cerebrovascular accidents between 19 and 119 months before. Each participant was subjected to 18 sessions, 3 sessions per week, the length of the sessions started from 20 minutes in the first weeks and went up to 40 minutes in the last three weeks. Also, the sessions became more difficult towards the end of the testing period by increasing the inclination of the BrightArm table from 0 degrees in the first week to 20 degrees in the last two weeks.

The outcomes of the experiment showed that all of the patients showed improvement in shoulder strength. All the participants could not lift wrist weights prior to the experiment and after they were all able to lift 1-2.5 lbs. Grasp strength improved in 4 out of the 5 participants. Shoulder extension and flexion increased with 5-30 degrees, while elbow flexion increased with as much as 25 degrees. Also the authors note uniform improved attention of the patients as well as improvements in memory.

ImAble

Jordan et. al. [51] present an upper limb rehabilitation system consisting of three devices dedicated to rehabilitation using virtual games, each targeted to a different kind of exercises. The Able-B system is used for self-assistive bilateral arm exercise that supports the hemi paretic arm against gravity and its movements are supported by the other arm. A web camera is used for arm motion tracking, by detecting a colored patch placed on the affected arm in order to be mapped in the game world.

The Able-M is a tabletop system designed for unilateral gravity supported exercises for the disabled arm. The affected arm is strapped onto a devices that can slide across a table surface thus controlling a mouse cursor. Several buttons can be attached for finger exercises.

The Able-X system is a lightweight handlebar designed for against-gravity bilateral exercises. The handlebar has an incorporated motion sensitive game controller (similar to the Wii but for computer interaction) that is placed onto the side of the disabled hand. Rotations of the bar in transversal and sagittal planes produce horizontal and vertical mouse movements.

The games designed for these systems include static, strategic and dynamic target hitting.

The results of the experiment were evaluated in improvements in the Fugl-Meyer upper limb disability scale.

With the Able-B the increases in the 5 subjects varied from 1 to 5 points after 6 weeks of therapy. For the Able-M the three post-stroke patients obtained increases between 1 and 11 points, while with the Able-X the mean improvement was 4.2 for the 14 subjects. The conclusions underline the potential of the ImAble system, the adaptability of its three versions to various disabilities as well as the increase in motivation observed in the tested subjects.

Gertner Tele-Motion Rehabilitation System

Kizony et. al. [52] investigated the feasibility of a telemotion-rehabilitation system using the Gertner System for acquired brain injury (ABI) patients. 18 subjects were included in the experiment (9 in the test group and 9 in the control group). The Gertner Tele-Motion Rehabilitation System was used to intermediate the communication between the client (in the experiment – a room in the hospital instead of the patient's home) and the clinician. For the 3D video motion detection a Microsoft Kinect was used. The system could be used in clinician-to-one-patient or clinician-to-many-patients modes, in synchronous or asynchronous (offline) modes.

The tele-rehabilitation sessions consist of video games that implement three key rehabilitation principles: control of difficulty, knowledge of results (the patient and the clinician are informed regarding the results the patient obtains in the session – also stored offline for further analysis) and knowledge of performance (the patient and the clinician receive ongoing feedback regarding the progress of the abilities of the patient). The system implemented five games of various difficulties, each requiring certain 3D movements. For each game, several files containing raw kinematic data of the movements are generated and stored for further analysis.

The results of the experiment show greater improvement in the test group compared to the control group, but the authors state they need to be interpreted cautiously due to the small sample size.

SEMUL

Hata et. al. [53] present a more interactive way of using the SEMUL rehabilitation system. According to the description provided by Hata et. al. [53] the SEMUL system stands for Simple Exercise Machine for Upper Limbs and is designed to help with patient rehabilitation. The authors state that the main components of the system are a handle that provides a force feedback, a display that presents the user with a scenario where he is required to perform a simple task using the force feedback handle, and eight predefined routines. The existing exercises are found by the authors to lack providing the user with quantitative evaluation and amusement. The authors therefore developed a coin-collecting type of game dedicated for the SEMUL system in order to increase the motivation for rehabilitation of the patients as well as to provide a quantitative evaluation. The experiment performed by Hata et. al. [53] was also followed by a questionnaire that concluded that the challenge in the coin collecting game provided more amusement for the users compared to the existing exercises and that a quantitative evaluation is possible based on the data acquired by the system.

Trackhold

Comani et. al. [54] present a proof-of-concept type of system that integrates high-resolution EEG (HR-EEG) with Trackhold (a robotic arm that compensates gravity using counter-weights) and five dedicated virtual reality training applications into a system for neuromotor recovery monitoring that can be adjusted to the motor abilities of each user and can perform quantitative measurements of both neural and motor recovery. The three involved patients all had disabilities in their non-dominant upper limb. MRIs were performed before the sessions in order to be used for EEG data post-processing.

In the experiment described by Comani et. al. [54], using the system, EEG data was acquired in association with the execution of specific training tasks in order to quantify task-related changes in the electrical activity of the cortex. The five tested VR applications simulate ADLs or require simple visual-

motor coordination capabilities. Some of the applications are: Sponge – that requires the user to clean the display with a virtual sponge using free arm movements in all four directions, three of them require reaching tasks in a plane or in 3D while the last applications needs that the patient follows a given trajectory.

The patients involved in the experiment presented by Comani et. al. [54] were required to perform 13 rehabilitation sessions using the given system and were evaluated at sessions 1, 7 and 13, using five different scales (Nine Hole Peg Test, Motricity Index, Barthel Index, FIM, canadian Stroke Scale). The movements of the patient were also evaluated by their duration, path length, smoothness (normalized jerk) and speed. The HR-EEG data was also evaluated in order to establish correlations between the active areas in each during the sessions. The results indicated significant improvements on all considered scales for two of the three patients. The correlations between the activated area of the brain and the motor progress indicated that some patients tend to over-recruit the cortex when performing simple tasks in the first sessions, a tendency that decreased with rehabilitation. For more complex tasks, the reverse tendency was observed: activation areas and intensity increased with exercise.

CAREN

Barton et. al. [55] studied the efficiency of a custom game run on the CAREN system (Motek Medical, Amsterdam, The Netherlands) for the improvement of core control in a child with cerebral palsy (CP). The child played a game called "Goblin Post Office" for 30 minutes twice a week for a period of six weeks. No other form of rehabilitation was performed beside the VR enhanced one. Improvements were observed in core control after the experiment.

The CAREN system, as described by Barton et. al. [55] contains an 8 camera Vicon 612 optoelectric motion capture system (Oxford Metrics, UK), a platform that moves with six degrees of freedom (DOF) and a video projection system.

BioTrack

Llorens et. al. [56] describe BioTrack, a virtual reality system aimed to support balance deficits rehabilitation. They [56] also present an experiment with 13 patients suffering from acquired brain injury that participated in 15 enhanced rehabilitation sessions whose progress on a Berg Balance Scale was evaluated and discussed. Considering the number of body systems that need to contribute for an accurate balance (visual, proprioception and vestibular) it is very probable that a brain injury may affect this capacity. Conventional therapies for balance recovery include posture control in stationary state, such as lifting weights, or while performing daily activities, such as reaching gestures. Novel approaches of rehabilitation processes involve task oriented activities, an area where virtual reality can contribute considerably.

As presented by Llorens et. al. [56] BioTrack was developed as a versatile balance rehabilitation system that requires the patient to perform game-oriented tasks through body movements. BioTrack can be adapted to various environments and allows the use of several tracking technologies (optical, kinetic, electromagnetic). Three modules can be identified in the BioTrack architecture: the manager – designed for the therapist, allows defining various sessions and study the evolution of the patient; the database – storing information regarding the users and the sessions archives – and the exercises – a bundle of six exercises, comprising movements that must be performed from standing as well as a sitting position. Examples of task-oriented games available in the BioTrack system include a sitting game that places the user in the center of a circle divided into 8 segments and when a segment changes color, the users must reach their hand in the direction given by the circle. A task that requires the users to stand would show visual indicators on the ground and the users would have to move their feet or cane to press to the position of the visual indicator.

For the clinical evaluation of the BioTrack, Llorens et. al. [56] chose a hardware configuration consisting of a PC, two infrared (IR) cameras and a LCD screen for video display. The chosen

participants were 13 patients who suffered balance disorders as a result of brain injuries. Each patient took a total of 15 sessions of 30 minutes each, three sessions per week. The balance conditions were assessed prior and after treatment, using the Berg Standing Scale (BSS), the Tinetti Balance (TBA) and Tinetti Gait Assessment (TGA). The results showed an improvement of six points on the BSS, one point on the TBA and 2.3 points on the TGA.

PneuGlove

The PneuGlove is a novel pneumatic glove dedicated to motor rehabilitation of the hand that provides assistance to each digit without restraining arm movement. It can be used to train grasp-and-release movements in real or virtual environments [57].

Tsoupikova et. al. [58], a heterogenous team of scientist, engineers and VR artists, developed a system dedicated to upper limb rehabilitation using VR. The components of this system are: two 30-inch LED displays placed at a 150 degree angle, head and hand trackers (Flock of Birds by Ascension Technology) and the PneuGlove, a pneumatic glove developed at the Rehabilitation Institute of Chicago. A previous study by the same team applied to 14 subjects with chronic hemiparesis concluded the system is appropriate and engaging for therapy but tiring as the configuration used to have a HMD instead of the dual monitor.

Through the presented scenario, in the experiment presented by Tsoupikova et. al. [58], the user is required to perform various ADLs repetitively while an avatar (the March Hare) guides and exemplifies a series of exercises. In many exercise scenarios, the users use a reach and grasp action and receive immediate feedback (if the grasp is too loose, the objects fall and shatter; if the grasp is too tight, the objects explode). Also, a score system is implemented and permanently displayed on the user's screen.

The system architecture of the presented system [58], consists of two communicating systems: the therapist and the patient. The therapist decides the exercise to be performed and its success criteria and the amount of assistance provided through the pneumatic glove (the glove can aid independent finger extension by inflatable air bladders). The client station controls the VR scene, created using 3DVIAVirtools (Dasssault Systems, France). The VR environment is updated according to the orientation of the user's head.

In the study[58], 9 patients followed the therapy 3 sessions every week, during 6 weeks. They were evaluated by a therapist previous to the sessions, immediately after the completion of the sessions and during a follow up meeting after one month. The experiment was still running at the time the article was published but 4 patients had already finished the therapy and three showed palmar pinch increase. The observed data is noted to not be statistically relevant – the article states – but a faster completion time was remarked for the performed tasks. Further development of the system plans to replace the magnetic trackers with Microsoft Kinect.

Another experiment involving PneuGlove is presented by Lord et. al. [59] and describes a low cost virtual reality rehabilitation system that trains the fingers of patients disabled as a consequence of stroke by playing a virtual piano. The virtual scene contains a piano pad and a virtual hand. For simplicity and for the patient to be able to focus on the movement of the fingers, the hand is permanently positioned above the piano keys, no hand or head tracking is involved. For tracking of the movement of the fingers, the PneuGlove is used.

The 5 key piano presented by Lord et. al. [59] was created in Autodesk Maya and was further imported in Virtools (Dassault Systèmes, Vélizy-Villacoublay, France) for animation in the VE. In the described system [59], a computer runs Virtools and renders the scene, while communicating to the second computer that runs a Visual Basic application that intermediates the control of a PneuGlove. The two computers communicate via Transmission Control Protocol (TCP). The system has three modes of functioning: train, learn and play and a further study is expected with clinical evaluation.

The conclusions after studying some of the research developed in the past five years were that the field of Virtual Reality assisted rehabilitation is a very dynamic one that seems to be evolving towards low-cost and easily available solutions. As all the researched experiments proved to bring an improvement in the motor abilities of the patients – even years after the cortex was affected by an accident – it appears to be critical that the technologies become available on a large scale for patients to continue their rehabilitation process on a longer term.

3.2   Potential issues regarding the use of Virtual Reality in the rehabilitation process

Parts of this chapter were disseminated or published in the following papers:

O-M. Ferche, A. Moldoveanu, F. Moldoveanu, V. Asavei, A. Voinea, I. Negoi, Challenges and Issues for Successfully Applying Virtual Reality in Medical rehabilitation. Proceedings of the International Scientific Conference on eLearning and Software for Education (eLSE), Bucharest, April 2015, vol. 1, pg. 494-501.

O. Ferche, A. Moldoveanu, F. Moldoveanu, An up to date survey of assistive technologies for neuro-motor rehabilitation using Virtual Reality. SpeD International Conference Speech Technology and Human-Computer Dialogue, October 2015. (unpublished).

This chapter lists the issues identified as a result of studying the available literature.

Accommodation
The first issue with using VR for medical rehabilitation is that it needs a greater time for the patient to accommodate to the virtual reality that is very probably quite different from the reality the patient is accustomed to.

After having suffered a stroke, patients are most certainly in a fragile psychical state and placing them in an unknown environment, or in one that is greatly different from the natural one may produce them a great shock.

It is vital for the success of the Virtual Reality therapy that the patients are given time to accommodate to the VE and that they are immersed gradually, to allow them to accept it and feel comfortable in it. Another way of making the environment comfortable is by reproducing a calming, known virtual world, where the patient can feel safe, or even use augmented reality in the first sessions to allow the patient to understand that the environment where the sessions take place is slightly different form known reality.

Another accommodation issue is related to the equipment necessary to create such a system. A head mounted display (HMD) imposes an extra weight to the head of the patient, that may take time to get accustomed to or may not even be an option as in some patients postural control muscles are also affected by the disability [12].

Transferring performance
One key issue with VR rehabilitation is pointed out by Holden et. al. [12] and refers to the transfer of the performance obtained, from VR into the real world. In this article it is stated that many studies examine learning in a virtual environment but do not asses the degree in which the achievements from the virtual world can be used in the real world, as the two are not equivalent and the discrepancies between them may affect the rehabilitation sessions in a negative way.

Holden et. al. [12], discuss an experiment [13] where three groups of subjects were trained to move a set of cans to matching positions: one set was trained in the real world, a set was trained in a Virtual

Environment (VE) and the third set received no training. The conclusion of the test was that the set of subjects trained in the VE obtained the same results in the real environment as the set that received no training, although their performance in the VE improved at the same rate as the real world trained set. The causes of this observation were related to the differences between the two environments.

To obtain a successful performance transfer, the actions exercised in the VE should match the movement necessary in real life as well as possible. Although the differences between virtual and real must be diminished, the effort should not be concentrated solely on obtaining the best possible accuracy of the real environment, as Holden et. al. [12] state that discrepancies between the two should be assessed permanently in order to avoid improving the fidelity beyond what is necessary to obtain an efficient training session.

Maintaining motivation

Although maintaining motivation seems to be one of the advantages of using VR enhanced rehabilitation solutions, the designers of such systems must take into consideration the fact that simply providing a virtual teacher that the patient must try to imitate is not sufficient. A regular rehabilitation session - assisted by a clinician - counts on the observation of the therapist for adjusting the performed exercises.

Methods for assessing the concentration levels of the patient, as well as ways of adjusting or changing the session contents according to these observations must be included in a VR rehabilitation system. These adjustments must be made with consideration, as very complex or realistic elements present in the environment may appeal to a normal subject but may overwhelm a rehabilitation patient [12].

User interfaces

The user interface must be adapted to the patient's degree of understanding of existing technology (a patient that has used a similar device pre-stroke may re-learn to use it fast, or may not even need a learning time) and to the disability, as it should not impose greater effort on the patients who must be fully concentrated to the exercises and movements that they make during the session and not to using the given user interface.

A solution to this drawback is using 3D motion capture hardware, such as a cyber-physical system consisting of a network of sensors placed on the exercised limb, that would permanently asses its position, therefore updating the virtual world according to the actions of the patient without him making any extra effort.

The second problem imposed by the user interface is the way the virtual world is displayed to the user. The use of a desktop screen may be more familiar, but it certainly does not provide a great degree of immersion. The solution of using virtual reality glasses, that display the virtual world in 3D provides a superior quality immersion but needs a greater time to get accustomed to. The patient could be given time to experiment with the display interface in a simple virtual reality before starting the rehabilitation sessions to acquire more familiarity.

Usability

Another aspect that is also related to the user interfaces is that the system needs to be as easy to use as possible.

This is especially difficult as the rehabilitation process is a very complex one, many parameters need to be taken into consideration, and it also needs to provide a variety of functionality and difficulty levels to adapt to the real sessions, therefore obtaining these results through a very simple graphical interface is a considerable effort.

One of the main usability issues imposed by VR is generated by the complex equipment involved in such rehabilitation sessions, and by the lack of maturity of this equipment. Complex technology requires

complex commands and is therefore difficult to use by the non-technical medical staff. Still in development, the VR technology has not yet reached its maturity and it has yet to achieve complete customer understanding and acceptance[19].

Another usability issue is strictly related to the use of VR technology for rehabilitation purposes and is due to the condition of its users. Disabled users may have a difficulty in re-learning to use a device that they were accustomed to before the accident and even more in getting used to a new technology and to new input devices.

Even considering usability as a priority in developing the user interaction system, there is still needed that the clinician has an end-user technical expertise, a problem that may be resolved by training the clinicians in using the system in a clinical location prior to appointing actual rehabilitation sessions.

Supervision
Even though VR rehabilitation systems could at one point in the future be used in an at home environment, because they are still a relatively newly researched field, supervision by a medical professional with technical expertise is still advised thus affecting the advantage of at-home rehabilitation.

An option for remote supervision would be telemedicine - providing remote medical assistance or monitoring through existing telecommunication technologies - that would request a supplemental effort from the clinician as well as for the clinic, to provide and get accustomed to the required technology.

Device compatibility
VR rehabilitation is still a newly emerging field and a VR system for the disabled is a complex one, that generally includes at least a motion tracking system or another user input device, display and sound equipment, cameras, various vital parameters monitoring systems, or even a Brain Computer Interface (BCI) all connected and able to transmit information to a central system, for the rehabilitation session to take place safely and with the best results. Each of these components has its own interface, and standardization has not yet been achieved, thus the engineering effort of developing such a system. In many cases, it is nearly impossible to replicate the same execution environment, because of differences between various existing configurations (graphic cards, trackers, drivers, etc.) [14].

Costs
There are two economic issues that must be taken into consideration: the profitability for the developer of VR rehabilitation systems and the cost for the end user. As it is a challenge to estimate the costs of such a system, many are discouraged to tackle developing this kind of product.

We have discussed the issue of producing a flexible VR rehabilitation system that needs to adapt to different hardware configurations, but it also has to adapt to different clinical situations, a problem that is even more difficult to assess, as it needs a deep understanding of the specific rehabilitation process, and thus cannot cover all possible situations, so the targeted market is generally narrowed to one or a few specific rehabilitation session types.

The second economic issue is the cost of such systems for the end user. Morrow et. al.[15] present a cost comparison between a possible low-end configuration of a VR system used for upper limb rehabilitation and a similar high-end system. The low-end configuration (including Xbox, a P5 glove for hand motion tracking, and the free Java 3D programming toolkit) adds up to a cost of $549, while

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the high-end system presented here[15] costs $17.800 (including more expensive hardware and software, a powerful PC, CyberGlove[20] motion capture glove, WorldToolKit[21] for VR development).

While the cost comparison of the two configuration is favorable in terms of cost to the low-end one, lower costs also imply lower performance. The P5 glove is less accurate than the CyberGlove. An even more expensive alternative, as Morrow et. al.[15] state would have been the Rutgers Master II glove that can also provide force feedback.

Although there are experiments that test the possibility of developing a VR rehabilitation system using more affordable devices such as Play Station II [17], a Wii console [18] or a Kinect[22] the prices for a full software and hardware commercial and immersive system can reach tens of thousands of dollars, and therefore, even if this would be acceptable for departments or hospitals it is still unaffordable for a single user [16].

Ethical issues

Ethical issues [19] must also be taken into consideration when using Virtual Reality in rehabilitation: the patients must be able to accept the virtual environment and to understand the immersion process in order to guard them from any emotional distress, and the patients must be asked to inform the therapist immediately if they feel discomfort or side effects.

Side effects

Holden et. al. [12] state that there seem to be no reports of negative side-effects from using a desktop version of a virtual reality system, and most of them are associated to immersive technologies created usually with head mounted displays.

The possible side effects of the virtual reality therapy must be explained to the patient and to its tutors previously to starting the sessions and the therapy must be halted if any of them are present.

According to Rizzo et. al. [14], there are two categories of side-effects related to VE: cybersickness and aftereffects. The term cybersickness was coined by McCauley and Sharkley in 1992, and it is used to describe a phenomenon resembling motion sickness produced by being immersed in a moving virtual environment while remaining still.

The symptoms of cybersickness are reported to include nausea, vomiting, eyestrain, disorientation, ataxia, and vertigo [20]. The after effects are generally due to the fact that the subject has adapted to the virtual world sensory and motor requirements and needs time to return to the real world ones.

The symptoms of after effects may include "disturbed locomotion, changes in postural control, perceptual-motor disturbances, past pointing, flashbacks, drowsiness, fatigue, and generally lowered arousal" [21].

Legal issues

According to Manhal-Baugus [19], some of the legal issues generally concern:

- informed consent – the patients, their legal guardian or other authorized party must be informed regarding the process, its potential risks, benefits and alternatives and they must provide their consent
- standard procedures – the clinician must also follow the standard procedure of the rehabilitation process when using Virtual Reality, the purpose of the technological system is to enhance the session, not to alter its fundaments

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[20] CyberGlove Systems LLC http://www.cyberglovesystems.com/. Last accessed October 2018.

[21] WorldToolKit - http://www8.cs.umu.se/kurser/TDBD12/HT00/lab/wtk/. Last accessed October 2018.

[22] Kinect Rehabilitation with Biofeedback | SeeMe > What is SeeMe system? http://www.virtual-reality-rehabilitation.com/products/seeme/what-is-seeme. Last accessed September 2018.

- emergencies – the procedure in case of emergency must be very well established and in case it was related to the enhancements of the VR technology, the patient must revert to the classical rehabilitation sessions.

4 Rehabilitation through altering perception

Parts of the contents of this chapter were published in the following paper:

This chapter presents a study of the available literature regarding the possibility of "fooling" the brain by providing augmented feedback to detected motor actions or commands, thus possibly stimulating the cortical reorganization process, the brain associating the perceived (augmented) result with the performed efforts. The research included here were selected to contain the presentation of real tests, to describe the used system, and to focus on the rehabilitation of the upper limb, to evaluate the validity behind the TRAVEE system.

The augmented feedback in the TRAVEE system consists in presenting the movements of the patients in an augmented manner, to be more easily observed and to encourage the patients to continue their rehabilitation efforts. The methods used by the system to provide multimodal feedback are numerous: visual augmentation (increasing the movement amplitude), haptic (through vibrating motors that provide tactile feedback on certain key-points of the exercised limb), functional electrical stimulation (FES) and motor assistance through a robotic glove.

4.1 Virtual Reality Box

A classical rehabilitation method that uses visual augmentation is mirror therapy [23], that uses a mirror placed vertically in front of the patient in the sagittal plane, in such a manner that the movements performed by the healthy hand and arm are perceived as being performed simultaneously by the disabled one, as can be seen in Fig. 4-1. This technique was first introduced by Ramachandran et al. [23] where it was successfully used to eliminate or reduce the pain in phantom limbs of amputees of the upper limb. Such experiments suggest the utility of a virtual feedback in rehabilitation.

Fig. 4-1 Mirror therapy [24]

The technique was named "mirror box" as not only a mirror was used, but a box with a mirror placed as described, so that the patients would place the stump of the missing limb inside the box, hiding it from their sight, in order for the visual effect of the existing, functional limb placed inside the box to be achieved.

Fig. 4-2 The Virtual Reality box created by Ramachandran et. al. [23]

The experiments described in this article are aimed at discovering the benefits brought by such a device regarding certain 'phantom limb' symptoms such as pain in the missing limb, a clenching spasm or the so-called paralysis of the missing limb. Such conditions are often experimented by the recently amputated as messages from the motor cortex continue to be sent to the missing limb, but no feedback is received. The experiments were performed on ten upper limb amputees, all neurologically intact that were first carefully questioned regarding their medical history.

The experiments described by Ramachandran et. al. [23] required the patients to imagine themselves performing symmetric, mirrored movements with their hands, at first while keeping their eyes closed and afterwards while looking in the mirror-box. All the performed experiments showed that patients were able to experiment the feeling of performing controlled movements with their amputated limb while using the device. They were able to send commands and – by receiving visual feedback – they had the feeling of unclenching the missing limb – thus relieving the pain. All the experiments showed that the patients were not able to 'perform' the movements while having their eyes closed – proving the importance of the illusion of the movement. The spasms were noted to disappear for up to several hours after the exercises were performed, and a repetition of the exercises would again relieve the pain.

The experiments of Ramachandran et. al. [23] also evaluated the possibility that the efficiency was a result of a placebo effect – by testing the application of TENS (transcutaneous electrical stimulator) on the healthy arm and informing the patient that this will relieve the pain. The patient reported that the pain persisted when the TENS were applied and was only relieved by the exercises in the virtual box thus proving that the effects were not related to a placebo effect – which could lead to the idea that the phenomenon is more than a result of autosuggestion. Another patient [23] exercised at home using the device 15 minutes a day for a few weeks in order to determine whether the effects could be permanent - if the voluntary control of the missing limb could be restored permanently. The voluntary control of a missing limb refers strictly to the sensations of the amputee. After losing a limb, some patients still experience vivid sensations in the missing part of their body, because the brain is not aware of the loss, therefore is sometimes still sending commands to that area of the body [23]. Sometimes, these discrepancies between command and feedback generate a feeling of lacking control that sometimes lead to a perceived pain in the missing part. The patient in the experiment discussed by Ramachandran et. al. [23] returned with the observation that the missing limb had disappeared completely - as a result of

the mirror-box exercises - leaving only the palm and fingers dangling from the shoulder stump – a phenomenon that could be described as the amputation of the missing limb.

The same work of Ramachandran et. al. [23] presented an experiment that evaluated the possibility of controlling the missing limb by observing the movements performed by a different person – visual feedback without sending the motor commands. The patients reported that the sensations were not as strong as when the movements were performed by their own healthy hands. A reason that may be behind these observations is that although the patients may imagine that the movements are performed by themselves – as this is the visual feedback they observe – their brain is not the one sending the respective commands – therefore the immersion feeling is decreased, and the perceived feelings are not as intense. The conclusions – as reported by all the patients involved – show that there is certainly an undebatable improvement in the conditions of the disabled patients when performing exercises that have a strong visual feedback – that are not related to a placebo effect or that are not a simple result of the imagination of the patients.

4.2 Mirror therapy

Chan et. al. [25] present an experiment completed by 18 subjects that evaluated the efficiency of mirror therapy for relieving phantom limb pain in amputees of one of the lower limbs. The experiment also compares the efficiency of mirror therapy to that of mental visualization. The involved patients were divided into three groups: one that used mirror therapy and needed to imagine themselves performing a movement with both their limbs while looking in the mirror at the reflection of the movements performed with healthy one, another group performed their exercises in front of a covered mirror while imagining themselves performing a movement with both their legs and one that used mental imagery – closing their eyes and imagining that they perform a movement with their amputated limb. The therapy was performed for 15 minutes daily for four weeks and the subjects were asked to keep a record (severity and duration) of their pain episodes during the therapy. In the mirror therapy, all the patients reported a decrease in their pain episodes in both duration and intensity, while 50% of the covered mirror group and 67% of the mental imagery group reported an actual increase in pain sensations. These observations lead to a correlation between mirror therapy and reduced pain symptoms as the authors noted that visual feedback of the missing limb might reduce activity in systems that perceive non-localized pain [26]

Young et. al. [27] present an explanation as to why mirror therapy is so effective, as well as the case of a patient for whom classical therapies such as medication or physical therapies did not work. Young et. al. [27] state that observing the reflected functional limb dissolves the mismatch between the command that the patient initiated and the observed feedback, thus improving the therapeutic efficiency. The same work [27] also presents information regarding the fundamentals of mirror therapy as stated by Rizzolatti [28][29]. This explanation is based on the discovery of a so called mirror neuron, that is activated both when a person performs a movement or when the person observes the movement performed by someone else (the neuron mirrors the action as if it were performed by the observer) thus helping in recognizing experiences, behaviors and intentions in others [28][29].

Young et. al. [27] also state that – according to Rossi et. al. [30] – these neural activations are specific to the disabled – the activation of a functional limb blocks this mirroring neural pathway through a non-mirror neuron block – which is not functioning for the disabled limbs.

4.3 Functional Electrical Stimulation

Moseley and Flor [28] tested the hypothesis that chronic pain in a phantom limb can be relieved by stimulation in a functional context. This presumption was tested on upper limb amputees by applying electrical stimuli with various frequencies on the stump and training them to distinguish between them. The subjects were divided into a test group and a control group. The test group received the described treatment for 10 days, 90 minutes per day. After the final evaluation, it was observed that the test group

reported decrease in phantom limb pain by more than 60%, the performance and tactile acuity improved, and in some cases, cortical reorganization reverted (certain areas of the brain regained their normal functions).

4.4 Augmented Reality

Regenbrecht et. al. [32] present a system designed to explore the benefits that come from fooling the brain into thinking that a movement was better than it actually was (such as amplifying a small movement). The study also validates a system, Augmented Reflection Technology (ART) that provides an augmented reality environment dedicated to support neuromotor recovery in stroke patients. The ART system consists of two cardboard boxes with curtains, lighting and web cameras, as well as a monitor with a keyboard and mouse for an operator to control the rehabilitation session. The patients place their hands inside the boxes and only see them on a screen; the images that appear to the patients are mediated by the system and the operator – thus allowing them to be controlled in various ways.

Regenbrecht et. al. [34] tested the ability of the ART Augmented Mirror Box to fool the brain in various setups. The first setup, named "Playing with ice and fire" mirrored the left hand on both sides of the screen – without the knowledge of the subject. The subjects – all healthy individuals with normal movement abilities in both their hands – were required to perform symmetrical movements with their hands placed inside the device. A different background was used on each side of the desktop screen – one presenting the inner part of an ice cube, and the other a burning coal. The assumptions in this experiment were that the subjects would not notice the mirror effect and that they would perceive different temperatures in the two boxes due to the suggestive backgrounds. The thirty-two participants were selected from the non-clinical staff and students of the Otago University. Only 28% of the participants observed that the hands were mirrored and just 12.5% were able to tell that their left hand was the mirrored one. The perceived temperature was not influenced by the background.

Another experiment described by Regenbrecht et. al. [34] – a therapeutic case – evaluates the efficacy of the system for treating chronic foot pain. The setup had to be slightly altered to be used for feet. The subject was evaluated using Likert scales for pain, comfort, temperature, sensitivity and itch. The fact that the subject reported improvements in comfort and decreases in pain and "stabbing" sensations while performing movements in "mirrored" mode shows that the mirroring provided by the AMB was able to "fool" the brain.

Regenbrecht et. al. [35] compare a classical optical mirror box (OMB) to the augmented mirror box (AMB). While the OMB is affordable, portable is an already familiar instrument and does not require any high-end technologies, it is bound to the laws of optics (it cannot alter reality apart from classical optical illusions). The AMB is able to perform image manipulations by mixing the real and the virtual and is very flexible, thus allowing multiple scenarios to be played out with a single setup. While similar from several points of view, the authors of the paper state that the AMB has a strong therapeutic potential due to its ability to fool the brain by creating perceptions that are beneficial to the therapeutic purposes.

Hoermann et. al. [33] describe another Augmented Reflection Technology concept, the TheraMem, dedicated to neuromotor recovery after stroke, based on the ART system. TheraMem is described as an augmented reality memory game. The user is presented with two black boxes – as is the case for the ART system – but inside the boxes, in the presented virtual environment, the users see twelve tiles that they must group in pairs by moving their hand above the tiles and flipping them by performing a pointing gesture. The system allows the operator to increase the amplitude of the movements, in order for the patients to perceive a movement that is larger on the screen than they actually performed in the box. The experiments with the TheraMem were performed on five patients recovering from stroke.

The 60 minute session required the patients to play the described memory game. All the subjects involved were able to finish a game round in under 4 minutes.

The results showed improvement on the Fugl-Meyer and in the MAS scale for two of the patients. The interviews that followed showed that the patients enjoyed the sessions and were highly engaged and motivated to continue, stating that such exercises should be included in the general rehabilitation process.

4.5   Virtual Reality

Feintuch et. al. [36] present and evaluate VirHab, a system that employs a motion capture system in order to process the image of the patients that see themselves in a virtual reality where small movements of the paretic arm are represented as full range ones of a healthy limb. The main purpose of the system is to accelerate the plastic recovery of the brain in order to treat chronic pain generated by conditions such as cerebrovascular accidents, traumatic brain injury or complex regional pain syndrome.

In his article on the works of Hadassah et. al., Siegel-Itzkovich [37], states that the authors of the VirHab classify the process of recording a small movement and providing the visual feedback of a correct one to be a "corrective learning" approach. This approach requires that the patient performs a small movement with a mouse or joystick to fully control virtual limbs that they observe on the screen – observing a full range healthy movement helps the patient re-learn the given action through the correction of the perceived visual feedback. The system is also stated to help relieve chronic headaches by helping the patients "to associate between relaxed behavior and the image of themselves as painfree" [37]. Based on the plasticity of the brain throughout life, it is expected that "seeing" the virtual environment and being immersed in it, when the users see the affected limb moving as a healthy one they may be tricked into thinking it has recovered and may "educate" the brain to alleviate the pain.

Similar to the presented research, the team involved in the research presented by Eng et. al. [38] believes in the premises that motor cortical observation, planning and execution is learned by correlating observed feedback with intended actions and that viewing mirrored movements of a healthy limb mirrored as movements of the paretic limb generates activation in the damaged parts of the motor cortex. The presented system is based on the Torque multi user 3D gaming environment and uses 3D digital compasses for arm position tracking to create a virtual environment in which the patients observe their hands on a wide LCD screen in the same orientation and position as their own, from a first person point of view. The mirroring effect can also be turned off (for the patient to observe the real movements) or on (in which movements from the healthy limb are transferred in the virtual world to the paretic one) with the use of mapping parameters – which establish the movements of which joint will be transferred to the other hand – thus making the system very versatile – the movement of one or more joints may be mirrored to the paretic limb and the moving speed may be easily increased or decreased.

4.6   Conclusions

All of the analyzed experiments were able to generate an improvement in the condition of the subjects by creating an altered visual feedback – either by using a mirror or a virtual or augmented environment. These findings are in accordance to the ideas that were implemented in the TRAVEE system: augmenting the feedback based on detected progress is highly probable to actually fool the brain into thinking the movements are real, thus supporting the process of relearning neural behaviors as well as increasing the motivation of the patients, as observable progress is most likely to be found encouraging.

5 Rehabilitation solutions with commercially available hardware

Parts of this chapter were disseminated in the following paper:

In this chapter we discuss about several hardware devices that are affordable and may be used for at-home motor rehabilitation.

Microsoft Kinect

A study by Cho et. al. [60] presents the development of a Virtual Box and Block test that can be performed in an at-home setting in order for patients who suffered a stroke to be evaluated remotely.

The classical Box and Blocks test requires the patient to be seated at a table and to be presented with two compartments. In one compartment there are 150 blocks and the patient has to move to the other compartment as many blocks as possible in 15 seconds[23].

Cho et. al. [60] present a virtual version of the classical test, a Virtual Box and Block game, developed in the Unity game engine. The game – as the classical one - presents the user with two virtual compartments and it requires moving a cube from one compartment to the other. As soon as the cube has reached its destination, another cube appears in the first compartment. The system can be adapted for the left hand as well as for the right one.

Data for hand motion tracking is acquired in the system presented by Cho et. al. using a Kinect and processed using the 3Gears Systems open source library[24].The 3Gears library processes 3D information from 3D cameras or Kinect in order to determine accurate data regarding the position of arms and wrists.

The conclusions of the experiment described by Cho et. al. [60] taken on 9 stroke patients with an age average of 67 ±8 years found correlations between the scores obtained in the BBT and in the VBBT but the scores in the virtual environment were found to be significantly lower, the authors concluding that this fact could be related to the interaction with the virtual reality.

Ballester et. al.[61] made an evaluation of the importance of socialization in motor rehabilitation of the upper limb. For this hypothesis, the Rehabilitation Gaming System (RGS) is used, in combination with an ICT Virtual Reality tool. The RGS system consists of a dedicated software (RGS), a common computer, a motion sensor (Kinect) and a tripod. The system can also be extended to include gloves for motion tracking or 3D glasses. In this experiment, the RGS was used in combination with two low cost key gloves. The Torque Game Engine was used to develop a memory game card for the patients to compete in. The game has a single player version, where the users would play the game on their own, as well as a two player version in which the patients would take turns and could also communicate. The game requires memory, attention, as well as a reach-and-grasp movement.

The experiment performed by Ballester et. al.[61] evaluated the performances of six patients with disorders related to the nervous system. Each patient was required to play one 10 minute game in each of the play modes. Two variables were used for evaluation of the movement: elbow and shoulder movement, and both improved better for the multiplayer group. The findings of this experiment[61]

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[23] Box and Blocks Test Instructions. http://www.rehabmeasures.org/PDF%20Library/Box%20and%20Blocks%20Test%20Instructions.pdf. Last accessed July 2017.

[24] 3Gears System SDK. http://nimblevr.com/latest/doc/CppAPI/. Last accessed July 2017.

reveal that patients affected by CNS disorders may benefit from the combination of new therapies and social networks.

WiiFit

Yeh et. al. [62] describe a VR system designed for vestibular rehabilitation. The system contains two subsystems: a training and an assessment system. The assessment system consists of a WiiFit used to determine the center of gravity of the patient in real time in order to observe the changes during the training. The training includes a setup of four tasks: head movement while eyes are focused on a point in space, eye movement while the head is not rotating, a Basketball exercise that requires the patients to move their hand according to the positions indicated by three basketballs, and a ball throwing exercise that requires that the patients perform a ball throwing movement. For the last two exercises, the movement of the body is recoded by a Microsoft Kinect. The direction of the head is determined using a LED marker and camera tracking. Over 50% of the 17 patients recorded progress in terms of evaluating balances indexes as a result of the training sessions.

Crotty et. al. [63] present a research regarding the efficiency and the safety of the Nintendo Wii Fit for physiotherapy in a hospital environment compared to classical therapy. 44 participants 65 years old or older with a score of 21/30 or more on the Mini Mental State Examination (without cognitive impairment) from the Geriatric Evaluation and Management Unit of a public Australian hospital for acute care in Adelaide were selected for the trial. 22 patients were assigned to 8 classical physiotherapy sessions while the other 22 took part in 6 sessions with the Nintendo Wii Fit of 25 minutes per session. Results found no adverse results during the Wii Fit sessions and a small increase in performance in the enhanced sessions over the classical ones for the Timed Up and Go test, which required the patient to stand up from an armed chair and to walk 3 meters in a straight line.

ioTracker

Schonauer et. al. [64] evaluated a system dedicated to chronic pain rehabilitation through serious games. The hardware setup includes a professional passive marker based infrared optical motion capture system (iotracker [65]) that calculates the 3D position from images taken by several cameras. The tracking system has a low latency (20-40 miliseconds) and an accuracy of approximately 0.5 cm. The system also integrates a low cost motion tracking alternative (Kinect). The second component is represented by the bio signal acquisition devices (Gtec g.MOBIlab and TMSI Mobi) which have several sensors out of which the most important for the purpose of the system is the electromyography sensor (EMG).

The workflow of the system [64] contains several steps: calibration, skeletal tracking, motion data transformation, game configuration and game play. The data acquired from the motion capture system and the bio signal devices is considered "raw" data. In order to extract the positions of the limbs and the filtered EMG data, an intermediate layer is needed between the sensors and the game engine. In this case, the intermediate layer consists of the Open Tracker framework that connects al input devices (using TCP sockets and XML messages for communication) and offers a unitary interface to the game engine. Aside from live manipulation of the data, Open Tracker also stores the raw information into files for further medical reference. Finally, the processed data is sent to the Unity 3D game engine.

Among the purposes of the system proposed by Schonauer et. al. [64], the authors list: improved reaching ability, improvement of cervical motion, increased movement smoothness. For these purposes, a set of three mini games was developed. One of the game requires the patients to run through a maze, collect items and avoid obstacles, thus improving their walking speed; in the second game the users exercise extending their arms and reach gestures and the third game requires the players to imitate a set of head movements performed by other game characters, thus increasing cervical motion smoothness and velocity.

The six patients with chronic pain involved in the testing of the system [64] reported a decrease in pain level (from 62 to 52 on a Visual Analog Scale of pain – a variation equal to or greater than 13 is stated

to be clinically relevant) after four weeks of gaming. On the pain disability index scale, the sum score dropped from 30 to 28. Three patients also reported increases in the six minutes walking test, with 37, 40 and 97 meters respectively.

Qualisys

Ustinova et. al. [66] present the testing of the results obtained through short term practice with a 3D immersive video game (Octopus) for patients with traumatic brain injury (TBI). The system consisted of a PC integrated with a 6-camera system for motion tracking (Qualysis AB, Gothenburg, Sweden) using three markers attached to each hand. The game was implemented using World Wiz software (WorldViz LLC, Santa Barbara, CA, USA) while the models and animations were made using Autodesk Maya (Maya®, Version 7.0.1; Autodesk, Inc., San Rafael, USA). The game scenario presents an underwater world where an octopus is placed in the center of the screen and creates bubbles that move towards the users – represented by the left and right hand avatars, who have to produce a movement with one of their hands in the direction of the bubble in order to intercept it.

Six participants with mild-to-moderate TBI were involved in the experiment presented by Ustinova et. al. [66]. The participants played the Octopus game 10 times during one session and received no previous instructions regarding the way the bubbles should be popped which resulted in the first movements of the hand to be longer and less accurate. By the end of the trial, the hand trajectory became shorter and less curved. All participants recorded improvements in game score during the sessions. After completion of the session, five out of the six participants displayed improved reaching distance.

Playstation and EyeToy

Sandlund et. al. [67] evaluated the efficiency of a low-cost at-home game-based system for rehabilitation dedicated to children suffering from cerebral palsy (CP). The proposed solution consists of a Sony PlayStation2 equipped with the game EyeToy Play 3. The fifteen children involved in the experiment, aged 6-16, were asked to play the EyeToy game for 20 minutes per day for 4 weeks, and were evaluated before and after this trial period. For the evaluation, the kinematics caption was made using a five camera analysis system (Proreflex, Qualisys AB, Gothenburg, Sweden) that uses infrared light and 27 markers. The data was recorded in two different conditions: virtual – when the children played the EyeToy game – and real – while they were performing a non-exercised real-world task, reaching for real objects.

The results of the experiment presented by Sandlund et. al. [67] showed decreased peak velocity in both scenarios. The movements in real-world tasks were smoother, without differences in the virtual world, while movement precision improved in the virtual world without affecting the real-world tasks. The conclusions underline the importance of studying the nature of the exercised task when interpreting kinematic data.

Myo armband

Lipovsky et. al. [68] described an experiment with a proof-of-concept system designed at the University of Lisbon that is dedicated to hand rehabilitation using video games – named "hand therapist". The system consists of a Myo armband, a home-made robotic glove and the Unity 3D engine for game development. With a 9-axis inertial measurement unit (IMU) and 8 electromyography sensors[25] the Myo armband provides information regarding the position of the hand as well as the hand poses (gestures) and communicates it via Bluetooth to the Unity engine.

The system [68] also included an approximately 100 euros home-built glove, consisting of a sports glove with nylon wiring and two motors controlled by an Arduino Uno board.

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[25] Myo Gesture Control Armband | Wearable Technology by Thalmic Labs. https://www.myo.com/. Last accessed July 2017.

In the Unity game proposed by Lipovsky et. al. [68], the user is required to grab, hold and transport a cube through puzzles of various difficulties. The operation of the described system is as follows: the movements of the healthy arm and hand as detected by the Myo armband are replicated on the disabled one by using a robotic glove The same movements are simultaneously represented into the VE. The system has only been tested with healthy subjects so far, but it shows great potential for a low cost (under 500 euros) rehabilitation system.

Head Mounted Display

The Head Mounted Display is a device that – when placed on the head of the user – has two small monitor screens, one in front of each of the user's eyes, thus it can provide a convincing 3D sensation and a great degree of immersion for virtual environments. The HMDs are not necessarily a good option for VR- based rehabilitation systems because they are usually not comfortable – especially for a disabled patient who is already in a distressed state of mind.

Gamito et. al. [69] present a research regarding the rehabilitation of memory and attention deficits for patients following stroke by using a VR training program. Two patients with both deficits due to an ischemic stroke were selected for the trials and were subjected to ten sessions of VR enhanced rehabilitation sessions using a system consisting of an eMagin Z800 Head Mounted Display[26] and a mouse for exploring the virtual environment. The virtual scenarios were developed using Unity 2.5 and involved various everyday life activities such as adding items to a shopping list, finding a way to get to a supermarket, finding a certain door number, memorizing information from outdoor advertisements in the virtual world, etc. The subjects were evaluated prior, during and after the sessions, using the Wechsler Memory Scale (WMS) and the Toulouse-Pieron (TP) scale for attention deficit.

The results of the experiment performed by Gamito et. al. [69] showed significant improvement on both the WMS (from 37 to 45) as well as on the TP scale (from 65 to 107).

SeeMe

Sugarman et. al. [70] validated the utility of a Virtual Reality system for unilateral spatial neglect (USN) tratment. The employed VR system is the SeeMe, a projected video capture system which only requires a webcam and a computer (no other special hardware) and can be used while standing, moving or sitting. The users can see themselves on the screen moving and interacting with the virtual world in real time, using trunk and limbs movement. The subject involved in the experiment was a woman aged 66, who had suffered a stroke 15 months before. She participated in one hour of rehabilitation every week for 8 weeks using the SeeMe system. Three applications used in the experiment were dedicated to rehabilitation and one for evaluation. Although the subject – at the time of the experiment – had no remaining disabilities as a result of the accident, she had signs of USN. For the evaluation, the React task of the SeeMe system was used, which require the patient to touch a presented ball within a given amount of time and records the hits and the misses. At the end of the experiment the movement times decreased for both sides as did the difference between the two hands and the reported collision rate with obstacles in real life which was happening frequently prior to the treatment.

Data gloves

The 5DT Data Glove[14] (with a price estimated at $995) was used in the experiment described by Tunik et. al. [71] that studied whether mirror feedback in VR could stimulate ipsilesional cortex activation in chronic stroke patients. Tunik et. al. [71] replaced the mirror with a virtual environment in which the patients can see their hands from a first-person point of view.

The experiment described by Tunik et. al. [71] involved five chronic stroke patients that were scanned using functional Magnetic Resonance Imaging (fMRI) while an MRI (Magnetic Resonance Imaging) compatible VR device recorded the movements of the healthy hand in order for the real time virtual

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[26] Products – eMagin. http://emagin.com/products/. Last accessed March 2018.

reality to be updated accordingly. For data acquisition, an MRI compatible 5DT Data Glove 16 MRI (Fifth Dimension Technologies) was used in order to interact with a virtual environment. The VE was created by using the Virtools development software. The study concludes that mirrored feedback in a VE can have a remarquable effect regarding the activation of motory cortical regions in the affected hemisphere. The observed activations could be related to the presented visual effect.

A low-cost alternative is the one employed in the experiment described by Crocher et. al. [72] that developed a low-cost VR rehabilitation system consisting of one P5 Data Glove (Essential Reality, LLC, New York, USA) and a Microsoft Kinect (Redmond, USA) as well as two games for this configuration developed using C++ in OpenGL and Glut. The games were a puzzle and a target shooting game aimed at upper limb rehabilitation processes. The experiment presented by Crocher et. al. [72] involved three patients who had suffered a stroke more than 2 years previously and was aimed at finding the expectations the patients have from a VR rehabilitation system and to evaluate the proposed system and games. The conclusions were the need for medical evidence concerning the effectiveness of the presented games as well as a low cost of a rehabilitation system, in order to be appropriate for at-home use.

Webcams

Borghese et. al. [73] tackled neglect rehabilitation with Virtual Reality using a low-cost system consisting of a personal computer (PC), a webcam and a projection system. Patients suffering from neglect disregard the side of their body that is opposite to the side of the brain that suffered a lesion. The video game proposed by Borghese et. al. [73] requires the user to explore a virtual environment by reaching various targets with an increasing level of difficulty. Each progress is rewarded with a video and audio feedback. The operation mode of the game is a simple one: the video camera records the image and the movements of the patients and clips their silhouette, then pastes it onto the existing scene. In order to detect that a target was reached, the system detects collisions between the silhouette of the patient and the virtual objects. The patient has to hit targets with the unpaired hand, while avoiding distractors.

The experiments described by Borghese et. al. [73] were performed on a 65 years old patient for a duration of one month, thirty minutes a day, five days a week. The patient improved in his cognitive function according to the Mini-Mental State Examination after the treatment. Also, the line bisection task (where the patient is required to mark the middle of a line) improved to a normal value after the sessions. Other remarks state that the patient improved his performances in the game, hitting less distractors, and – as reported by the patient and the family of the patient – improved performance in several everyday life activities.

Particular observations found by Borghese et. al. [73] that the patient felt more comfortable with background music than in a silent environment and also that the patient was distressed when not being able to see his whole body on the screen, a fact was classified by the authors to be an "uncanny" valley effect that suggests that immersion is affected when the user is not able to see his entire silhouette in the virtual world.

Hennes et. al. [74] focused on low-cost at-home individualized rehabilitation systems and proposes a low-cost intelligent training system (ITS). The system has two operation modes: a training phase - that is performed under therapist supervision that trains both the patient and the system and that results in data about the patient movements stored in order to evaluate exercises performed without supervision – and an at-home operation mode that compares the patient movements to the reference data stored during the training phase, the results being stored or sent to the therapist for further review.

The training system described by Hennes et. al. [74] uses conventional therapy elements such as gymnastic bands or tubes. The amplitude of the movement is therefore proportional to the applied force (because a greater force is needed for a greater deformation of these devices). The visual feedback is

presented as an analog signal, the path describing the variation of forces in time needed for a correct execution, as well as the actual applied forces. The deviations from the expected path represent incorrect movements.

The purpose of the research of Hennes et. al. [74] is to assess the importance of visual feedback in rehabilitation. For this purpose, 46 healthy subjects were selected and were randomized into two groups: the first group received no visual feedback while the second group did receive the described visualization.

Both groups of subjects involved in the experiment described by Hennes et. al. [74] performed two sets of twelve repetitions each of the same exercise that were later evaluated using the cross-correlation coefficient, the relative amplitude error and the relative duration error. The deviations were found to be ten times smaller for the feedback group, which proves that visual feedback can improve the capability of the subject to reproduce a given force path.

Doyle et. al. [75] debated the importance of visual feedback for therapeutic *exergaming* (exercise through video games), more precisely whether apart from maintaining motivation it could also help the patient improve execution technique and maintaining the appropriate posture.

The system evaluated by Doyle et. al. [75] consists of an iPhone device strapped onto the monitored limb (the system could be employed for upper as well as lower limb) that sends accelerometer information via wireless to a server in order to control a Flash game type application. The game used in the experiment required the patient to maintain a spaceship on a trajectory marked on a computer screen by executing movements of the affected limb. 8 healthy participants with an average of 28 years were selected for the experiment that required the game to be controlled via tight movement in a squat-type exercise. Three settings were evaluated: control (without feedback), video (a video exemplified the movement) and exergame (real time feedback during execution). The third method helped the subjects maintain the most appropriate posture during the exercise (angle variation form the reference movement) and also to keep a steadier pace.

6 The TRAVEE Project

TRAVEE (Virtual Therapist with Augmented Feedback for Neuromotor Recovery) is a national PNCD-II project, aimed at developing an original system to help rehabilitation of the upper limb of patients with impairment because of brain damage, through stroke, trauma or other brain injuries.

The main original idea of TRAVEE is that of creating a system that provides augmented feedback to the patient to stimulate recovery through neuroplasticity. The purpose of the system is to help in fulfilling the *causal chain/loop* of recovery, consisting mainly of three steps:

1. The **attempt** of the patient to perform the desired movement;
2. The **observation** – by the patient – of the resulted effects;
3. The **association** of the observed effects with the efforts made in the first phase – this phase takes place at the level of the patient cortex and – in time, with repetition – may lead to the re-learning of the lost ability.

TRAVEE attempts to close this loop by providing additional feedback that reinforces the association phase. It also implements an innovative method of communication with the patient, through the Virtual Therapist – a virtual avatar that executes the movements that the patient needs to reproduce in the real world.

In order to fulfill its goals, TRAVEE uses several modern technologies:

- Virtual Reality for an improved immersion sensation,
- Optical tracking devices to follow the movements of the patient in real life,
- Brain-Computer Interface (BCI) through an Electroencephalography (EEG) helmet to detect intention of movement of the affected limb,
- Electromyography (EMG) to detect muscle activation in the limb,
- Functional Electrical Stimulation (FES) to artificially stimulate the muscle and perform the movements,
- Robotics – a robotic glove, part of another project at POLITEHNICA University of Bucharest (PUB) - project IHRG (Intelligent Haptic Robot Glove for Patients Suffering Cerebrovascular Accident), led by prof. Nirvana Popescu. This has the role of supporting mechanical movement when necessary,
- Haptic – vibrating motors attached to the exercised limb that provide feedback through vibrations.

In the following chapters are presented the contribution brought through this research to the TRAVEE system.

6.1 Functionality overview

Parts of this chapter were published in the following paper:

From a user's point of view, TRAVEE has two main components: one that is dedicated to the patient that undergoes the rehabilitation process after stroke, and one that is dedicated to the therapist – the clinician that guides the rehabilitation session.

The complex component dedicated to the patients involves devices and software that immerse them in a Virtual Environment to identify themselves with the presented avatar, as well as devices dedicated to supporting their movements and providing complex feedback during the exercises.

The component for the therapist is aimed mostly at providing intuitive tools for configuring the rehabilitation session composition and the devices used for each exercise, as well as to monitor the activity of the patient.

6.1.1 TRAVEE for the patient

The main features of the TRAVEE system are dedicated to the patient – the subject of the upper limb rehabilitation process. The patient is immersed in a Virtual Environment where there is an avatar (a 3D humanoid) representing the therapist, that exemplifies the movement that the patient needs to try to reproduce in the real environment, and a second avatar – viewed from a first-person point of view, representing the user – that mimics the real-life movements of the patient.

Fig. 6-1 The VE, the patient from a first-person point of view, with the therapist exemplifying the correct current movement

Other devices that the patients interact with are: the Oculus Rift[27] Head Mounted Display placed on their head, where they see all of the above; a robotic glove (IHRG project [100]) that supports the execution of certain movements and a Haptic device (whose hardware and software was developed at the "Gheorghe Asachi" Technical University of Iasi) that provides vibrations on certain key-points of the upper limb during each exercise, as a form of feedback.

In certain configurations of the TRAVEE system the patient is also connected to an EEG (electroencephalography device) an EMG (electromyography device) as well as a FES device (for Functional Electrical Stimulation). All these devices work together in various settings for acquiring data regarding the performances of the patient during the session and providing accurate feedback.

To track the body of the patient, TRAVEE uses two low-cost devices [101]: Microsoft Kinect v2 for the movements of the shoulder and elbow joints, and Leap Motion[40] for the fine movements of the hand and fingers. Kinect v2 tracks up to 25 joints of the body. For our project, we used Kinect for tracking movements of the shoulder and of the elbow. Leap Motion provides tracking of the rotation of the elbow joint, palm joint, and for each phalange in the five fingers of both hands. We used Leap Motion for tracking of the rotations of the palm and for the movements of the fingers.

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[27] Oculus DK2. https://www3.oculus.com/en-us/dk2/. Last accessed May 2017.

6.1.2 TRAVEE for the therapist

The TRAVEE functionalities dedicated to the therapist are related to patient and session configurations (patient profile, session content and length, selecting the devices used by each exercise and their configuration) and to session supervision, through graphs that represent in real time the essential parameters regarding the session.

The available exercises were selected by the doctors in the project consortium, to cover the most common rehabilitation exercises. These include the Finger Flexion-Extension, the Palm Flexion-Extension, the Forearm Flexion-Extension and the Arm Adduction-Abduction movements.

6.2   Rehabilitation movements

The rehabilitation movements implemented by the TRAVEE system were chosen by the doctors in the project consortium. The selected movements are:

Forearm Flexion-Extension

This movement exercises the elbow joint, requiring the patients to bring their forearm towards the anterior side of their upper arm, followed by the extension, that brings the forearm back on the direction of the upper arm.

Fig. 6-2 Forearm in Extension (left) and Flexion (right)

Forearm Pronation-Supination

This movement consists of a rotation of the palm around the axis of the forearm, clockwise and counterclockwise, as shown in the figures below.

Fig. 6-3 Forearm Supination (left) and Pronation (right)

Palm Flexion-Extension

This movement exercises the wrist joint, by bringing the palm closer to the anterior side of the forearm, followed by the extension, that brings the palm closer to the posterior side of the forearm.

Fig. 6-4 Palm in Extension (left) and Flexion (right)

Fingers Flexion-Extension

This movement requires closing the palm, by flexing all the fingers, followed by the extension of the fingers.

Fig. 6-5 Fingers Extended (left) and Flexed (right)

Thumb Opposition

This movement exercises the thumb, consisting of successive flexions that bring the tip of the thumb finger towards the base of the pinky finger, followed by extensions of the thumb away from the palm.

Fig. 6-6 Thumb Extended (left) and Flexed (right)

Thumb Touches

These movements exercise the "pinch" movement, consisting of successive flexions of the thumb and one of the other four fingers, that bring the tip of the thumb finger to touch the tip of the opposing finger, followed by extensions that straighten the fingers.
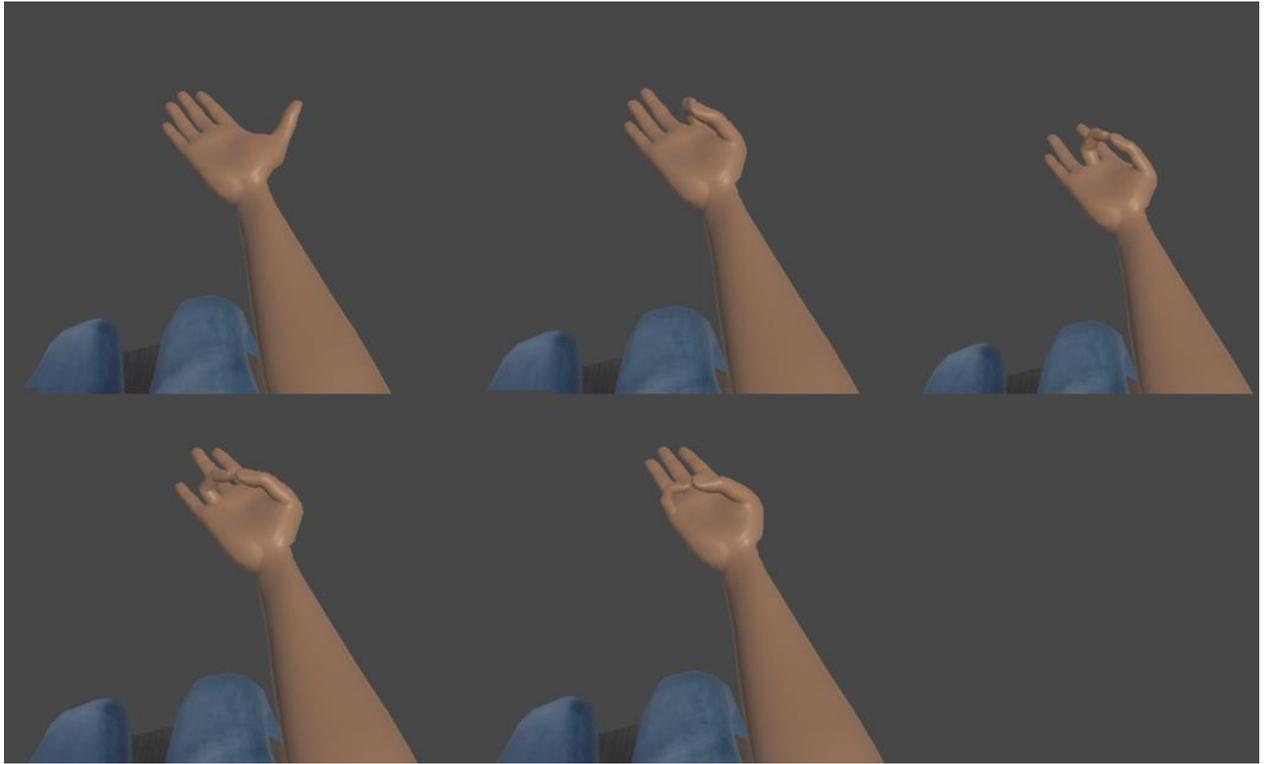
Fig. 6-7 Thumb touches

Arm Abduction-Adduction

This movement requires that the arm is moved in a frontal plane, away from the body for abduction and towards the body for adduction.

Fig. 6-8 Arm Adduction (left) and Abduction (right)

Arm Anteduction-Retroduction

This movement also exercises the shoulder joint, consisting of a movement of the arm in a sagittal plane, away from the body for anteduction and towards the body for retroduction.

Fig. 6-9 Arm Retroduction (left) and Anteduction (right)

Shoulder Raise

This movement exercises the shoulder joint, consisting of successive movements of raising and lowering the shoulder.

Fig. 6-10 Shoulder lowered (left) and raised (right)

6.3 TRAVEE architecture overview

Parts of this chapter were published in the following papers:

<u>O. Ferche</u>, A. Moldoveanu, F. Moldoveanu. The TRAVEE system for neuromotor recovery: Architecture and implementation. EHB E-Health and Bioengineering Conference, pg. 575-578, Sinaia, Romania, 2017.

<u>O. Ferche</u>, A. Moldoveanu, M. Dascalu, C-N. Bodea, R. Lupu, D. Irimia, F. Moldoveanu. The TRAVEE neuromotor rehabilitation system: In-vivo testing. ZINC, Zooming Innovation in Consumer Electronics International Conference, vol. 1, pg. 30-33, Novi Sad, Serbia, 2017.

This chapter presents briefly the architecture of the TRAVEE system. The preliminary architecture for the TRAVEE system was presented by Caraiman et.al. [102] but as the project evolved, the architecture was improved and updated to better fit the purpose of TRAVEE.

The figure below presents a simplified diagram of the main components and devices.
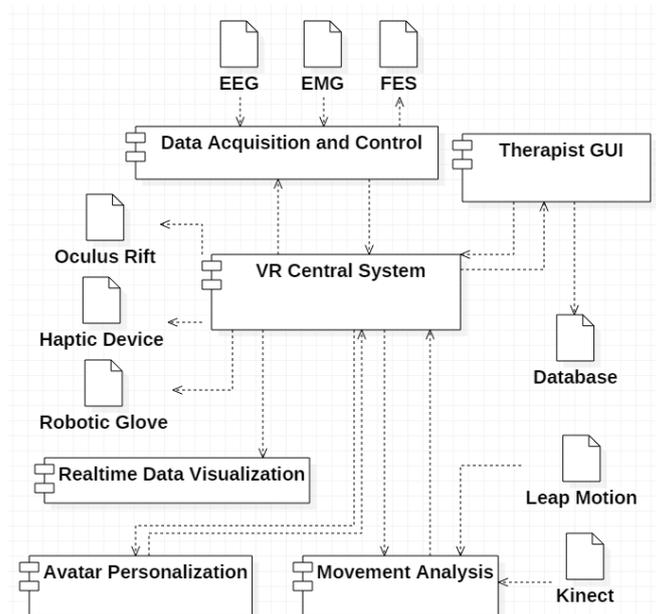
Fig. 6-11 TRAVEE architectural overview

As can be seen in the diagram, the system has one central component, the VR Central System, which communicates with the other two main components - Therapist GUI and Data Acquisition and Control components to ensure the correct functionality of TRAVEE.

The Data Acquisition and Control component
This component is in charge with taking data from the BCI (Brain Computer Interface – the EEG device) and the EMG sensors and controlling the FES device. This module receives commands from the Central System and provides data received from the controlled acquisition devices. It was implemented by the team at "Gheorghe Asachi" Technical University in Iași.

The Therapist GUI
The Therapist GUI (Graphical User Interface) is the control interface dedicated to the therapist. Here the therapist is able to add patients into the system, to define rehabilitation sessions as well as control the functionality of the entire system, through start, stop, pause type actions that are sent to the Central System. This component is also connected to a database, where it stores information regarding the

patients, the defined sessions and the executions. This component was implemented by the OSF Global Services Bucharest project partner.

The VR Central system

The Central System is also named here VR Central System because it was implemented using the Unity game engine[28] that allows fast creation of VEs and is easily integrated with Oculus Rift. In Unity we used the C# language with the .NET framework[29] to write all the necessary scripts for the TRAVEE functionality. It was implemented at the POLITEHNICA University of Bucharest, and – apart from the Avatar personalization module, which was developed upon an existing solution – represents my original work.

It is the central component that connects all the components together, it communicates with the Therapist GUI, receiving the commands from the interface, it communicates with the Acquisition and Control system, sending commands for the controlled devices and receiving data to be sent to the Visualizations module. It also interacts with the Movement Analysis and the Avatar personalization modules and controls the Haptic device and the Robotic Glove.

Movement analysis

This component is in charge with analyzing the data taken from the motion trackers: the Kinect and the Leap Motion. Based on the calculations made in this module, the Central System decides taking actions such as providing any of the available forms of feedback.

The data taken from Leap Motion and Kinect consists of rotations for the joints involved in the movement: shoulder, elbow, palm, and for each phalange in the fingers. For each movement, we chose one or more joints that are of interest, for example, for the arm adduction-abduction movement, the joint of interest is the shoulder joint, while for the forearm flexion-extension movement the joint of interest is the forearm joint. On the joint of interest, we made an evaluation of the degree up to which the movement is performed based on one or more parameters (angles and distances). The system allows the users (therapists) to define a set of threshold values for these parameters (a degree of execution) up to which they consider the movement needs improvements. As long as the movement is evaluated to a degree of execution below the threshold, the patients see an improved version of their real movement.

Movement analysis is detailed in chapter 8.

Real-time Data Visualization

This is a separate component with the purpose of displaying graphical representations for the data acquired by the system during the sessions. It receives data from the Central System and creates the graphs in real-time. It is dedicated to the therapist, that – based on the info presented here – may decide to make changes and adapt the session to the performances of the patient.

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[28] Unity. https://unity3d.com/. Last accessed May 2017.
[29] .NET framework. https://msdn.microsoft.com/en-us/library/ z1zx9t92 .aspx. Last accessed May 2017.
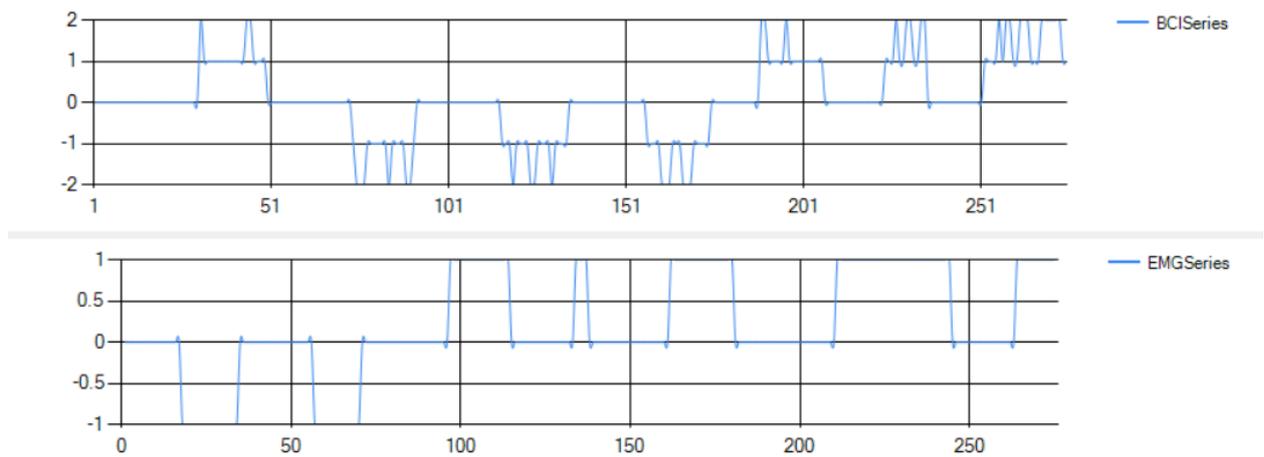
Fig. 6-12 Capture from the data visualization tool

Avatar personalization

The avatar personalization is a module dedicated to creating a better immersion sensation for the patient by changing certain elements in the aspect of the avatar, such as gender, size (Small, Medium, Large), clothes, hair, etc.

Fig. 6-13 Personalization mode

Components communication

The components communicate with one another through messages with an established format, in JSON serialization, through TCP sockets.

Each command has a generic format, containing a name and a set of parameters with either a string or numeric value. The generic format allowed us to communicate between heterogenous technologies.

This way of communication was chosen because it allows each component to run on a different computer – thus decreasing the processing overload on a single computer. Also, the implementation of the components was assigned to various members of the consortium, and an increased modularity provided separation of tasks, that could be implemented at various sites, with periodical meetings for integration tests.

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All the components were successfully implemented, with the UPB partner implementing the VR Central System, Real-time Data Visualization, Movement Analysis, Avatar Personalization as well as the control of the associated devices: Kinect, Leap Motion, Oculus Rift, Haptic device, Robotic glove.

Configuration

Due to its complexity (high number of available technologies for feedback), TRAVEE allows the doctor to select – from the dedicated GUI - the desired devices to be used for each configured rehabilitation exercise that will be included in each defined session.

For example, some of the available configurations allow the FES to be controlled exclusively from the detected EEG signals, while others may control the FES depending on the movements detected from the optical tracking devices, EMG signals, or any of these combined [104].

7 Contributions to the evaluation of the available technologies for TRAVEE project

One of my initial tasks for TRAVEE were to study available technologies in the areas of BCI and hand tracking, in order to choose the most appropriate ones (medically, technologically and financially) for the purpose of the system.

7.1 Hand tracking technologies

The analysis presented in this chapter was disseminated within the International Congress World Psychiatric Organization (WPA) 2015 that took place in Bucharest, in the following work:

O. Ferche, A. Moldoveanu, F. Moldoveanu, V. Asavei, A Survey of Motion Tracking in Automated Neuromotor Rehabilitation after Stroke. WPA 2015 Bucharest International Congress. June 2015.

The purpose of a motion tracking system is to assess and represent in real time the pose changes of the body or of a part of the body of a subject.

In neuromotor rehabilitation, precisely assessing the current position of the patient is used for determining any progress the patient may have made during the sessions.

For IT systems such as TRAVEE, the exact position of the patient is to be used to represent the avatar in the virtual environment in the actual position of the patient, and to copy the movements he/she makes during the session into the virtual world. This would benefit from two points of view:

- The patients will be able to better identify their body with the virtual avatar, increasing immersion.
- This may also prove to help the cortical recovery process, as the patients will be able to associate the provided effort with the observed result.

As the device is used with patients recovering from neural damage, it is important to take into consideration several aspects regarding motion tracking devices:

1. Lightweight equipment
2. Should not require specific motor abilities
3. Precision – to detect fine movements of the palm, fingers, arm and forearm
4. Low cost – TRAVEE is desired to evolve into an at-home care system
5. Easy to install, reliable.

Classification of motion tracking technology:
1. Non-visual: inertial, magnetic
2. Visual: optical sensors

Motion tracking using non-visual tracking devices
Xsens MTw. According to the producer specification[30] it is a digital inertial measurement unit that can detect: 3D rate of turn, acceleration and earth magnetic field (3D angular orientation to 1 degree precision). Up to 32 devices can be used to track key points.

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[30] xSens MTw Awinda. https://www.xsens.com/products/mtw-awinda/. Last accessed July 2017.

TRIVISIO Colibri Wireless[31] consists of an IMU with accelerometer, gyroscope and magnetometer. Up to 10 devices can be used in a setup. The output is represented as quaternions.

Polhemus Patriot[32]. Magnetic sensor that provides 6 degrees of freedom and runs with up to 50 updates per second. Among the uses of Polhemus technology: simulations of weightlifting motion at the US Olympic Center[33] and measuring hand tremor for Parkinson's patients[34].

The table below compares the three devices in terms of price, number of measuring units, and maximum distance up to which they are able to track movements.

Table 7-1 Comparison of non-visual tracking technologies

	Price	Number of measuring units	Maximum distance
Xsens MTw	6350 EUR	6	20 meters
TRIVISIO Colibri	700 EUR	1	10 meters
Polhemus Patriot	2000 EUR	4	3 meters

Motion tracking using visual tracking devices
Classification: Marker-based and Non-marker based.

Microsoft Kinect v2. RGB camera with infrared depth sensor for human body identification and motion tracking. Detects 25 joints, finger movement, face expressions. Errors 1mm-2.5mm.

Its potential for rehabilitation enhancement was tested in an experiment with patients with spinal cord injury (SCI) using a Unity3D game that identified the correct execution of a set of movements [77]. It had issues detecting rotation movements of the shoulder when placed directly in front of the patient.

An experiment presented by Lange et. al. [78] tested Kinect for upper body motion tracking in a Unity3D game for SCI, traumatic brain injury (TBI) and stroke patients. The potential of the system was supported by the initial feedback.

Leap motion. Close-range movement detection of the hand and lower arm. Accuracy of approximately 0.7mm of the detected movements.

An experiment [79] presented by Khademi et. al. found a correlation between the scores patients obtained in a virtual game played using gestures and their score on the Fugl-Meyer upper limb disability assessment scale[35].

Another experiment [80] presented by Regenbrecht et. al. tested the Leap Motion as an interface for augmented reality interaction.

Intel Realsense. A small device that can track close-range movements of the hand, having also other features, such as face detection, 3D scanning, object tracking. It was also used in systems for assessing

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[31] TRIVISIO Colibri Wireless – Inertial Motion Tracker (Wireless). https://www.vrlogic.com /Downloads/VRLOGIC_TRIVISIO_Colibri_Wireless.pdf. Last accessed July 2017.

[32] Polhemus Patriot. https://polhemus.com/motion-tracking/all-trackers/patriot/. Last accessed March 2018.

[33] Polhemus – innovation in motion. Case study: Assisting olympic weightlifting with motion tracking. http://polhemus.com/case-study/detail/assisting-olympic-weightlifting-via-motion-tracking-at-the-u.s.-olympic-tra. Last accessed July 2017.

[34] Polhemus – innovation in motion. Case study: neuroscience application powered by Polhemus tracking. http://polhemus.com/case-study/detail/polhemus-motion-trackers-enable-measurem ent-of-the-effectiveness-of-brain-s. Last accessed July 2017.

[35] Fugl-Meyer Assessment - Clinical Neuroscience, University of Gothenburg, Sweden. https://neurophys.gu.se/english/departments/clinical_neuroscience_and_rehabilitation/rehabilitation-medicine/fugl-meyer. Last accessed July 2018.

upper extremity motor disfunctions [81] as well as to detect gestures in a gesture-controlled image processing tool [82].

<u>Video camera + markers</u>. Acquires high resolution video data and determine the current body position by identifying known markers in the images and based on a known human body model.

In Table 2 we compare the prices as well as the abilities of the analyzed devices to accurately assess position in close range and long-range scenarios.

Table 7-2 Comparison of visual tracking technologies

Device	Price	Range	Markers
Kinect v2	200 EUR	Long range	no
Leap Motion	70 EUR	Close range	no
Intel RealSense	130 EUR	Close range	no
Video camera	150 EUR	Both	yes

Discussion
Several of the presented solutions will be analyzed as part of the TRAVEE project.

Non- visual

- Advantages: no overlaps, precision measurements.
- Disadvantages: no motion tracking included, data usually as quaternions, jitter.

Visual

- Advantages: no limited measuring units, integrated tracking.
- Disadvantages: depth issues when using one camera, occlusion.

The chosen solutions for the initial prototype are Kinect v2 and Motion Leap.

First experiments with Motion Leap shown promising data acquisition capabilities.

Conclusions
The analyzed solutions have great potential in the area of rehabilitation as the cited experiments prove, but improvements need to be made regarding the accuracy of the measurements.

Out of the multitude of options, we chose to integrate several motion tracking technologies – given the sensitivity of the medical rehabilitation field.

7.2 **Brain-Computer Interface devices**

The contents of this chapter were presented within the International Congress World Psychiatric Organization (WPA) 2015 that took place in Bucharest, in the following work:

O. Ferche, A. Moldoveanu, F. Moldoveanu, Brain Computer Interfaces for Neuromotor Recovery – Achievements, Issues, Trends. WPA 2015 Bucharest International Congress. June 2015

TRAVEE desires to use BCI as an additional communication path for the patient recovering after stroke, by detecting his/her intention of executing a movement and using robotics or FES to aid the patient in executing the desired movement.

Issues of using BCI in rehabilitation

The main challenges of using BCI in rehabilitation are related to:

1. Cost vs. Precision and Connectivity
2. Comfort
3. Prohibitions imposed by producer regarding medical use

BCI

Out of the several options for monitoring cerebral activity (EEG, MEG, fMRI etc.) the most commonly used is EEG (electroencephalography).

According to Wolpaw et. al. [84], an efficient communication involves two phases:

1. The user encodes his/her intentions into neural signs
2. The system decodes these signals translating them into the associated command.

BCI can be classified by whether the electrodes that measure the electric impulses are implanted onto the surface of the brain or are placed on the scalp of the user.

Another classification takes into consideration the signals of interest (their frequency and the area of the brain where they are located):

1. Slow Cortical Potentials
2. P300 evoked potentials
3. Sensorimotor rhythms
4. Steady state evoked potentials

EEG

Slow Cortical Potentials [86]

- The user generates a cortical potential greater or lower that a reference value. Decrease => raised excitability. Increase => lowered excitability.
- In an experiment presented by Birbaumer et. al. [85] two patients were able to send simple text messages by controlling their SCP levels.

Sensorimotor Rhythms [86]

- Event related synchronizations/desynchronization
- ERD – preparing a movement/ERS – after a movement

P300

- Most commonly used signal in BCI systems
- Signal that appears when the user is presented with remarkable stimuli amongst a series of similar stimuli.
- Donchin et. al. [87] described an experiment where subjects were presented with a 6x6 blinking character matrix and were requested to choose a character and count the number of times it blinks. Using P300 evoked potentials the BCI system was able to detect the chosen symbol.

Steady state visual evoked potentials:

- A periodical signal modelled by a known pattern detected in the occipital region of the brain
- The oscillation of the detected signal varies according to the frequency of the observed stimuli

- A BCI using SSVEP could determine chosen stimuli out of a set blinking at different frequencies
- This method has a lower accuracy decrease for peripheral vision and could be used for locked in patients [88].

Analyzed solutions

Taking into account the challenges BCI faces in medical rehabilitation, the available signals that should be detected and the published experiment results, three BCI solutions were considered for the purpose of TRAVEE [89]:

Emotiv

- EPOC EEG headset[36], dedicated SDK libraries for detecting mental commands and facial expressions. Accessible price. Limited by connectivity issues.
- Paper [90] describes an experiment that tested the usability of the Emotiv with BCI2000 system for signal interpretation in order to move a mouse cursor on the screen, with a success rate of 90%.

Biosemi ActiveTwo[37]

- Very good quality EEG measurements, low noise, electrodes can be placed according to the 10-20 electrode location systems. Very prohibitive costs and not intended to be used for medical purposes, according to manufacturer. Cannot be worn in bed position as needed by TRAVEE project.
- Sarac et. al. [91] described an experiment using this BCI device where users were able to control the movements of a mobile upper limb rehabilitation platform using ERD/ERS patterns.

g.Tech Nautilus[38]

- Wireless EEG recording system, with high signal to noise ratio, many channels, but a high price.

Table 7-3 Comparison of BCI technologies

	Price	Number of electrodes	Wireless
Emotiv	700 EUR	14	yes
ActiveTwo	11000 EUR	24	no
Nautilus	6000 EUR	32	yes

Discussion

From the analyzed solutions the most appropriate was determined to be the gTech Nautilus. It would provide a great accuracy – that is much needed in a rehabilitation system as TRAVEE – and the cost – although very high – is good for the performances that it provides.

In the TRAVEE consortium the team in Iaşi has experience in working with gTech technologies and also has access to a gTech EEG acquisition device therefore it was the one integrated with TRAVEE.

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[36] Emotiv Epoc+ - 14 Channels Wireless EEG Headset. https://www.emotiv.com/epoc. Last accessed March 2018.
[37] Biosemi EEG ECG EMG BSPM NEURO amplifier electrodes. https://www.biosemi.com/products.htm. Last accessed March 2018.
[38] G.Nautilus – g.tec's wireless EEG system with active electrodes. http://www.gtec.at/Products/Hardware-and-Accessories/g.Nautilus-Specs-Features. Last accessed March 2018.

Long term, the Emotiv system, due to its affordable price and wireless technology is more appropriate for an at-home care system, as TRAVEE wishes to evolve into.

As it will be used by disabled patients, it is important for the device to be as comfortable as possible. Emotiv EPOC is easy to place without assistance but may not be comfortable for long use periods [92] fact which must be taken into consideration when designing the sessions.

Emotiv has less channels that the other two considered systems but it can provide sufficient information for P300 signals evaluation, as documented by Duvinage et. al. [92]. Also, the experiments led in this article show that although its precision is lower than that of professional medical BCI systems, Emotiv Epoc is able to achieve satisfying results.

7.3 Comparison between Leap Motion and Intel® RealSense hand tracking devices

The contents of this section were published in the Romanian Journal of Human-Computer Interaction, in the following paper:

O. Ferche, A. Moldoveanu, F. Moldoveanu, Evaluating Lightweight Optical Hand Tracking for Virtual Reality Rehabilitation, Revista Română de Interacțiune Om-Calculator, 2016, vol. 9, no. 2, pg. 85-102.

7.3.1 Motivation

The TRAVEE project requires a device for a precise tracking of the movements of the human hand. The main characteristics of the optimal device are usability and comfort of the user, therefore an optical tracking solution was chosen. Two optical tracking devices were evaluated: Leap Motion and Intel RealSense.

As the TRAVEE system wishes to be affordable and easy to use by people without technical background, we focused on lightweight, low cost solutions. We chose the Microsoft Kinect for body tracking, but for more detailed movements of the hand we found it did not provide enough detail (only the direction of the forearm, the palm and that of the thumb[39].) For detailed tracking of each finger we found two solutions that would fit our system: Leap Motion and Intel RealSense.

This chapter presents the rehabilitation exercise movements that are considered in the TRAVEE system and identifies – for each movement - a placement that we thought would be best for each of the two tracking device, discussing the results.

All of the presented experiments were performed on an Asus G551J laptop (Intel Core i7 4750HQ, 8 GB RAM, Nvidia GeForce GTX 960M, 64-bit Windows 10 Education operating system). The RealSense device is the VF0800 model equipped with the F200 camera. We used Intel Realsense SDK version 7.0.23.8048. The Leap Motion device is the LM-101 model, with the Leap Motion SDK version 3.1.2.40841.

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[39] MSDN, Jointype Enumeration. https://msdn.microsoft.com/en-us/library/microsoft. kinect.jointtype.aspx. Last accessed May 2016.

Leap Motion

Leap Motion is a small device that incorporates two infrared cameras and three infrared LEDs[40]. According to the developer[41] the interaction area of the device is a cube of dimension approximately 2 feet, above the controller.

For best results, the user's hands are guaranteed to stay within the field of view of the device as long as they are within an interaction box[42]. This box has 235x235x147 mm dimensions (width x height x depth) and is situated above the Leap Motion controller, at a height preset in the device's control panel or that is automatically determined by the device if the automatic option is chosen in the control panel).

Intel RealSense F200

Intel RealSense[43] cameras combine infrared optical tracking technologies - an infrared laser projector and an infrared sensor[44] - with a 1080p RGB camera (color sensor) into a small device that combines 3D depth information with 2D images, in order to create a high quality 3D depth close range video[45]. As presented in the same source, the F200 camera was replaced by a newer model, the SR300 in currently available developer kits.

Intel RealSense provides multiple functionalities, including 3D scanning, face detection, hand tracking, object tracking, etc. [45,46]. Out of these possibilities we are currently interested in the hand tracking features of the F200 camera.

The recommended ranges for the hand tracking feature of the F200 are a distance between 20-60 cm away from the camera and a speed of maximum 0.75m/s [46].

Other work evaluating the precision of the considered devices

From our research, related works assessed the precision of the tracking devices by using a robotic arm that can be precisely placed and moved from one point in space towards another through comparing the variations in the detected positions or movements compared to the established ones, by using a robotic arm with a pointing device (that the Leap Motion device has the ability to detect) placed at the end [94] or by placing a plastic arm model holding a pointing device at the end of the robotic arm, such as in [95]. Both experiments evaluated the measurement precision in both static and dynamic scenarios. [94] discovered sub-millimeter precision in both static and dynamic scenarios, while [95] determined a submillimeter precision for the static experiments but stated that an inconsistent performance was obtained for the dynamic scenario.

We did not find extensive research regarding the evaluation of the performances of the Intel RealSense. In [96] the authors developed a simple Virtual Reality system for medical rehabilitation of the shoulder using Kinect and Intel Realsense for movement tracking. In the preliminary evaluation, four experts working in the field of physiotherapy tested the system containing the two devices and reported that they found all the animations of the movement in the virtual world to be fluid.

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[40] Leap Motion Home Page. https://www.leapmotion.com/. Last accessed May 2016.
[41] Leap Motion Specs. http://blog.leapmotion.com/hardware-to-software-how-does-the-leapmotion-controller-work. Last accessed May 2016.
[42] Leap Motion Coordinates. https://developer.leapmotion.com/documentation/csharp/ devguide/Leap_Coordinate _Mapping.html. Last accessed May 2016.
[43] Intel Realsense Home Page. http://www.intel.com/content/www/us/en/architecture-andtechnology/realsense-overview.html. Last accessed May 2016.
[44] Intel Realsense Hardware. https://software.intel.com/en-us/blogs/2015/01/26/can-yourwebcam-do-this. Last accessed May 2016.
[45] Intel Realsense Comparison. https://software.intel.com/en-us/articles/a-comparison-ofintel-realsensetm-front-facing-camera-sr300-and-f200. Last accessed May 2016.
[46] Intel Realsense Ranges. https://software.intel.com/sites/landingpage/realsense/ camerasdk/v1.1/documentation/ html/index.html?doc_advanced_module_range_specification.html. Last accessed May 2016.

In [97] 35 participants with various degrees of experience with a professional image editing tool were presented with a special graphics editor that was controlled by either classical user input (mouse and keyboard) or by using special gestures recognized by the RealSense. The participants completed a survey regarding the usability of the two user interfaces. The authors discovered that users that were more accustomed to the professional editing tool were more inclined to prefer the classical input methods, while novice users preferred the non-conventional input methods. All groups found the second one to be more engaging.

Another experiment assessing a possible use of the Intel RealSense is presented in [98]. Here, the authors created 3D biometric hand recognition system. The results were stated to be comparable to some of those based on more expensive sensors.

All the aforementioned experiments show promising results regarding the precision of the two devices.

7.3.2   Evaluated movements

The TRAVEE system implements 10 rehabilitation movements, out of which only four involve movement of the fingers and are thus relevant for this research:

- Finger flexion-extension

- Thumb flexion-extension

- Palm flexion-extension

- Thumb touches

Finger flexion-extension

This exercise involves flexing and extending four fingers (index, middle, ring, pinky) while the thumb remains still. The correct execution of the flexion movement starts with the four fingers extended and consists of bending the fingers so that the angle between them and the palm is decreased [47]. Oppositely, the extension part of this movement involves increasing the angle between the fingers and the palm[47].

Fig. 7-1 Finger flexion (left) and extension (right)

We will also consider the execution of the flexion-extension movement for each finger, separately.

Thumb flexion-extension

This movement involves moving the thumb across the palm in the coronal plane towards the palm (flexion) and away from the palm (extension)[47].

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[47] GetMedEdu Movements. http://www.getmededu.com/movements-of-the-thumb-fingersand-toes.html. Last accessed May 2016.

Fig. 7-2 Thumb flexion (left) and extension (right)

Palm flexion-extension

This movement requires that – while holding the fingers extended – the palm is moved towards the forearm (flexion) and away from the forearm (extension).
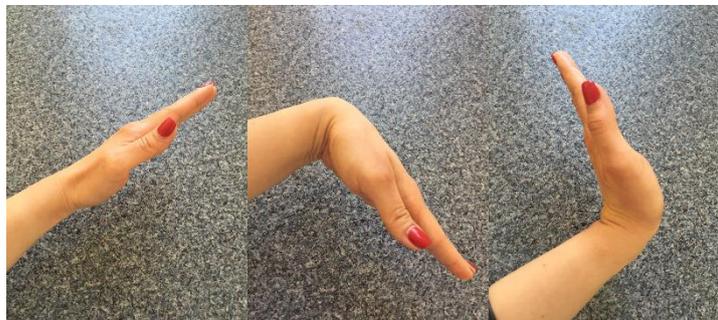
Fig. 7-3 Palm straight (left), flexed (center) and extended (right)

We will also consider the execution of the flexion-extension movement for each finger, separately.

Thumb touches

This movement[48] requires touching each of the fingertips with the thumb while holding the wrist straight.
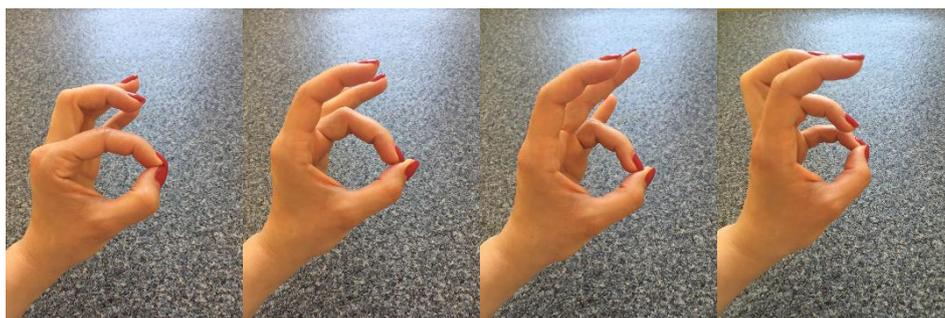
Fig. 7-4 Thumb touches: index (1), middle (2), ring (3), pinky (4)

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[48] WebMd Movements. http://www.webmd.com/osteoarthritis/oa-treatment-options-12/slideshow-hand-finger-exercises. Last accessed May 2016.Human hand division. Mariana Ruiz Villarreal (LadyofHats); retouches by Nyks – Own work. Image renamed from Image:Human hand bones simple-edit1-2.svg. Created January 2007. Last accessed May 2016.

7.3.3 Evaluation methods

As a disclaimer, the experiment does not precisely assess qualitatively or quantitatively the tracking abilities of the two devices. The subjects performed the exercises in front of the cameras of the devices and decided for each repetition whether they felt immersed in the VE – thus they could have been "fooled" that the virtual hand was actually theirs. This method allows a great degree of subjectivism. Also, as the experiment was performed by humans, and not by a robotic hand that could have maintained the same posture and executed the movements in an identical manner for each repetition – we are aware and insist that there is an important degree of human error involved. One aspect that must be mentioned is that – although they were instructed to keep their hand within the range of the device, it is obvious by the provided feedback (some loss of precision for certain movements but in singular cases) that sometimes the tested users were not able to maintain their hand within that exact area.

In order to determine the most appropriate configuration for our system we applied two evaluation methods that we believed are sufficient for a decision in our particular situation.

In the first method we established classes of movements –approximate angles to which we bent four fingers (index, middle, ring, pinky) and the thumb respectively – in order to observe the detection of movements of smaller or greater amplitude with each of the selected devices (30 repetitions of each movement).

In the second method we executed each movement of the four movements of the hand included in the TRAVEE system and observed the accuracy with which the tracking follows the movement for a longer period of time (50 repetitions). One execution was considered correct if the subjects felt that the movement of the virtual hand represented their own to an immersive degree.

Tracking for movements with various amplitudes

As we are interested in the detection of the movement by the tracking devices, we considered that an approximate approach would suffice for determining whether various degrees of movement are detected by the devices.

Movement classes

As we mentioned, we established distinct sets of exercises for the group of fingers consisting of index, middle, ring and pinky fingers and another set of movements for the thumb.

Therefore, for the group of five fingers we established five classes of movement amplitude for the flexion of the fingers:
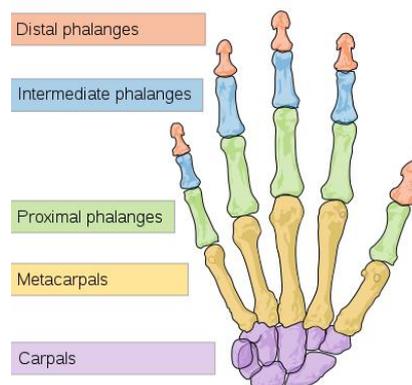
Fig. 7-5 Main divisions of the human hand [49]

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[49] Human hand division. Mariana Ruiz Villarreal (LadyofHats); retouches by Nyks – Own work. Image renamed from Image:Human hand bones simple-edit1-2.svg. Created January 2007. Last accessed May 2016

-        Very small (XS) – the fingers are kept in a straight position and are bent with approximately 30 degrees.

-        Small (S) – the finger is slightly bent (the angles between the distal and intermediate phalanges and the one between the intermediate and

the proximal phalanges are of about 150-160 degrees) and the angle between the proximal phalanx and the metacarpal bone is of approximately 45 degrees.

-        Medium (M) – the finger is bent in the shape of the letter "C" (between each two of the phalanges there is an angle of approximately 120 degrees)

-        Large (L) – the finger is bent event further, the angle between the intermediate and the proximal phalanges is decreased to approximately 90 degrees, but the fingertip does not touch the palm.

-        Full (F) – the fingertip touches the palm.

Each of these classes is represented in the figures below.
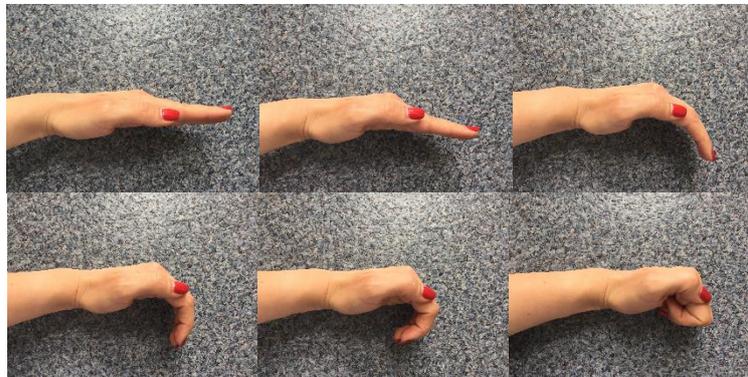
Fig. 7-6 The established classes of movements: None (top left), Very small (top center), Small (top right), Medium (bottom left), Large (bottom center), Full (bottom right)

For the thumb, we established four exercises:

-        Extending the thumb away from the other four fingers – bringing the thumb towards them to a position of the palm where all fingers are kept straight and pointing in the same direction;

Fig. 7-7 Extending and flexing the thumb toward the other fingers

-        Flexing the thumb towards the palm (the pinky) with three degrees of flexion:

o   Small (S): the thumb is brought from an extension (where it is placed in the same plane as the other extended fingers) to a position where it is straight and just above the palm, approximately perpendicular to the plane of the extended fingers;

o   Medium (M): the thumb is bent towards the pinky so that its distal phalanx is approximately parallel to the plane determined by the other four fingers;

o   Full (F): the fingertip of the thumb touches the palm.

Fig. 7-8 Extending and flexing the thumb with various degrees toward the pinky finger (1-extension, 2-small, 3-medium, 4-full)

Observations

We experimented with each device in the following manner:

- For the movements of the four fingers and those of the thumb we tested both settings (more or less lighting);

- 30 repetitions of each class of movements, as presented in figures Fig. 7-6, Fig. 7-7, Fig. 7-8;

- Counted the repetitions that were represented accurately in the VE (accurately was defined subjectively in this experiment – we considered that a movement was accurate if the users felt immersed in the VE while performing it – they felt that the hand in the VE could have been their own, no additional movement was apparent and the movement of the virtual hand was the one that the subjects were testing at the time);

- To observe the tracked movements in a VE we used one of the applications provided by the producer in order to eliminate possible third-party errors in mapping movement onto avatar:

  o For the Leap Motion we used the AllHandModels scene from the Leap Motion Core Assets[50].

  o For the Intel RealSense we used the Hands Animation (Unity) from the Intel RealSense SDK Sample Browser[51].

Device placement

We selected the positions of the devices so that the movement is performed in the distance range recommended for the devices, as we mentioned in their description. As for the actual location of the device, we chose it so that all the important elements of the movement would be visible to the IR cameras, for the device to observe the differences in depth – as we thought would be most appropriate.

More precisely, for the Leap Motion we performed the movements with the device placed on a flat surface, as can be seen in the image below. We respected the official recommendation that the hands should be perpendicular to the field of view[52] for best tracking reliability. We also placed the hand perpendicular to the field of view for the Intel RealSense.

Also, we wanted to see whether more or less (indirect) light will have any effect on the tracking reliability.

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[50] Leap Core Asset. https://www.assetstore.unity3d.com/en/#!/content/17770. Last accessed May 2016.
[51] RealSense Support. https://software.intel.com/en-us/intel-realsense-sdk-support/ training. Last accessed May 2016.
[52] Leap Motion Best Practices. https://developer.leapmotion.com/assets/Leap%20 Motion%20VR%20Best%20 Practices%20Guidelines.pdf. Last accessed May 2016.

Fig. 7-9 Placement of the devices on a flat surface with less (top) or more (bottom) indirect lighting

Both devices were placed on the same flat surface, in an environment with sufficient lighting but away from direct sunlight – in order to avoid interference in the infrared light spectrum.

We tested the configurations separately, in order to avoid interference with one another – while one of them was working, the other was disconnected from the computer.

We placed the hand performing the movements straight in front of the device, as we believed it is most suitable, and made 30 repetitions of each movement.

Leap Motion
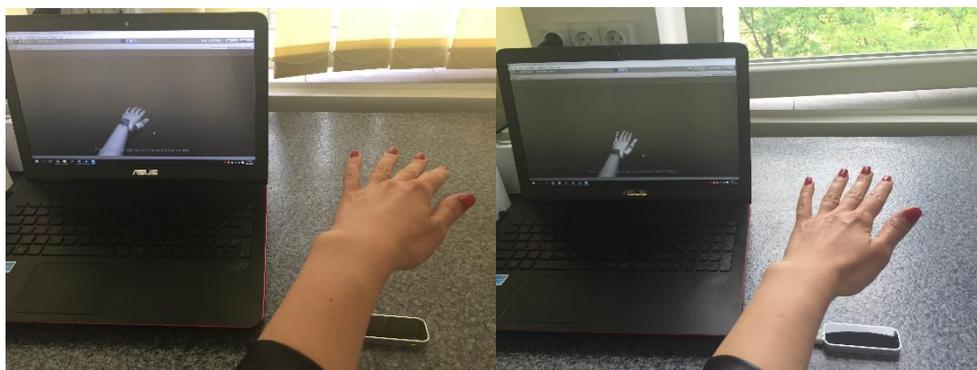
Fig. 7-10 The evaluated position for the Leap Motion, in both more and less lighting setup

Table 7-4 Visually observed performance of Leap Motion for the five classes of movements of the group of four fingers

	Less lighting					More lighting				
	XS	S	M	L	F	XS	S	M	L	F
User 1	100%	100%*	100%*	100%*	100%*	100%	100%*	100%*	100%*	100%*
User 2	100%	100%	100%	100%*	100%	100%*	100%*	100%*	100%	100%*
User 3	100%	100%	100%	100%	90%**	100%	100%	100%	100%	90%**

*The measurements seemed to be very precise as long as the fingertips were straight above the controller – if the fingers were stuck together. If there was space in between the fingers then they could be held close to the edges of the field of view and the tracking was not affected.

**The user did not observe a clear visual difference in the representation of the fully closed movement (F) and the one where the large flexion (L).

Table 7-5 Visually observed performance of Leap Motion for the four types of movement of the thumb

	Less lighting				More lighting			
	Close	S	M	F	Close	S	M	F
User 1	100%	100%	100%	95%*	100%	100%	100%	95%*
User 2	100%	100%	100%	100%	100%	100%	100%	100%
User 3	100%	100%	100%	90%*	100%	100%	100%	90%*

*The user stated that the difference in the visual representation of the M and F movements of the thumb was not easily observable.

The difference in lighting did not produce any differences that could be observed, therefore for the rest of the exercises we chose to test only in the setup with more lighting.

Realsense
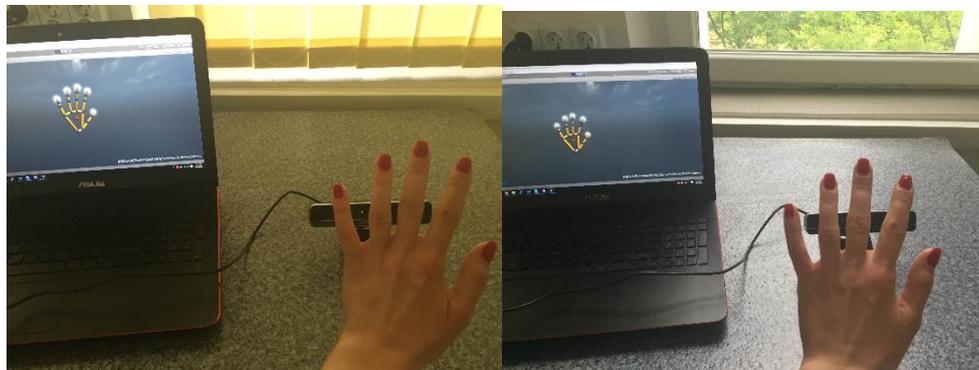
Fig. 7-11 The evaluated position for the RealSense, in both more and less lighting setup

Table 7-6 Visually observed performance of RealSense for the five classes of movements

	Less lighting					More lighting				
	XS	S	M	L	F	XS	S	M	L	F
User 1	100%	100%	100%	100%*	100%*	100%	100%	100%	100%*	100%*
User 2	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
User 3	99.5%	100%	99%	100%	90%**	99.5%	100%	99%	100%	90%**

*For the movements with more amplitude, when the fingertips become less visible because they approach the palm, there seems to be a slightly decrease in the accuracy of the movement of the virtual hand.

**The user stated that the difference in the visual representation of the L and F movements of the fingers was not easily observable.

The presence of more indirect light does not seem to affect in any way the tracking process.

Table 7-7 Visually observed performance of RealSense for the four types of movement of the thumb

	Less lighting				More lighting			
	Close	S	M	F	Close	S	M	F
User 1	100%	100%	100%	100%	100%	100%	100%	100%
User 2	100%	100%	100%	100%	100%	100%	100%	100%
User 3	100%	100%	100%	100%	100%	100%	100%	100%

Results for the TRAVEE movements

Since the variation in lighting did not have an observable influence on the tracking ability of the two devices, we tested each of the four movements only in the setup with more light.

Finger flexion-extension

Table 7-8 Visually observed performance for the finger flexion-extension movement

	RealSense	Leap Motion
User 1	80%	100%
User 2	100%	100%
User 3	100%*	100%*

* The user stated that the fingers did not appear to be touching the palm although in reality they were fully flexed.

Thumb flexion-extension

Table 7-9 Visually observed performance for the thumb flexion-extension movement

	RealSense	Leap Motion
User 1	100%*	100%
User 2	100%	100%
User 3	90%**	90%**

*Perfect performance if the fingers are spread. If the four fingers (index, middle, ring, pinky) are stuck together, very often for a thumb flex it detects another finger flexing as well.

** The user stated that the thumb did not appear to be touching the palm although in reality it was fully flexed.

Palm flexion-extension

Table 7-10 Visually observed performance for the palm flexion-extension movement

	RealSense	Leap Motion
User 1	100%*	100%
User 2	100%	100%
User 3	98%*	98%*

*The detection of this movement seems to be of 100% as long as the movement is executed with the palm facing the device and the fingers spread. If the fingers are touching or if they are held into a fist the accuracy is diminished.

Thumb touches

Table 7-11 Visually observed performance for the thumb touches movement

	RealSense	Leap Motion
User 1	100%*	90%**
User 2	100%	100%
User 3	99%*	95%**

*The RealSense has perfect accuracy for this movement, as long as the hand is positioned as discussed (parallel to the field of view of the device).

**For the Leap Motion all the misses were observed for the thumb touch of the middle finger.

Conclusions

From observing the accuracy of the tracking process (visually – comparing the movements in the real world with those indicated by the visualization software provided by the producers) and by the feedback we received from our subjects, we determined that for the movements that must be tracked by our system, the best placement for the Leap Motion device is the classical one, with the hand directly above the controller, especially if the movement involves keeping some of the fingers together. For the RealSense we evaluated a similar placement, with the hand parallel to its surface.

We observed that the two degrees of lighting that we tested did not interfere in any way (that could be observed in the visual representation of the movements of the avatar hands) with the precision with which our specific exercises were tracked.

For the gradual exercises that we classified into five degrees, we noticed that both devices were able to detect each movement as well as to track the movement with a satisfactory precision. By holding the palm approximately parallel to the RealSense it would seem that hiding the fingertips, by performing some of the exercise movements may slightly interfere with the tracking process.

The TRAVEE movements were represented quite well in the VE in the configuration that we tested. The RealSense seemed to add some additional visual movement for the finger flex movement and the Leap Motion did not always detect the thumb-middle finger touch.

Details were provided alongside the tables Table 7-4 - Table 7-11 dedicated to the movements for which the user felts that the degree of immersion was less than 100%.

By performing these experiments we found a placement for each of the two devices that provides good tracking capabilities. For this purpose we performed some experiments that were based exclusively on visual observations. Given the fact that the TRAVEE system must be highly immersive we believe that an accurate representation of the real movements in the VE is critical and that the purpose of such accuracy is to have a credible aspect – therefore this was our main expectation when choosing the optimal configurations for our situation.

As we did not mean to obtain a qualitative measurement or comparison between the two, we believe our goal of finding what works best for each of the movements in our system was accomplished. Further studies are necessary for an accurate evaluation of these tracking devices.

We also found out more information regarding the way the two devices track our desired movements and the opinion of a healthy subject that tries to perform them while being immersed in a VE.

8 Contribution to the implementation of the VR Central System

Parts of this chapter were published in the following papers:

O. Ferche, A. Moldoveanu, M. Dascalu, C-N. Bodea, R. Lupu, D. Irimia, F. Moldoveanu. The TRAVEE neuromotor rehabilitation system: In-vivo testing. ZINC, Zooming Innovation in Consumer Electronics International Conference, vol. 1, pg. 30-33, Novi Sad, Serbia, 2017.

O. Ferche, A. Moldoveanu, F. Moldoveanu. The TRAVEE system for neuromotor recovery: Architecture and implementation. EHB E-Health and Bioengineering Conference, pg. 575-578, Sinaia, Romania, 2017.

Apart from immersing the patient in the VE and enabling the communication between all the components, the VR Central System also controls the main logic of the application and is in charge of the optical tracking system, the robotic device, the haptic device and the feedback process. The VR Central System may also control the FES if the therapist chose this option in the session configuration tool.

The VR Central System was implemented using the Unity game engine[28].

Unity
Unity is a complex game engine that provides game development functionalities through the aid of an easy to use editor. In Unity, the developer creates scenes containing the elements of the game/application as Game Objects. The user can then add functions to these objects using various mechanisms. Among the features of the Unity game engine are: 2D and 3D graphics, Physics, Scripting, Networking, Animation, UI elements or integration with VR equipment. Another important feature is the asset store that can be accessed to add various functionalities to the game.

The main features used in TRAVEE were the Virtual Reality, Scripting, UI and several assets from the Unity asset store[53].

Virtual Reality – Unity provides seamless integration with several VR equipment amongst which Oculus was used in TRAVEE.

Scripting – either Visual Basic or C# scripts can be used to add functionality to the Unity scene. In TRAVEE we used C# scripts as we had more experience with the language.

UI – Unity allows the user to add GUI elements in the application, as it provides Canvases, Buttons, Sliders and other specific UI elements. All these elements can have attached scripts to control more complex functionality.

Assets – the main assets used in TRAVEE were the Kinect v2 Examples with MS-SDK[54] for applying the movement detected by Kinect onto the virtual avatar of the patient, and the Avatar Hand Controller[55] for the Leap Motion movements.

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[53] Unity Asset Store. https://assetstore.unity.com/. Last accessed March 2018.
[54] Kinect v2 Examples with MS-SDK. https://assetstore.unity.com/packages/3d/characters/kinect-v2-examples-with-ms-sdk-18708. Last accessed March 2018.
[55] Avatar Hand Controller for Leap Motion. https://assetstore.unity.com/packages/tools/input-management/avatar-hand-controller-for-leap-motion-29806. Last accessed March 2018.

Body tracking

For the optical tracking process, we used two devices: Leap Motion[40] for tracking the fine movements of the palm and fingers and Kinect[56] for tracking the rest of the hand (forearm, arm and shoulder) [101].

Oculus Rift

To immerse the patients in the VE we used the Oculus Rift HMD. On the displays of the Oculus Rift[11] the patients observe the scene where they can see their body seated on a chair, from a first-person point of view, and in front of them, also in a seated position, the avatar of the trainer, as can be seen in the figure below.

Fig. 8-1 Screen capture from the perspective of the patient immersed in the VE

Haptic device

For the haptic feedback, the system integrates a haptic device that generates vibrations to the place where they are positioned. During the in-vivo tests, the doctors indicated the appropriate placement of the haptic device for each movement, in order to provide the most suitable feedback to the patient.
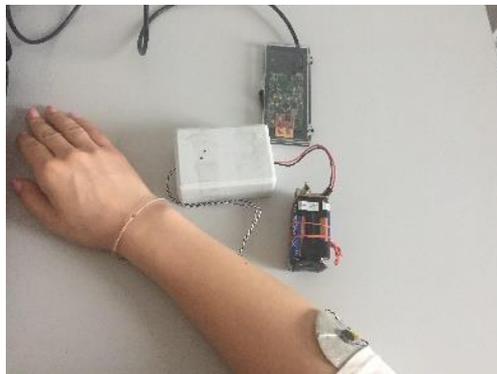
Fig. 8-2 The haptic device

Robotic glove

Another option to support the patient in the correct execution of the movements is the use of a robotic glove [105]. TRAVEE integrated a robotic glove that is part of a different project in PUB, the IHRG [100][106] project. The robotic glove is controlled by the VR subsystem to help the patient perform the movement correctly. When using the robotic glove, the visual magnified feedback is no longer necessary, as the correct movement is already performed by the hand and tracked using the tracking

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[56] Kinect – Windows app development. https://developer.microsoft.com/en-us/windows/kinect. Last accessed May 2017.

devices. The fact that the glove is lightweight is a great advantage, due to the provided comfort, as well as for the fact that it does not change the shape of the hand, thus allowing the optical tracking devices to detect the hand as usual.
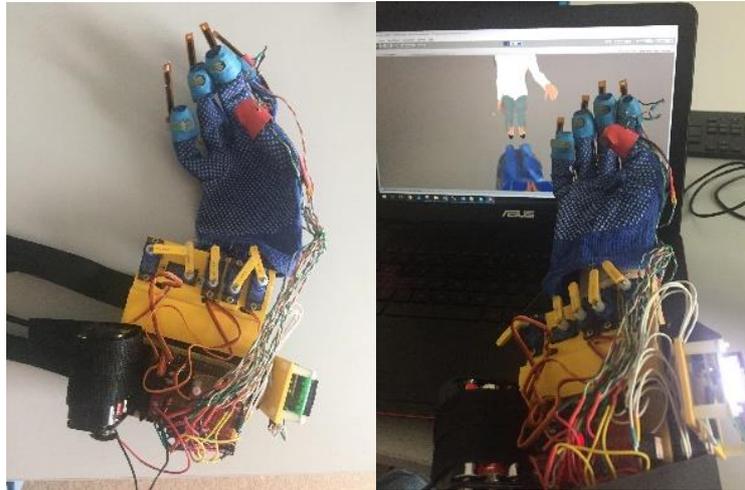
Fig. 8-3 The original IHRG robotic glove

Initially, the original IHRG was used, but in the final implementation stage of the project, a dedicated glove was made, that was more appropriate for TRAVEE – more lightweight, without various sensors that were not used by the VR Central System, and supporting the extension movement, not the flexion as the original glove did. The TRAVEE-dedicated robotic glove is presented in the figure below.

Fig. 8-4 The IHRG designed specifically for TRAVEE

My main contributions to the TRAVEE system are included in the VR Central System. I contributed to the following activities/components, mainly on the implementation and testing parts:

- Definition and server-side implementation of the communication protocol between the system components and the VR central system
- Body tracking for the patient avatar
- Recording of body movements for the therapist avatar
- Contributions to the avatar personalization module
- Rehabilitation session execution
- Visual movement augmentation
- Haptic movement augmentation

- BCI controlled mode
- Robotic hand controlled mode

The contributions are detailed in the following chapters. The entire implementation was made using C# scripts in the Unity engine.

8.1 Communication protocol between the VR central system and other system components

The messages and commands to be exchanged between the main components of the TRAVEE system were defined by the consortium in meetings held in the phase II of the project. It was decided that the system will have a client-server architecture, the VR central system being the server and the Therapist GUI and the Acquisition & Control components being the clients.

I proposed a communication between the three components based on TCP sockets[57] with messages being sent in a serialized JSON format[58] due to its understandability and ease of use with the .Net framework through JSON serialization and deserialization libraries (in particular I used JSON.NET by Newtonsoft[59] in my implementation). I also defined a standardized format of all messages in order to simplify the serialization and deserialization process.

The generic command JSON format that I proposed is defined as follows:

```
Command
        Name: string 1..1
        Parameters: Parameter 0..*
Parameter
        Name: string 1..1
        Value[x] 1..1

Where Value[x] is either
        ValueNumeric: number or
        ValueString: string
```

An example of command is:

```
{
        Name: "command_name",
        Parameters: [
                {
                        Name: "param1",
                        ValueNumeric: 5.3
                },
                {

                        Name: "param2",
                        ValueString: "value2"
                }
        ]
}
```

---

[57] TCP and UDP Socket API. https://www.w3.org/TR/tcp-udp-sockets/. Last accessed March 2018.

[58] JSON. http://json.org/. Last accessed March 2018.

[59] Json.NET – Newtonsoft. https://www.newtonsoft.com/json. Last accessed March 2018.

Another contribution was the implementation of the server within the VR Central system. Using C# scripting, I implemented a socket server that listens for connections from clients. The communication with each main component is made on a different port. As soon as the connection is established, the server listens for and sends commands, as necessary, according to the communication protocol.

The server listens for connections from clients on three ports, one for the Therapist GUI, one for the Data Acquisition and Control and one for the Data Visualization Tool. Each listener has its own thread, waits for connections from clients ant then serves their requests as long as the client remains connected.

8.2   Patient body tracking

The body tracking of the patient avatar was made using two Unity assets: Kinect v2 Examples with MS-SDK[54] created by RF Solutions for the movements detected by the Kinect v2 device and Avatar Hand Controller for Leap Motion[60] created by Ivan Bindoff for the movements detected by the Leap Motion.

1. Head	6. ElbowLeft	11. ThumbRight
2. Neck	7. ElbowRight	12. HandLeft
3. SpineShoulder	8. WristLeft	13. HandRight
4. ShoulderLeft	9. WristRight	14. HandTipLeft
5. ShoulderRight	10. ThumbLeft	15. HandTipRight

16. SpineMid	21. KneeRight
17. SpineBase	22. AnkleLeft
18. HipLeft	23. AnkleRight
19. HipRight	24. FootLeft
20. KneeLeft	25. FootRight
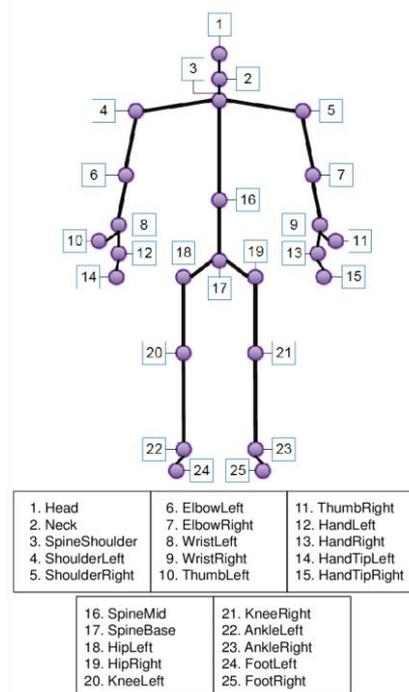
Fig. 8-5 Joints tracked by Microsoft Kinect v2 [107]

As can be seen in the images above, the Kinect tracks over 20 joints, giving the general position of the body, while Leap Motion provides detailed data for the joints of the hand fingers, as presented in the figure below. As a result, for each exercise only one of the devices is necessary for tracking.

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[60]   Avatar   Hand   Controller   for   Leap   Motion.   https://assetstore.unity.com/packages/tools/input-management/avatar-hand-controller-for-leap-motion-29806. Last accessed March 2018.
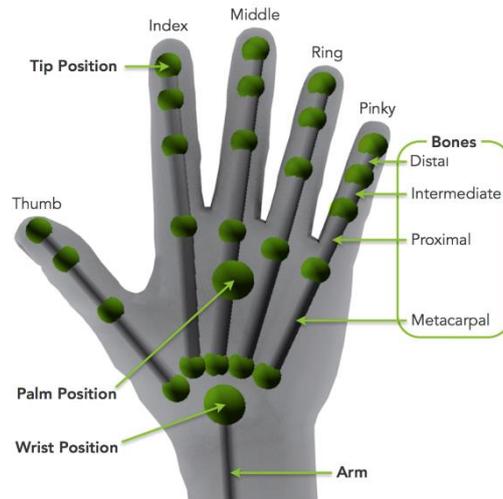
Fig. 8-6 Joints tracked by Leap Motion[61]

Each movement was classified as either a Kinect movement or a Leap Motion movement, based on the segments of the hand that require tracking.

The classification of the TRAVEE movements according to this criterion is presented in the table below.

Table 8-1 Classification of TRAVEE movements based on the tracking device used for detection

Kinect movements	Leap Motion movements
Forearm flexion-extension	Palm flexion-extension
Arm adduction-abduction	Finger flexion-extension
Arm anteduction-retroduction	Thumb opposition
Shoulder raise	Thumb touches
	Forearm pronation-supination

8.3   Recording of body movements for the therapist avatar

For the recording of the therapist body movements I created a separate Unity project, containing only the avatar of the therapist, connected to the body tracking assets. This component is necessary to create recordings with the correct movement execution to be played continuously on the therapist avatar during sessions, for the patients to observe the correct movement they need to perform.

Each asset has a record and play functionality, but for TRAVEE we needed a common recording format for all movements, with all the tracked joints. As a result, I created the TRAVEE Recordings project that is dedicated to recording movements of the therapist. In recording mode, all the movements of the therapist are recorded in a file, by serializing the position, rotation and scale of each tracked joint in its skeleton.

The serialization for a joint in the skeleton looks as follows:

[(2.220446E-18, 0.09706733, 0) (0, 0, -2.913793E-19, 1) (1, 1, 1)]

---

[61] Getting started with the Leap Motion SDK. http://blog.leapmotion.com/getting-started-leap-motion-sdk/. Last accessed March 2018.

The serialization contains three vectors, each delimited by round parentheses: position (given by coordinates on the OX, OY and OZ axes), rotation (given by rotations around the OX, OY and OZ axes) and scale on each of the three axes.

The joints whose position, rotation and scale are recorded by the system for each frame are presented in Table 8-2.

Table 8-2 Joints tracked by the TRAVEE system

	Left Side	**Right Side**
Shoulder	LeftClavicle LeftDeltoid	RightClavicle RightDeltoid
Arm	LeftUpperarm	RightUpperarm
Forearm	LeftForearm	RightForearm
Hand	LeftHand	RightHand
Fingers	LeftIndex1 LeftIndex2 LeftIndex3 LeftMiddle1 LeftMiddle2 LeftMiddle3 LeftRing1 LeftRing2 LeftRing3 LeftPinky1 LeftPinky2 LeftPinky3 LeftThumb1 LeftThumb2 LeftThumb3	RightIndex1 RightIndex2 RightIndex3 RightMiddle1 RightMiddle2 RightMiddle3 RightRing1 RightRing2 RightRing3 RightPinky1 RightPinky2 RightPinky3 RightThumb1 RightThumb2 RightThumb3

In the TRAVEE scene, when the movements are played on the therapist avatar, the recording file is de-serialized and the stored positions are applied to the avatar frame by frame.

I made recordings for each movement for each side of the body, as the functioning scenario of the system is that the patient and the therapist avatar are placed face-to-face, and the therapist avatar will demonstrate the movements in a mirrored fashion – on the right side of the body when the patient is exercising the left hand or arm, and vice-versa. For each movement, depending on the currently exercised side of the body, the corresponding movement will be played on the therapist avatar.

8.4   Contributions to the avatar personalization functionality

The avatar personalization module was also implemented in Unity. It consists of a scene in which only one 3D model for the avatar is present, and the user can also see a simple GUI. The GUI contains controls for changing the characteristics of the 3D model.

This functionality is used by the therapist, that chooses the most appropriate features for the patient avatar to obtain an optimal degree of immersion.

My contributions to the avatar personalization module were brought upon an existing prototype solution implemented by another colleague at UPB, Alexandra Voinea, that allowed the user to personalize the

Gender and Age of the avatar (five options), the Weight of the avatar (5 options), the Height of the avatar (6 options), the Hair color and the Skin color. The existing solution was not integrated with the TRAVEE system, as it was still a standalone project designed specifically for personalizing the patient avatar.

My contributions to this module were: integrating it with the TRAVEE system and adding two options of clothing and two options of hairstyle for each gender, removing the Height changing option as the user had no elements of rapport to approximate the avatar's height. I also optimized the number of necessary models for the customizations.

Initially, in the prototype avatar personalization scene, the configurable characteristics were Age, Gender, Height, Weight, the color of the Skin and Hair.

In the final personalization module, the customization of the patient avatar contained options for changing: Gender of the avatar (Male/Female), the Age (Young, Adult, Old), the Hairstyle (2 options for each gender), the Clothes (2 options for each gender), the color of the Hair and Skin and the Weight (Small, Medium, Large).

In the original solution, there were many 3D models used for the avatars: a model for each combination of characteristics (all present in the scene but only one visible at once) and as the user changed the selected characteristics by using the provided controls would hide the currently displayed model and show the 3D model with the selected characteristics.

The avatars, in the personalization module were created using the open source 3D character creation tool Make Human[62]. Characters created in Make Human can have various geometries (hair, clothes, shoes, etc.), various poses (in TRAVEE we needed the avatar to stand in a T-pose – standing with the arms at 90 degrees) as well as various (more or less detailed) skeletons. In animations (in TRAVEE the characters are animated with the movements tracked by the sensors) the skeleton of the character is critical as the meshes representing the outer layers are deformed and moved according to its movements. We need a skeleton that has details in the bone structure of the hand.
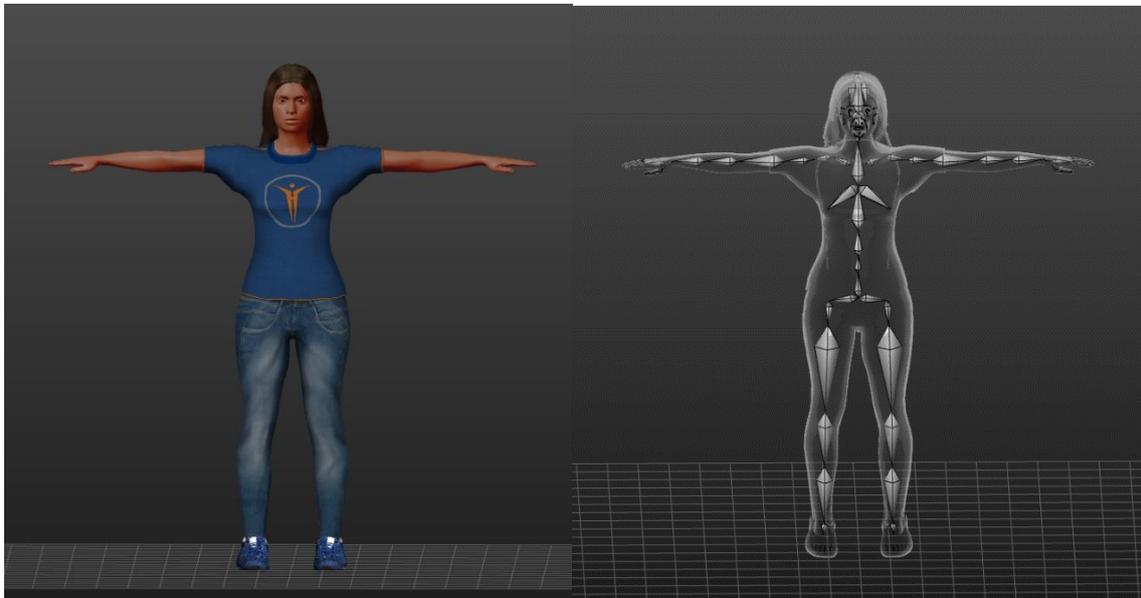
Fig. 8-7 Avatar as visible in the scene (left) and its associated skeleton (right)

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[62] MakeHuman | Open source tool for making 3d characters. http://www.makehuman.org/. Last accessed March 2018.
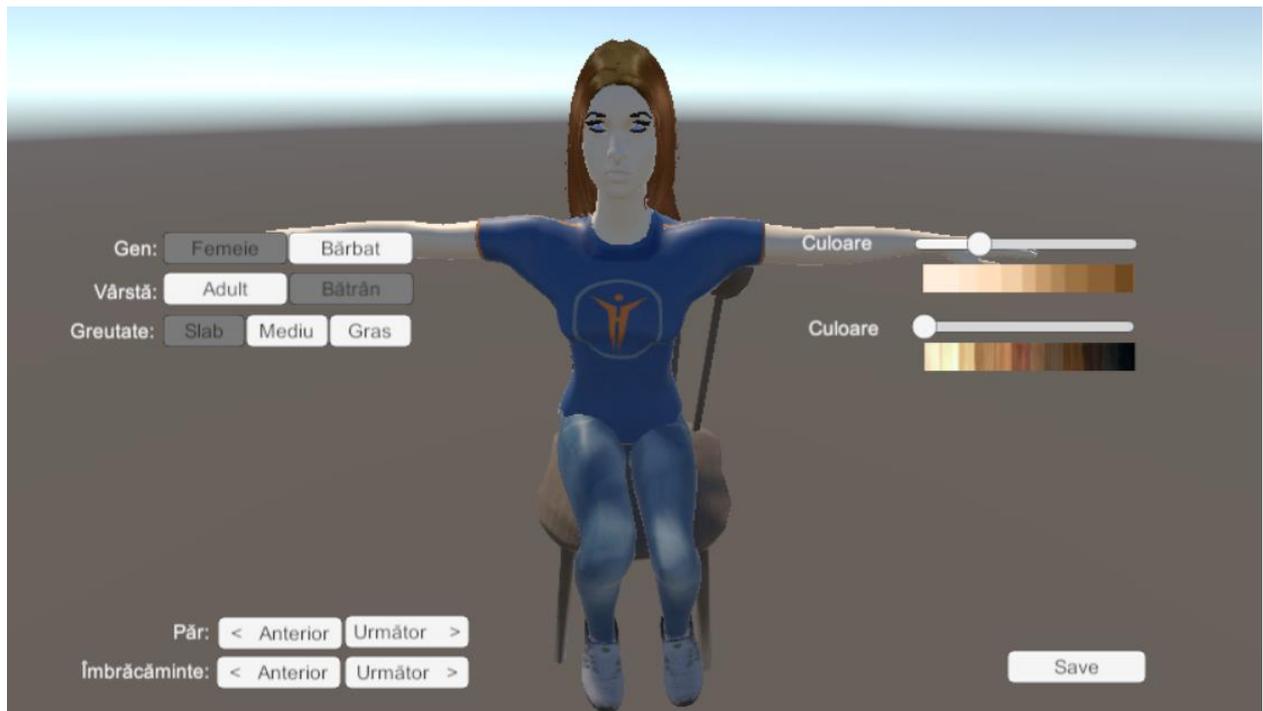
Fig. 8-8 Avatar personalization options including Hair and Clothing

Due to the considerable number of possible combinations, the loading of the prototype scene took a long time, as many avatars (approximately 60 in the original module) needed to be loaded in order to be available at runtime. By adding two different clothes and two different hairstyles for each avatar, the total number of avatars to be loaded without optimizations would have been 2 x 2 x 2 x 60 = 480 avatars.

My solution was to generate a number of avatars equal to the number of unique skeletal structures in the 480 avatars, and to switch pieces of the meshes attached to them when the user changes a characteristic.

More precisely, I observed that the skeleton of the avatar only changed when switching the gender, the age or the weight. The height of the avatar seemed not to be relevant as in the TRAVEE scene there are no elements of rapport. Therefore, I generated 3D models for each skeletal structure with all the possible meshes (for each skeleton I had to have the appropriate mesh for each clothing and hairstyle), therefore for each combination of Gender, Age and Weight I created two avatars, one with one clothing and hairstyle and one with the others.

Thus, changing a configuration of the avatar included several or all the following steps:

1. If the new avatar has a different skeletal structure, find in the existing models the one with the appropriate skeleton (based on Gender, Age and Weight). There are two avatars with this skeleton. Display one of them. This becomes the current avatar.
2. From the two models with the current skeleton, select the one with the appropriate clothing. Find the mesh corresponding to the clothing of this avatar and replace the one on the current avatar.
3. From the two models with the current skeleton, select the one with the appropriate hairstyle. Find the mesh corresponding to the hairstyle of this avatar and replace the one on the current avatar.
4. Set the selected hair color (functionality existing in the prototype of the module).
5. Set the selected skin color (functionality existing in the prototype of the module).

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Each personalization option is encoded, and there is a Save option that associates the current configuration with the current patient – part of functionality discussed as follows.

Integration in the TRAVEE system

The avatar personalization feature is accessed in the TRAVEE system from the Therapist Graphical User Interface. Here, the therapist passes through the Search Patient screen to get to the Patient Configuration form. In the right side of the form there is a picture of the current patient avatar underneath which there is a *Personalize patient avatar* button.
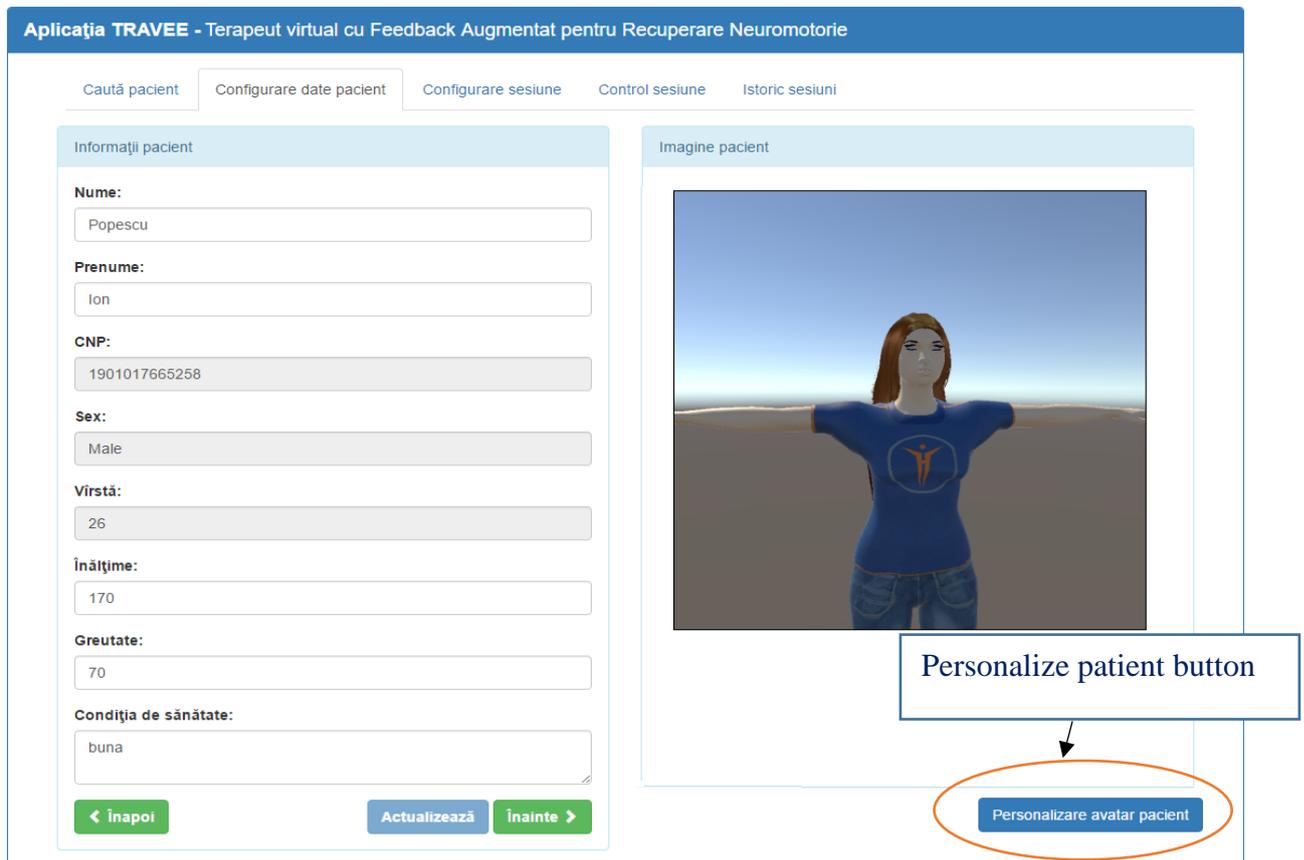
Fig. 8-9 Patient configuration screen in the Therapist GUI component of the TRAVEE system

Clicking this button will result in sending a configure avatar command to the Virtual Reality Central System, that looks like:

```
{
        Name: "GET_AVATAR",
        Parameters: [
                {
                        Name: "PATIENT_ID",
                        ValueNumeric: 115
                },
                {
                        Name: "SEX",
                        ValueString: "F"
                },
                {
                        Name: "SIZE",
                        ValueString: "S"
                }
        ]
}
```

On the server side, in the Virtual Reality Central System, when the GET_AVATAR command is received, the state of the virtual environment is changed to the avatar personalization mode, which implies that:

- The camera is moved from the first-person point of view for the patient avatar, to face the patient avatar, for the therapists to be able to see the changes they make
- The personalization options are displayed as a simple GUI consisting of buttons and sliders, as well as a Save button
- If the same patient ID (received in the command on the PATIENT_ID parameter) was already personalized before, it will have a personalization file associated on the server, and it will be loaded with the previously established characteristics. If the same PATIENT_ID was never personalized before, the avatar is pre-loaded with the Sex and Size configurations given in the GET_AVATAR command as parameters.
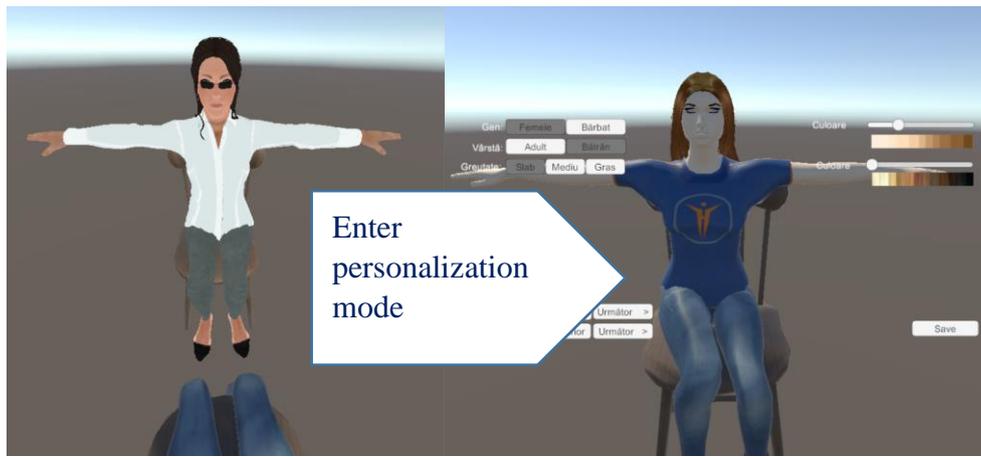
Fig. 8-10 The change of perspective and the display of GUI controls when entering Personalization mode after receiving the GET_AVATAR command on the server

The therapist performs the desired changes to the avatar by using the simple GUI and then presses the Save button. This results in two actions:

1. The avatar personalization is saved on the Virtual Reality Central System server as a text file containing the current avatar state (chosen Gender, Age, Hair, Clothing, Hair and Skin colors) identified by the avatar ID, in order to be loaded when sessions are started for the patient with this ID.
2. The Virtual Reality Central System server responds to the Therapist GUI system with a COMMAND_SUCCEEDED message containing a screenshot of the personalized avatar, in order to be displayed to the therapist in the GUI.

```
{
        Name: "COMMAND_SUCCEEDED",
        Parameters: [
                {
                        Name: "IMAGE",
                        ValueString: "data:image/png;base64,iVBORw0KGgoAAAANSUhEUgAAAXcAAAF3CAIAAA
DRopypAAAgAE1EQVR4Aey9e9RtWVUfe..."
                }
        ]
}
```

Fig. 8-11 Response for the GET_AVATAR command

I implemented the Virtual Reality Central System part of this functionality, the server listening for connections and commands from the clients. After the Therapist GUI client is connected, the Server can receive the GET_AVATAR command. When receiving this command, the Server enters the personalization mode, by changing the camera position to focus the patient avatar and displays the personalization GUI controls

8.5   Rehabilitation session execution

A session consists of a list of exercises. Each exercise has an associated: body side (either left or right), a duration and an associated list of devices or features that will be used for it. The available devices and features in the TRAVEE system are: visual augmentation, vibrations, Functional Electrical Stimulation (FES), Electromyography, Brain Computer Interface, Robotic glove. Each of these will be described in the following chapters.

The therapist defines the list of exercises to be executed in the current session and then navigates to the Session control form by pressing the Start session button. This will redirect the therapist to the Session control screen that provides controls to start, stop, pause or continue the session, as shown in Fig. 8-12.
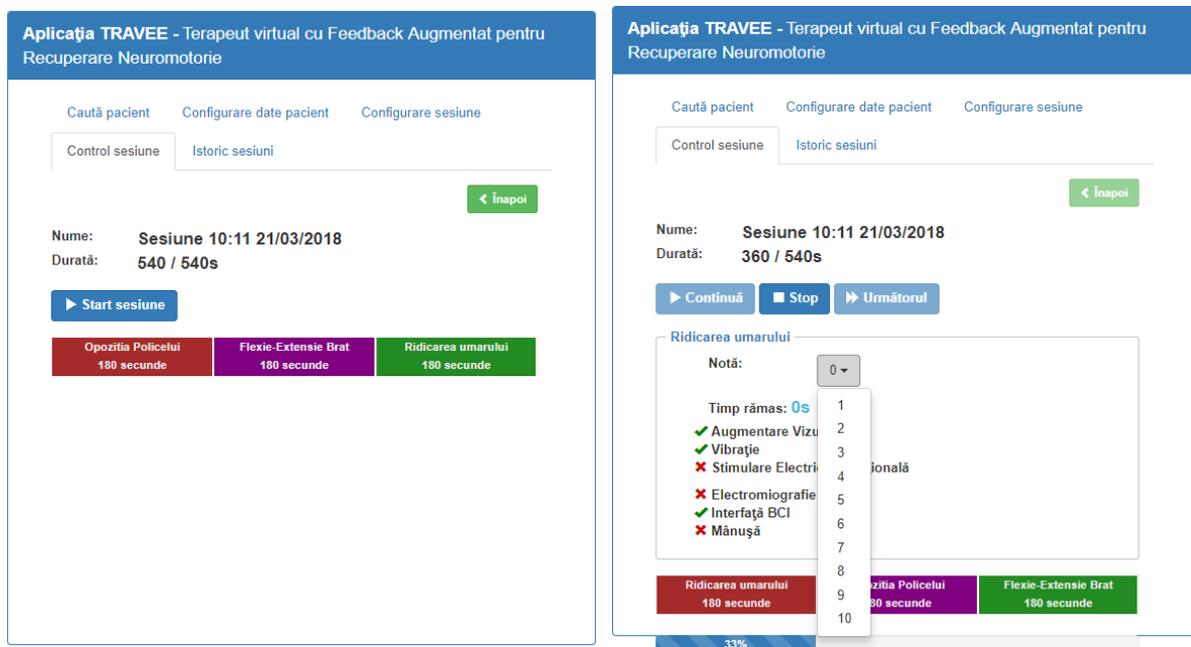
Fig. 8-12 The Session control screen of the Therapist GUI

From the Session control screen, when the user clicks the Start session button, the rehabilitation session is started and a CONFIGURE_SESSION message is sent to the Virtual Reality Central System with all the data about the current session. An example of such message is presented below:

```
{
        Name: CONFIGURE_SESSION,
        Parameters: [
                {
                        Name: SESSION_ID,
                        NumericValue: 1212
                },{
                        Name: DURATIONS,
                        StringValue: "10, 15, 20"
                },
                {
                        Name: EXERCISE_CODES,
                        StringValue: "FM, EU, FC"
                },{
                        Name: DEVICES,
                        StringValue: "BCI, FES/ VIBRATION,EMG/BCI,EMG"
                },{
                        Name: BODY_SIDE,
                        StringValue: "RIGHT, LEFT, RIGHT"
                }
        ]
}
```

Fig. 8-13 Example of SESSION_CONFIGURATION message

The VR Central System receives the message and as a result builds its own current Session object that contains all the received information regarding the contents of the currently executed session.

As soon as the CONFIGURE_SESSION message was received, the server gets into a state where it is ready to receive the mentioned session control commands: START, PAUSE, SKIP or STOP. The UML activity diagram for the session control process with the messages sent from the Therapist GUI is presented in Fig. 8-15.

Each of these commands does not require any parameters, therefore the JSON format is the simplest, as presented in

{ Name: "START" } { Name: "PAUSE" } { Name: "SKIP" } { Name: "STOP" }

Fig. 8-14 Format of simple Session control commands
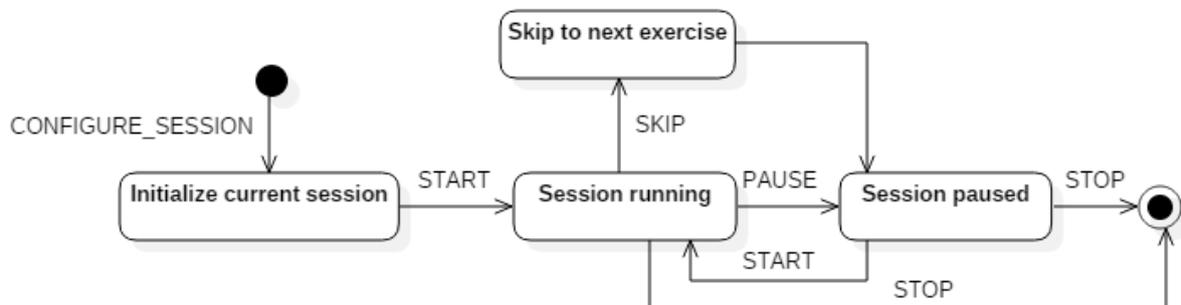
Fig. 8-15 UML activity diagram for the Session control process

Initialize current session

Within this activity, the server initializes the current session with the information received from the Therapist GUI and initializes the current exercise.

Session running

While the session is running, the following operations are continuously performed:

- The pose of the therapist avatar is updated according to the corresponding recorded file. Based on the current exercise, the appropriate animation for the therapist avatar is selected. As the patient regards the therapist avatar face-to-face, the therapist will always play the current movement animation for the opposite hand/arm. For example, if the current exercise is for the left hand of the patient, the animation on the therapist avatar will be played on its right hand, for the patient to observe the movement in a mirrored fashion.
- The movement of the patient is analyzed and augmented according to the settings established by the therapist for the current exercise, based on information received from the Acquisition and Control system, as well as on the tracking data. The augmentation process will be described in the following chapters.

Skip to next exercise

Skipping to the next exercise involves interrupting the currently executed exercise, setting the current exercise counter to the next exercise index and entering the Session paused state.

Session paused

While the session is paused, the therapist avatar is standing still, without displaying the current movement, while the patient avatar is still displaying the movements of the patient, but no analysis or augmentation is performed for these movements.

Commands

The following commands that can be sent from the Session control screen, START, PAUSE, STOP all result in changes of the current state of the system.

The START command received from the Therapist GUI determined the Virtual Reality Central System to perform the following operations:

- Check whether it is an initial START session command or it comes after a PAUSE command.
- If it is the initial START, set the current exercise to be the first one in the session configuration.
- If it comes after a PAUSE message, just continue the current exercise.

The SKIP command received from the Therapist GUI determined the Virtual Reality Central System to perform the following operations:

- Check whether the current exercise is the last one
- If so, just pause the session
- Else, increase the current exercise number, and take all the necessary actions (change the animation on the therapist avatar and the movement evaluation algorithm – to suit the new movement)

The PAUSE command pauses the animation on the therapist and the evaluation of the current movement, while still displaying the movements of the patient on the patient avatar.

The STOP command ends the current session. After a STOP command, the system expects another SESSION_CONFIGURATION command before receiving any of the other control commands.

Fig. 8-16 The Session configuration screen in the Therapist GUI

My contributions to the rehabilitation session execution feature were in the implementation of the server-side logic and functionality. I implemented the socket server on the VR central system, that listens for connections from the Therapist GUI. After the Therapist GUI is connected it can send any of the commands that will be interpreted and executed accordingly.

8.6 Movement analysis

While the session is running, tracking data is provided by the tracking devices at each frame. I will refer to the current data from the tracking devices as the current *pose* of the patient, meaning the positions, rotations and scales of all the joints in their body – as observed by the tracking devices. The VR Central System knows the current movement in the session, that the patient must try to execute, and, using the Movement Analysis component – that is tight coupled with the VR Central System - it analyzes the current pose to determine to which degree the movement was performed.

The evaluation of the degree to which a movement was performed differs for each movement: for each movement we identified a joint or a set of joints that are most relevant and used them to calculate a score. The score is represented by a number whose values vary for each movement, as it can be represented by a relevant angle or a distance between two bones or joints of the hand.

The joints used for the movements are presented in Fig. 8-17 and Fig. 8-18. 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 series of predefined parameters – that were refined based on the information discussed with the medical partners:

- A maximum score up to which the movement is considered to be needing visual augmentation
- A maximum factor of augmentation (the maximum multiplier for the current score – the multiplier has this maximum value when the score is minimal and decreases either linearly or quadratically to 0 for the maximum angle up to which the movement is augmented. The score multiplied by this factor is added to the current score evaluated from the patient pose).

The joints evaluated for each movement are presented in Fig. 8-17 and Fig. 8-18.

Forearm Flexion-Extension

For the forearm flexion-extension movement the elbow joint was considered the most relevant parameter for this movement. It was the one being augmented if the calculated score for the pose was beneath the established threshold. 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.

Thumb Opposition

For the thumb opposition movement, 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 parameter. It was the one being augmented if the calculated score for the pose was beneath the established threshold. Therefore, the given score was the described angle.

The maximum augmentation score, up to which the movement was augmented, was set to 60 degrees.

Arm Adduction-Abduction

For the arm adduction-abduction movement, the angle between the direction of the arm and the direction of the spine is considered the relevant parameter. It was the one being augmented if the calculated score for the pose was beneath the established threshold. Therefore, the given score was the described angle.

The maximum augmentation angle, up to which the movement was augmented, was set to 60 degrees.

Arm Anteduction-Retroduction

For the arm anteduction-retroduction movement, the angle between the direction of the arm and the direction of the spine is considered the relevant angle. Therefore, the given score was the described angle. This angle was the parameter being augmented if the calculated score for the pose was beneath the established threshold.

The maximum augmentation angle, up to which the movement was augmented, was set to 60 degrees.

Palm flexion-extension

For the arm anteduction-retroduction movement, the angle between the direction of the hand and the direction of the forearm is considered the relevant angle. Therefore, it was used as the score for the movement. This angle was the parameter being augmented if the calculated score for the pose was beneath the established threshold.

The maximum augmentation angle, up to which the movement was augmented, was set to 45 degrees.

Forearm pronation-supination

For the arm pronation-supination movement, the local Euler roll rotation angle of the forearm relative to the arm is considered the relevant angle. Therefore, it was used as the score for the movement. This angle was the parameter being augmented if the calculated score for the pose was beneath the established threshold.

The maximum augmentation angle, up to which the movement was augmented, was set to 30 degrees.

Finger flexion-extension

For the finger flexion-extension movement, all the angles between the phalanges of the fingers were analyzed. The minimum angle between either two phalanges was chosen as the score for the movement. The parameters being augmented if the movement was below a threshold were all the angles between all the phalanges of the fingers.

The maximum augmentation angle, up to which the movement was augmented, was set to 60 degrees.

Shoulder raise

The shoulder raise 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. This distance was used as a score and was the parameter being augmented if its value would be below the maximum distance threshold, 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 augmented distance.

Fig. 8-17 The angles considered for evaluating the movement score for Forearm Flexion-Extension, Thumb Opposition, Arm Adduction-Abduction, Arm Anteduction-Retroduction

Fig. 8-18 The angles considered for evaluating the Palm flexion-extension, Forearm pronation-suppination, Finger flexion-extension and Shoulder raise movements

8.7 Visual augmentation of movements

During the rehabilitation session execution, the data from the input devices – tracking devices, BCI, EMG – is analyzed by the VR Central System and, if the system decides it is necessary, the movement is visually augmented.

I implemented the visual augmentation of the movement for two use cases: when it is generated by analysis of movement tracking data, and when it is generated by BCI data. The visual augmentation based on BCI data will be detailed in the BCI and visual augmentation

Movement visual augmentation 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 observes on the patient avatar will be a slightly improved version of the real movement, as detected by the tracking devices.

The movement visual augmentation based on movement tracking data uses the score calculated for the movement and a previously set threshold. The movement is augmented if the score is below the threshold with a factor given, which is calculated with a quadratic or exponential formula such that the augmentation factors are inversely proportional with the current score, becoming zero at the established threshold. A graphical representation for the desired variation of the augmentation factor is represented graphically in Fig. 8-19.
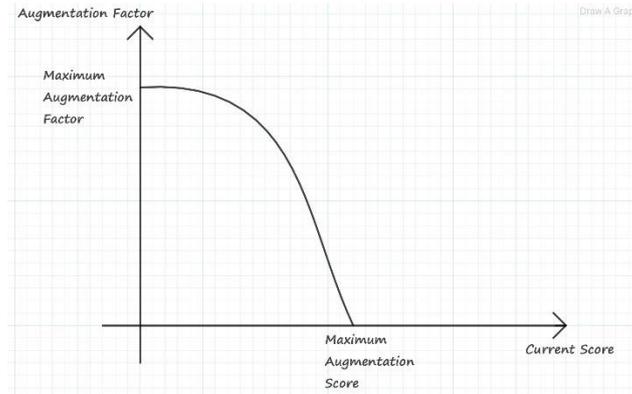
Fig. 8-19 The desired shape of the variation graph for the augmentation factor

Several functions for calculating the augmentation of various parameters in the movement were evaluated, but the one that was determined to be most appropriate for the idea of TRAVEE would have the following form:

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

Such a formula would determine a more or less abrupt variation in the augmented parameter (which can be either an angle or a distance involved in the movement, whose augmentation would be appreciated as an improved movement) depending on the chosen augmentation factor (in the formula marked as

augmentationFactor). A smaller augmentation factor determines a more abrupt increase of the augmented parameter, can be observed in the graphical representations below.
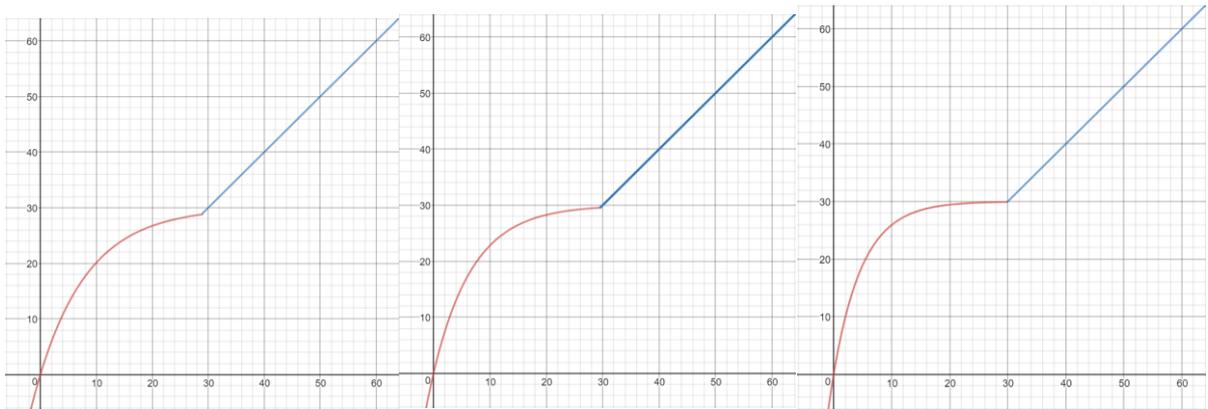
Fig. 8-20 Graphical representations of the augmentation functions with a threshold of 30, and augmentation factors of 9 (left), 7 (center), 5 (right)

The augmentation algorithm is the following:

- Calculate the score for the currently executed movement.
- If the score is beneath the threshold for the currently executed movement, calculate the augmented value for all the parameters involved in the movement before applying them onto the virtual avatar of the patient.
- Otherwise, display the avatar in the position that was detected by the tracking devices.

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".

8.8 Haptic feedback

The haptic feedback for a movement is realized by applying vibrations on certain key areas of the exercised limb when the degree of realization of the current movement passes of a certain pre-established threshold. This is used as an additional feedback, to inform the patient of his or her progress, and to stimulate the continuation of the rehabilitation process.

The vibrations are applied using a device built at the "Gheorghe Asachi" Technical University in Iasi. This device has two small engines that vibrate, attached to electrodes that are placed on the surface of the skin. The placement of the haptic device was decided by the doctors at the moment of testing.
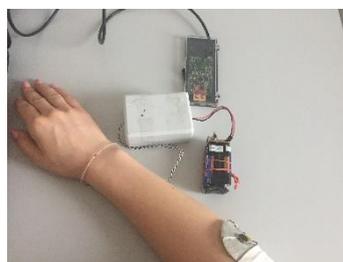
Fig. 8-21 Haptic device placed on the forearm

This feature was implemented by considering predefined parameters for each movement. The evaluation of each movement is made using the previously described method. The predefined parameters define the threshold that determines whether the vibrations are active or not. The poses detected by the optical tracking devices are monitored. When the calculated score for a pose increases

above the threshold, the haptic device is started, in order to apply the vibrations as a form of feedback. The haptic device vibrates for as long as the detected pose has a score for the currently executed movement that is above the predefined threshold.

For the control of the haptic, and robotic devices, I implemented the DeviceController class within the VR Central System. This class is in charge with the serial communication towards the haptic device and the robotic glove.

The controls for the haptic device – as they were implemented by the team at "Gheorghe Asachi" Technical University in Iasi – require that an executable program is called with a series of arguments, representing:
- the identifier of the engine to be controlled (as the device has two motors, the identifier can be either 1 or 2);
- a code for the vibrations type;
- a code for the number of repetitions.
The codes were chosen from the ones provided in the documentation of the device to ensure a feedback that is continuous and easily perceived by the patient.

8.9   BCI and visual augmentation

In BCI controlled mode, the VR Central System receives from the Acquisition system data taken by an EEG device.

The EEG system requires calibration, based on which it identifies EEG patterns associated with the imagination of movement in the left or right hand. After the calibration process, the Acquisition system starts to continuously read EEG values from the patient and to identify the learned patterns in the signals detected by the EEG device. For each reading it calculates a degree of similitude with either the left hand movement brain activation patterns or right hand movement brain activation patterns which is translated into a value in the [-1, 1] interval, where -1 represents the best detection of the patterns for the movement of the left hand and 1 is the best detection of the patterns for the movement of the right hand. Values close to 0 represent a weak detection of patterns and are considered resting periods. This value is sent to the VR Central System to be recorded and processed.

In the BCI controlled mode visual augmentation, the VR Central System presents the patient with the rehabilitation scene, in which the patient sees the patient avatar from a first-person point of view. The VR Central system receives values from the Acquisition system and based on the received value may decide to play a pre-recorded movement on the avatar of the patient on either the left or the right hand, based on the following algorithm:

- The patient is indicated to imagine alternatively movements on the left and on the right hand
- When the values calculated by the Acquisition system are in the interval (-0.5, 0.5) they are considered to be too close to 0 to be relevant, therefore the avatar of the patient stands still, in a resting position.
- When the values calculated by the Acquisition system go outside the (-0.5, 0.5) interval to a value that is greater than 0.5, the VR Central system interprets that the patient started to imagine the movement of the right hand, therefore plays an animation of raising the right hand on the patient avatar in the virtual environment.
- When the value received from the Acquisition system increases, re-entering the (-0.5, 0.5) interval, the system plays an animation lowering the right hand on the patient avatar in the virtual environment.
- When the values calculated by the Acquisition system go outside the (-0.5, 0.5) interval to a value that is lower than -0.5, the VR Central system interprets that the patient started to imagine

the movement of the left hand, therefore plays an animation of raising the left hand on the patient avatar in the virtual environment.

When the value received from the Acquisition system decreases, re-entering the (-0.5, 0.5) interval, the system plays an animation lowering the left hand on the patient avatar in the virtual environment.

8.10 Robotic hand controlled mode

This mode is dedicated to patients with less motor control of their hand. In this mode of functioning, the patient is immersed in the virtual environment, while the movements of the palm are detected by the Leap Motion device.

First IHRG glove and initial integration with the TRAVEE system
The robotic glove is part of the IHRG project. Initially, I integrated the original IHRG glove with the TRAVEE system, which is presented in Fig. 8-3.

In the initial implementation of this functionality, I used the API of the IHRG glove to send commands on the serial ports for each movement. The API of the glove, as implemented by the IHRG project of Prof. Nirvana Popescu at POLITEHNICA University of Bucharest, includes several one-byte codes that – when sent to the glove via the serial port, determines an activation of the 5 motors placed on the wrist of the hand in the correct configuration and sequence to provoke one movement.

The integration of the initial IHRG glove consisted in the following mode of functioning of the TRAVEE system:

- The patients – wearing the IHRG glove - are immersed in the virtual environment, where they see the patient avatar that moves according to the movements detected by the Leap Motion device – without visual augmentation.
- When an exercise that includes the IHRG glove as a form of augmentation is played, the system periodically sends – via the serial port – a code representing the currently executed movement, that determined the glove to perform one repetition of the selected movement. In this manner, the glove continuously assists the patient hand in performing the current movement.

TRAVEE-dedicated IHRG glove and final integration with the TRAVEE system
After the integration of the initial IHRG glove with the TRAVEE system, there were several ideas of improvement, suggested by the teams at UBP and INRMFB regarding the way of functioning of the glove. Therefore, a glove dedicated to the TRAVEE system was created by prof. Nirvana Popescu's team, that was more in sync with the purposes of TRAVEE. The IHRG developed especially for the TRAVEE project is presented in Fig. 8-4.

The main changes that were brought to this glove compared to the one initially integrated are:

- The initial glove assisted the patient in the flexion movement. The doctors at INRMFB remarked that much more useful it would be for the glove to perform the extension movement. Therefore, the TRAVEE-dedicated IHRG glove has the actuating motors placed on the upper side of the wrist, assisting the extension of the fingers. The existing commands remained but due to the new placement of the motors they now control the extensions.
- New commands were added that were more appropriate for the new mode of functioning within the TRAVEE system. More precisely, new options for the ALL movement were introduced – new movement codes that represent the extension of all fingers followed by their flexion, but that also control the number of seconds that the extension is maintained before allowing the fingers to return to a flexed position. These new commands also have one-byte codes, with values from 91..99, the second digit representing the number of seconds of extension. The

flexion of the fingers is obtained by releasing the fingers from the extended position, allowing them to return to their flaccid state.

The TRAVEE functioning mode with the TRAVEE-dedicated IHRG glove implied the implementation of a configuration screen, that allows the doctor to select three parameters for the robotic movement:

- Seconds of extension: the number of seconds the extension of the fingers is maintained before allowing the fingers to flex. This parameter is set using a dropdown containing numbers from 1 to 9, as the commands implemented on the glove allow between 1 and 9 seconds of extension. Will refer to this parameter in the following paragraphs as extension_seconds.
- Seconds of inactivity: the number of seconds after which – if the system detects from the Leap Motion no significant movement in the palm – it considers the patient is not able to perform significant movement and starts the robotic glove automatically, to perform the movement for the patient. I will refer to this parameter in the following paragraphs as inactivity_seconds.
- Seconds of blockage: this parameter is especially useful if the patient has a small mobility in the hand. If the system detects from the poses detected by the Leap Motion that the patient started extending the fingers but then cannot complete the movement because at a certain point of the extension the hand of the patient is blocked for a number of seconds in an approximately static pose, the robotic hand will start, assisting the patient in completing the movement. I will refer to this parameter in the following paragraphs as blockage_seconds.

These parameters are set in the configuration screen presented in the image below.

Fig. 8-22 Configuration screen for robotic augmentation functioning mode

After the doctor defined the specified parameters he will press the start button, which will start the following functioning mode of the system, for the extension-flexion movement of the fingers:

- At each moment of time, analyze the tracking data from Leap Motion, to detect whether any change in the pose of the patient took place. This is made by continuously evaluating the score of the fingers flexion-extension movement, as described previously. If the score changes, then so did the patient pose. If the score grows, therefore the patient is flexing the hand, whereas if the score decreases, the patient is extending the hand.
- To avoid jitter in the detection of fingers flexion and extension, I implemented the following algorithm:
  o I maintained a queue, containing all the scores for all the poses detected by the Leap Motion device during the last *blockage_seconds* seconds. For this, every time the Leap Motion detects a reading, the pose of the patient is analyzed to obtain the current score, the new score is added to the queue in a structure that also includes the time it was generated. At the same time, the entries in the queue that are older than *blockage_seconds* are eliminated, in order to not be used in the following evaluations.
  o The next step is to analyze the entries that remained in the queue. They are divided into 5 approximately equal sets. For each set, an average score is calculated for the first half of entries and for the second half of entries in that set. If the first average is greater than the second average in a set, that set could represent an extension of the fingers and is marked accordingly. If the first average is lower than the second average, then that set will be marked as representing a flexion of the fingers. Each of the five sets in the queue are marked as either flexion or extension. The movement is declared as being a flexion or extension only when 4 or all of the 5 sets are marked the same way. Otherwise, the movement is declared unknown, so the current state (flexion or extension) is not changed. This way, I obtained quite an accurate classification of the current movement of the hand.

By using timers, and knowing the current movement state, I was able to implement the desired algorithm for the TRAVEE-dedicated IHRG glove integration, described as follows.

At each moment of time:

  o evaluate the scores in the described queue, to detect if there was a movement state change (flexion to extension or reversed)
  o If the robotic movement is off, and no movement was detected within the last *inactivity_seconds*, start the robotic glove movement, with an extension equal with *extension_seconds*.
  o If the robotic movement is off, the current state of the movement is extension, and no considerable progress was detected in the past *blockage_seconds*, start the robotic glove movement, with an extension equal with *extension_seconds*.

During this mode of functioning, the perspective of the patient is the same as in the visual augmentation mode, a first person view of the patient avatar, with the therapist avatar in front of the patient, continuously exemplifying the finger flexion-extension movement on the opposing hand, in a mirrored fashion.

Fig. 8-23 Screen capture from the patient point of view in the VE

8.11 Session recording

In order to be able to analyze the data generated during the sessions with the patients, the VR Central System of TRAVEE also includes a recording functionality. This functionality is integrated with the VR Central System and stores all the relevant information for each session in a .session file.

For this feature, I created a dedicated class, SessionRecorder, that is instantiated for each session created within the system. The SessionRecorder class creates and opens an associated file in a preset location of the file system in its constructor and provides logging functions for all the information that must be logged for a session: avatar poses, EMG values, BCI values, exercise codes. Having these information is enough to be able to use the session player and re-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. It creates and writes all the information in a recording file that includes in its name the session and patient identifiers and the body side for which the exercises are performed. The file is created and opened when the session is created and is closed when the session is stopped.

The data stored in the recording files was fundamental for the analysis that was performed regarding the performances of the patients during the clinical tests with the TRAVEE system.

Each information in the recording files is written on a new line that begins with a descriptor of the information on that line. The information is:

- Current exercise: when the session progresses to a new exercise, its code is logged in the file on a new line with the descriptor [EXERCISE], followed by the exercise code.
- Un-augmented posture: this information represents a serialization of all the positions, rotations and scales of all the tracked joints in the body of the patient avatar. By de-serializing this information, the session analyzer can simulate all the states through which the system passed at runtime during the effective sessions and – by applying the same logic – can take the same

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decisions, actually playing the exact session and providing the doctor with the same experience as the patient, in order to extract all the relevant data.

- EMG value. If for a certain frame the VR Central System also processed an EMG value received from the Acquisition system, it will also be logged in the recording file on a line marked by the descriptor [EMG].

- BCI value. If for a certain frame the VR Central System also processed a BCI value received from the Acquisition system, it will also be logged in the recording file on a line marked by the descriptor [BCI].

8.12 Session analysis

This functionality was implemented to obtain data regarding the evolution of each of the patients tested using the VR Central System functionalities during the clinical trial that took place in April-May 2017. For this purpose, the session analysis tool can analyze automatically many session recording files that have the format previously described, and extract from them synthetic data, so that the therapist can gather information without visually inspecting all the sessions.

This tool consists in a new Unity project 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 it analyzes the poses in the file (the lines marked with the descriptor [P]) 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, it determines the following information:

- The execution times for each session
- 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
    - The average score for all the poses detected for the execution of a given exercise

One repetition is evaluated as two successive changes in the direction of variation of the calculated score for the current movement. A change in the direction of variation of the score is evaluated using an algorithm similar to the one used in the robotic hand-controlled mode (described in the associated chapter):

- For each line in the session recording file representing an avatar pose, analyze it to detect whether any change in the pose of the patient took place. This is made by evaluating the score of the current movement, as described in the Movement analysis chapter. If the score changes, then so did the patient pose.
- To avoid jitter in the detection of the change in direction of evolution of the score, I implemented the following algorithm:
    o At each moment, I maintained a queue, containing all the scores for the last 70 poses of the patient. For this, each pose in the session recording is analyzed to obtain the current score, the new score is added to the queue. If the queue was already at maximum capacity (70 scores) then the oldest score is eliminated from the queue, to not be used in the following evaluations.
    o The next step is to analyze the entries that remained in the queue. They are divided into 3 approximately equal sets. For each set, an average score is calculated. If the average of the first set is greater than the average of the second set and the average of the second set is greater than the average of the third set (the average scores of the three sets are in an arithmetic progression with positive rate) then the score is considered to be increasing. Similarly, if the average score of the first set is lower than the average score of the second

set and the average score of the second set is lower than the average score of the third set (the average scores of the three sets are in an arithmetic progression with negative rate), then the score is considered to be decreasing. 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 results of an analysis process is a file containing the obtained information, in the following format:

- For each file containing the recording of a session, the file contains the name of the file, followed by the information extracted from it:
    - Average score, labeled "Score average:"
    - The number of repetitions as perceived from the score variations, labeled "Repetitions"
    - The total session duration of the session.

An example of an entry in the result file is presented in the following lines.

C:/Recordings/Recording_1057_4_LEFT.session
FEA
Score average: 63.44876
Repetitions count: 148
Duration:
FED
Score average: 33.81826
Repetitions count: 206
Duration:
Duration: [180993]

The results presented in chapter 10 were obtained analyzing the recordings of the sessions during the clinical trials in 2017.

9 In-vivo tests

Parts of this chapter were published in the following papers:

The in-vivo tests took place in two sessions, one in November 2016, and one in December 2016. Both sessions were held at the National Institute for Recovery, Physical Medicine and Balneoclimatology (INRMFB) in Bucharest. The purpose of these tests was to validate the initial prototype of the TRAVEE system. The session in November made use of several configurations of the system: BCI and FES, BCI and VR visual augmentation, VR with visual augmentation with optical tracking. The session in December tested the system with visual and haptic augmentation.

The results of these initial in-vivo tests were promising and provided details on what had to be improved in the final prototype of the system.

9.1 The first set of in-vivo tests

In this set of tests, November 2016, one patient has tested the BCI and VR visual augmentation functioning mode, and three patients tested the VR and optical tracking with visual augmentation functioning mode.

Results

The patients were asked to answer several questions regarding their experience with the TRAVEE system. The questions referred to their comfort during the session, the quality of the images presented on the HMD and of the avatars and their movements as well as their opinion regarding the utility of such a rehabilitation system. Each question had five answer options, on a scale from 1 to 5.

Sessions

Each of the patients performed the exercises while in a seated position, to better identify their body with that of the avatar. The Oculus Rift device was placed on the head of the patient and was not removed until the end of the session. Also, the Oculus served as a support for the Leap Motion tracking device – as it was used in the head-mounted configuration – placed on the HMD.

9.1.1 BCI with VR visual augmentation

Exercises

For the BCI and visual augmentation mode, the palm flexion-extension movement was chosen.

Results

The responses of the patient for this mode are presented in the table below.

Table 9-1 Questionnaire responses of the patient for the BCI and VR visual augmentation mode

Question	#1
During the test, what was the perceived level of tiredness?	5
During the tests did you feel dizziness?	1
During the tests did you feel nauseous?	1
During the tests did you feel any anxiety or fear?	1
The image perceived on the virtual glasses/monitor was clear?	4
Did you feel physical discomfort due to the system components?	1
Did you feel pain due to the electrical stimulation?	1
How real did the avatar movements seem to you?	3
How useful do you find such a rehabilitation system?	4

9.1.2 VR visual augmentation with optical tracking

Exercises

The exercises chosen by the doctors for the VR visual augmentation with optical tracking mode for this in-vivo testing session were:

- Forearm flexion-extension
- Arm anteduction-retroduction
- Palm flexion-extension
- Fingers flexion-extension

Results

The responses of the three patients for this mode are presented in the table below:

Table 9-2 Questionnaire responses of the patients regarding the VR visual augmentation with optical tracking mode

Question	#1	#2	#3	Average
During the test, what was the perceived level of tiredness?	3	3	1	2.33
During the tests did you feel dizziness?	1	4	4	3
During the tests did you feel nauseous?	1	1	1	1
During the tests did you feel any anxiety or fear?	1	1	3	1.66
The image perceived on the virtual glasses/monitor was clear?	3	4	3	3.33
Did you feel physical discomfort due to the system components?	1	2	1	1.66
How real did the avatar movements seem to you?	1	1	5	2.33
How well do you identify your movements to those of the avatar?	3	2	5	3.33
Did you feel that the movements of the avatar were different than yours (greater)?	2	2	1	1.66
Are the indications of the virtual therapist useful for the exercise execution?	3	3	5	3.66
How useful do you find such a rehabilitation system?	4	4	1	3

Conclusions

The patients reported that they felt tired after the session with an average of 2.33 out of 5. Two of the patients reported dizziness from the visuals on the virtual reality glasses, but they perceived no nausea and very little anxiety. The image of the virtual environment was quite clear, as they rated it above average, with 3.33. No major discomfort was reported. The movements of the avatar needed improvements as two of the patients did not think they looked realistic. None of the patient was disturbed by the visual augmentation of the movements, therefore we concluded it was well applied, in a non-disruptive manner. The virtual therapist needed improvement, and that fact was also remarked by the patients.

The conclusions of this round of testing were that the system can be used in a medical rehabilitation session for patients with various degree of disability, but there were also certain improvements to be made.

One such improvement was that of helping the patients to maintain their gaze in the direction of their hand. As the Leap Motion device is attached to the Oculus Rift, the hand of the patient must always remain in its field of detection, therefore the patient must always look towards the hand. For this we concluded it would be necessary to add visual cues when the direction of gaze strays too far away from the direction of the hand, to inform the patient to look closer to the hand, for better detection.

Another improvement that was included in the final prototype consisted in improving the quality of the recordings played on the therapist avatar, for seamless looping motions, as well as to improve the settings for the Leap Motion asset to ensure better representation on the patient avatar.

9.2   The second set of in-vivo tests

In December 2016, the second set of In-vivo tests took place at the INRMFB in Bucharest. The tested system included the VR Central System with optical tracking devices, the HMD and provided visual and haptic feedback.

Patients

The patients were selected by the doctors and had different degrees of disability of one of their upper limbs. Each patient was required to sign a consent form and at the end of the testing session was asked to answer a series of questions regarding the system, that will be detailed below.

Sessions

Each of the patients performed the exercises while in a seated position, to better identify their body with that of the avatar. The exercise sessions consisted of two sets of 2 minutes for each exercise, with a break between each set. The Oculus Rift device was placed on the head of the patient and was not removed until the end of the session. Also, the Oculus served as a support for the Leap Motion tracking device – as it was used in the head-mounted configuration – placed on the HMD.

Exercises

The exercises in the test session were chosen specifically to include a smaller movement (Palm flexion-extension) - that is tracked by the Leap Motion device – as well as a larger movement (Forearm flexion-extension) – that is tracked by the Kinect device – in order to test both tracking devices and their ease of use in a clinical settlement.

Results

The three patients were asked to answer several questions regarding their experience with the TRAVEE system. The questions regard their comfort during the session, the quality of the images presented on the HMD and of the avatars and their movements as well as their opinion regarding the utility of such a rehabilitation system. Each question had five answer options, on a scale from 1 to 5.

The received feedback is summarized in the table below, presented in [103].

Table 9-3 Questionnaire responses of the patients participants to the second set of in-vivo tests with the VR system

Question	#1	#2	#3	Average
During the test, what was the perceived level of tiredness?	1	1	3	1.67
During the tests did you feel dizziness?	1	1	1	1
During the tests did you feel nauseous?	1	1	1	1
During the tests did you feel any anxiety or fear?	1	1	1	1
The image perceived on the virtual glasses/monitor was clear?	3	5	5	4.33
Did you feel physical discomfort due to the system components?	1	2	1	1.67
Did you feel pain due to the haptical stimulation (vibrations)?	1	1	1	1
How real did the avatar movements seem to you?	5	4	4	4.33
How well do you identify your movements to those of the avatar?	4	4	2	3.33
Did you feel that the movements of the avatar were different than yours (greater)?	1	5	4	3.33
Are the indications of the virtual therapist useful for the exercise execution?	5	3	2	3.33
How useful do you find such a rehabilitation system?	4	5	1	3.33

Conclusions

All the patients seemed to accept all the components of the system, as they graded the discomfort levels to be very low. Only one of them reported a level of tiredness, none of them experienced dizziness, nausea or anxiety – as we knew might happen when using such technologies in rehabilitation [42].

The image on the HMD seems to be clear in most cases and the patients seem to be able to identify easily with the avatar and to recognize the movements as their own at an acceptable level.

The VT appears to have been useful but supports some improvements and two out of the three patients appreciated that our system would be quite useful. We need to specify that the third patient had very low activity in the affected hand and could not perform the movements at a level that would be most recommended for the system in the tested configuration. TRAVEE is designed to adapt to various levels of disability, and for more affected patients would have to include the robotic device that was not tested at the session described here.

Because of the feedback received from the patients from this testing session, as well as our own observations during the tests, we have pointed out another improvement that had to be included in the final prototype.

This improvement regarded the use of the positioning sensor of the Oculus Rift. During our testing phase, we found that the Oculus Rift could work just as well without the position sensor, as we only need the rotation of the HMD, to change the perspective in the VE, because our patient avatar always remains on the same position – therefore we excluded the position sensor from our configuration. During these in-vivo tests though, we observed that after extended periods of use, if the position sensor is not found, the Oculus Rift may lose its accuracy, providing erroneous rotations[11].

10 Clinical trial

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.

A total of 21 patients tested the TRAVEE system with visual augmentation. The patients or their representatives had given their accord for participating in the experiments, and an approval was obtained from the ethical council of the INRMFB.

The recordings of the sessions were analyzed using the Session analysis component, as previously described, and 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 angles based on which it is evaluated, the scores cannot be compared between movements. Also, the average scores for each patient are individual, based on his/her abilities in the exercised hand. Usually, a greater score indicates a larger amplitude of movement, therefore possibly a more complete execution.

Another important observation is that the performed clinical test evaluated more patients for less 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 a few months.

A total of 21 patients exercised using the VR Central System with visual augmentation, with an average of 4.09 exercise executions per patient.

10.1 Evaluations based on the automated analysis made by the system

Patient RV1
Took part in three sessions with the TRAVEE VR Central System. In each of the three sessions the patient performed other exercises, therefore we cannot estimate any progress.

Date	Exercise	Duration (seconds)	Repetitions	Average score
26.04.2017	Arm Flexion-Extension	180	11	21
26.04.2017	Shoulder Raises	180	6	0.26
04.05.2017	Forearm Flexion-Extension	180	74	63.44
04.05.2017	Palm Flexion-Extension	180	53	37.22
05.05.2017	Fingers Flexion-Extension	300	103	33.81

Patient RV2
This patient had the most remarkable evolution with the VR 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 and the session started and 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.

Date	Exercise	Duration (seconds)	Repetitions	Average score
04.05.2017	Forearm Flexion-Extension	200	17	65.85
04.05.2017	Forearm Flexion-Extension	180	18	62.65
08.05.2017	Forearm Flexion-Extension	200	26	59.91
08.05.2017	Forearm Flexion-Extension	200	24	67.14
09.05.2017	Forearm Flexion-Extension	200	26	59.92
10.05.2017	Forearm Flexion-Extension	200	40	33.91
10.05.2017	Forearm Flexion-Extension	200	17	24.4
11.05.2017	Forearm Flexion-Extension	200	41	40.86
12.05.2017	Forearm Flexion-Extension	200	26	65.97
12.05.2017	Forearm Flexion-Extension	180	29	62.99

Evolution of the Forearm Flexion-Extension movement

Fig. 10-1 Average scores evolution (left) and average seconds/repetition evolution (right)

Patient RV3

This patient only executed one session with the TRAVEE VR Central System, which exercised the Shoulder Raise movement. This movement has a low amplitude and is detected with difficulties by the system.

Date	Exercise	Duration (seconds)	Repetitions	Average score
27.04.2017	Shoulder Raises	300	49	0.26

Patient RV4

This patient executed one session with the VR Central System that contained the Forearm Pronation-Supination movement. Given the scores that can be given by the system for this movement, the average obtained by the patient shows a good execution.

Date	Exercise	Duration (seconds)	Repetitions	Average score
26.04.2017	Forearm Pronation-Supination	300	49	0.26

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.

Date	Exercise	Duration (seconds)	Repetitions	Average score
09.05.2017	Forearm Flexion-Extension	200	19	92.64
09.05.2017	Forearm Flexion-Extension	200	23	89.28
11.05.2017	Forearm Flexion-Extension	200	44	79.77
11.05.2017	Forearm Flexion-Extension	200	26	74.1
12.05.2017	Forearm Flexion-Extension	200	25	84.12
12.05.2017	Forearm Flexion-Extension	180	23	83.74
19.05.2017	Forearm Flexion-Extension	220	26	76.15
19.05.2017	Forearm Flexion-Extension	200	27	87.83

Evolution of the Forearm Flexion-Extension movement

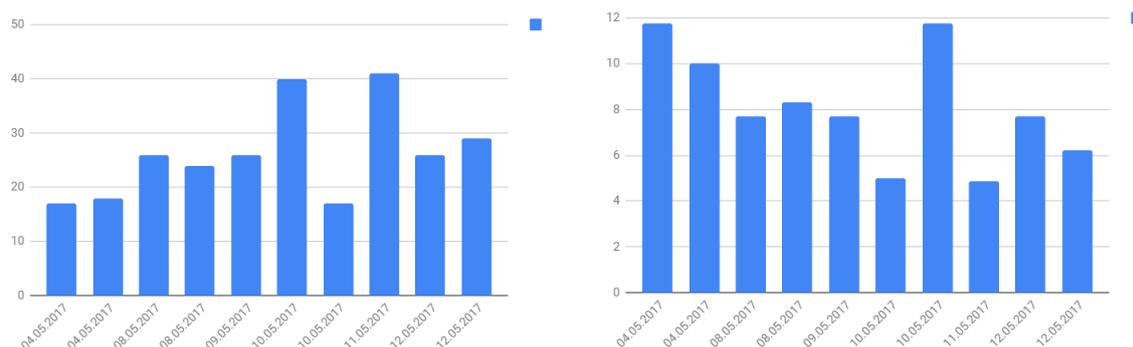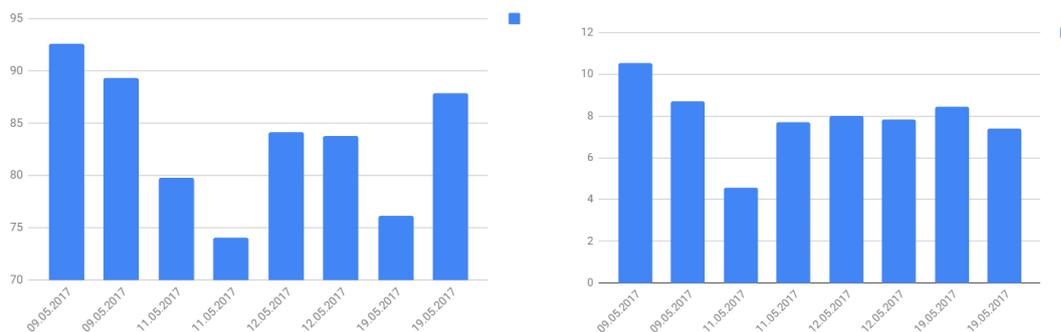*Fig. 10-2 Average scores evolution (left) and average seconds/repetition evolution (right)*

Patient RV6

The patient only took part in one rehabilitation session, and the average scores obtained for the only executed movement, Fingers Flexion-Extension shows a lack of motor control for the execution of this movement.

Date	Exercise	Duration (seconds)	Repetitions	Average score
26.04.2017	Fingers Flexion-Extension	200	46	19.29

Patient RV7

The patient took part in two testing sessions. According to the detections of the system, in the first session the patient performed 42 repetitions, and during the second session the number of repetitions increased to 60. Both times, the patient reported tiredness after the session.

Date	Exercise	Duration (seconds)	Repetitions	Average score
08.05.2017	Fingers Flexion-Extension	200	42	22.94
12.05.2017	Fingers Flexion-Extension	200	60	20.59

Patient RV8

The patient participated in only one rehabilitation session with the TRAVEE VR system, that comprised three exercises, as instructed by the doctor of the patient. The scores obtained for the Forearm Flexion-Extension exercise reveal a good control of the elbow joint. The average scores for the finger movements are relatively low, therefore could imply that progress was necessary for distal movements.

Date	Exercise	Duration (seconds)	Repetitions	Average score
27.04.2017	Fingers Flexion-Extension	200	48	19.64
27.04.2017	Forearm Flexion-Extension	200	27	91.39
27.04.2017	Thumb Opposition	180	53	24.16

Patient RV9

The patient took part in only one session with the system. The average scores reveal good motion in the elbow joint but less optimal movement in the palm and finger joints.

Date	Exercise	Duration (seconds)	Repetitions	Average score
25.05.2017	Fingers Flexion-Extension	200	91	12.89
25.05.2017	Palm Flexion-Extension	180	52	18.77
25.05.2017	Forearm Flexion-Extension	180	34	85.74

Patient RV10

This patient took part in one session with the system. The average scores show low motor control of the movements, according to the evaluation given by the system.

Date	Exercise	Duration (seconds)	Repetitions	Average score
19.05.2017	Forearm Flexion-Extension	220	43	57.97
19.05.2017	Palm Flexion-Extension	230	45	27.72
19.05.2017	Fingers Flexion-Extension	200	14	16.18

Patient RV11

The patient participated in two rehabilitation sessions with the system. The average scores are relatively small according to the scores that can be given by the system. Between the two sessions, we can observe a slight increase in the number of repetitions for the Palm Flexion-Extension movement alongside a decrease in average score for this movement.

Date	Exercise	Duration (seconds)	Repetitions	Average score
25.05.2017	Palm Flexion-Extension	200	44	36.05
25.05.2017	Forearm Flexion-Extension	200	33	64.06
29.05.2017	Palm Flexion-Extension	180	48	32.96
29.05.2017	Forearm Flexion-Extension	200	33	40.04

Patient RV12

The patient took part in only one rehabilitation session but showed a good enough tonus to execute longer exercise sessions, along obtaining very good average scores. The forearm movement as well as the palm and fingers ones were evaluated by the system as having a very good quality.

Date	Exercise	Duration (seconds)	Repetitions	Average score
27.04.2017	Forearm Flexion-Extension	300	40	90.68
27.04.2017	Palm Flexion-Extension	300	64	30.32
27.04.2017	Fingers Flexion-Extension	180	44	21.06

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.

Date	Exercise	Duration (seconds)	Repetitions	Average score
09.05.2017	Forearm Flexion-Extension	200	42	68.95
09.05.2017	Palm Flexion-Extension	200	56	20.16
11.05.2017	Forearm Flexion-Extension	200	30	75.38
11.05.2017	Palm Flexion-Extension	180	47	27.57
19.05.2017	Forearm Flexion-Extension	200	34	75.69
19.05.2017	Palm Flexion-Extension	220	33	30.05

Evolution of the Forearm Flexion-Extension movement
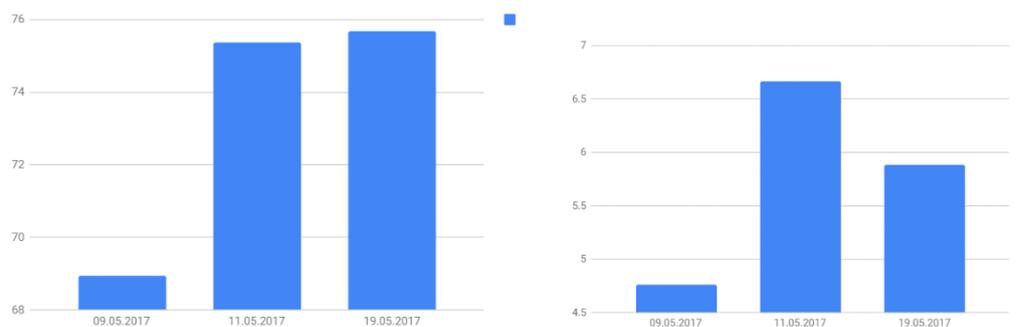
Fig. 10-3 Average scores evolution (left) and average seconds/repetition evolution (right)

Evolution of the Palm Flexion-Extension movement
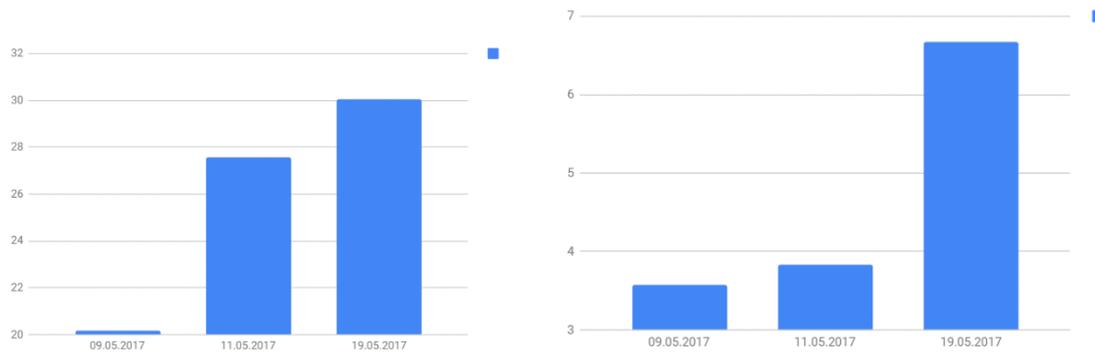
Fig. 10-4 Average scores evolution (left) and average seconds/repetition evolution (right)

Patient RV14

The patient executed one session with the system, and the doctor of the patient recommended the execution of movements for the control of the fingers and the palm joint. The patient performed the exercises with a good precision, without reporting any tiredness, completing two sessions of the Fingers Flexion-Extension movement.

Date	Exercise	Duration (seconds)	Repetitions	Average score
11.05.2017	Fingers Flexion-Extension	200	40	31.46
11.05.2017	Fingers Flexion-Extension	180	30	27.4
11.05.2017	Palm Flexion-Extension	200	42	19.12

Patient RV15

The patient took part in three 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.

Date	Exercise	Duration (seconds)	Repetitions	Average score
04.05.2017	Fingers Flexion-Extension	200	32	17.86
04.05.2017	Palm Flexion-Extension	180	10	31.82
04.05.2017	Forearm Pronation-Supination	180	18	125.78
04.05.2017	Forearm Flexion-Extension	180	35	71.5
05.05.2017	Fingers Flexion-Extension	180	40	22.05
27.04.2017	Fingers Flexion-Extension	310	80	18.29
27.04.2017	Palm Flexion-Extension	300	37	35.42
28.04.2017	Forearm Flexion-Extension	300	57	79.7

Evolution of the Fingers Flexion-Extension movement
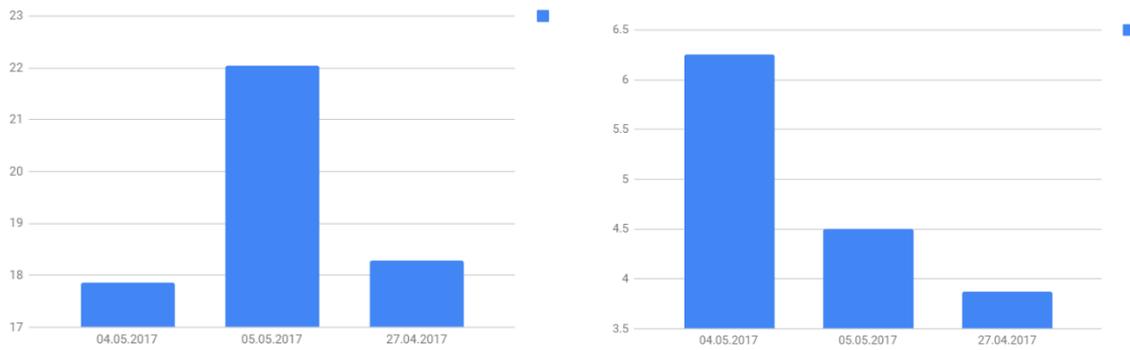
Fig. 10-5 Average scores evolution (left) and average seconds/repetition evolution (right)

Patient RV16

The patient performed two rehabilitation sessions with the system. During the first session the patient did not report tiredness, therefore three sets of repetitions were executed. During the second session the duration of the session was adjusted accordingly to a longer duration. The evolution between the sessions cannot be established, as multiple sessions would be needed for a conclusive result.

Date	Exercise	Duration (seconds)	Repetitions	Average score
10.05.2017	Fingers Flexion-Extension	200	40	18.79
10.05.2017	Fingers Flexion-Extension	200	46	18.22
10.05.2017	Fingers Flexion-Extension	180	20	21.67
26.04.2017	Fingers Flexion-Extension	500	116	19.65

Patient RV17

The patient executed one rehabilitation session with the system, performing three types of exercises. The increase in score between the two repetitions of the Palm Flexion-Extension movement can be attributed to the patient adjusting to the use of the system and its equipments.

Date	Exercise	Duration (seconds)	Repetitions	Average score
25.05.2017	Fingers Flexion-Extension	200	44	26.85
25.05.2017	Thumb Flexion-Extension	200	32	13.76
25.05.2017	Palm Flexion-Extension	200	56	24.17
25.05.2017	Palm Flexion-Extension	180	31	29.09

Patient RV18

The patient performed one rehabilitation session with the system. According to the scores evaluated by the system for the executed movements, the patient seemed to have a better control of movements in the palm and fingers and weaker motor abilities in the elbow joint.

Date	Exercise	Duration (seconds)	Repetitions	Average score
04.05.2017	Forearm Flexion-Extension	200	55	62.8
04.05.2017	Palm Flexion-Extension	180	102	35.7
04.05.2017	Fingers Flexion-Extension	180	41	26.6

Patient RV19

The patient took part in one rehabilitation session with the system executing the Arm Adduction-Abduction movement with a satisfactory quality – as evaluated by the system.

Date	Exercise	Duration (seconds)	Repetitions	Average score
26.04.2017	Arm Abduction-Adduction	220	51	36.29

Patient RV20

Despite the speech disabilities, this patient was extremely cooperative, and the obtained scores show the patient was able to adjust very well with the system, although accusing tiredness during the second set and asked to take a break, but was then willing to perform another repetition of the Forearm Pronation-Supination movement.

Date	Exercise	Duration (seconds)	Repetitions	Average score
19.05.2017	Forearm Pronation-Supination	200	23	83.06
19.05.2017	Forearm Pronation-Supination	180	20	25.75
19.05.2017	Forearm Pronation-Supination	180	11	61.23

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.

Date	Exercise	Duration (seconds)	Repetitions	Average score
19.05.2017	Forearm Flexion-Extension	200	29	101.75
19.05.2017	Palm Flexion-Extension	200	43	26.97
19.05.2017	Fingers Flexion-Extension	200	31	28.14
19.05.2017	Fingers Flexion-Extension	120	31	29.13
22.05.2017	Palm Flexion-Extension	200	22	21.28
22.05.2017	Fingers Flexion-Extension	200	55	28.18
22.05.2017	Palm Flexion-Extension	180	61	21.57
22.05.2017	Forearm Flexion-Extension	200	36	96.17
25.05.2017	Fingers Flexion-Extension	200	62	21.98
25.05.2017	Palm Flexion-Extension	200	61	21.57
25.05.2017	Forearm Flexion-Extension	200	36	96.17

Evolution of the Forearm Flexion-Extension movement

Fig. 10-6 Average scores evolution (left) and average seconds/repetition evolution (right)
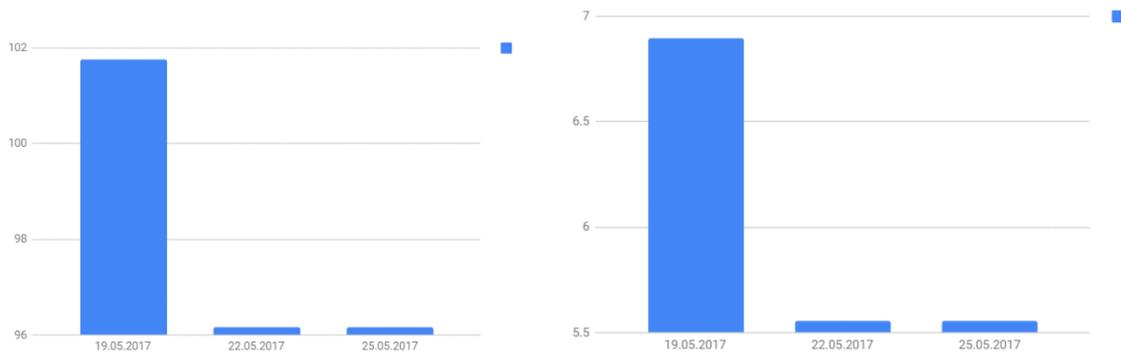
Evolution of the Fingers Flexion-Extension movement
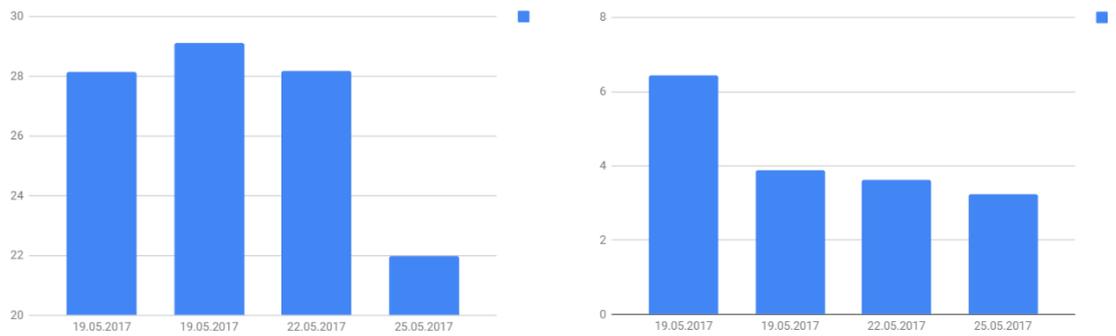

Fig. 10-7 Average scores evolution (left) and average seconds/repetition evolution (right)

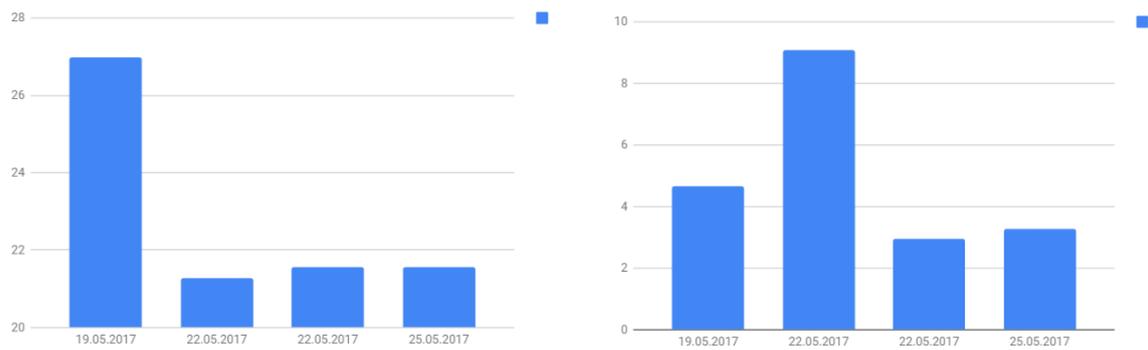# Evolution of the Palm Flexion-Extension movement

Fig. 10-8 Average scores evolution (left) and average seconds/repetition evolution (right)

10.2 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.

Questions

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

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?

Answers

Table 10-1 Questionnaire answers of the patients participants to the clinical trial with the TRAVEE system

Patient	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
Average	3.00	2.00	1.25	1.71	3.10	3.29	1.62	2.38	2.71	2.57	2.60	2.57

10.3 Discussion

The results of the clinical trial are specific to a qualitative study and not a clinical one, because of the reduced number of sessions with each patient. We used the responses received to draw several conclusions regarding the TRAVEE system.

Tiredness (Q1)

The responses of the patients revealed an above-the-average level of tiredness. Considering that for many of the patients the system was the first interaction with VR, and the equipment included an Oculus Rift placed on the head of the patient, which weights 440 grams[63], that could generate tension and pressure on the head of the patient and a tiredness feeling. Also, that could also be a sign of motivation for the rehabilitation session, but further research should take place before any conclusions are drawn.

Dizziness (Q2)

Relatively low degrees of dizziness were reported. The fact that the sessions were generally no longer than 5 minutes, and that between the sessions the VR equipment was removed, to allow the patient to relax, could be explanations of the low rate of dizziness experienced by the patients.

Nausea (Q3)

With an average of 1.27 it seems that the patients did not have intense feelings of nausea, which is encouraging for a system using VR in a rehabilitation environment, as it appears it did not create such an intense discomfort.

Anxiety or Fear (Q4)

Low scores were reported for feelings of anxiety or fear. The patients were informed regarding the process of rehabilitation involving the TRAVEE system, to ensure the experience will not produce anxiety, and it seems that the dialogue with the patient as well as the fact that the sessions were initially performed in the presence of the patient's doctors had a good impact for lowering stress levels.

Image (Q5)

With an average of 3.1 out of 5 it appears that the image perceived by the patients on the HMD was mostly a clear one and that the positions of the avatars in the scene was good, as the patients did not have trouble in observing the scene.

Physical discomfort (Q6)

The reported physical discomfort of 3.29 out of 5 reflects that the system components are not yet as comfortable as they should be for a rehabilitation system. A lower-weight alternative should be found for the Oculus Rift DK2 used, as well as a more optimal solution for the optical tracking – keeping the hand in the field of detection of the Leap Motion device was a challenge, and it often required that the patients hold their hand in a less comfortable position, as it was placed on the HMD, at eye level.

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[63] Oculus Rift Specs – DK1 vs DK2 comparison – Rift Info. https://riftinfo.com/oculus-rift-specs-dk1-vs-dk2-comparison. Last accessed March 2018.

Pain (Q7)

As the average score for the perceived pain during the sessions is 1.62 out of 5, it is a positive observation that the patients, although they felt a degree of physical discomfort it was not as intense as to produce pain.

Avatar movements – realism, immersion (Q8, Q9)

With scores of 2.38 and 2.71 out of 5, the degree of realism of the avatar movements was perceived on average as moderate, while the immersion was evaluated to be slightly above an average of 2.5. The realness of the movements could be improved by using other tracking devices and methods, with a wider range of detection and improved precision. As TRAVEE desired to be a low-cost solution for VR rehabilitation - the devices used provided acceptable tracking capabilities.

Augmentation (Q10)

The obtained average for the evaluation of the observability of the visual augmentation effect is slightly above the middle of the interval, 2.57 out of 5. The purpose of the visual augmentation implementation was for it to not be observed by the patients, and we evaluate that it is a low enough score but that also reveals a point where the system could also be improved substantially, to create a more seamless visual augmentation effect.

Virtual Therapist (Q11)

The usefulness of the indications of the Virtual Therapist were evaluated with a 2.60 out of 5, a good score but one that shows that the indications could be improved, possibly by using a distinct perspective or a different position of the avatar of the Virtual Therapist.

System utility (Q12)

The overall utility of the system was also evaluated above 2.5 with an average of 2.57. Further improvements are needed for the system to be able to be used on a larger scale, and further research needs to take place – extensive testing sessions, with more sessions per patient, to draw a clear conclusion regarding the utility of the ideas implemented by the TRAVEE system. Given the small number of sessions performed by the patients during the clinical trial, we find that the obtained score for this question is encouraging, showing the enormous potential behind such a system.

11 Conclusions and future work

This chapter includes my conclusions about the TRAVEE system, a summary of my contributions to its development and some future work directions as a continuation of my doctoral research.

The TRAVEE project fulfilled all of its purposes: designing and developing a relatively low-cost rehabilitation tool for the upper limb, with multiple use modes, multimodal input and feedback, novel ideas through the presence of the Virtual Therapist and the use of visually augmented feedback, as well as validating this complex system through tests in a medical environment. My perception is that TRAVEE was a great opportunity to design, implement and test a multitude of possible tools that could enhance a rehabilitation session, and that each of them has great potential if it were integrated into a commercially available system.

TRAVEE was also an exercise of collaboration between heterogenous teams from various environments. Engineers, doctors, rehabilitation therapists, both from academia and from industry brought their contribution to the system in all of its phases. The result has a great potential, from all of its perspectives.

TRAVEE is a state of the art system, combining multiple new and heterogenous technologies in a complex architecture : VR, robotics and haptics, real time data acquisition from an EEG device monitoring the patient, and others. There were many technical challenges that had to be overcome for the system to become viable. Medically, TRAVEE proved to be a system that can be used practically in rehabilitation; it was easily accepted by a variety of patients, with feedback that is generally positive. It also aggregates all the data acquired during the sessions, and obtains a synthetic representation that can be interpreted by doctors, while also providing a tool to organize and retreive information regarding patients and their sessions.

11.1 Summary of the original contributions

My original contributions included in this thesis are especially linked to the design and implementation of several key parts of the TRAVEE system. Also, I contributed to the study of the state of the art in the field and to the selection of the most appropriate technologies to be used in the implementation of the system. Other important contributions are to the system testing: test cases conception, questionnaires conception and the qualitative study based on user answers, conducting to the two in-vivo testing sessions and the clinical trial.

Contributions to the design and implementation of the VR Central System:
- The definition and implementation of the communication protocol between the VR Central System and all the other components of the system. The results were disseminated at the EHB E-Health and Bioengineering Conference, Sinaia, Romania, 2017 [99].
- The implementation of the rehabilitation session execution on the VR Central System. The results were disseminated at the EHB E-Health and Bioengineering Conference, Sinaia, 2017 [99].

- The implementation of the Movement analysis component, that is coupled with the VR Central System.
- The implementation of the visual augmentation of the movement, based on the movement analysis. The results of this implementation are included in a pending patent with the title: "System, method and computer program for augmenting human movements".
- The implementation of the haptic feedback control and logic, using the existing haptic device. The results were disseminated at the ZINC, Zooming Innovation in Consumer Electronics International Conference, Novi Sad, Serbia, 2017 [103].
- The implementation of the BCI with visual augmentation functioning mode of the TRAVEE system.
- The implementation of the robotic hand-controlled functioning mode of the TRAVEE system. The results were briefly disseminated at the ZINC, Zooming Innovation in Consumer Electronics International Conference, Novi Sad, Serbia, 2017 [103].
- The implementation of the session recording module.
- The implementation of the session analysis module.
- Several contributions to the avatar personalization module.

Contributions to the TRAVEE system testing
- Test cases conception for the two in-vivo testing and the clinical trial
- In vivo testing during two short testing sessions. The results were disseminated at the ZINC, Zooming Innovation in Consumer Electronics International Conference, Novi Sad, Serbia, 2017 and at the EHB E-Health and Bioengineering Conference, Sinaia, Romania, 2017 [103].
- Questionnaires conception
- In vivo testing during a clinical trial.
- The qualitative study based on user answers

Contributions to the dissemination of the TRAVEE project
Throughout all the phases of TRAVEE, my contributions in this area consisted of disseminating the following:

- the research I made in the initial phases of the project, through:
  - state of the art research regarding technologies used in similar projects [11][76][83],
  - issues that may arise from implementing VR and ICT solutions for rehabilitation [42],
  - the use of similar ideas for stimulating the rehabilitation process [3],
  - comparisons between two finger and hand tracking technologies [93].
- the chosen solution, architecture and implementation details [99][103];
- the summarized and processed results of the testing sessions [99][103];
- possible future directions of research that could be derived from the work in TRAVEE [108].

11.2 Future work

Parts of this chapter are published in the journal Revue Roumaine des Sciences Techniques Série Électrotechnique et Énergétique[108].

Optimization of the augmentation of the feedback sent to the patient

Simple or multiple feedback pathways and various degrees of augmentation can be used, with several well-defined purposes:

- Observing the differences between the classical and augmented rehabilitation and understanding the cerebral mechanisms that create these differences.

- Analyzing the importance of variations in the augmentation factors and the evolutions of the patients. Finding the reasons why the changes in the patient's evolution took place during the TRAVEE clinical trial, and whether these are consistent and with medical relevance.

- Testing the utility of augmentation for patients with spasticity, which is a condition that often appears as a result of the interrupted communication between the brain and the muscle that causes it to contract involuntarily for long periods of time[64].

- Studying the influence of the rehabilitation environment on the evolution of the session and the emotional state of the patient. The TRAVEE system only implemented one scene that presented only the patient and therapist avatar.

- Comparing the results obtained with visual augmentation versus robotic support of the movement.

Using the observations made during testing

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.

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.

For the comparison between augmented and classical rehabilitation, the same subjects would need to perform the same sessions with augmentation and without augmentation. 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 would need to be analyzed to search for patterns in cortical areas activity during each type of session.

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.

A solution where the augmentation level is configurable would need to be implemented. Then, the same session should be tested with various degrees of augmentation to search for each patient to acquire relevant data.

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[64] What is spasticity? http://www.stroke.org/we-can-help/survivors/stroke-recovery/post-stroke-conditions/physical/ spasticity. Last Accessed February 2018.

The EEG activity of the patients should be recorded during each of these sessions and analyzed to observe differences in cortical activation patterns between sessions with various augmentation levels and the patient evolution in terms of rehabilitation progress.

Other effects

A very interesting observation that was made during the clinical trial has remained unanswered and could be better studied during this research. One of the patients that took part in the clinical trial had – because of multiple brain surgeries – a very pronounced tremor in his left arm. The patient was unable to execute a simple movement such as to take his hand towards his forehead, as his hand would tremble away from the desired trajectory. As soon as the TRAVEE system was installed, and the patient was immersed in the Virtual Environment, observing the therapist, the doctor asked the patient to execute the forearm flexion-extension movement, which – as taking the hand towards the forehead – requires flexing the elbow joint.

The amazing fact was that the patient was able to make this movement perfectly, with barely any tremor. After the session ended, the progress was still maintained in real life, and the patient continued to participate in the trials. We still haven't found an explanation for this happening, as we cannot make any assumptions without a rigorous testing of various parameters, such as an observation of the EEG signals in the brain during classical and Virtual Reality enhanced rehabilitations sessions.

To study any possible effects of the system such as the relationship to the tremor observed in a patient during the clinical trial, it is necessary that for the tests to also include patients with a similar condition, to verify if the effect is repeatable and if it can be attributed to a Virtual Reality feedback-augmenting system.   Any other effects that may be observed will be studied with the proposed methods, to understand them clearly and to connect them – if they are related – to the system.

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[65].

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.

This would also be tested similarly to the functionality regarding the various augmentation levels, 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 – to also study the importance of the degree of augmentation and the optimal values for various situations.

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[65] What is spasticity? http://www.stroke.org/we-can-help/survivors/stroke-recovery/post-stroke-conditions/physical/ spasticity. Last Accessed February 2018.

In this manner, it would be possible to test whether there are differences when a patient executes the exercises in the VE with augmentation against spasticity or without augmentation. The differences would be analyzed for 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.

Virtual environment influence

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.

This idea could 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, several VEs could be implemented, each representing a different scenario. At least, a medical facility environment and an at-home style environment will be tested – but preferably as many scenarios as possible.

The scenarios could also be studied from a heart-rate point of view, by analyzing the differences in possible signals of distress or relaxations in patients in various VEs, while observing the evolutions in these variations during successive rehabilitation sessions.

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

Visual vs. Mechanical augmentation effect

During the TRAVEE testing sessions the robotic glove was tested very briefly. Further tests are required 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.

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.

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

Further research must ensure the continuation of the efforts made during the development and testing of the TRAVEE system. As described, the TRAVEE project ended too soon after the qualitative clinical trial, and left many questions, as well as a well-established foundation for further research.

With continued research, the effects TRAVEE can obtain could be assessed in a longer, quantitative study, while also determining the mechanisms behind these effects, what would be its greatest potential in rehabilitation and how it could be achieved.

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

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