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Remote Biofeedback Method for Biomedical Data Analysis

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Abstract

In recent years, the introduction of methods supported by technology has positively modified the traditional paradigm of rehabilitation. Interactive systems have been developed to facilitate patient involvement and to help therapist in patient's management. ReMoVES (REmote MONitoring Validation Engineering System) platform addresses the problem of continuity of care in a smart and economical way. It can help patients with neurological, post-stroke and orthopedic impairments in recovering physical, psychological and social functions; such system will not only improve the quality of life and accelerate the recovery process for patients, but also aims at rationalizing and help the manpower required monitoring and coaching individual patients at rehabilitation centers. In order to help and support therapist work, the Remote Biofeedback Method is proposed as an instrument to understand how the patient has executed the rehabilitation exercises without seeing him directly.

Therefore, the purpose of this method is to demonstrate that through the joint observation of data from simple sensors, it is possible to determine: time and method of execution of the exercises, performance and improvements during the rehabilitation session, pertinence of exercise and plan of care.

The system, during the rehabilitation session, automatically transmits patient's biofeedback through three different channels: movement, physiological signals and a questionnaire.

The therapist uses patient's data to determine whether the plan of care assigned is appropriate for the recovery of lost functionalities. He will then return a remote feedback to the patient who will not see any kind of graphical or verbal output, but you will see lighter rehabilitative session if it was too difficult or more intense if one assigned was too simple.

The rehabilitation protocol proposed consists of the performance of different exercises, which begins with a breathing activity, designed to relax the patient before the "effective" rehabilitation session. To make the subject comfortable, and to bring again the heartbeat to a basal value, before the rehabilitation session, the patient, in a sitting position, is leading to breathing with a regular rhythm by following a "breath ball".

From the results obtained in the breathing exercise, it can be concluded that the negative trend of the regression line that approximates the heartbeat signal is an index of relaxation, principal goal for which the exercise was designed.

The proposed activities include execution of reaching and grasping, balance and control posture functional exercises, masked through serious games to simulate some of the most common gestures of daily life. In some exercises, a cognitive component will also be involved in achieving the goal required by the activity.

For each activity, heart rate, gameplay scores, and different motion parameters were captured and analyzed depending on the type of exercise performed.

The heart rate was used as an indicator of motivation and involvement during the execution of several rehabilitative exercises. Others parameters analyzed are the score obtained during the execution of the task, and the time interval between the execution of one exercise and the following one. In addition to the analysis of the individual signals, a preliminary analysis of the correlation between the trend of the heart rate and the performance of the score was also carried out. The results showed that heartbeat in conjunction with score and inter-exercise time could be a high-quality indicator of a patient's status. The indicators extracted, in fact, in most cases, correspond to the information reported from the therapist who observed the patients during the rehabilitation session.

A deep analysis of movement signal was carried on, with the extraction of several indicators for the different body segments involved in rehabilitation, such as the upper limb, the hand, the lower limbs and the posture, included the detection of compensation strategies to reach the targets proposed by the exercise.

The results have been extracted by comparing the patient performance to a model extracted by a healthy subjects group.

Of particular importance is the spatial map for patients with neglect, an innovative tool that traces the positions where the movement was performed and also provides the therapist with the spatial coordinates where the targets were proposed.

Another innovative aspect is the analysis of Center of Pressure (CoP) without the use of a specific footboard, but only through the processing of data from the motion sensor.

The results obtained by the application of the Remote Biofeedback Methods to the signals acquired during ReMoVES testing phase show interesting applications of the method to the clinical practice. In fact, the indicators extracted show a realistic correspondence

between the disabilities affected the patients and the performance obtained during the execution of the exercises.

From the study of the different exercises it can be concluded that the analysis of the signals and the parameters extracted individually, do not provide enough information to outline how the rehabilitation exercise has been executed. By combining the different indicators, it is possible to outline an accurate picture that allows the therapist to make decisions about the assigned plan of care.

In conclusion, the Remote Biofeedback Method proposed is now ready to be tested on a wider dataset in order to be consolidated on a larger number of pathologies and to associate, if necessary, particular indicators to a particular disease.

The future steps will be, a creation of a model starting from patients signals, in order to have a better comparison term, and a testing phase on a larger number of patients, following a clinical protocol, subdividing subject by disease.

Chapter 1: Introduction

1. Rehabilitation process

Motor rehabilitation following neurologic diseases is often a slow and challenging task. [2][3]

This group may include wrong posture related pain. The setting of rehabilitation is usually a professional rehabilitation center. The kinetic functional evaluation performed by a physiotherapist is commonly the first step to identify the motions and motor functions affected. Complete recovery of the motor function is pursued through the damage related evaluation of the physiotherapist who chooses the type and amount of exercises. A reevaluation is frequently performed to improve outcome and analyze the efficacy of the treatment and eventually to determine new therapeutic strategies. The timing and way of recovery of a movement depend on the cause and degree of injury, as well as the damaged anatomical area. For example, simple orthopedic lesions such as a first-degree ankle sprain normally recover in a few weeks,⁶ whereas brain and spine injuries normally take many months.[3][4][5][6][7] The same exercise is performed several times, in order to improve kinetic gains as soon as possible.[8][9][10]

Especially for the neurological patient, the repetition of the same exercise is crucial for re-education to the correct movement with simultaneous muscular articular gain and at the same time with implicit learning by copying the previous movement. This last aspect of necessary to repeat the same exercise able the patient to perform their exercise at home.

Usually the patient spends more time at home with no supervision than during the recovery for clinical therapy.[7][10]

Normally, during rehabilitation therapy at home there are two problems: 1) the patient without the presence and control of the rehabilitator is less motivated and 2) the exercises can be performed in the wrong way causing further injury. [13][14][15][16][17]

In recent years, the introduction of methods supported by technology has positively modified the traditional paradigm. Interactive systems have been developed to facilitate

patient involvement. Virtual reality systems are applied to increase motivation of the patient and make repetitive exercise more interesting in a controlled manner. [18][19]

Other useful tools for these purposes are biosensors that inform the patient about their internal activities and help him to better control the movement. In this way, for example, the patient can monitor muscle activity and immediately predict which muscle contract to perform the movement properly. [20]

About these recent advances in technology, Microsoft (Redmond, WA) launched Kinect[21], a low-cost and portable markerless motion capture sensor to facilitate and integrate many clinical applications.

2. Rehab@Home and ReMoVES platforms

2.1. Rehab@Home Project

The project was focusing on solutions for patients after a stroke to supply them with a sustainable progress in rehabilitation. The research refers to the upper part of the body, especially the movement of the arms, the grip and the wrists. As medical and technical partners are involved in this project as well as patients, an ongoing rehabilitation process can be evaluated in depth. The project's aim was to design and develop an open- solution IT-device (concept, hardware/software) that allows the patient to exercise at home to reduce his disabilities. The device offers features and functionalities as a set of exercises based on personalised serious games adapted to the patient's needs. The challenge on the one side was to develop games which are motivating for the patient and allow him to improve at the same time. The plan is to have the first training with the device during the patient's stay at the hospital, enabling him to continue his training at home. The games used for a patient are selected individually by the physician and are calibrated to the patient's needs and abilities, ensuring and optimum degree of exercise. The player collects

rewards as a real-time feedback during his training. As a socialisation component, the patient can also compete with friends or family members.

During the training with this user-friendly IT-device, information about the quality of the performance is provided to the medical personnel. The physical and medical parameters are monitored and evaluated by an on-line/off-line management at the medical centre. The rehabilitation protocol provides a good overview of the patient's progress to the medical personnel and allows the challenges of the games to be adjusted to the patient's condition. The device consists of commercial products like Microsoft Kinect and using Web2.0 social networks. In this way an effective, efficient and attractive virtual environment for a successful rehabilitation can be built at the patient's home.

Because of the individual handicaps of the game's users, the challenge was to optimise the games in such way that the training is sufficient for the patient and has enough stimulation to keep the patient exercising. The components themselves are low-cost, robust, good to handle and easy to use. Also, the therapeutic data, physical as well as physiological, are collected via the sensors, and are evaluated with the software developed during the project. In this way the medical care can be online as well as off-line.

2.2. ReMoVES Project

ReMoVES (REmote MONitoring Validation Engineering System) platform addresses the problem of continuity of care in a smart and economical way. It can help patients with neurological, post-stroke and orthopedic diseases in recovering physical, psychological and social functions; such system will not only improve the quality of life and accelerate the recovery process for patients, but also aims at rationalize and help the manpower required monitoring and coaching individual patients at rehabilitation centers[22].

The ReMoVES platform employs three off-the-shelf devices for motion tracking and biophysical data acquisition which are turned on during the execution of functional exercises.

On the back-end a cloud architecture has been deployed to provide web-services and data processing.

The idea behind the proposed architecture consists in providing a personal rehabilitation program that is performed at home by the patient itself, while, from any internet connected device, the therapist can track the performances and effectiveness of the training. In detail,

the built-in algorithms aim to provide a clear and concise report to the therapist, in order to facilitate the interpretation of the evolution of therapy.

The following technologies are deployed by ReMoVES platform:

- Serious-games are digital games that have been developed exclusively for ReMoVES platform in collaboration with physiotherapist and physiatrist. The system currently includes 10 main serious-games and 60 variations: they encourage the patient to carry out functional exercises autonomously along with the traditional motion rehabilitation.
- Microsoft Kinect V2 is a motion sensing input device based upon a high resolution color camera and an infrared emitter for depth analysis, that can 3D-track simultaneously up to 25 fundamental joints of the framed human body. It offers a wide field of view (70°x60°) and recognition up to 4.5 meter far from the device.
- Leap Motion is a explicitly targeted at hand gesture recognition device and computes the position of the fingertips and the hand orientation. Its interaction zone is limited to semi-sphere of radius 0.60m around the device.
- Microsoft Band 2 is a physiological sensor used for the acquisition of the two signals chosen as measure of involvement during the rehabilitation program: Heart Rate (HR) and Electrodermal Activity (EDA). It offers these key features: real time reading of the data stream and access to the device through Software Development Kit (SDK). Moreover it includes other sensors that could be used for future improvement of the system: accelerometer, gyroscope, barometer, GPS, skin temperature sensor, ambient light and UV sensor and finally it is reasonably inexpensive.
- Cloud back-end has been developed using state-of-the-art techniques to provide scalable, secure and efficient data processing and storage.

The core of the ReMoVES platform consists in the remote delivery of a report to the therapist, though which she/he can understand if the home-based rehabilitation process proposed to the patient is effective and carried on correctly.

3. Telemedicine and Remote Monitoring

Over the last years, the impact of telemedicine is still growing thanks to the adoption of the concept of "continuity of care" by the Health Community. Operators have access to all needed information, regardless of where they are located, and this helps to improve access to health services for patients and end users. [23]

The societal changes drive the evolution of the healthcare sector, both in Europe and in the rest of the world. Some of the big issues such as aging population, chronic diseases, and spread of disabilities as stroke and all degenerative diseases have a great impact on health care strategies and care solutions.

Thanks to the new technology solutions, the patient is more and more attentive and aware of his state of health trying to maintain the highest quality of life level, that requires a continuous assistance and care. [24]

Remote Monitoring is a crucial, and in most situations, an exclusive capability to provide medical assistance to the population.

Therefore, in the last decades, the telemedicine aim is researching, developing, and testing, new solutions that are able to integrate the tremendous technological advances with the current medical practices, in order to offer a cheaper, a more efficient and a more effective health care service.

In this respect, Norris (2002) states that telemedicine uses information and telecommunications technology to transfer medical information for diagnosis, therapy and education. Besides, World Health Organization (WHO) defines that telemedicine is an area including (i) the remote clinical services related with the health care and (ii) the education between practitioner and patient to optimize the process's efficiency.

In this contest, Guerreiro [25] in his work speak about telemonitoring as a core component to enforce Remote Biofeedback control systems.

Biofeedback, a term derived from the contraction of English biophysical feedback, is a therapeutic technique used to treat various disorders and illnesses in medicine, psychiatry and psychosomatics. The principle on which it is based is the ability to learn to control and

to self-regulate various physiological functions (such as muscle tension, skin temperature, skin conductance, blood pressure, heart rate etc.) that are normally outside consciousness and voluntary control.

The theoretical basis of the biofeedback technique is the evidence that by detecting, by appropriate electronic instrumentation, the activity of a biological function of the organism, of which the subject is unaware and returning it to the subject in the form of return information (feedback) as an immediately perceptible signal, he can progressively learn to control and autoregulate it. Biofeedback uses this principle across a wide variety of pathologies where this type of self-control can be exploited for therapeutic purposes. The functions up to date more frequently monitored and used in biofeedback therapy are muscle tension (electromyography or EMG-biofeedback) at various levels of body muscle, skin temperature, electrodermal activity (skin conductance and potential skin activity), heart rate, blood pressure, some electroencephalographs, and many others. They are chosen in relation to the type of disorder or pathology to be treated.

Biofeedback is a method of treatment that provides patients with physiological information of which they are normally unaware. Biofeedback may be used to improve health or performance, as physiological changes often occur in conjunction with changes in thoughts, emotions, and behavior [26].

To support the therapist's work, a Remote biofeedback method is necessary to return data in an appropriate format to both the therapist and the patient's family.

In the presented work, this method is used as remote biofeedback instead of direct feedback for the patient. In fact, the feedback is useful to the therapist for revising a patient's plan of care, as shown in Figure 1.

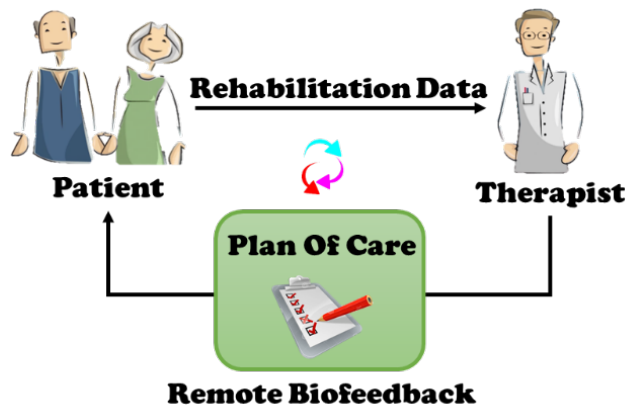


Figure 1: *Remote biofeedback schematic.*

The remote biofeedback is implied. The therapist uses biofeedback from the patient to determine whether the plan of care assigned is appropriate for the recovery of lost functionalities. He will then return a remote feedback to the patient who will not see any kind of graphical or verbal output, but you will see lighter rehabilitative session if it was too difficult or more intense if one assigned was too simple.

4. Data Analysis

4.1. Heart Rate and Galvanic Skin Response

During daily rehabilitation therapy, it is very important to monitor the patient's emotional involvement in order to inform the therapist about the proper performance of the assigned plan of care [27]. For this reason, Heart Rate (HR) and Electrodermal Activity (EDA) were recorded and analyzed to monitor major changes during different phases of a rehabilitation session. These data were compared with those from motion sensors, to monitor the progress of therapy and the patient's involvement in the rehabilitation session.

Heart rate is the speed of the heartbeat, which is measured by the number of contractions of the heart per minute (bpm). The heart rate can vary according to the body's physical needs, including the need to absorb oxygen and excrete carbon dioxide [28]. It is usually

equal or close to the pulse measured at any peripheral point. Activities that can provoke changes in heartbeat include physical exercise, sleep, anxiety, stress, illness, food intake, and drugs [29].

Several factors affect heartbeat in different ways:

- Anxiety and emotions: People who suffer from anxiety may experience palpitations more frequently when they are in difficult and emotionally disturbed situations. Most of the complications that affect the heart have, for the most part, a psychological basis [28].
- Body temperature: When body temperature increases, as a response, blood vessels dilate, and the heart has to pump faster in order to maintain blood pressure.
- Body position: Usually, even in different body positions, the heartbeat does not dramatically change. Sometimes, when a person goes from a lying to a standing position, their pulse increases slightly for the first 15-20 seconds. However, after a couple of minutes, it usually returns to normal values.
- Drugs: The use of beta blockers stops the normal production of adrenalin, thus slowing the heart rate, whereas other medicines that cause the opposite effect on adrenalin production will raise the heart rate [28].

Heart rate has been used to estimate different parameters, such as total energy consumption, to detect and prevent fatigue [29][30], and to classify the intensity of physical activity [31], among others. Human involvement and emotions during therapy can be expressed through different physiological responses, such as the acceleration and deceleration of the heartbeat [32][33], and channels such as facial expressions and voice.

In this study, time domain analysis was chosen as the best way to extract significant parameters within a short period (from 1 to 3 minutes).

Often, the heartbeat is not considered a significant indicator of the patients' condition or their emotional state during the course of an activity. However, in this study, we wanted to show that the heart rate considered in conjunction with other information (such as the execution performance of the rehabilitative exercises and the fluidity of the rehabilitation session) could determine the degree of patient involvement and fatigue due to too much effort being required to perform a movement.

The innovative aspect of this work is the application of heartbeat analysis as a reliable outcome metric for the assessment of the involvement of the patient in the rehabilitation programme. There are many fitness sensors on the market that can report on performance and heart rate, but the interpretation of the data is left to the user.

Heartbeat is a measure of the psychophysiological signals originating from the peripheral nervous system and has been successfully used as a measure of valence and emotion [34][35].

The heart forms part of the cardiovascular system and includes the organs that regulate blood flow in the body.

There are a variety of cardiovascular system measurements that can determine valence or arousal, including heartbeat, which has been previously correlated with player arousal based on the 2007 and 2008 studies from Mandryk et al. [35][36].

Martinez et al. presented correlations between basic psychophysiological measures (i.e., heartbeat, blood volume, pulse, and electrodermal activity), showing that there were correlations between heart rate and self-reported values of fun, frustration, or boredom [37]. Nake et al. reported that a fast heartbeat was indicative of players feeling tense and frustrated. Similarly, a slow heartbeat was indicative of a positive effect, achieving the flow-state and feelings of competence and immersion [38].

The heart rate is an informative biological parameter that is easy to record and therefore easy to introduce in the home setting. In other words, a simple fingertip sensor or a bracelet is sufficient to understand the patient's condition during the rehabilitation program. Thus, a pulse oximeter was chosen as the physiological sensor in the home-based rehabilitation system [39].

Heartbeat was introduced as a signal that correlates with performance and other signals from movement sensors included in the remote biofeedback, can help the therapist in management of the plan of care [39][40].

Together with HR, Electrodermal Activity (EDA) was chosen as biophysical signal to be correlated with HR and activity performance in order to detect a particular state of stress during the rehabilitation process. The EDA is defined as a change in the electrical properties of the skin [35]. The EDA signal is composed of both tonic and phasic components. The slowly varying base signal is the tonic EDA part, also called the Skin

Conductance Level (SCL). The faster changing part (phasic activity) is related to external stimuli or non-specific activation and it is called Skin Conductance Responses (SCRs). GSR was first documented over one hundred years ago. Carl Jung explored this signal for psychiatric evaluation and therapy in the early 1900's [41]. Most of the applications for GSR since then have been focused on psychiatry [42], utilizing it to gauge emotional states such as agitation or anxiety. Recently, EDA has been used as a biofeedback mechanism in order to teach meditation or emotional control, and to treat anxiety disorder [36]. EDA signal was also widely used as an indicator of the affective state, related in particular to changes in the arousal level. Many studies reported that magnitude of electrodermal change and the intensity of emotional experience are almost linearly associated in arousal dimension. For example in [37], the authors used EDA and HR to evaluate immersive virtual reality environment, finding significant results of correlation between the two signals and the environmental.

Many studies [43-46] were been conducted on GSR in patients with MS, giving a many information about the response of this type of pathology.

As explained above, HR and EDA are respectively indexes of valence and arousal. Both signals were normalized and represented in the Valence-Arousal circumplex chart. On the X axis the valence (HR variation) and on the Y axis the arousal (EDA variation) are represented.

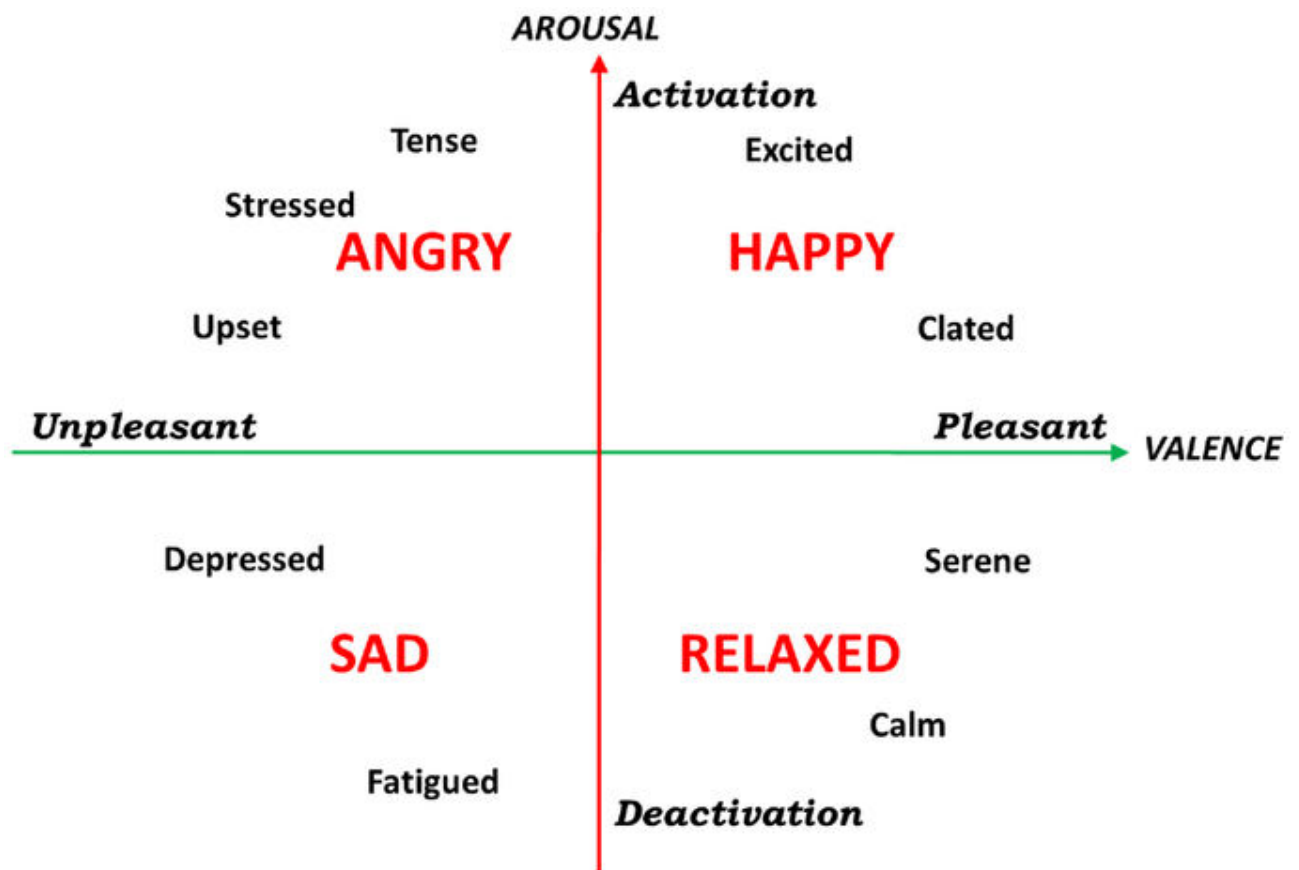


Figure 2: Valence-Arousal Graph, the emotions are mapped subdividing the emotion on the four different Cartesian quadrants.

Emotions, in fact, can be mapped out, as shown in Figure 2, classifying arousal (from high to low) and valence (from pleasure to displeasure) experienced during a particular task. In the right part of the graph, positive emotions like for example happy, serene, calm and relaxed are represented. On the contrary, the left part contains negative emotions like sad, depressed, fatigued and tense.

The aim of this part of the study is to detect and classify the emotions felt by patient during the rehabilitation session, in order to personalized the plan of care and for example simplify an exercise if the patient, not achieving the goal, feels himself/herself fatigued.

4.2. Kinect and Leap Motion sensors for Motion Capture

Motion capture techniques are used in a wide range of applications ranging from digital animation for entertainment to biomechanics analysis for clinical and sports applications. Nowadays, the use of optical reflector marking systems is the most common technique[47],[48], even if there are other technologies, such as inertial sensors [49] or electromagnetic ones[50].

In spite of their popularity marker based methods have several limitations: High-quality data collection requires a controlled environment and marker placement can take a long time [51][52].

Several recent review articles have summarized the common shortfalls of skin based marker techniques [53] [54] [55]. Markerless motion capture offers an attractive solution to the problems associated with marker based methods, but the general problem of estimating the free motion of the human body is limited without the spatial and temporal correspondence guaranteed by the tracked markers. From the powerful game industry new devices like Kinect [56] have come out, allowing to interact with game consoles in real time.

Furthermore, this new hardware is considerably less expensive than the usual complex multi-camera systems. Kinect can be described as a 3D markerless motion capture system because it gives you a simplified skeleton in real time. No especial dresses or other equipment are required. The skeleton is made of 15 joints and because of its simplification it cannot be used (by now) for very accurate studies. So in this phase we aim to use it when such accuracy is not necessary, as in clonical rehabilitation, where the correctness of a motion can be validated without been extremely precise.

In recent years the interest of some videogames researchers towards use videogames in physiotherapy, occupational therapy, and psychotherapy increased. Many physical therapies are based on repetition to achieve a range of motion or control over a specific muscle group. This process is done without any external encouragement [57] and patients lose motivation during the therapy and the rehabilitation becomes slower and frustrating. By developing a serious game as a rehabilitation tool, we achieve the motivation associated to games. The employment of low cost technologies like webcams bring the possibility to

capture patient movements finalizing the process of rehabilitation, without losing patient's control when he stay at home [58][59]. Although, that systems are limited by their motion capture capacity. Other approaches use sensors tracking user movements, to improve capture precision,. In [60], they used Wiimote device, another low cost peripheral from videogames industry. More recently, the appearance of Kinect causes a great improvement in low cost motion capture performance, allowing the implementation of some Kinect-based rehabilitation systems [61][62].

Upper Limb Rehabilitation

The recovery and rehabilitation of the arm and hand after neurological injury, illness or disease is often slow and difficult. The arm and hand is designed to perform very skilled movements which allow us to do day to day activities. These can include, using our phones and tablets, picking up objects, opening jars, turning pages, sorting coins, eating food, the list goes on. To allow us to perform all of these intricate tasks the brain is wired to the hand for speed and accuracy. This makes it very vulnerable to injury and consequently rehabilitation can be slow.

It is important to keep the muscles and joints of the hand and arm as healthy as possible and this remains a key focus throughout rehabilitation. The aim of physiotherapy is to achieve as much function as possible and work towards an individual's own goals.

Recently, many of the suggestions in neurological rehabilitation research and, specifically, post-stroke rehabilitation, have developed in the field of treatments for motor upper limb recovery. The size of the problem justifies this particular attention if we consider that the proportion of subjects susceptible to developing a persistent deficit of the upper limb following strokes is close to 20%, while those who show a residual function only 15% have a complete recovery. Functional recovery of the upper limb represents a short and medium-term objective of the rehabilitation project. Acute rehabilitation tends to focus attention on the early recovery of postural, walking and general mobility, and this has in the past contributed to emphasizing patient training in the use of compensatory strategies of the non-paretical upper limb in order to promote the recovery of autonomy in ADL and early home reintegration. This trend appeared contradicted by the indications that in the

meantime came from studies on post-lesional cortical reorganization and its close dependence on the repetitive and intense motor training of the paretic limb. In the perspective of making a re-learning engine effective from the subacute stage, even in subjects with severe upper limb movement control deficits, different technological solutions have been developed, the heterogeneity of which reflects the incomplete definition of mechanisms at the base of post-lesion neuroplasticity, whose actual effectiveness is still to be defined in an absolute way. Over the decades, the proposals for post-stroke rehabilitation treatments have multiplied. Generally, neurological rehabilitation has seen success, but not substitution, of techniques inspired by different theoretical assumptions. Therefore, the first model of re-education proposed is "orthopedic", based on muscle training; the role of isolated muscular reinforcement and aerobic exercise has recently been emphasized and therapeutic exercise in water has been proposed as a generator of stable and effective learning, characterized by a level of complexity superior to the spontaneous adaptations created in a gravitational environment. In the '50s and '60s with Rood and Kabat were proposed on the basis of neurophysiological principles of neuromuscular facilitation, technical applications aimed at soliciting and reinforcing voluntary movement. In 1969, Bobath spouses completed a rehabilitative intervention that required knowledge of the reflexive mechanisms of postural responses, achieving a success still recognized in the management of stroke-related spasmatic hemiparesis. Only in 1982, a "task-oriented" learning technique was introduced, inspired by studies on functional recovery in animal models, which advocated a central control theory of motion, according to which all sense-motive systems cooperate to achieve a specific task and this is binding for the purpose of motor recovery. Accumulation of evidence of neuroplasticity in adult brain injury and the relevance of sensory afferents in promoting the reorganization of cortical areas has thus produced the flourishing of therapeutic proposals based on various techniques. Some approaches focus on the therapeutic strategy on intensive activation of the paretic artery, at the same time as the restraint of the healthy limb, called "constraint-induced movement therapy and forced use" (CIM), hypothesizing that preferential use of healthy limb compensation can inhibit the cortical reorganization processes that are responsible for the recovery of the paretic limb. Others, on the other hand, promote the development of techniques to facilitate the training of the paretic limb through the bilateral repetition of motions, arguing that both planning and carrying out bilateral movements have a favorable impact on the cortical plasticity processes on implied recovery. Among

the most innovative approaches to neurological rehabilitation emerges the virtual reality, which sometimes integrates or is combined with mental practice. The discovery of the "mirror neurons" system, which is activated both during the execution and during the observation of a movement, was the neurophysiological basis for introducing the concept of gesture observation as therapy.

Generally, patients are placed in front of a PC screen or wearing modified glasses with which they observe movements of varying complexity, allowing considerable flexibility in the possibility of exercises but at the same time ensuring a deep dive into a virtualized environment.

Lower Limb Rehabilitation

Hemiplegia is one of the most common impairments after stroke and contributes significantly to reduce gait performance. Although the majority of stroke patients achieve an independent gait, many do not reach a walking level that enable them to perform all their daily activities [63]. Gait recovery is a major objective in the rehabilitation program for stroke patients. Therefore, for many decades, hemiplegic gait has been the object of study for the development of methods for gait analysis and rehabilitation [64].

The primary goals of people with stroke include being able to walk independently and to manage to perform daily activities [65]. Consistently, rehabilitation programs for stroke patients mainly focus on gait training, at least for sub-acute patients [66].

At present, gait rehabilitation is largely based on physical therapy interventions with robotic approach still only marginally employed. The different physical therapies all aim to improve functional ambulation mostly favouring over ground gait training. Beside the specific technique used all approaches require specifically designed preparatory exercises, physical therapist's observation and direct manipulation of the lower limbs position during gait over a regular surface, followed by assisted walking practice over ground.

According to the theoretical principles of reference that have been the object of a Cochrane review in 2007 [67], neurological gait rehabilitation techniques can be classified in two main categories: neurophysiological and motor learning.

The neurophysiological knowledge of gait principles is the general framework of this group of theories. The physiotherapist supports the correct patient's movement patterns, acting as problem solver and decision maker so the patient becomes a relatively passive recipient [68]. Just opposite to the passive role of patients implied in neurophysiological techniques, motor learning approaches stress active patient involvement [69]. Thus patient collaboration is a prerequisite and neuropsychological evaluation is required [70], [71]. This theoretical framework is implemented with the use of practice of context-specific motor tasks and related feedbacks. These exercises would promote learning motor strategies and thus support recovery [72], [73].

Trunk and Balance Rehabilitation

The use of the commercial video games as rehabilitation tools, such as the Nintendo WiiFit, has recently gained much interest in the physical therapy arena. Whilst anecdotal evidence suggests that games have the potential to be powerful motivators for engaging in physical activity, limited published research exists on the feasibility and effectiveness of leveraging the motion sensing capabilities of commercially available gaming systems for rehabilitation [74-78]. Initial case studies have demonstrated that the use of video games has some promise for balance rehabilitation following stroke and spinal cord injury [76-79]. However, currently available commercial games may not be suitable for the controlled, focused exercise required for therapy. Usability studies have found that some commercially available games provide negative auditory and visual feedback during therapy tasks [75,80]. These observations demonstrate the importance designing games specifically for rehabilitation, a design approach that has been investigated by several recent researchers [80-82]. However, the limitations of the commercial video game motion sensing technology have been a challenge to achieving this goal. Motion tracking controllers such as the Nintendo Wiimote are not sensitive enough to accurately measure performance in all components of balance. Additionally, users can figure out how to "cheat" inaccurate trackers by performing minimal movement (e.g. wrist twisting a Wiimote instead of a full arm swing). Physical rehabilitation requires accurate and appropriate tracking and feedback of performance.

Hand Rehabilitation

Hands and fingers play an important role in human life. With their motion under a delicate control, hands and fingers are involved in almost all human activities. Being one of the fullest areas of nerve endings [83], fingers also represent the most intense source of tactile feedback in the human body. The importance of hand and finger use can be easily understood by exploring the human brain. One of the largest areas of the cerebral cortex is dedicated only to controlling, receiving and processing sensations from hands and fingers [84]. The human hand consists of 27 bones [85], 27 joints, more than 120 ligaments, 34 muscles, 48 nerves and 30 arteries. Due to the complexity of the anatomical system and the intense use during life, the hand is subject to injuries and diseases.

In case of hand motion disabilities an adequate rehabilitation is needed to increase patient's quality of life.

The rehabilitation commonly includes physical therapy, and if performed appropriately and frequently, it can help regaining partial or full functionality of hand/fingers. There are three types of exercise used in rehabilitation for hand motion disabilities: 1. Range-of-motion exercises, 2. Strengthening exercises, 3. Aerobic or endurance exercises.

Lots of different sensory devices are used for hand/ finger motion therapy, such as grip force measurement devices [86], finger pinch force sensors [87], VR gloves and exoskeleton systems [88], [89], [90], [91]. Currently, the most advanced device for hand/finger motion tracking is a hand exoskeleton system with functionalities in both directions, input and output. The device collects measurements of joint angles and forces as input to the system. On the other hand, the output is provided as physical force feedback from VR environment. The importance of monitoring for the effectiveness of rehabilitation treatment is well recognized and represents the foundation of evidence-based health care [92]. However, systems used actually are not enough precise to detect and measure small differences that need to be monitored for adequate rehabilitation. In addition, in case of severe hand disabilities (such as last stages of rheumatoid arthritis and osteoarthritis), most of the systems are inadequate. For this goal, the Leap Motion, a novel hand/finger motion tracking instrument can be used. It is a simple, contactless, non-invasive and inexpensive sensor that has the ability to detect small changes in hand/finger positions with high precision and very fast acquisition rate. These characteristics make this device ideal for hand rehabilitation. In fact it is an optical sensor specially designed for acquisition of 3D

positions and orientations of hands and fingers. The main purpose of the sensor was to extend current input devices with 3D control for VR environments. The sensor was also found to be a good choice for a wide spectrum of other applications [93], [94], [95]. The Leap Motion controller consists of three infrared light (IR) emitters and two IR cameras. The implementation of IR spectrum makes the projected rays invisible for the human eye, which makes the device comfortable for usage.

According to the official announcement of the manufacturer, the Leap Motion controller should be able to acquire positions with sub-millimetre accuracy. Accuracy and robustness of the controller were further analysed and discussed [96], [97]. The analysis showed that accuracy of less than 2.5 mm could be obtained, with an average of 1.2 mm [96].

Chapter 2: Remote Biofeedback

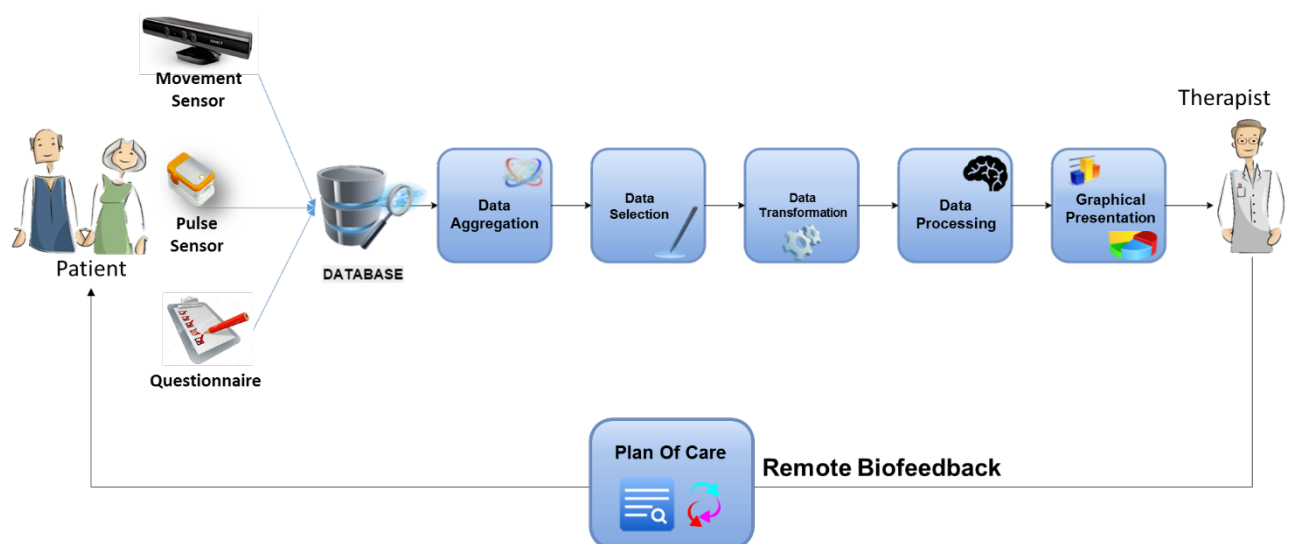
1. Introduction

By remotely monitoring a patient's improvement, a therapist can modify the plan of care to facilitate the recovery and avoid a potential problem of home-based systems: the “abandonment” of the patient and the loss of regularly supervised patient monitoring.

To support the therapist's work, a remote biofeedback method is necessary to return data in an appropriate format to both the therapist and the patient's family.

Biofeedback is a method of treatment that provides patients with physiological information of which they are normally unaware. Biofeedback may be used to improve health or performance, as physiological changes often occur in conjunction with changes in thoughts, emotions, and behavior [98].

In this study, this method is used as remote biofeedback instead of direct feedback for the patient. In fact, the feedback is useful to the therapist for revising a patient's plan of care, as shown in Figure 1.



The remote biofeedback is implied. The therapist uses biofeedback from the patient to determine whether the plan of care assigned is appropriate for the recovery of lost functionalities. He will then return a remote feedback to the patient who will not see any kind of graphical or verbal output, but you will see lighter rehabilitative session if it was too difficult or more intense if one assigned was too simple.

As shown in Figure 1, the patient transmits his/her biofeedback through three different channels: a movement sensor (e.g., Kinect), a physiological sensor and a questionnaire.

Figure 3: *Remote biofeedback schematic.*

The current remote biofeedback method provides useful and easy-to-read information to the therapist at the end of each rehabilitative session.

2. Tele monitoring as a Core Component to Enforce Remote Biofeedback Control Systems

Remote Monitoring is a crucial, and in most situations, an exclusive capability to provide medical assistance to the population.

Therefore, in the last decades, the telemedicine aim is researching, developing, and testing, new solutions that are able to integrate the tremendous technological advances with the current medical practices, in order to offer a cheaper, a more efficient and a more effective health care service.

In this respect, Norris (2002) states that telemedicine uses information and telecommunications technology to transfer medical information for diagnosis, therapy and education. Besides, World Health Organization (WHO) defines that telemedicine is an area

including (i) the remote clinical services related with the health care and (ii) the education between practitioner and patient to optimize the process's efficiency.

In this contest, Guerreiro [99] in his work speak about telemonitoring as a core component to enforce Remote Biofeedback control systems.

Chapter 3: The Method

1. Introduction

This method has been developed through close collaboration between different professionals who, thanks to the various skills, have contributed to achieving the results. During the three years of the project, in fact, every new step was subjected to the judgment of the therapists, project partners, which evaluated whether the output graphs and extracts proposed indicators could be easily understood and aid in the evaluation of rehabilitation progress of patients. It was therefore not necessary to make a usage / satisfaction test with a population of therapists, because the method has been constructed precisely with their support.

Through data processing, the most important features are extracted and represented with graphs and figures. Thus, these data are better understandable and immediately available to therapists and medical staff, helping them to achieve an accurate interpretation.

As a project guideline, it was chosen not to show all rehabilitation data to the patient, but only the score collected at the end of each rehabilitative exercise.

The purpose of this method is to demonstrate that through the joint observation of data from simple sensors, it is possible to determine the following:

- Time and method of execution of the exercises
- Performance during the rehabilitation session
 - Speed
 - Score
 - Fluency

- Improvements in the performance of the exercises
 - Perseverance
 - Regularity
- Pertinence of exercise / plan of care
 - Fatigue / stress
 - Motivation / gratification
- How the exercises have been performed
 - Range of Motion
 - Repetitions
 - Strategy of Compensation

Once the data are analyzed, by processing heart rate, score and inter exercise time, three key process indicators (KPIs), Φ , Ψ and Ω , which encompass the concepts expressed above, are calculated and used to evaluate the rehabilitation process as explained in the data processing step.

About motion execution modes, different indicators have been extracted, differentiated by type of exercise and explained in the second part of the method.

The remote biofeedback method has been structured to extract the KPIs through the following basic principles:

- Data aggregation, where multiple data sources may be combined.
- Data selection, where data relevant to the analysis task are retrieved from the database.
- Data transformation, where data are transformed and consolidated into forms appropriate for processing.
- Data processing, the essential process where intelligent methods are applied to extract information of interest.

- Graphical presentation, where visualization and knowledge representation techniques are used to present mined information to the therapist.

The first three phases are different forms of data manipulation that prepare data for processing.

The last phase uses the results obtained from the processing stage to propose different views that make information direct, clear and easy to read. By processing the data and extracting the patient performance indicators, it is possible to provide the therapist with aggregated information of a single session, an entire therapy, a single patient or different patients; the therapist could then compare these parameters.

By applying this method, therapists can easily access daily or periodical patient information without having to process the data or read long reports.

In addition, this approach does not exclude physicians from viewing individual patient data of interest.

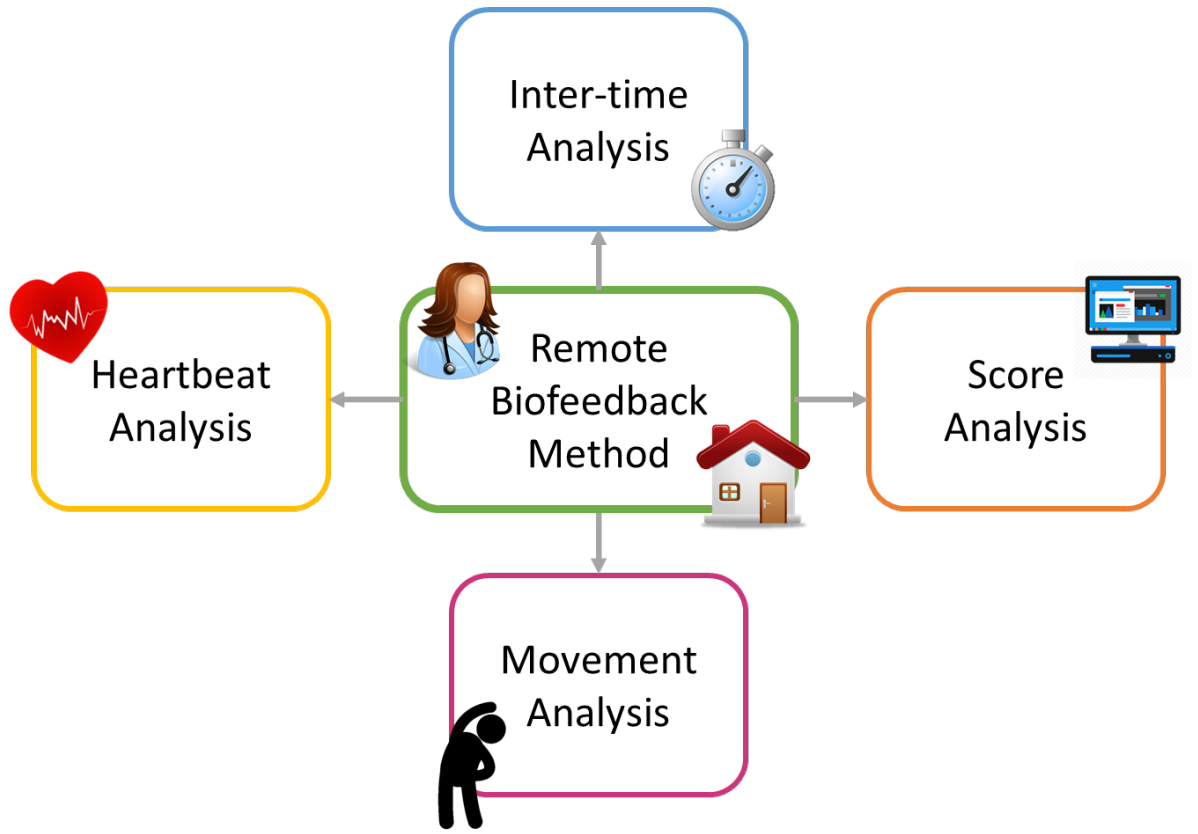


Figure 4: Remote biofeedback method schematic.

2. The proposed method

The traditional signal analysis is carried out independent of the data that are used to apply the method. This approach can be defined as static data analysis. Therefore, it is necessary to know exactly what information needs to be extracted before collecting the data and carrying out the analysis. In contrast, in this work, we chose our methods based on the data. In other words, we adapted our methods to the rehabilitation data (Figure 5) [100]

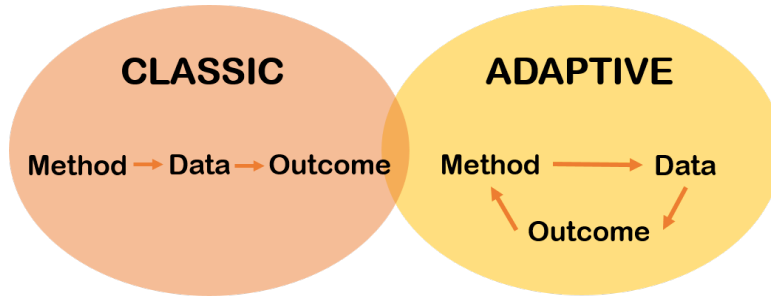


Figure 5: Classical vs adaptive approach to data analysis.

Scores of the 4 different exercises were analysed for each patient. The patient's performance in a game was compared with only one of the rehabilitation sessions in order to determine any improvements. In several sessions, patients could run the games for 60, 120 or 180 seconds based on the instructions of the physiotherapists. Subsequently, in order to achieve a global picture of the progress attained during the rehabilitation programme, the overall scores of the 4 games during the 12 sessions were also evaluated.

A score of 100 points was assigned to every acquired target, whereas 50 points were subtracted for every missed target.

The therapist can choose the order in which the patient has to perform the exercises, thus achieving better solutions for improving his/her movements without causing too much fatigue and effort.

Based on a previous study [101], another evaluated parameter was the rest time that elapsed between the end of one exercise and the beginning of the following one, which was obtained from the combination of the game log and the duration as follows:

$$InterTime_{n-(n+1)} = LEx_{n+1} - (LEx_n + Duration_n) \quad (1)$$

where

LEx_n = the beginning of the exercise

$Duration_n$ = the duration of the exercise

LEx_{n+1} = the beginning of the next exercise.

This parameter is considered to be important for therapists, because it allows for the determination of whether the patient was too fatigued while performing an exercise and, therefore, whether there was a need to rest before performing the next one.

To deepen the analysis, the average inter-exercise time and standard deviation and the maximum and minimum inter-exercise times were evaluated. Then, the 12 sessions were divided into two groups to evaluate whether the efficacy of the therapy also affected the length of the breaks and, therefore, the execution flow of the exercise sessions.

After the score and inter-time evaluation, the analysis focused on the heartbeat, which was acquired using a pulse oximeter that transmits data via Bluetooth to the central system for the duration of the rehabilitation session. The signal was then divided into several parts within each session (Figure 6), which was possible due to the availability of a time log of the exercises that indicated the beginning of the activity. In this way, the signal was analysed for each type of exercise, taking into account the difficulty of the different movements. An adaptive signal analysis was then carried out.

To randomize the quantization error introduced by the pulse oximeter, a post-processing technique called "dithering" was applied to the whole signal. This technique involves adding a random noise with a uniform distribution from -0.5 to +0.5 to the samples, thereby minimizing the distortion introduced by truncation in order to obtain a more realistic signal.



Figure 6: Heartbeat signal before and after the dithering process. X-axes: time; Y-axes: heartbeat. Coloured rectangles represent the different parts in which the rehabilitation session is divided.

It became clear that the dithered signal was less affected by the distortion introduced by the truncation, and the parameters extracted were not influenced by the application of this technique, as shown in Figure 6.

The adaptive analysis of the heartbeat began with signal segmentation into the different parts of each exercise performed by the patient. For inter- and intra-patient uniformity, only the first 60 or 120 seconds were considered for the analysis.

The next step consisted of the extraction of first-order features from each part of the heartbeat data, including the following:

- Average
- Standard deviation
- Maximum value
- Minimum value
- Range
- Trend.

2.1. Linear regression

Since the trend is a common data point used in data evaluation and since it is extractable from both the score and heartbeat, it was used to calculate the angular coefficient of the regression lines (β_{bpm} and β_{score}) to evaluate the presence of a relationship between the two signals.

Linear regression attempts to model the relationship between two variables by fitting a linear equation to observed data [102]. An example is shown in Figure 7, where the linear regression of bpm is presented.

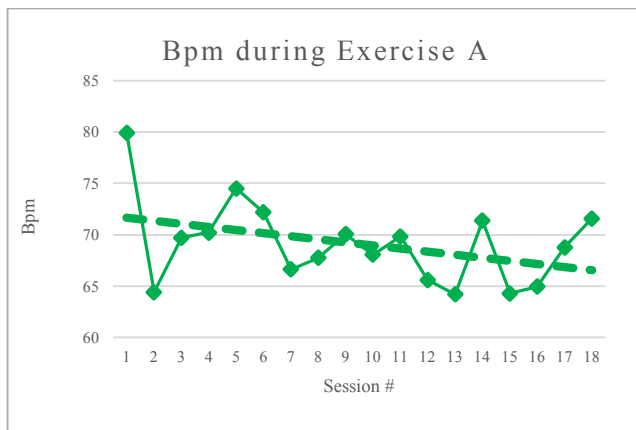


Figure 7: Example of the score signal during the 12 rehabilitation sessions, including the regression line.

We used a linear model for the statistical analysis, which was based on the following linear regression formula:

$$Y = \alpha + \beta X$$

where X is the explanatory variable and Y is the dependent variable. α is the intercept (the value of y when $x = 0$), and β represents the slope 140.

2.2. Least-squares regression

The least-squares method calculates the best-fitting line for the observed data by minimizing the sum of the squares of the vertical deviations from each data point to the line (if a point lies exactly on the fitted line, then its vertical deviation is 0). Since the deviations are first squared and then summed, there are no removals between the positive and negative values.

Suppose there are n data points $\{(x_i, y_i), i = 1, \dots, n\}$, then the function that describes x and y is as follows:

$$y_i = \alpha + \beta x_i + \varepsilon_i \quad (2).$$

The goal is to find the equation of the straight line

$$y = \alpha + \beta x \quad (3)$$

that would provide a "best" fit for the data points. Best (or optimal) fitting refers to the minimization of the square error. In other words, the α (the y-intercept) and β (the slope) solve the following minimization problem [102]:

$$\text{Find } \min_{\alpha, \beta} Q(\alpha, \beta),$$

$$\text{for } Q(\alpha, \beta) = \sum_{i=1}^n \varepsilon_i^2 = \sum_{i=1}^n (y_i - \alpha - \beta x_i)^2 \quad (4)$$

where:

$$\alpha = \bar{y} - \beta \bar{x} \quad \beta = \frac{\sum xy - n\bar{x}\bar{y}}{\sum x^2 - n\bar{x}^2}$$

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad \bar{y} = \frac{1}{n} \sum_{i=1}^n y_i.$$

After applying this method on both the signals from the movement sensor and the pulse oximeter, the slopes of the straight lines, β_{bpm} and β_{score} , were calculated and applied in the data processing step.

2.3. Data processing: key process indicator (KPI) extraction

As seen in several clinical studies like [103] stroke and MS patients often show serious difficulties in the movement and control of the upper limbs. A patient's emotional status is also likely to influence rehabilitation; in fact, most studies have demonstrated both a greater incidence and prevalence of depression in MS patients compared to patients with other neurological conditions. [104][105][106]

Given the abovementioned point and the correlation between heartbeat and the psychological or physical state of a person, this second step in the data analysis followed the logic described below.

A patient's improvement (confidence acquisition, improvement in the mobility of their limbs and decreased stress) is indicated by an increasing trend in the score curve and a decreasing trend in the heartbeat curve.

The heartbeat, which was recorded during the execution of each exercise, provided two samples per second; therefore, before performing score normalization, heartbeat downsampling was computed in order to generate a one-to-one correspondence between the two signals.

The following equation (5) was used for the normalization of the score data:

$$S' = \frac{S_i - S_{min}}{\left(\frac{S_{max} - S_{min}}{B_{max} - B_{min}} \right)} + B_{min} \quad (5)$$

Where

S' = score points normalized

S_i = each score point (i)

S_{Min} = minimum among all the score points

S_{Max} = maximum among all the score points

B_{Min} = minimum among all the beats per minute points

B_{Max} = maximum among all the beats per minute points.

2.4. Heartbeat and score data

For each session, the mean of the heartbeat was computed as follows:

$$M_{bpm} = \frac{1}{n} \sum_{i=1}^n bpm_i \quad (6)$$

where n is the number of bpm samples.

The two parameters (βbpm and $\beta score$) are represented as the coordinates of a dispersion diagram in order to evaluate their influence on the session trend.

The following four cases can be distinguished:

- $\beta bpm > 0$ and $\beta score > 0$:

patient is stressed but exhibits an improvement in the rehabilitative performance

- $\beta bpm > 0$ and $\beta score < 0$:

patient is stressed and exhibits worsened rehabilitative performance

- $\beta bpm \leq 0$ and $\beta score < 0$:

patient is relaxed but exhibits worsened rehabilitative performance.

- $\beta bpm \leq 0$ and $\beta score > 0$:

patient is relaxed and exhibits an improvement in the rehabilitative performance

(the ideal situation).

This analysis reveals the tre and graphically evaluates the presence or absence of a correlation between the score and heartbeat.

Therefore, KPIs were designed by normalizing the data in the range -1 to +1; β_{score} indicates performance, β_{bpm} indicates involvement, and ΔT indicates the session fluidity. Once all of the patients were evaluated and a general view of the score improvement during the rehabilitation sessions was obtained, an indicator (Φ , showing the patient's improvement (7)) was associated with the slope of the straight line obtained during the linear regression computation.

$$\Phi \propto \beta_{score} \quad (7)$$

$$for -1 \leq \Phi \leq 1$$

The same method was applied to the heartbeat according to the degree of involvement, thus obtaining the indicator Ψ (8).

$$\Psi \propto (\beta_{bpm})^{-1} \quad (8)$$

$$for -1 \leq \Psi \leq 1$$

Finally, the average inter-exercise time of the first and the last six sessions was calculated to evaluate the average improvement of the subjects in order to assess the presence of an improvement ($\Delta T < 0$ (9)) in the fluidity of the execution of the rehabilitative exercises.

$$\Delta T = \bar{T}_{last\ six} - \bar{T}_{first\ six} \quad (9)$$

According to the values obtained from the computation of ΔT , an indicator Ω (10) based on the improvement in the fluidity was assigned.

$$\Omega = \begin{cases} 1 & \text{in case of improvement} \\ 0 & \text{if no improvement} \\ -1 & \text{in case of worsening} \end{cases} \quad (10)$$

2.5. Data presentation

The mined information was shown to the therapists using the following data presentation methods.

One of the methods proposed is the “Patients’ Cube”, where patients are represented by coloured spheres positioned in a 3D space formed by the three indicators (Φ , Ψ , and Ω) computed during the data processing step.

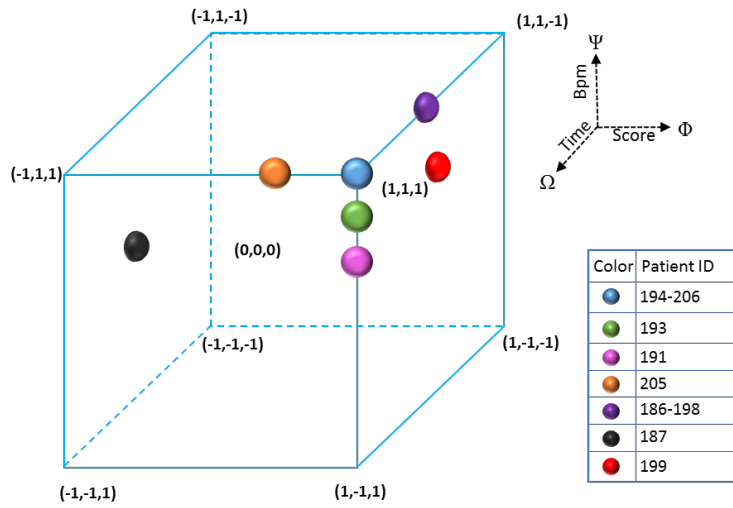


Figure 8: Graphical representation of the “Patients’ Cube”.

The spheres representing patients with a good global performance are located around the vertex of coordinates (1,1,1), whereas those representing patients with a bad performance are located around (-1, 1, 1), as shown in Figure 8.

Therefore, by combining the three indicators, patients 194 and 206 improved in their game performance, in the session fluidity and they felt in good condition during playing exercises without stress and fatigue.

The same behavior cannot be confirmed for patient 187, which has worsened his/her gaming performance in two types of exercises out of three, even worse in the fluidity of the rehabilitation session, with a stressed condition in playing all exercises.

2.6. Movement Features Extraction

In this section, we are focusing on the movement feature extraction phase, aiming to highlight the patient motion performance during the execution of the functional exercises proposed through serious-games.

Upper limb movements

Microsoft Kinect V2 is deployed in this analysis: the patient interacting with digital games is encouraged to reach on-screen target with the arm motion (Reaching Task) in order to collect high in-game score. The main movements at the shoulder joint (glenohumeral joint) tracked during the execution of functional exercises are: Flexion-Extension, Abduction-Adduction. From the motion data, we extract these fundamentals features:

- Detection and measurement of a spatial neglect in hemiplegic patients who ignore a part of the in-game space. The hand measured coordinates on the coronal plane, acquired over time, are used to populate a visual "heat-map" from which the therapist can evaluate the neglected areas (Fig. 9c).
- Detection of an undesired strategy of compensation adopted by the patient during the execution of the exercise. In detail, when the shoulder-hand distance remains constant and the in-game target is reached anyway, ReMoVES platform reports this behaviour to the therapist since the patient rotated the trunk instead of training the upper limb.

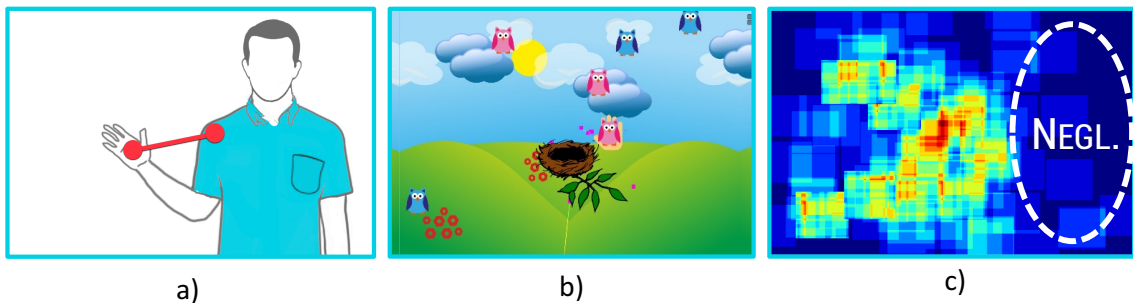


Figure 9: a) Abduction-Adduction exercise scheme b) Gameplay during a serious-game session c) Heatmap to detect neglected areas.

Indicators extraction

Spatial map

Spatial negligence affects approximately 30-40% of patients with acute stroke and consists in ignoring part of the space as a result of brain damage. It is therefore very important to rehabilitate this feature and to resume the complete visual and perceptual field.

In this case spatial neglect will not cause the patient to make the wrong moves, but to ignore the targets that are offered to him in a certain part of the space.

For this reason, it was decided to introduce the spatial map, a tool that traces the locations where the movement was performed and also provides the therapist with the spatial coordinates where the targets were proposed.

In addition, all the proposed activities are customizable, and this exercise can then be parameterized so that targets can only be seen in the part of the space ignored by the patient, assisting them in visual field re-education.

The spatial map is presented with a color scale ranging from dark blue, where no movements were performed, to red, where there was the greatest occurrence.

An example of a graphic result derived from a patient suffering from right negligence is shown in the figure below, as can be seen the central part, corresponding to the "nest", shows the maximum concentration of movements as the exercise is to move the target represented by "owls", right towards the center. The left side has several areas with yellow color, a target for reaching the target, as opposed to the right side where they are completely absent.

In addition to the spatial map, the following parameters were chosen as significant:

- Maximum height reached

$$MaxHeight = \max(HandY(t))$$

- Score collected: Total Score
- Movements distribution over the space

In order to study the distribution of the movements in space, the action area was divided into 3 parts, right area, central area and left area.

$$Range_x = \max(HandX(t)) - \min(HandX(t))$$

$$Range_{xright} = \max(HandX(t)) - \frac{Range_x}{3}$$

$$Range_{xleft} = \min(HandX(t)) + \frac{Range_x}{3}$$

The number of position in the left and right area are computed:

$$Pos_{left} = count(Pos_i < Range_{xleft})$$

$$Pos_{right} = count(Pos_i > Range_{xright})$$

by obtaining the following parameters:

$$NPos_{left} = dim(Pos_{left})$$

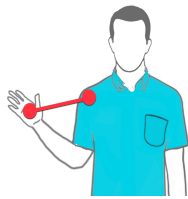
$$NPos_{right} = dim(Pos_{right})$$

$$NPos_{tot} = NPos_{left} + NPos_{right}$$

so, the two indicators Θ_{left} e Θ_{right} , representing the movement percentage executed on the left and on the right are found as follow:

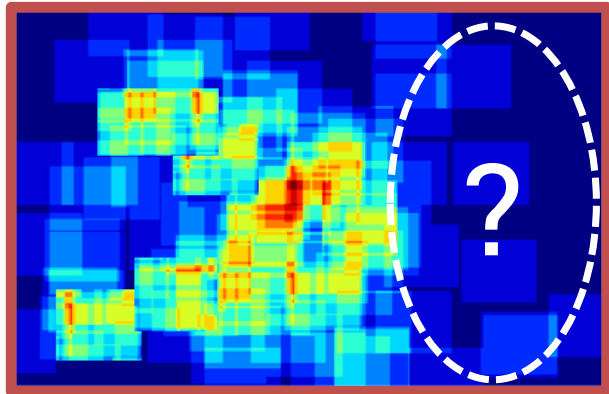
$$\Theta_{left} = \frac{NPos_{left}}{NPos_{tot}} \times 100 \quad \text{left hemifield}$$

$$\Theta_{right} = \frac{NPos_{right}}{NPos_{tot}} \times 100 \quad \text{right emifield}$$



Neglect

Exercise: Owls in the Nest



Hand-Shoulder Distance

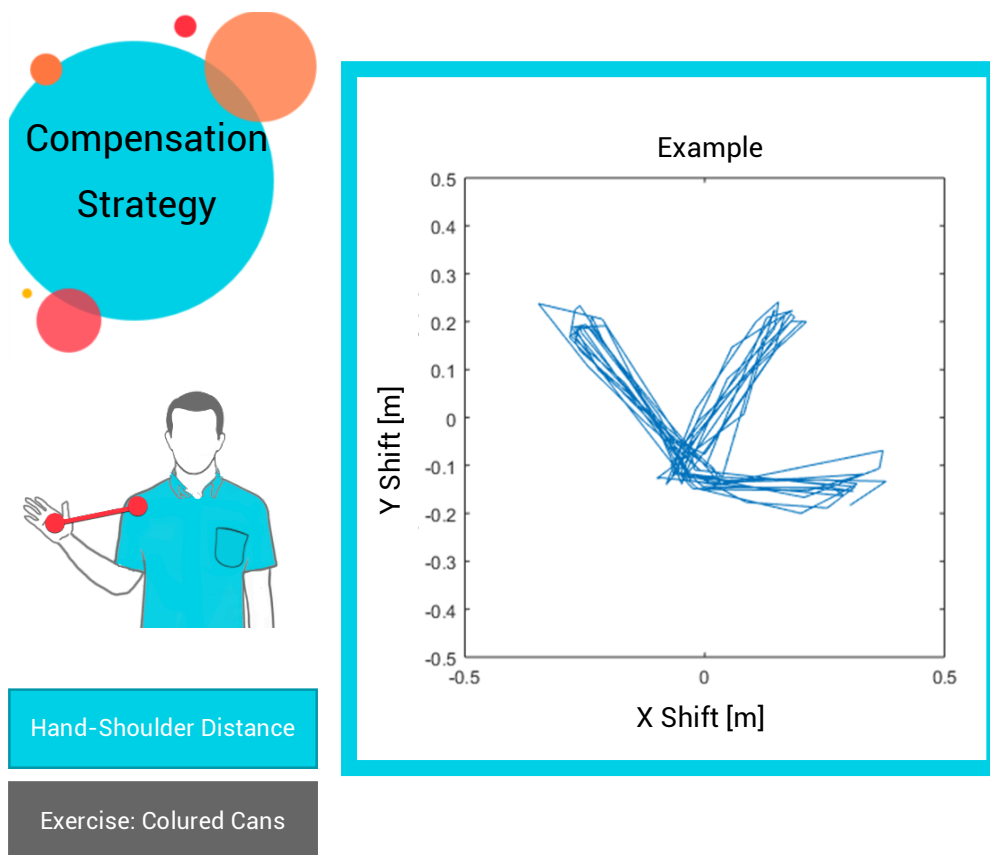
For the exercises involving the upper limb, it was decided to evaluate the distance between the hand and the shoulder while performing the movement in order to assess whether the patient reaches the targets using the upper limb and shoulder, or moves the whole body while maintaining the angles between the arm and the forearm and between the arm and the body almost constant.

The parameter, index of the correct movement was extracted as follows:

$$\Theta_8 = \sqrt{\frac{\sum_{i=1}^N (x_i - \mu)^2}{N}}$$

Proper motion execution implies a value of $\Theta_8 \gg 0$, which indicates a very variable signal, on the contrary a patient who has made a compensation strategy will have a lower value.

The study of trajectories will be presented to the therapist with a graphic representation accompanied by the parameter just described as shown in the following graph:



Sit to Stand analysis

The exercise of the Sit To Stand is defined as the movement that involves the transition from the sitting position to the upright position with transfer of the center of gravity from a wider base to a narrower one, without loss of balance.

In patients who face a rehabilitation path linked to the rehabilitation of the lower limbs, a simple gesture like getting out of a chair is difficult and tiring. It is at the same time one of the first basic gestures to be learned again, both because it is very frequent in everyday life, and because if performed poorly it can lead to falls and recurrences.

In order to evaluate the correct execution of the movement, the displacement in the coronal and sagittal plane of the point of the vertebral column corresponding to the center of the shoulders, indicated in the figure by the red marker, was then mapped. As can be seen from the graph on the sagittal plane, a correct movement provides a sinusoidal trajectory since in the first phase it is essential to carry on the shoulders to begin the phase of detachment from the chair. On the coronal plane the trajectory of the movement must be linear and constant around the zero value. During the exercise developed for the posture of the shoulders the angles of inclination of the shoulders towards the right and left were also extracted during the ascent from a sitting position to a standing position, both during the descent phase.

A correct movement provides very small angles of inclination with a tolerance of about 10° , the average value must therefore be around 0° .

Microsoft Kinect V2 is deployed in this analysis: the patient must stand up and sit down repeatedly (Sit to Stand) keeping the trunk as straight as possible. To analyze the execution performances, we extract these fundamentals features:

- Number of repetition in a given time (linked to the in-game score displayed to the player).
- Detection of erroneous twist on one shoulder while standing or sitting (Fig. 10b).
- Verification of the correct strategy used by the patient to stand up, considering the trunk tilt on both coronal and sagittal plane (Fig. 10a).

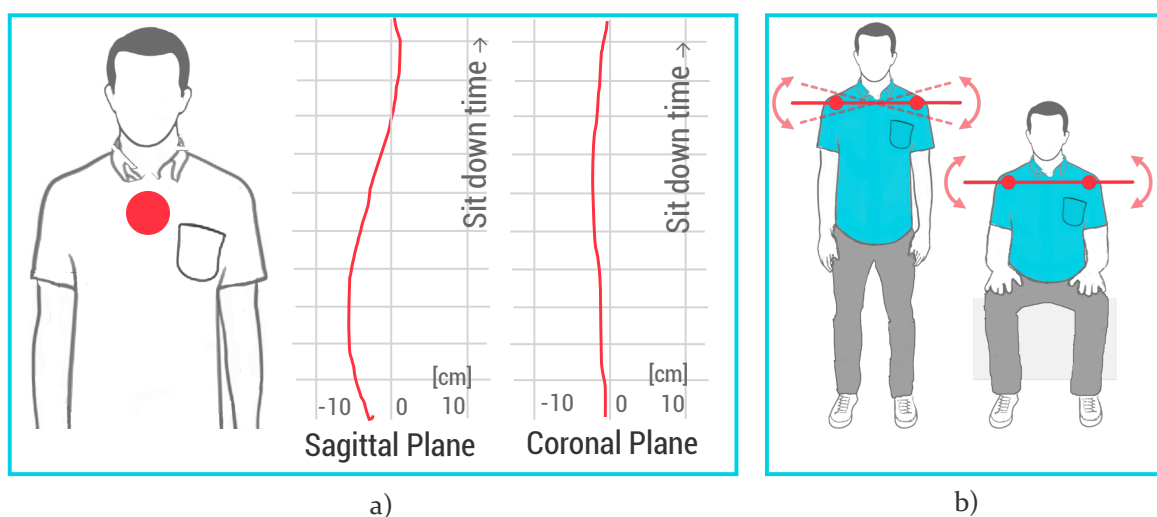


Figure 10: a) Trunk tilt on sagittal and coronal plane b) Shoulder tilt detection.

Indicators extraction

The indicators extracted for this type of exercise are based on three main parameters:

- Sit to Stand (STS) number performed during the entire duration of the exercise prescribed by the therapist (60, 120, 180 seconds).
- Range of Motion (ROM) on the coronary plane of the upper extremity of the spine (Spine Top)
- The time required for transition from sitting to standing position.

The first extracted indicator provides the therapist with information on how many times the patient has been able to get up and sit down from the chair by processing the spine top point motion signal, combined with the score collected.

The Spine Point motion signal shown in the figure is processed by studying the pattern and extracting the peaks.

Before applying the peak detection algorithm, the signal was filtered with a median filter to eliminate non-significant oscillations.

Peaks of a positive array of data are defined as local maxima. For doubled-sided data, they are maxima of the positive part and minima of the negative part.

The function “findpeaks” finds local peaks in the data vector $Spine_{top}$. A local peak is defined as a data sample which is either larger than the two neighboring samples or is equal to Inf.

$$[Pos_{Peaks_max}, N_{peaks_max}] = findpeaks (Spine_{top}, 'MinPeakHeight', 0.2)$$

$$[Pos_{Peaks_min}, N_{peaks_min}] = findpeaks (Spine_{top}, 'MinPeakHeight', 0.2)$$

By indicating the MinPeakHeight, only those peaks that are greater than the minimum peak height, 0.2, are found.

Once the number of local maxima within the signal is found, an inverse calculation of the score collected is made to check the reliability of the peaks detection algorithm.

For each transposition from the sitting to the standing position, 300 points are assigned to the patient, by dividing the total score collected for 300, an estimation of the number of times the patient has stood up is obtained.

The Nsts-score obtained does not always match the exact number of transitions because the final score consists of the sum of different contributions due to the patient's execution mode and the shoulder position.

This value is then compared with the number of peaks previously calculated and the average is made between the two values.

$$N^{\circ} STS = \text{mean} (N_{\text{sts-score}}, N_{\text{peaks}})$$

The first extracted indicator is then calculated as follows:

$$\theta_1 = (N^{\circ} STS_p / N^{\circ} STS_m) \times 100$$

Where:

$N^{\circ} STS_p$ = Number of Sit To Stand executed by the patient

$N^{\circ} STS_m$ = Number of Sit To Stand executed by the model

The second parameter is extracted by calculating the maximum left and right displacement during each transition from upright sitting position.

$$ROM_x(i) = \max(X_{STS}) - \min(X_{STS})$$

Where:

$\max(X_{STS})$ is the maximum right shift

$\min(X_{STS})$ is the maximum left shift

For each transition then the goodness of motion of the movement is calculated according to the oscillations on the coronal plane as follows:

$$\theta_{2i} = (ROM_{xi} STS_p / ROM_{xi} STS_m) \times 100$$

So many indicators are provided as to how many times the patient has been up and sitting. To give a final information, the average of all θ_2 is obtained, obtaining the parameter θ_3 , as follows:

$$\theta_3 = \frac{1}{N} \sum_{i=1}^N \theta_{2i}$$

The fourth parameter that has been chosen as a significant indicator is the time a patient takes to move from sitting to standing position.

Again, in this case, as done for the Range Of Motion, the time needed for each transition is calculated and then the average value is calculated to give a general picture of the session. Times are calculated in such a way as to give an index of fatigue and tiredness of the patient with the repetition of movement.

In this way, the therapist can decide whether to decrease the duration of the exercise if the repetition rate of the movement decreases significantly during the session, conversely if the frequency is regular.

The time intervals are extracted from the maximum and minimum calculated by the findpeaks function. Knowing the peak positions contained in the Pos_{Peaks_max} e Pos_{Peaks_min} vectors it is possible to discriminate the ranges as follows:

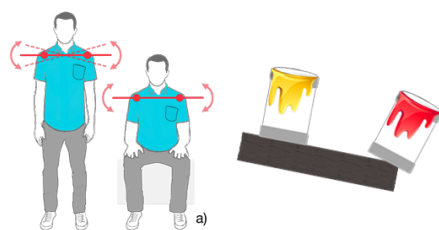
$$Time\ STS_N = Pos_{Peaks_max_N} - Pos_{Peaks_min_N}$$

Parameter θ_4 provides the therapist with the percentage of goodness compared to the healthy subject as the average value over the entire session:

$$\theta_4 = \left\{ \left[\frac{1}{N} \sum_{i=1}^N (Time\ STS_{N_p}) \right] / Time\ STS_{N_s} \right\} \times 100$$

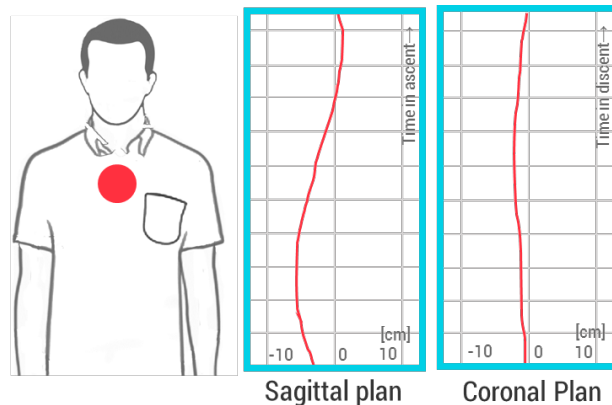
The fifth parameter extracted was designed as an indicator of the goodness of motion execution, in fact, all the shoulders angles, $\alpha_{Shoulders}$, are recorded during the transition from sitting to standing position and vice versa., for each session executed, $2 \times N^\circ$ STS angles are obtained. The mean value is computed obtaining a single value that represents the fifth indicator extracted:

$$\theta_5 = \frac{1}{N} \sum_{i=1}^N \alpha_{Shoulders}$$



Sit to Stand

Exercise: Equilibrium Paint



Maximum tilting of the shoulders during the ascent



Maximum tilting of the shoulders during the descent

Center of Pressure Estimation

The Nintendo Wii Balance Board (WBB) has been already validated as a suitable alternative to a laboratory-grade force platform in the measures of Center of Pressure (CoP) in contexts where clinical assessment of balance is required without an elevated precision level [105][106]. ReMoVES platform do not employ the WBB despite its adequate performances in the serious-games context: in fact, according to the preliminary studies we have carried on, the Microsoft Kinect V2 can be exploited for the estimation of the oscillation of the CoP on the mediolateral axis and WBB would be redundant and anti-economic.

The following procedure will disclose the method for the CoP estimation using the Microsoft Kinect V2:

- Track the position in the space of these fundamental body joints provided by Kinect SDK: right ankle (A_r), left ankle (A_l), the base of the spine (S_{bottom}) and the spine at the shoulder height (S_{top}) (Fig. 12a).
- Compute the position in the space of the middle point (M) between the Right Ankle and the Left Ankle.
- Compute the difference between the angles related to the shift of lower and higher section of the trunk:

$$\begin{aligned} Tilt_{bottom} &= \angle(A_r, M, S_{bottom}) - \angle(A_l, M, S_{bottom}) \\ Tilt_{top} &= \angle(A_r, M, S_{top}) - \angle(A_l, M, S_{top}) \end{aligned} \quad (1)$$

- Calculate the average between the $Tilt_{bottom}$ and $Tilt_{top}$ to get the estimated CoP:

$$CoP = \frac{Tilt_{bottom} + Tilt_{top}}{2} \quad (2)$$

We used this experimental setup for evaluate the performance of the proposed algorithm: 3 subjects repeated a 2 minutes-long serious-game for postural assessment for 10 times. Data synchronously recorded from WBB and Microsoft Kinect V2 and the CoP oscillation on the mediolateral have been normalized to a -1/1 range (corresponding to maximum shift on left and right side respectively) and compared calculating the Pearson correlation coefficient. The average of the coefficients calculated for each test sessions brought to the result of ~0.89. Fig. 11 shows a sample of synchronized and normalized data in a 2-minutes long test session.

- CoP oscillation on the mediolateral axis with a sufficient precision (similar to Wii Balance Board).
- Verification of the correct strategy used by the patient during balance shift exercise by computing the difference between $Tilt_{bottom}$ and $Tilt_{top}$ (Fig. 12c).

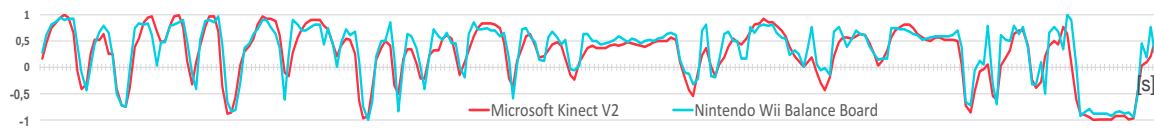


Figure 11: Normalized CoP oscillation acquired both with Microsoft Kinect V2 and Wii Balance Board during a comparison test. On the X axis the time (2 minutes long trial).

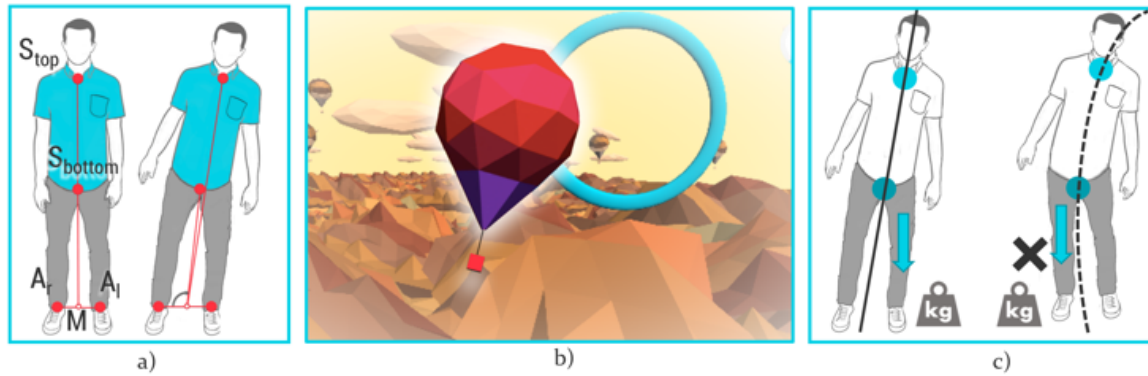


Figure 12: a) Tracked joints for CoM estimations b) Gameplay during a serious-game session c) Erroneous balance shift detection.

Indicators extraction

Another very important element for the re-education of the lower limbs and the gait is the handling of the load. For the re-education of this faculty, an exercise has been designed in order to inducing the patient to alternate the load on the lower left and right limbs without compensating the movement by shifting the upper part of the body as shown below in Figure 13. The first graph shows that when the load shift is correct, the two curves representing the movements of the two markers corresponding to the spine ends (*Spine Top* and *Spine Down*) coincide, in contrast as can be seen in the second graph, deviate when the patient compensates for the displacement of the trunk.

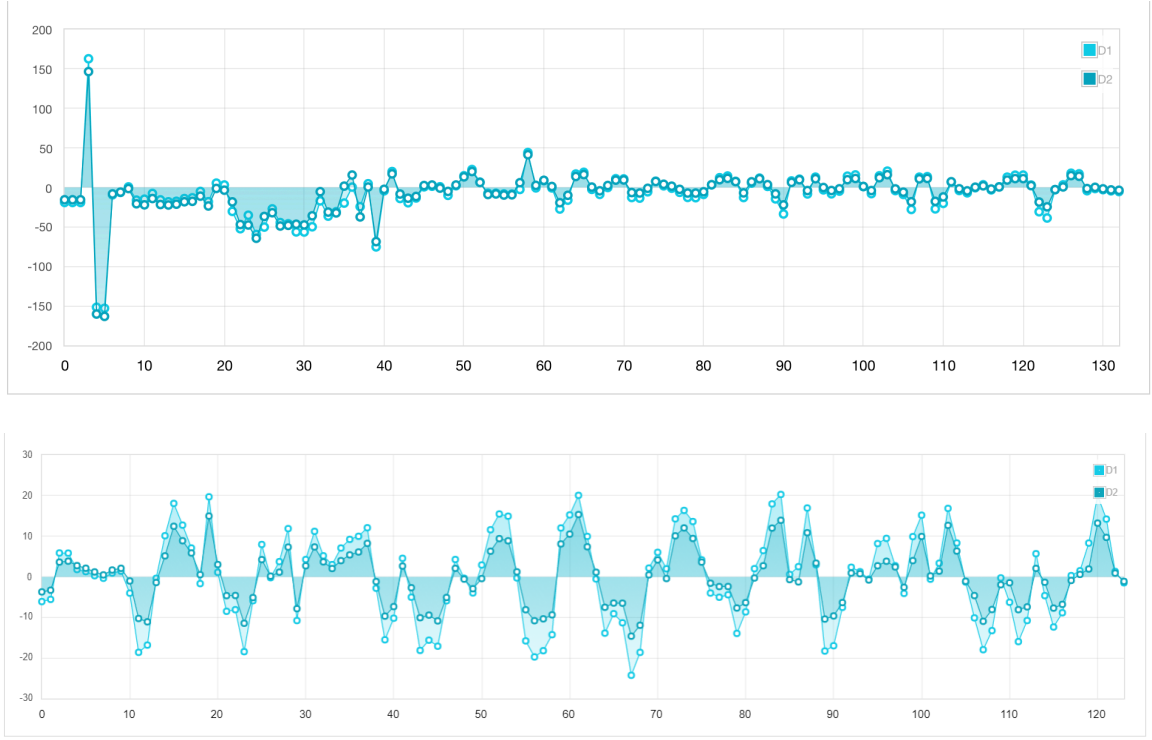


Figure 13: The two curves of each graph represent the movements of the two markers corresponding to the spine ends (Spine Top and Spine Down): on the top, a movement executed correctly, on the bottom a wrong execution.

For the evaluation of the number of compensations performed by the patient during the load shifting movement, the difference between the Spine Top signal and the Spine Down signal is calculated and its absolute value and its mean are extracted.

$$\Delta_{Top-Down}(t) = |Spine\ Top(t) - Spine\ Down(t)|$$

$$\bar{\Delta}_{Top-Down} = \frac{1}{N} \sum_{i=1}^N \Delta_{Top-Down}(i)$$

In order to give the therapist an information about the maximum shifting of the load on the left and the right side the ROM_{Left} and ROM_{Right} values are computed as follows:

$$ROM_{Left} = |Min(Spine\ Down(t))|$$

$$ROM_{Right} = |Max(Spine\ Down(t))|$$

A healthy subject performing the movement correctly has a value $\bar{\Delta}_{Top-Down} = 2,89 \pm 2,35$, obtained from the study of a healthy subjects group from whom a model was extracted.

The motion goodness indicator is extracted as follows:

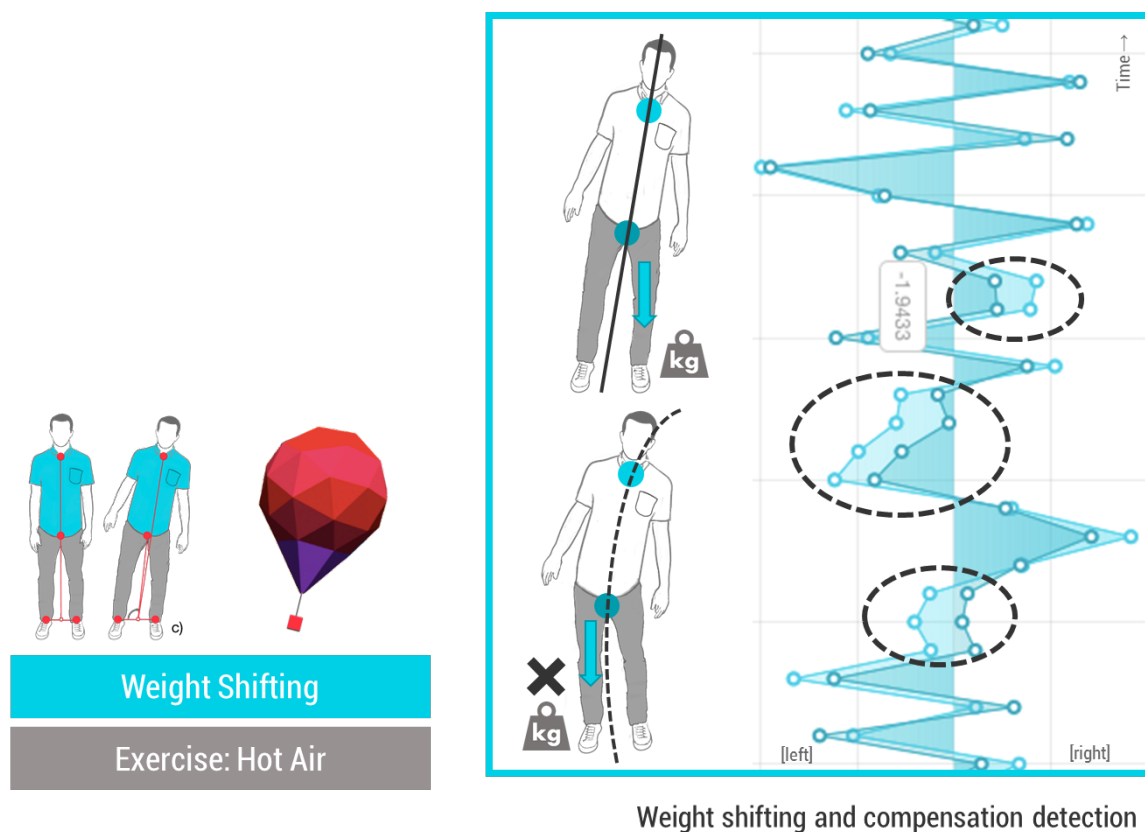
$$\Theta_7 = \frac{\bar{\Delta}_{Top-Down\ model}}{\bar{\Delta}_{Top-Down\ patient}} \times 100$$

$$\Theta_8 = \frac{ROM_{Left-patient}}{ROM_{Left-model}} \times 100$$

$$\Theta_9 = \frac{ROM_{Right-patient}}{ROM_{Right-model}} \times 100$$

The information coming from this parameter is completed with the score, as the patient may have performed the movements correctly, but for example in the opposite direction to the targets to reach. The score (Total Score) can be classified as follows:

- Total Score < 0 insufficient
- 0 < Total Score < 3000 sufficient
- 3000 < Total Score < 6000 good
- Total Score > 6000 great



Lower Limb Movements

Currently the FlappyCloud is the only serious-game included in the ReMoVES platform that is developed around a functional exercise for Lower Limb. The user must accomplish the Abduction-Adduction movement with his impaired leg while he is standing (Figure 1c). The therapist can suggest to the patient to hold to a physical support like the back of a chair in order to prevent falls or equilibrium instability.

The elevation of the leg and additional body joints position are tracked with the Microsoft Kinect V2 to detect the balance status of the user body: to accomplish the exercise correctly the patient must keep the trunk erected and straight. Currently the FlappyCloud is the only serious-game included in the ReMoVES platform that is developed around a functional exercise for Lower Limb. The user must accomplish the Abduction-Adduction movement with his impaired leg while he is standing. The therapist can suggest to the patient to hold to a physical support like the back of a chair in order to prevent falls or equilibrium instability.

The elevation of the leg and additional body joints position are tracked with the Microsoft Kinect V2 to detect the balance status of the user body: to accomplish the exercise correctly the patient must keep the trunk erected and straight.

This exercise is the only one in which it was decided to give the patient a direct biofeedback. The game, in fact, becomes more difficult, if the patient does not keep the trunk straight, and the targets, green by default, becomes red.

Indicators extraction

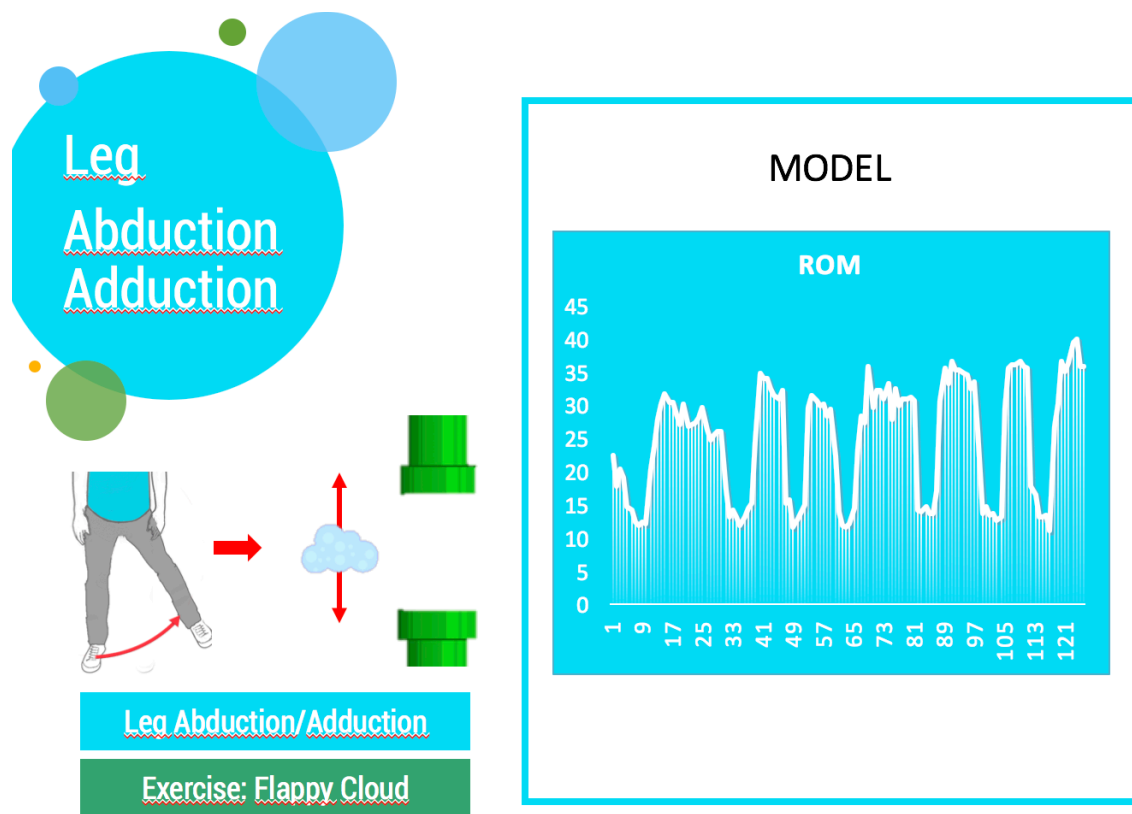
For the lower limb evaluation, in addition to the load distribution analysis, an exercise involving abduction of the leg was also designed.

The parameters chosen as indicators are based on the maximum height reached during leg abduction, and the time the subject maintains the leg raised.

$$\Theta_{12} = Max_{Abduction} = \max(Leg(t))$$

$$\Theta_{13} = Fly_{Time} = \frac{\dim(Leg(t) > 25^\circ)}{\dim(Leg(t))} \times 100$$

In addition to the movement parameters, for this exercise too, the score acquired in relation to the model is evaluated.



Hand movements

Leap Motion is deployed in this analysis: the digital games encourage the patient to control in-game objects with the hand, wrist and finger motion. The main movements tracked during the execution of functional exercises are: Radial-Ulnar Deviation (Fig. 14a), Flexion-Extension (Fig. 14b), Pronation-Supination (Fig. 14c), Grasping (Fig. 14d).

From the motion data, we extract these fundamentals features:

- Number of repetition of the movement in a given time (linked to the in-game score displayed to the player).
- Maximum angle reached in each of the proposed movement (corresponding to yaw, roll and pitch).
- Evaluation of the grasping exercise with Grab Strength function provided by Leap Motion SDK that returns values between 0 and 1 respectively when the hand is open or when it is closed in a grabbing pose.

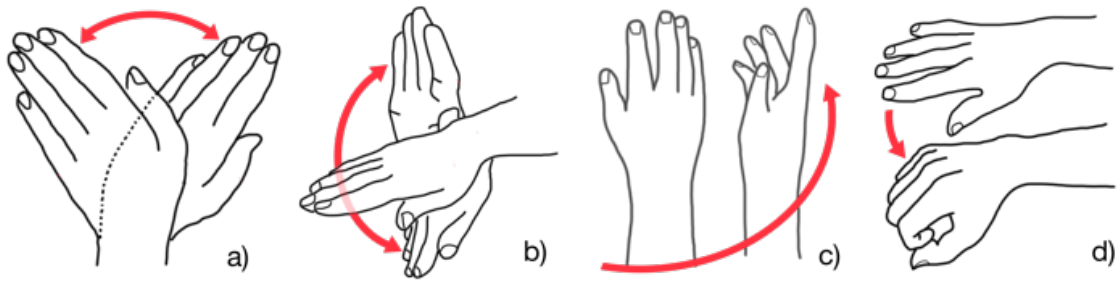


Figure 14: Movements detected during hand rehabilitation with Leap Motion.

Table 1 provides an example of performance indicators variability during the repetition of the activity (hand Pronation-Supination / Roll rotation clockwise and counterclockwise) along 6 sessions, performed in different days.

Table 1: Progress over time of a subject executing an exercise for hand Pronation-Supination (roll rotation)

Session	Game Score	Clockwise	Counter Clockwise
#1	1260	77.43°	-78.06°
#2	3660	75.94°	-79.89°
#3	3650	82.53°	-81.83°
#4	4250	87.59°	-81.08°
#5	3640	94.82°	-30.20°
#6	3680	102.19°	-77.34°

Indicators extraction

As regards the exercises dedicated to the hand rehabilitation, they were designed based on the repetition of the same movement for the re-education of elementary gestures.

For this reason, a key parameter is the number of correct movements performed over a period of time. The quantity is always accompanied by the quality with the movement was

performed, so it is a more complex parameter, consisting not only of a simple number, but also of a movement-performance indicator.

By analyzing the signals from the roll movement of several patients, it was noted that the average value of the signals was not for everyone around zero.

The average value of each signal was then subtracted setting it around zero as follows:

$$Roll_0(t) = Roll(t) - \left| \frac{1}{N} \sum_{i=1}^N Roll_i(t) \right|$$

Once the signal is reset to zero then the positive and negative values are counted, thus obtaining N_+ and N_- .

The number of movements performed is then calculated by dividing the total score collected during the session by the “*Target Score*”, the scoring value assigned for each target correctly reached.

$$N_{Target} = \frac{Total\ Score}{Target\ Score}$$

this value is then compared with the model obtaining the indicator:

$$\Theta_N = \frac{N_{Target-Patient}}{N_{Target-Model}} \times 100$$

which gives information on the number of repetitions performed, compared to the reference model.

Once these two values are obtained, they are used to extract the two parameters δ_+ and δ_- as follows:

$$\delta_+ = \frac{N_+}{N_{Target}}$$

$$\delta_- = \frac{N_-}{N_{Target}}$$

If the movement is executed in a correct way the value of δ_+ has to be about $2\delta_-$.

Both values δ_+ and δ_- are compared to those of the healthy model, and then the two final parameters are extracted as follows:

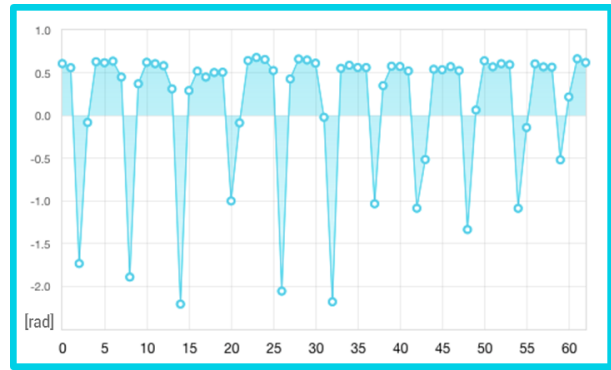
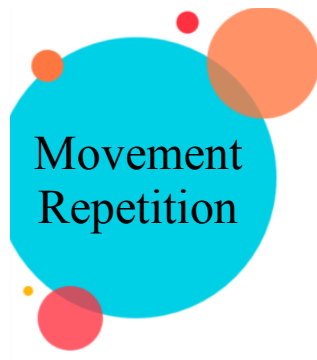
$$\Theta_+ = \frac{\delta_{+model}}{\delta_{+patient}} \times 100$$

$$\Theta_- = \frac{\delta_{-model}}{\delta_{-patient}} \times 100$$

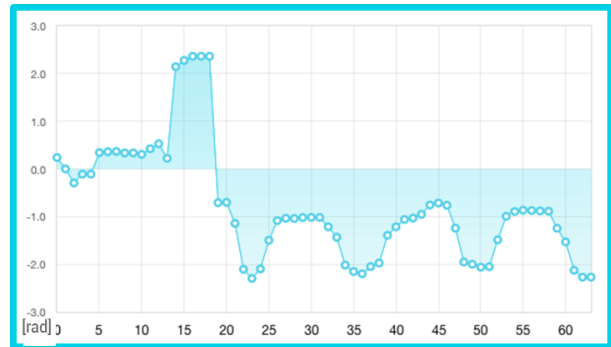
Both parameters must be as near as possible to 100%.

To give a general picture the average of the two values can be provided to the therapist.

$$\Theta_6 = \frac{\Theta_+ + \Theta_-}{2}$$



Glass filled quickly 11 times



Glass filled only 3 times

For the different exercises involving the hand, in addition to the score collected, the range of motion was evaluated as follows for each ripe of hand movement:

$$Range_{Pitch} = \max(Pitch(t)) - \min(Pitch(t))$$

$$Range_{Yaw} = \max(Yaw(t)) - \min(Yaw(t))$$

$$Range_{Grab} = \max(Grab(t)) - \min(Grab(t))$$

from which the following three indicators were extracted:

$$\Theta_9 = \frac{Range_{pitch-patient}}{Range_{pitch-model}} \times 100$$

$$\Theta_{10} = \frac{Range_{yaw-patient}}{Range_{yaw-model}} \times 100$$

$$\Theta_{11} = \frac{Range_{Grab-patient}}{Range_{Grab-model}} \times 100$$

Progress Over Time

The parameters so far illustrated concern the analysis of the single session, which the therapist daily analyzes to modify the rehabilitation plan if necessary.

In order to have a global vision after the execution of several sessions, what is going to analyze is the progression over time.

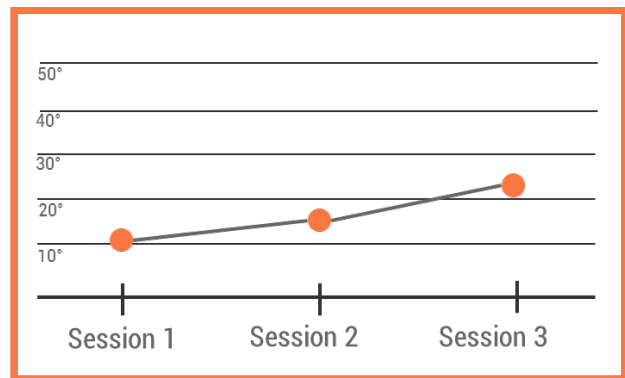
So, all of the parameters extracted for single session analysis are compared to each other to see if the patient has improved his/her performance session by session, then tracking the rehabilitation path and making changes if necessary. The progression will be shown to the therapist in graphic form, giving global information session by session. The following figure shows an example of wrist flexural activity, highlighting as the significant parameter the maximum angle of extension and flexion achieved during each session.

Progress Over Time

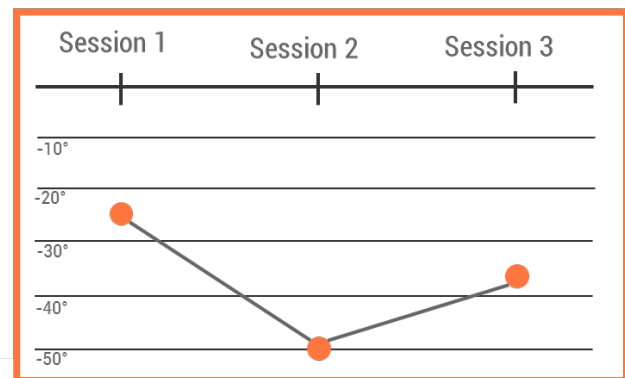


Wrist Flexion/Extension

Exercise: City Car



Maximum angle reached during ecixtension



Maximum angle reached during flexion

Chapter 4: Rehabilitation protocol

1. Relaxing phase

1.1. Introduction

To establish how to promote and to configure such a system it is really useful to define who the users are and how to approach them. Users are human beings who interface with the product in order to achieve the wanted objectives.

It is therefore important to understand the characteristics of the users when defining the product usability requirements. [107]

The main aspects to be analyzed are:

- Learnability: How easy is it for users to accomplish basic tasks the first time they encounter the system?
- Efficiency: Once users have learned the system, how quickly can they perform tasks?
- Memorability: When users return to the system after a period of not using it, how easily can they establish proficiency?
- Errors: How many errors do users make, how severe are these errors, and how easily can they recover from the errors?
- Satisfaction: How pleasant is it to use the product?

The aim of this study is to understand if, through the analysis of heartbeat and heart-rate variability, it is possible to evaluate the user condition during the viewing of two different relaxing videos.

In particular, for the heartbeat, the work was conducted through an analysis in the time domain and mean value over the entire length of the first video and the entire duration of the second video were extracted. For the interbeat, through a non linear analysis, four parameters were extracted: two are indices of the short and long term variability, while the other two are the contributions of acceleration and deceleration of the heartbeat.

Through the comparison between these five physiological parameters and with the support of a direct feedback from the user, the purpose is to understand if, from heartbeat and interbeat it is possible to define if the user is relaxed and what is the best relaxation method.

This preliminary study was conducted on a population of nine subjects: eight healthy controls from twenty to eighty years old and one patient with multiple sclerosis (66 years old).

To make the subject comfortable, the rehabilitation session has been divided into two main parts, a relaxation phase and a game phase. For the first phase two methods have been developed, a landscapes video and a "Breath Ball". The analysis of the effect of both on the heartbeat and interbeat has led us to define which should be the best method to relax the subject. Both methods require that the subject, in a sitting position, watch to a monitor.

1.2. Landscapes Video

In 1984, Ulrich [110] demonstrated that patients whose windows faced a park recovered faster as compared with patients whose windows faced a brick wall. After that one, several studies have demonstrated restorative effects of natural environments like increased well-being, decreased physiological stress responses and negative influences [110][111][112][113][114] Ulrich [115] in his work suggested that natural environments induce positive emotional states, decrease physiological activity, and sustain attention. This agrees with Kaplan and Kaplan's theory, [117], that natural environments facilitate recovery of directed attention capacity and thereby reduce mental fatigue, with results showing that positive emotions improve physiological recovery after stress [118]. Previous research in this area has mainly used visual stimuli, for example videos and photographs of nature settings and urban areas [110][114][119].

Soundscape research has shown that natural sounds are typically perceived as pleasant and technological noise as unpleasant components of the sound environment [110]

Ulrich et al. [115] used video films with sound and found faster physiological stress recovery during exposure to films depicting nature.

Jesper J. Alvarsson [120] conducted a study only with sounds and he suggested that after psychological stress, physiological recovery of sympathetic activation is faster during exposure to pleasant nature sounds.

The video used for this work consists of 19 images depicting natural landscapes like forests, seaside, lakes and fields, with a music in the background that reproduces the sounds of nature for a period of three minutes.



Figure15: Example of frames from the landscapes video of the relaxation phase. They all represent natural environments with a music that reproduces sounds of nature for a period of three minutes.

1.3. Breath Ball

Breathing is a natural and essential functionality for the maintenance of physical and physiological health and for the balance of several functions of our body. Ley [121] suggested that breathing can be viewed as an independent variable which affects emotion, cognition, and behaviour as well as a dependent variable which reflects changes in emotion, cognition, and behaviour.

Blumenstein [122] show that breath pattern is strongly associated with the regulation of mental states.

From this literature background, the second method was developed with the use of the “breath ball”.

To make the subject comfortable and to bring back his/her heartbeat to a basal value before the rehabilitation session, the patient is leaded to breath with a regular rhythm by following a "breath ball" displayed on the monitor. The ball changes its dimension simulating inspiration and expiration (Figure 16): when it grows, the patient should inhale, then exhale when it shrinks. When the patient encounters difficulty to follow the ball rhythm, we ask him to relax and not strain himself/herself.

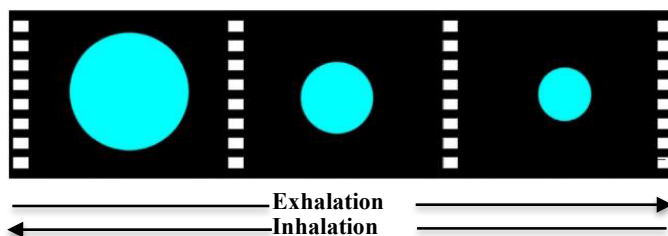


Figure 16: Three frames from the "Breath Ball" video: a sphere changes its size to help the subject to breathe with a given frequency.

1.4. Heartbeat analysis

The study of the heartbeat was conducted through a time domain analysis in which the average on the entire duration of the video was extracted. For each subject the two values obtained from both methods are compared.

Poincarè Plot

To evaluate which is the best method, some parameters have been extracted through a non-linear analysis by means of a Poincarè Plot. Such a plot is a useful tool able to provide information about the Heart Rate Variability (HRV), allowing at the same time to summarize in one image a time series of inter-beats (RR) values as derived from an electrocardiogram or from a simple photoplethysmograph.

Inter-beats are the time intervals between consecutive heartbeats, measured in milliseconds. The Poincarè diagram is made of a cloud of points (RR_i, RR_{i+1}) , that is, each point corresponds to two consecutive RR intervals.

The cloud of points is characterized by two main parameters: the spread along the main diagonal and in the orthogonal direction [108].

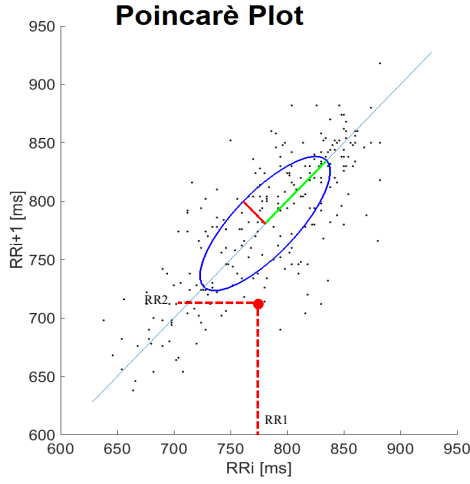


Figure 9: Example of Poincaré plot from one of the nine subjects, in which the line of identity, one point (R1, R2) in red, and the two parameters SD1 and SD2 are highlighted.

The central second moment of the cloud distribution is called SD_1^2 . The central second moment around the identity line of the plot is defined as

$$SD1_I^2 = \frac{1}{n} \sum_{i=1}^n D_i^2 \quad (1)$$

where D_i is the distance of each point of the cloud to the main diagonal [108]. From the formula (1), we can derive two parameters that provide additional information about the heart rhythm: SD_{1UP} represents decelerations and SD_{1DOWN} represents accelerations of the heart rate.

$$SD1_{UP}^2 = \sum_{i=1}^{n_U} (D_U^i)^2, \quad SD1_{DOWN}^2 = \sum_{i=1}^{n_D} (D_D^i)^2 \quad (2)$$

where D_U^i is the distance of the i^{th} point above the line of identity and D_D^i has the same meaning for the points below. Some kind of normalization of the above parameters might be helpful, because HRV is different between subjects. Then the following relative contributions to $SD1_I^2$ from accelerations and decelerations of heart rate are defined:

$$C_{UP} \equiv \frac{SD1_{UP}^2}{SD1_I^2} \text{ for decelerations} \quad (3)$$

$$C_{DOWN} \equiv \frac{SD1_{DOWN}^2}{SD1_i^2} \quad \text{for accelerations}$$

These parameters (expressed in percent values) can be compared from among subjects and used for data analysis, for example in bar plots, histograms, etc.

1.5. Exercise phase

The platform is currently used as integration to the traditional rehabilitation program. The system includes a set of additional exercises from where the therapist can choose the most useful.

These activities are presented to the patient as serious-games: they are digital games that have been developed exclusively for ReMoVES platform in collaboration with physiotherapists and physiatrists.

The system currently includes 10 different exercises that can be tweaked according to the patient requirement: level, duration, movement pattern, speed and other parameters can be set for a total of 60 game variations.

ShelfCans: This serious game introduces the patient to a virtual environment similar to a kitchen. With the arm movement, the patient grabs one of the colorful drink cans appearing in the middle of the screen and drags it to the corresponding shelf. This game is appealing because requires the user to be attentive to drop off the drink cans in the correct shelf according to its color (Figure 17a).

OwlNest: The patient is encouraged to reach on-screen target with the arm motion (Reaching Task) in order to collect high in-game score. Many colorful owls appear randomly in any position of the screen for a given time-frame: the user should carry them in the nest before they disappear (Figure 17b).

FlappyCloud: This is a functional exercise for lower limb. The leg Abduction-Adduction movement reflect the position of a cloud object in the game: the patient should make it move forward without hitting some obstacles (Figure 17c).

HotAir: This is an activity to improve control of the patient's body balance. The user can control the direction of a hot-air balloon, floating in the sky with the balance shift: in-game score is collected when it is leaded towards the bonus targets (Figure 17d).

EquilibriumPaint: This serious game is an interactive version of the Sit to Stand exercise, typically used in traditional rehabilitation to evaluate the patient performances. The user should stand up and sit down repeatedly to collect in-game score, while his/her trunk must remain erect: an erroneous lateral shift causes the fall of the cans of paint leaning on an unstable wooden beam (Figure 17e).

WineBottle: This exercise mimic a real world scenario: pouring liquids from a bottle. With the Pronation-Supination movement of the hand, the patient should control the rotation of a bottle of wine appearing on the screen. He must fill a glass over and over again to collect as many points as possible (Figure 17f).

EndlessZig: In this activity, the patient drives a marble along a zigzag path appearing on the screen. Going out of the boundaries causes score loss; similarly, some bonus gems appears on the path. The patient controls the marble movement with Radial-Ulnar deviation (Figure 17g).

CityCar: In this game, the patient drives a car along a road randomly generated. The user should steer in presence of curves and crossroads with the movement of Flexion/Extension of the wrist. The penalties are introduced when the user goes off track (Figure 17h).

FloatingTrap: In this serious game, the patient is leaded to open his hand and make a fist alternatively. This exercise requires a good level of concentration: in fact, the user moves a floating raft on the left or on right according to the finger Flexion/Extension in order to avoid some objects in the scene (Figure 17i).

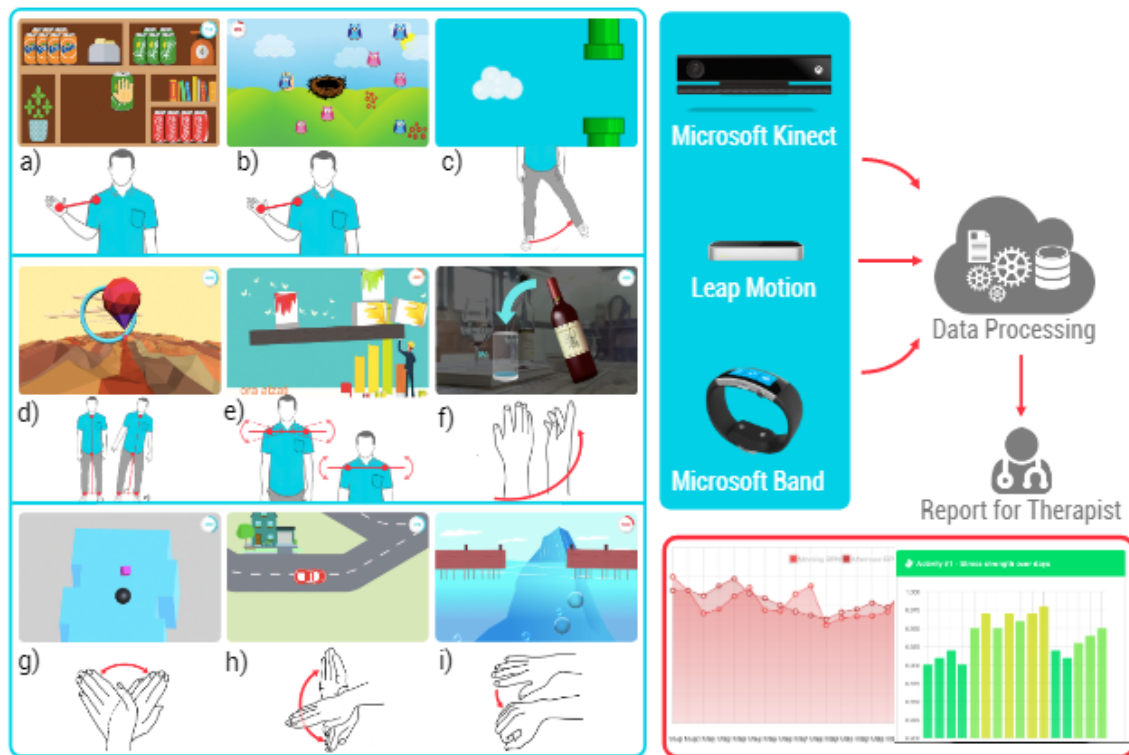


Figure 17: Summary of ReMoVES architecture and list of serious games and their corresponding movement: a) ShelfCans for arm Flexion-Extension and Abduction-Adduction b) OwlNest for Flexion-Extension and Abduction-Adduction c) Flappy Cloud for leg Abduction-Adduction d) HotAir for Balance Shift e) EquilibriumPaint for Sit to Stand f) WineBottle for hand Pronation Supination g) EndlessZig for hand Radial-Ulnar Deviation h) CityCar for Flexion-Extension i) FloatingTrap for Grasping.

Chapter 5: Preliminary study of Emotions during the Rehabilitation session

During daily rehabilitation therapy, it is very important to monitor the patient's emotional involvement in order to inform the therapist about the proper performance of the assigned plan of care. For this reason, Heart Rate (HR) and Electrodermal Activity (EDA) were recorded and analyzed to monitor major changes during different phases of a rehabilitation session. These data were compared with those from motion sensors, to monitor the progress of therapy and the patient's involvement in the rehabilitation session.

In this work, it is analyzed hoe window W , corresponding to each exercise duration, standard statistical parameters like mean, variance, maximum and minimum value and the Pearson correlation coefficient between HR and EDA were computed.

For the EDA signal, in order to obtain the phasic data by removing the tonic level of the signal, unrelated to arousal, a median filtering process was applied. For each sample, the median EDA value of the surrounding samples based on a ± 4 second time interval centered on the current sample was computed and the average from the current sample subtracted.

After obtaining the phasic data, a peak detection algorithm was applied in order to find skin conductance responses to external stimuli, that can influence patients during the execution of rehabilitation activity.

A value of $0.01\mu S$ was chosen as a significant threshold to discriminate skin conductance variations.

The same processing method was applied to the HR signal.

To evaluate the general pattern of the two signals, a trend analysis was computed and evaluated by applying the least-squares method. After applying it, the slopes of the straight lines, β_{HR} and β_{EDA} were calculated.

As explained above, HR and EDA are respectively indexes of valence and arousal.

Both signals were normalized between -1 and 1 as follows:

$$X = \{x_1, x_2, \dots, x_n\}, \quad n = |X|, \quad x_i \in \mathbb{R} \quad i = \{1, n\} \quad (1)$$

$$y_i = x_i - \frac{\max(X) + \min(X)}{2}, \quad i = \{1, n\} \quad (2)$$

$$y'_i = y_i \cdot 2, \quad i = \{1, n\} \quad Y = \{y'_1, y'_2, \dots, y'_n\} \quad (3)$$

$$X^n = \{x'_1, x'_2, \dots, x'_i\}, \quad x'_i \in [-1, 1], \quad i = \{1, n\} \quad (4)$$

Once normalized the two signals, the β variable and θ angle were used to define the emotional index (Ie) as follows:

$$HR_{norm} = \{hr_1, hr_2, \dots, hr_n\}, \quad n = |HR| = |EDA| \quad (5)$$

$$EDA_{norm} = \{eda_1, eda_2, \dots, eda_n\}, \quad \forall i = 1, \dots, n \quad (6)$$

$$\theta_i = \tan^{-1}(hr_i, eda_i) \quad (7)$$

$$IF \theta_i < 0 \Rightarrow \beta_i = |\theta_i| + \frac{\pi}{2}$$

$$IF \theta_i \leq \frac{\pi}{2} \Rightarrow \beta_i = \frac{\pi}{2} - \theta_i$$

$$IF \theta_i > \frac{\pi}{2} \Rightarrow \beta_i = \frac{5}{2}\pi - \theta_i$$

$$\forall i = 1, \dots, n \quad ie_i = 1 - \frac{\beta_i}{\pi} \quad (8)$$

$$Ie = \{ie_1, ie_2, \dots, ie_n\} \quad (9)$$

The emotional index was represented as a graphical parameter (Fig. 18) by evaluating how strong the emotion has been experienced in a given second in relation to all the emotions perceived throughout the whole rehabilitation activity.

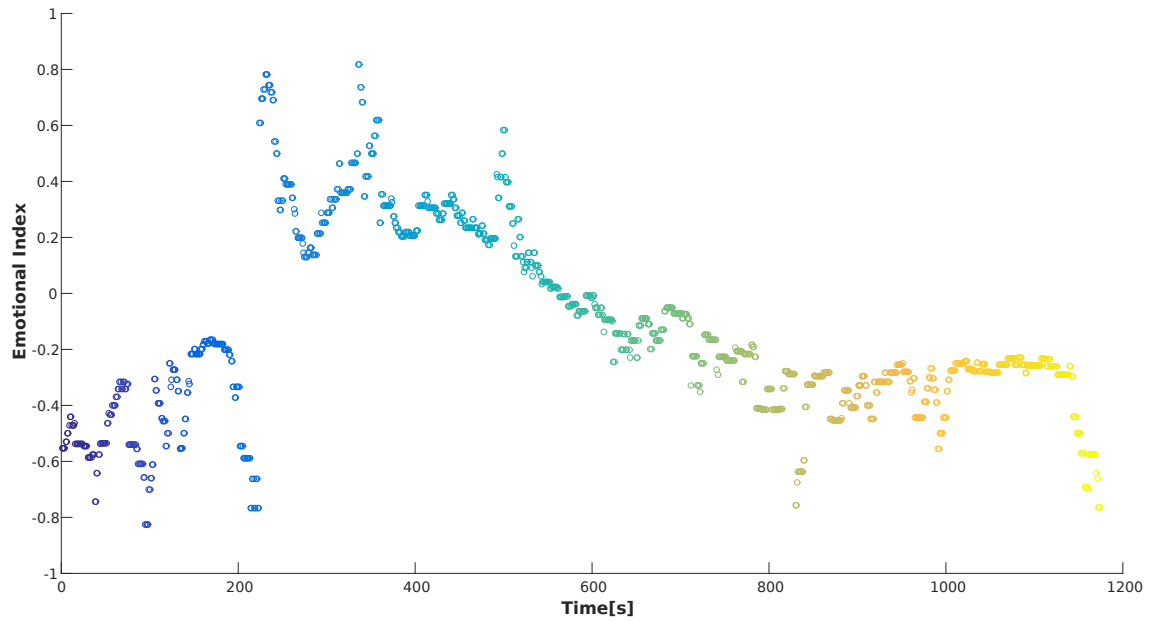


Figure 18: The emotional index graph: on the X axis the time and on Y axis the emotional index in terms of emotion experienced during the execution of rehabilitation exercise.

The two normalized signals HR_{norm} and EDA_{norm} were also represented in the Valence-Arousal circumplex chart. On the X axis the valence (HR variation) and on the Y axis the arousal (EDA variation) are represented (Fig. 19).

Emotions, in fact, can be mapped out classifying arousal (from high to low) and valence (from pleasure to displeasure) experienced during a particular task.

In the right part of the graph, positive emotions like for example happy, serene, calm and relaxed are represented. On the contrary, the left part contains negative emotions like sad, depressed, fatigued and tense.

The aim of this part of the study is to detect and classify the emotions felt by patient during the rehabilitation session, in order to personalized the plan of care and for example simplify an exercise if the patient, not achieving the goal, feels himself/herself fatigued.

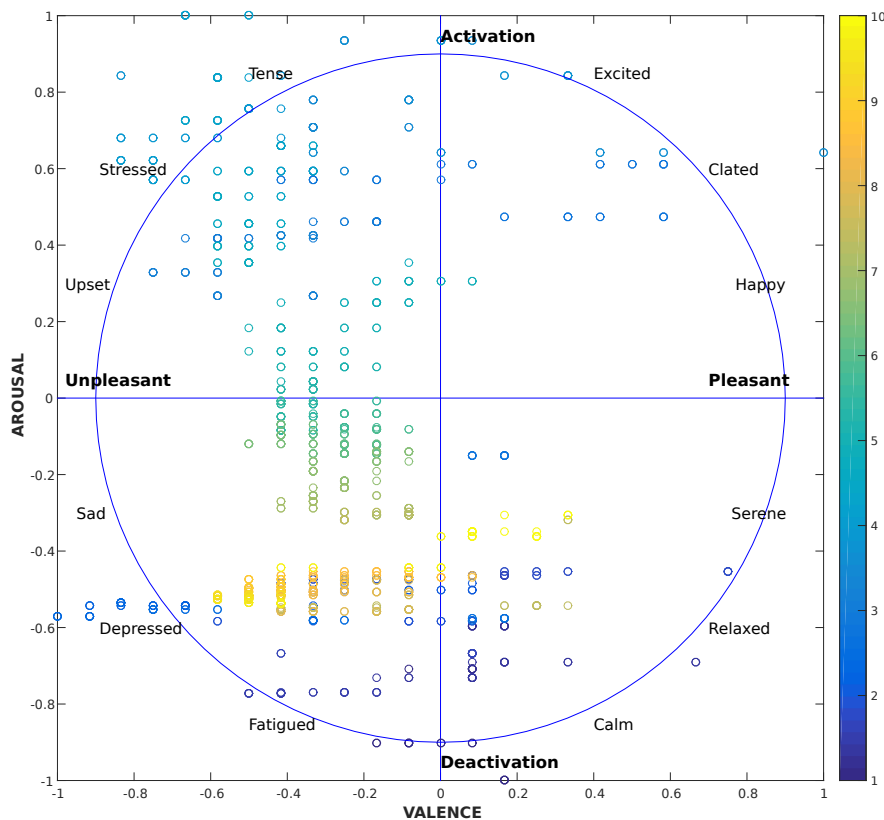


Figure 19: Valence-Arousal circumplex chart: on the X axis the valence and on Y axis the arousal of emotions. Data concentration in the left part of the graph, could mean that the type of exercise assigned by the therapist is too difficult.

For each second of the acquisition, a point that represents the emotion perceived is plotted. The dots are printed with a color that varies from dark blue to yellow in order to have a clear indication of the start and the end point of the recording, and therefore the trend over time.

A preliminary study on the emotions was performed with the aim of analyzing the responses of physiological heartbeat signals (HR) and galvanic skin response (GSR) during the administration of a known video sequence in augmented reality with a 3D visor, with a final feedback from the subject on the emotions experienced during each phase.

The results found are used for the real application to the rehabilitation field in which the emotions that are experienced by patients during exercise are not known and do not belong to a standard set for classification.

For this preliminary study, ten healthy participants (average age of 28 ± 5) were recruited. The participants sat on a comfortable chair wearing headphones and saw six types of video in a randomize order, wearing a 3D Virtual Reality device (3D Virtual Box); below, an example of trial:

- A- Relaxing Sea
- B- Underwater immersion
- C- Snakes
- D- Roller coaster
- E- Skyscraper climber
- F- Horror scenes

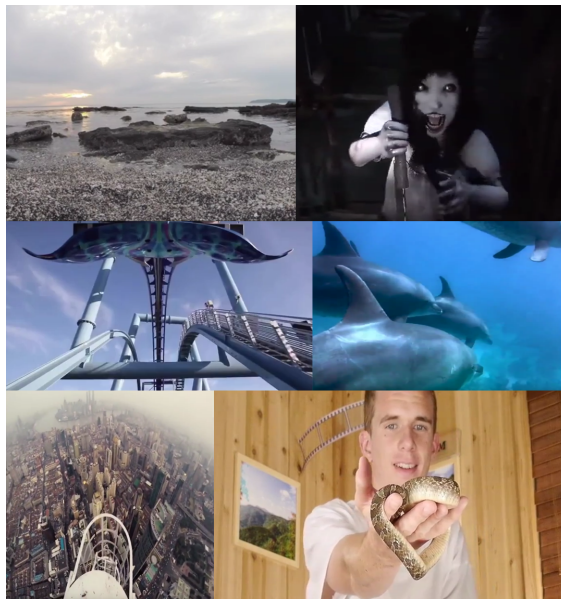


Figure 20: Screenshot of the six 3D video segments: relaxing sea (top left), horror scenes (top right), roller coaster (middle left), underwater immersion (middle right), skyscraper climber (bottom left), snakes (bottom right).

Contemporary to the videos, we recorded GSR and HR of the participants, collecting data on the minimal and maximal value of both, as well as their peaks. The goal of this part of the study was to investigate how the GSR and the HR signals could vary between different video inputs that cause different stresses.

At the end of the session, participants were asked to express their emotions, felt while watching the videos.

The use of the 3D visor allowed participants to be fully involved into living the scenes provided with our videos, evoking feelings as close as possible to the real ones, compared to the feelings evoked by simply watching a 2D video.

The session lasted for a total of 9 minutes and 30 seconds, where heart rate and galvanic skin response, with a sample rate for acquisition of 2 sample/second are acquired.

After the phasic component was taken out from the data, and after having isolated the different sequences by sampling the video, we analyzed the peaks of both signals. After calculating the first order statistical parameters, a Pearson correlation was applied to the entire data.

Below it can be found an example of the pre-analyzed signals, with the peak detection analysis.

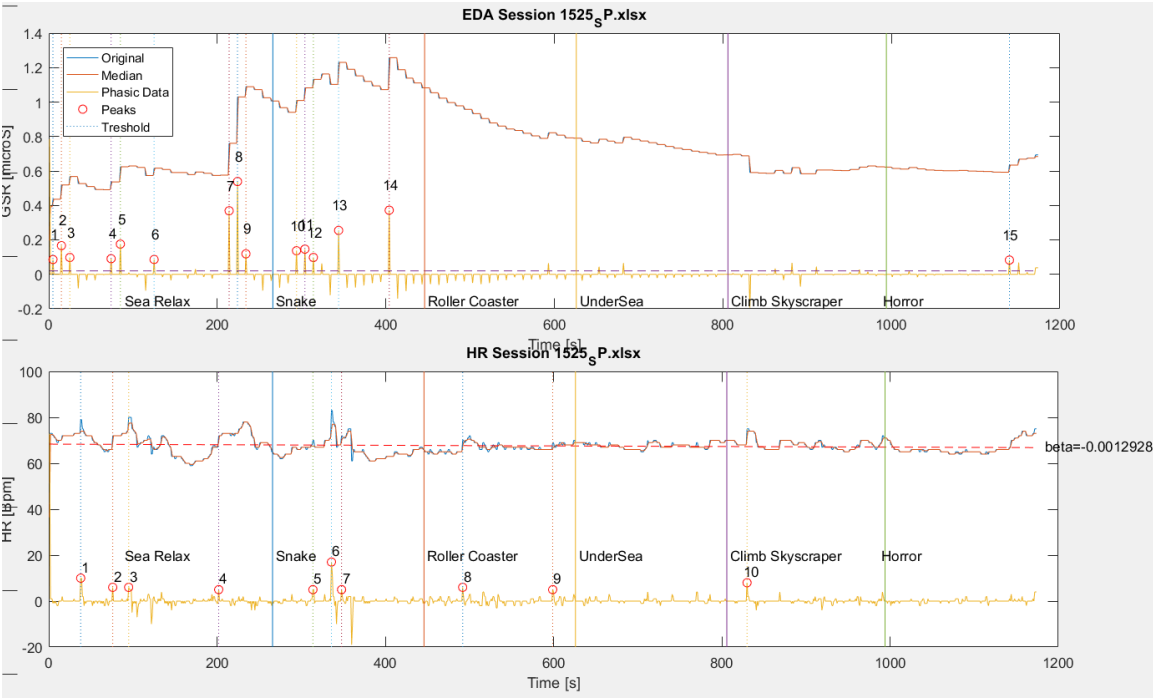


Figure 21: Example of GSR and HR signals during the 3D Sensation video.

RESULTS

Variations of the GSR and the HR are reported in the Table 1 and table 2 below. Pearson's correlation was not able to show any relation between the peaks of the two signals (see table III). Contrarily to what expected from previous literature studies [115-120], video A

(relaxing video) elicited the maximal amount of peaks for the GSR. The maximal amount of peaks for HR was recorded during video D.

In table 3, the Pearson coefficients computed on the number of peaks of the two signals analysed on the 6 different video segments, are reported.

The only video in which a significant correlation is recorded is the Snake one, with a Pearson value $r=0.79$.

Subject	GSR					HR						Pearson
	Mean	Std	Max	Min	Peaks	Mean	Std	Max	Min	Peaks	Beta	
6185	0,18	0	0,31	0,003	9	71	7,09	103	63	10	-0,007	-0,32
1525	0,76	0,2	1,26	0,39	15	68	3,41	83	59	10	-0,001	-0,13
1527	0,79	0,7	2,16	0,19	21	73	5,25	92	62	20	0,004	0,17
1536	0,22	0	0,27	0,14	7	70	13,52	136	60	19	-0,007	-0,07
1537	0,21	0,1	0,68	0,09	14	59	5,55	77	48	14	-0,006	-0,18
1538	2,04	0,4	2,83	1,07	29	79	10,36	109	64	11	0,02	0,49
1539	0,28	0	0,33	0,23	0	76	3,55	85	66	7	0,005	0,25
1535	0,51	0	0,74	0,43	12	68	4,48	82	58	16	0,004	0,45
1531	0,08	0	0,12	0,002	1	59	5,53	74	50	14	-0,0002	-0,11
1540	0,62	0,1	0,89	0,36	18	74	6,15	88	61	19	0,06	0,24

Table 1: Statistical parameter of first order for the two signals analysed.

Subject	GSR						HR					
	A	B	C	D	E	F	A	B	C	D	E	F
6185	1	1	1	5	2	0	4	2	2	1	1	0
1525	9	0	5	0	0	1	4	0	3	2	1	0
1527	0	6	0	1	9	5	5	4	1	4	3	3
1536	4	0	1	0	0	2	4	5	2	4	2	2
1537	2	1	3	0	2	6	3	2	2	3	2	2
1538	8	5	3	4	3	6	0	1	3	6	1	0
1539	1	0	0	0	0	0	2	0	1	5	1	3
1535	0	0	4	2	2	4	1	1	5	2	3	4
1531	1	0	0	0	3	0	2	0	1	2	0	2
1540	2	2	3	3	5	4	3	4	2	4	4	2

Table 2: Number of peacks detected in the different video segments.

PEARSON					
Relax	Snake	Roller Coaster	Under Water	Climber	Horror
-0,14	0,79	-0,02	0,34	0,50	0,15

Table 3: Pearson coefficients between the number of peaks detected in the different video segments.

DISCUSSION

Despite a large number of studies regarding GSR, a limited number of work has been published in the current literature taking in consideration GSR and HR [123], and even less when applying them together with 3D videos. For the first time, we can demonstrate that GSR vary under different stresses caused by different videos. This novel technique could surely be implemented, but might be an alternative to a previous device [124], without the need for the participants of focus. This will lead for a larger use, since it is also of interest for MR scans [125] in clinical trials [123]. The results found were consistent with what the participants felt during the experiment, supporting the existing knowledge regarding cognitive research [126].

Significant differences were shown when the subject reported a relaxed status. This is suggesting that both signals are characterized by variations large enough to overcome the minimum level of significance, when acquired during a session of virtual reality.

A particular situation was found for subjects 1538, where 8 GSR peaks were recorded, despite 0 HR peaks, or 1539, where no variation was recorded for GSR, while 12 HR peaks were recorded.

In conclusion, only three subjects out of ten showed large differences.

Despite its novelty, this specific part of the work is currently under structural development, but it is not unknown the need for new studies focusing on this particular branch [127], never forgetting about the application to clinical trials and therefore its practicality [128]. Therefore, we suggest that future studies should investigate the correlation between the two signals with a larger population, to confirm or disprove our theory.

Chapter 6: Results

1. Relaxation phase

From the non-linear analysis conducted through the study of the parameters extracted from Poincaré plot it was possible to compare and evaluate the contributions of accelerations and decelerations C_{DOWN} and C_{UP} for all considered subjects. The results are shown in the next figures. In particular, in Figure 22, the two parameters extracted for both methods are presented, and in Figure 23, to clarify the gap between the two methods studied, the difference of the percentage between C_{UP} and C_{DOWN} is shown.

By analyzing the values obtained with the landscape video, one can notice how subject N.2 is the only one with a value of C_{UP} greater than C_{DOWN} . The maximum value reached by C_{UP} is 53% and that by C_{DOWN} is 72%. In Figure 23, subject N.3 shows a great gap between C_{UP} and C_{DOWN} during the relaxing video, whereas, for the other method the subject with the highest value of gap is N.5.

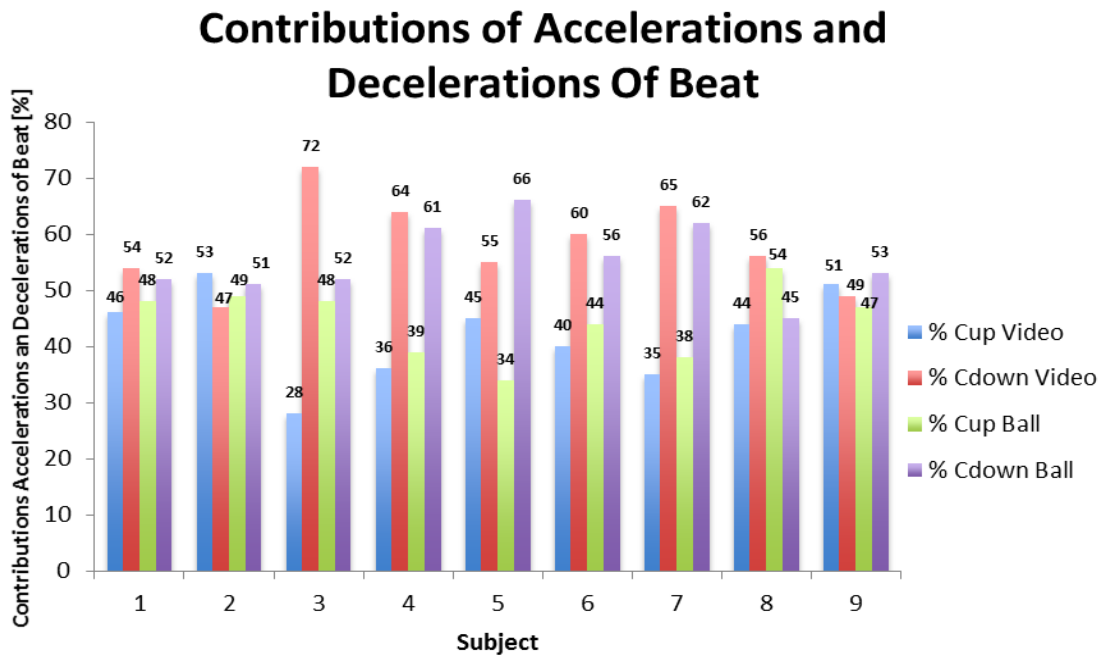


Figure 22: The bar plot represents the percentage of the accelerations and decelerations of heart beat during relaxation phases for the landscapes video (red and blue) and for the breath ball method (purple and green).

For the breath ball method, the only subject with a value of C_{UP} greater than C_{DOWN} is N.8. From Figure 22 and Table 1 the maximum value reached by C_{UP} is 54% and that by C_{DOWN} is 66%.

From the analysis in the time domain, mean values were compared between the two methods, but as it can be seen in the bar plot in Figure 24 in the majority of subjects there are no significant differences and neither method prevails over the other. Only in subject N.4 and N.8 there is a slightly more significant gap between the two mean values.

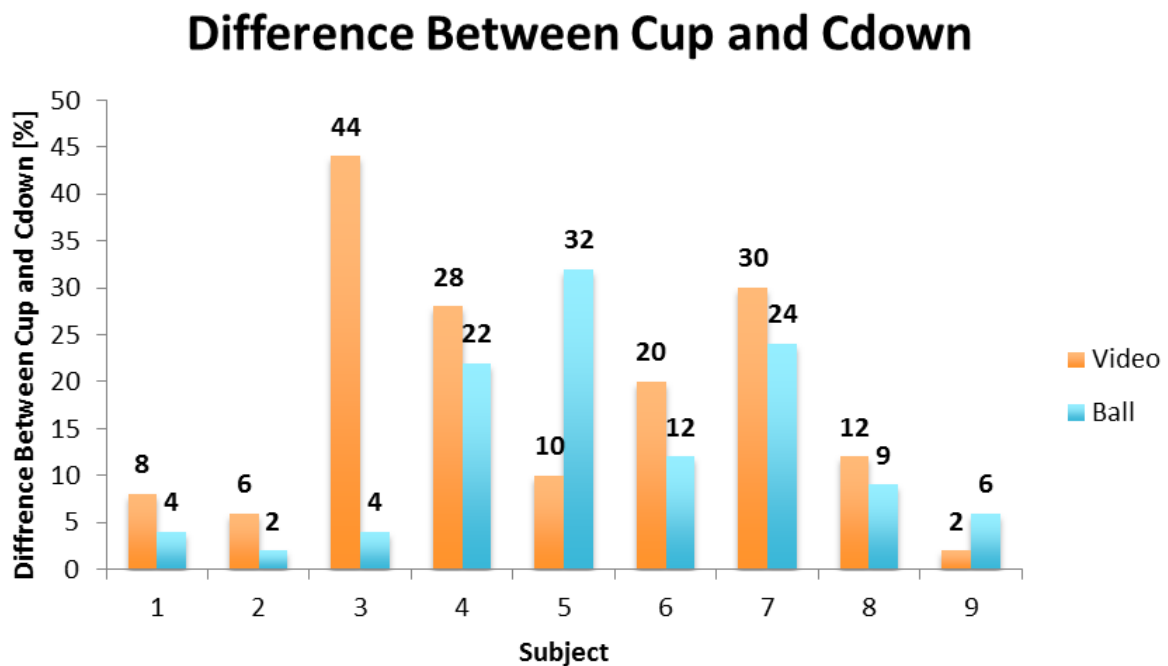


Figure 23: The bar plot represents the difference of the percentage between the two parameters C_{UP} and C_{DOWN} during the video (orange bar) and during the breath ball method (light blue bar).

TABLE I. RELAXING VIDEO

	Parameters				
<i>Subject</i>	<i>Mean</i>	<i>SD₁</i>	<i>SD₂</i>	<i>C_{UP}</i>	<i>CD_{OWN}</i>
1	75	98,09	254,76	46%	54%
2	77	27,13	76,69	53%	47%
3	71	81,56	160,43	28%	72%
4	77	31,41	79,316	36%	64%
5	76	118,11	310,62	45%	55%
6	65	53,94	123,65	40%	60%

7	73	167,49	256,83	35%	65%
8	64	131,38	326,62	44%	56%
9	65	28.61	606.32	51%	49%

TABLE II. BREATH BALL

	Parameters				
<i>Subject</i>	<i>Mean</i>	<i>SD₁</i>	<i>SD₂</i>	<i>C_{UP}</i>	<i>C_{DOWN}</i>
1	75	81,13	166,18	48%	52%
2	70	35,64	75,73	49%	51%
3	70	56,24	100,01	48%	52%
4	89	44,56	109,09	39%	61%
5	74	44,99	84,24	34%	66%
6	65	60,77	104,39	44%	56%
7	68	124,44	192,75	38%	62%
8	74	85,08	229,72	54%	45%
9	66	26.62	581.128	47%	53%

After the relaxation session, each subject was asked to indicate the most relaxing method and it emerged that the natural landscapes video is felt to be the best one, only two persons said that both methods are indifferently relaxing.

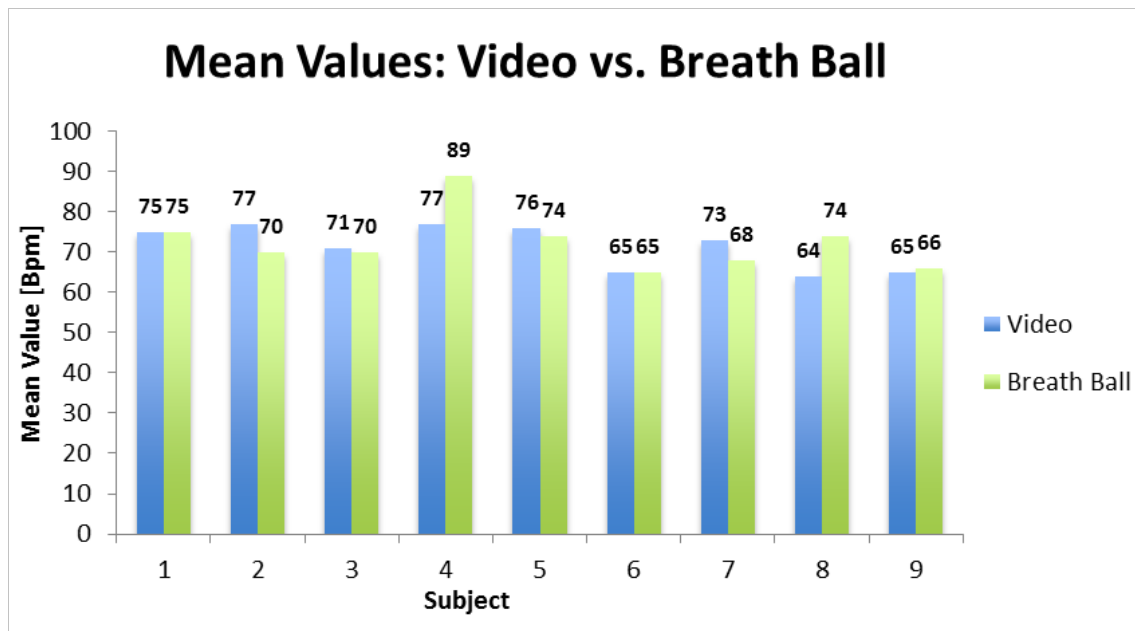


Figure 24: Histogram of the comparison between mean values of the heartbeat for Breath ball method and Video.

Discussion

As already proved in previous works, also in the present case it seems that heart-rate variability is more significant than the absolute rate value in representing a good descriptor for human feeling and physiological monitoring.

The parameters extracted from Poincarè plot prove that most of the subjects experienced a smaller variability gap between contributions of accelerations and decelerations of the heartbeat when watching at the Breath-Ball than at the landscape video.

As a conclusion, even though the subject opinion chooses the video with natural landscapes as the preferred method, the quantitative analysis tends to prove that the breath ball method is a better way to regularize the frequency of heart rate and relax the subject. To minimize the impact of rehabilitation technology, it will be important to establish if it is more important the psychological aspect or the physiological condition of the subject.

The methods used for the heartbeat analysis will also be extended to analyze the Galvanic Skin Response (GSR), that is an important signal during the rehabilitation phase to evaluate stress and fatigue. This should also be helpful to understand the engagement and the overall condition of the subject when facing the technology.

In addition, it will be interesting to undertake an analysis of the correlation between the different sensors used and the signals derived from them. Within a session of rehabilitation, or simple monitoring, it may be very interesting to analyze simultaneously the heartbeat and the galvanic response, in such a way that the occurrence of a particular event in heart may be more or less related to a change in the galvanic response.

A secondary study on a population of patients with motor disabilities is under development, to understand how their impairments affect the relationship with rehabilitation technologies. In conclusion, this new method has given satisfactory results both as regards the subjective opinion of the user and for the acquisition of the signal. Finally, “landscapes video” might be a good way to break down the barrier between user and technology within a rehabilitation session that allows a subject with hemiparesis to return to everyday life.

The results of the study were confirmed by medical staff who defined Breath Ball as the best method for the preliminary phase of the rehabilitation session.

So, following the results found, this method of relaxation has been tested at the Complex Recovery and Rehabilitation Facility of the Colletta Hospital (Asl3, Genoa - Italy) and at Fondazione Don Gnocchi of Fivizzano (Massa - Italy) in order to test it on 20 users. Each patient involved in the study had an average of 10 rehabilitation sessions completed within a two-week period.

No specific inclusion criteria were used since the recruitment process was conducted by physiotherapists involved in this study, who, knowing the patients undergoing treatment, were able to identify those eligible for participation in the study.

The breathing exercise was tested through 56 sessions by the population described in Table I.

During the 30 seconds in which this exercise is executed, the Heart Beat (HR) and the Galvanic Skin Response (GSR) are acquired. The trend analysis is performed and the angular coefficient β_{bpm} of the straight line that best approximate the heart beat is computed together with the mean values of the two signals, in order to understand the general pattern.

The patient can be considered ready for the execution of physical rehabilitation if β bpm is equal or lower than zero. In fact, a positive coefficient means a state of fatigue and excitement, not suitable for the aim of the rehabilitation process.

In order to understand the correlation between HR and GSR signals, the Pearson coefficient r is computed, in fact, this is the most widely used correlation statistic to measure the degree of the relationship between linearly related variables.

The following formula is used to calculate the Pearson r correlation:

$$r = \frac{N \sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \sum (y - \bar{y})^2}}$$

As it can be seen in Table II, the mean of the angular β bpm coefficients on the total sessions is negative: more precisely, it can be seen that for men the β bpm is around zero and for women is negative. In both cases, the goal of being relaxed with the breathing exercise was achieved.

<u>Gender</u>	<u>Age</u>
Male	MEAN=69; SD=13.7
Female	MEAN=65; SD=11.5

Table I: Population features

<u>Gender</u>	<u>Mean βbpm</u>
Male	$\beta = 0.0070$
Female	$\beta = -0.0414$
General	$\beta = -0.0164$

Table II: β bpm subdivided by gender

From the results obtained in the breathing exercise, it can be concluded that the negative trend of the regression line that approximates the heartbeat signal is an index of relaxation, principal goal for which the exercise was designed. In fact, it is very important that the patient is in a comfortable and relaxed status to perform in the best way the actual physical exercises.

In the Table below the results of the Pearson Correlation coefficient are reported. As confirmed from the two graphs, shown in Figure 25 and Figure26, the two variables are positive correlated with a Pearson value of $r=0.91$ for men and $r=0.62$ for women. The Pearson value for the whole population studied is $r=0.86$.

POPULATION	AGE	PEARSON COEFFICIENT	
WOMEN	Mean= 69; SD=13.7	TOTAL	$r=0.86$
MEN	Mean= 65; SD=11.5	WOMEN	$r=0.62$
		MEN	$r=0.91$

This high correlation probably means that the two variables give the same information about the patient status during the relaxing phase with the breathing ball exercise, and together don't give more information that each one considered individually.

Finally, it can be concluded that since the galvanic skin response is a signal difficult to acquire because it is influenced by many environmental variables, between the two signals, the heartbeat is best suited to be applied in the rehabilitation field. In fact, it is easier to acquire and more reliable in the results obtained.

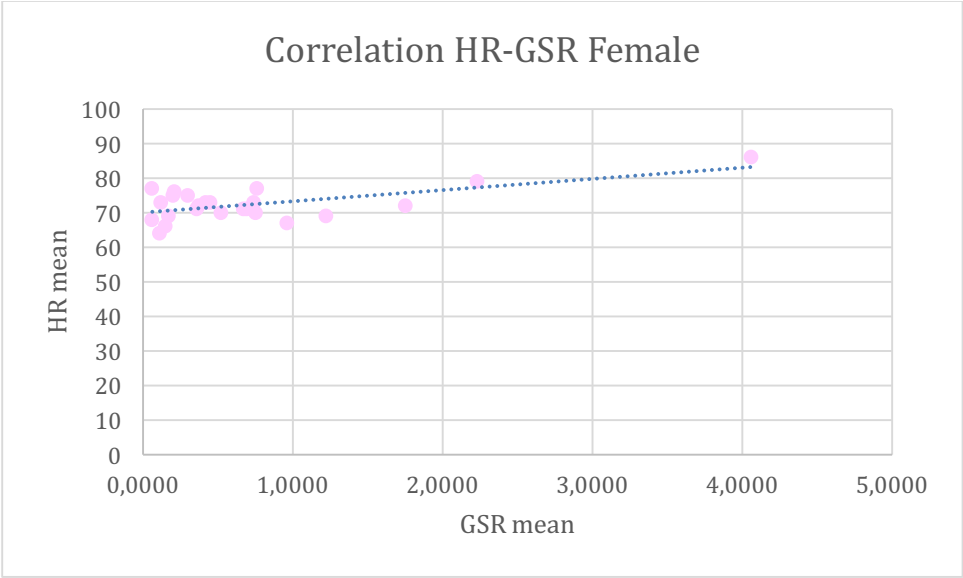


Figure 2510: Graphical correlation between GSR mean and HR mean in women population.

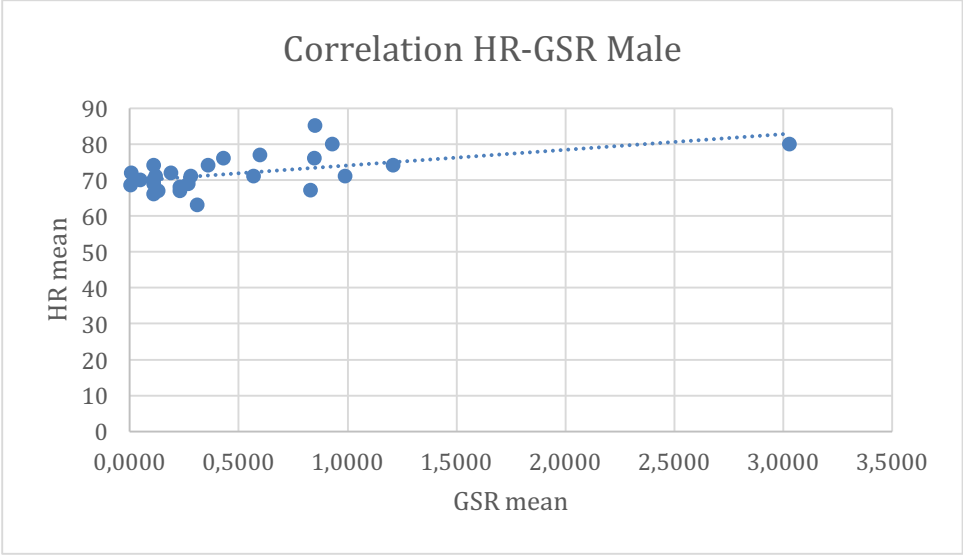


Figure 26: Graphical correlation between GSR mean and HR mean in men population.

2. Remote Biofeedback Method

Results

The remote biofeedback method has been tested for more than 700 sessions on more than 50 users with different pathologies.

The objective of this research project is not to validate the rehabilitation effectiveness of the exercises, but to understand if the indicators proposed by the biofeedback method are applicable to all the cases that are analyzed and if above all they are consistent with the actual execution of the rehabilitation session, which was given direct feedback from the therapists.

This chapter is mainly divided into two macro parts, the first which shows the results related to the heartbeat, at the time between two consecutive exercises and the score. These three parameters are put in relation to each other giving a maximum picture on the patient's involvement and on performance by providing qualitative information, without giving any details on how the exercises were performed.

The second part focuses on the analysis of the movement accompanied by the score collected. In this part, the real rehabilitation results are then illustrated, giving quantitative values on the session performed.

2.1. Heartbeat, Inter-Exercise Time and Score

The parameters chosen for the evaluation of the involvement during the rehabilitation therapy and the method of analysis were score, heart rate and inter-exercise time together with verbal feedback provided by patients at the end of the last session.

The evaluation of the score's trend during the 12 sessions showed that there was a general improvement in all patients. In particular, the score charts displayed a constant trend during the first six sessions, whereas an increase in the curve slopes was observed during the final

six sessions, which was indicative of an effective improvement. There was also a consistency between the comments of the physiotherapists and the results obtained from the data analysis. The total game score curves for patients 193 and 198 are shown in Figure 27 and Figure 28.

As shown in Figure 27, both patients showed improved performances in the latter sessions compared to the initial sessions.

The improvement range of patient 198 was limited compared with that of patient 193; this could have been due to the shoulder pain that affected the first patient, as stated by the physiotherapist's report: *“Generally tired but motivated. Pain at the shoulder sometimes affected session.”*

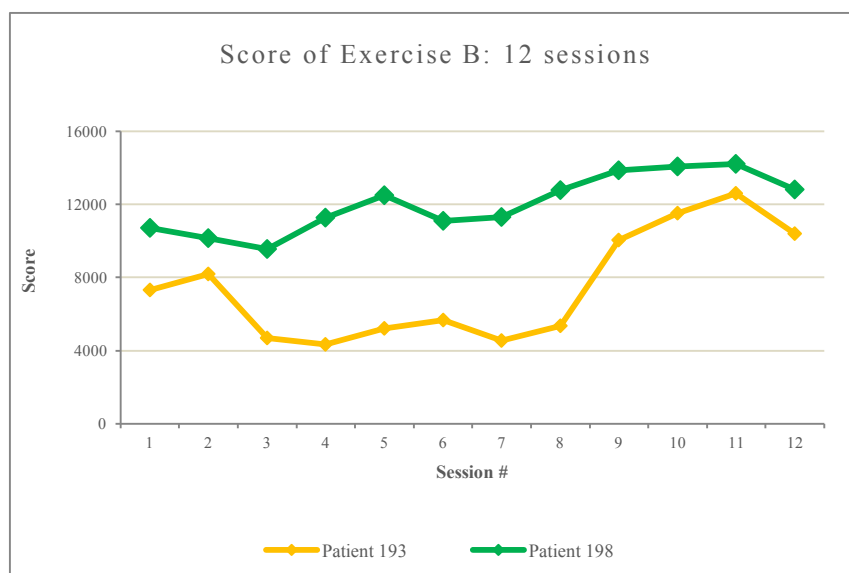


Figure 27: Total game score curves for patients 193 and 198.

At the same time, the limited range of improvement in the score of patient 198 compared to that of patient 193 may have been because the score collected in the first session for patient 198 is almost equivalent to that collected from the last session for patient 193.

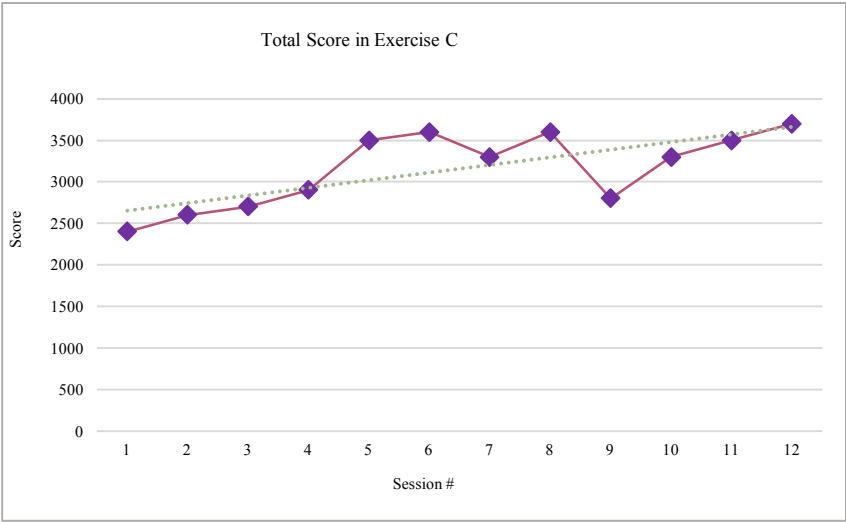


Figure 28: Example of score trend during the whole rehabilitation program, including the regression line.

Hence, it is easier to reach a higher target when starting from a lower score.

The average heartbeat during each exercise was calculated and compared with values calculated during all sessions.

To evaluate the overall performance at the end of therapy, the angular coefficient of the least-squares straight line, which best approximates the trends for the unknown samples, was calculated as explained in section III-C. An example of the score is shown in Figure 28.

The overall evaluation of the patients' behaviours doesn't show a state of stress and excessive fatigue in the execution of the plan of care.

As shown in Figure 29, only two patients experienced stress related to the rehabilitation therapy. Overall, patient 187 exhibited an increase in heartbeat during all of the exercises.

ID	A	B	C	D	
186	↑	↑	↑	↓	
187	↓	↓	↓	×	
191	↑	↑	↑	↑	
193	↑	↑	↑	↑	
194	↑	×	↑	×	
198	↓	↑	↑	↑	
199	↑	↓	↓	↓	↓ Stressed
205	↑	↑	↑	↑	↑ Relaxed/Motivated
206	↑	×	↑	×	×
					Not recorded

Figure 29: Summary of heartbeat indicator

Patient 199 displayed a similar trend in heartbeat as patient 187; however, an associated worsening of the score was not observed. The trend may be explained by the patient's state of mind, which was reported as “*bored during the execution of the exercises to the point of performing the exercise in the worst way*”.

Although patient 198 faced three exercises out of four with great motivation, during the execution of exercise A, the patient exhibited a pulse with a growing trend. This may be explained by the fatigue caused by persistent arm pain when performing certain movements, such as the anterior and lateral flexion of the arm, which were necessary for the execution of this type of exercise.

As it can be seen from therapist’s comments in Table 1 and Figure 30, the KPI Ψ , is also indicator of fatigue or pain.

TABLE I INTER-EXERCISE TIME PARAMETERS	
Patient ID	Comments
186	A little bit stressed due to difficulties playing games.
191	Generally plaintive.
193	Very engaged in playing games, motivated.
199	Generally tired but motivated. Pain at the shoulder sometimes affected sessions.

Table 1: Example of Therapist’s comments about

In fact, for both subjects 186 and 199 it can be seen a growing trend, particularly marked in patient 199 who has also an absolute value higher than 186. Patients 191 and 193, motivated during the execution of rehabilitation sessions show a decreasing trend with low absolute values of Ψ . It is important to take into account that in most of the sessions, the exercise A is performed first, and then the patient is in a resting condition with respect to the following exercises.

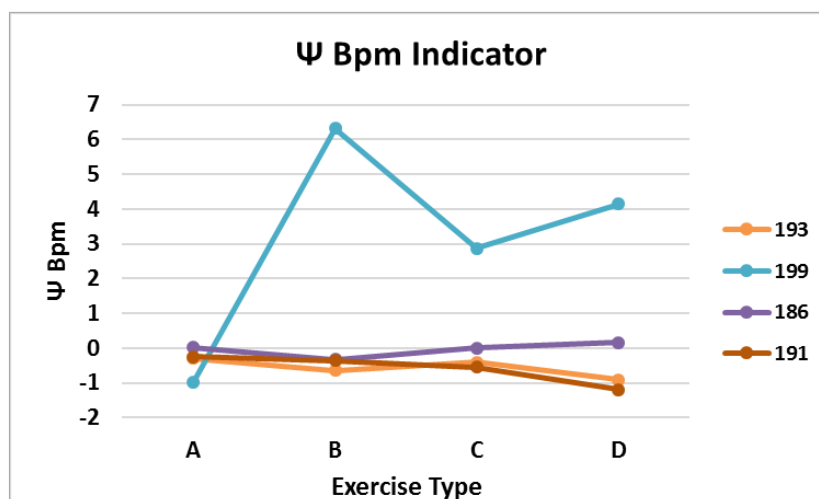


Figure 30: Example of heartbeat mean and total score representation for a single patient during the 12 rehabilitation sessions. X-axes: session number; Y-axes: score and heartbeat.

The inter-exercise time is important in order to determine whether a patient is too tired while performing an exercise and thus needs to rest before performing the next exercise.

The results showed that in a regular session, a healthy subject spends approximately fifteen seconds between the end of one exercise and the beginning of the next.

Thus, the normal range for an unhealthy subject can be estimated to be between 20 and 30 seconds, if certain parameters, such as the slowness and the difficulty of movement, are taken into account.

The standard deviation, maximum and minimum were calculated from each average inter-exercise time.

As shown in Table 2, patient 187 showed the maximum inter-exercise time, which is a symptom of exertion and fatigue during therapy.

TABLE II
INTER-EXERCISE TIME PARAMETERS

Patient ID	Mean	Standard Deviation	Min	Max
186	00:01:35	00:00:33	00:00:51	00:03:56
187	00:01:28	00:01:13	00:00:42	00:08:04
191	00:01:20	00:00:45	00:00:28	00:05:48
193	00:01:16	00:00:34	00:00:33	00:03:11
194	00:01:30	00:00:40	00:00:29	00:03:25
198	00:00:42	00:00:11	00:00:17	00:01:11
199	00:01:19	00:00:49	00:00:34	00:05:17
205	00:00:41	00:00:10	00:00:19	00:01:03
206	00:00:41	00:00:11	00:00:32	00:01:37

Table 2: Inter-exercise time parameters

The subject who showed the minimum inter-exercise times also presented one of the maximum values recorded. This result is confirmed by the exercise performance, which shows a decline in the performance of the first two exercises, A and B.

In descriptive statistics, a box plot is a convenient way of graphically depicting groups of numerical data using their quartiles. Box plots may also have lines (i.e., whiskers) extending vertically from the boxes, indicating variability outside the upper and lower quartiles.

The bottom and top of a box and whisker plot always represent the first and third quartiles, and the band inside the box always represents the second quartile (i.e., the median).

The ends of the whiskers represent the minimum and maximum of all the data. As shown in Figure 31a, the parameters necessary for the development of the box plot were computed.

The two patients who did not improve their performance in the score and heartbeat analyses in this investigation presented the two largest error bars, which indicates the overall poor performance of their rehabilitation therapy.

Patient 194 exhibited the most widely dispersed data, despite his/her overall good performance. A similar behaviour was observed in patient 191. These results show that the maximum value recorded is the discriminating parameter extracted from the inter-exercise time. Patient 198 exhibited a very good distribution of inter-exercise time, with very small error bars and a very concentrated distribution.

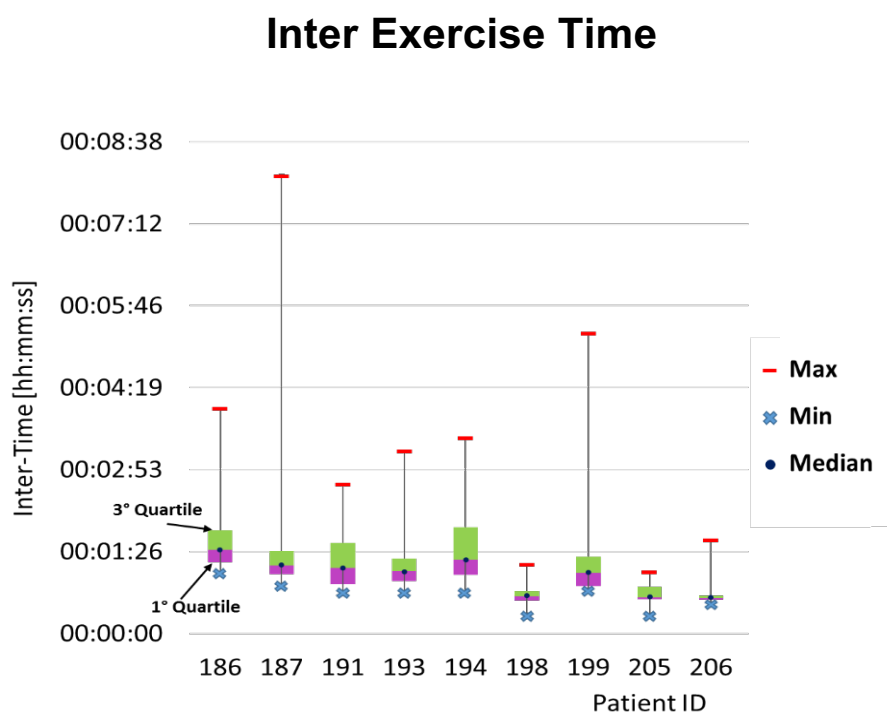


Figure 31a: Box Plot of the inter-exercise times of all patients. The x-axis shows the patient's ID, while the y-axis shows the inter-exercise time expressed in hh:mm:ss.

The 12 sessions carried out by the patients were divided into two groups, each composed of six sessions, to evaluate whether the efficacy of the therapy would also be affected by the length of breaks and the execution flow of the exercise sessions.

The average inter-exercise times of the first and last six sessions were then calculated to evaluate the average improvement of the subjects. Considering all the patients analyzed, as

shown in Figure 31b, only two did not improve in inter-operating time, even when the maximum recorded worsening was 4 seconds.

Thus, from the analysis of these parameters, we can infer that the performance of each exercise and the fluidity within the rehabilitation sessions are generally improving from session to session.

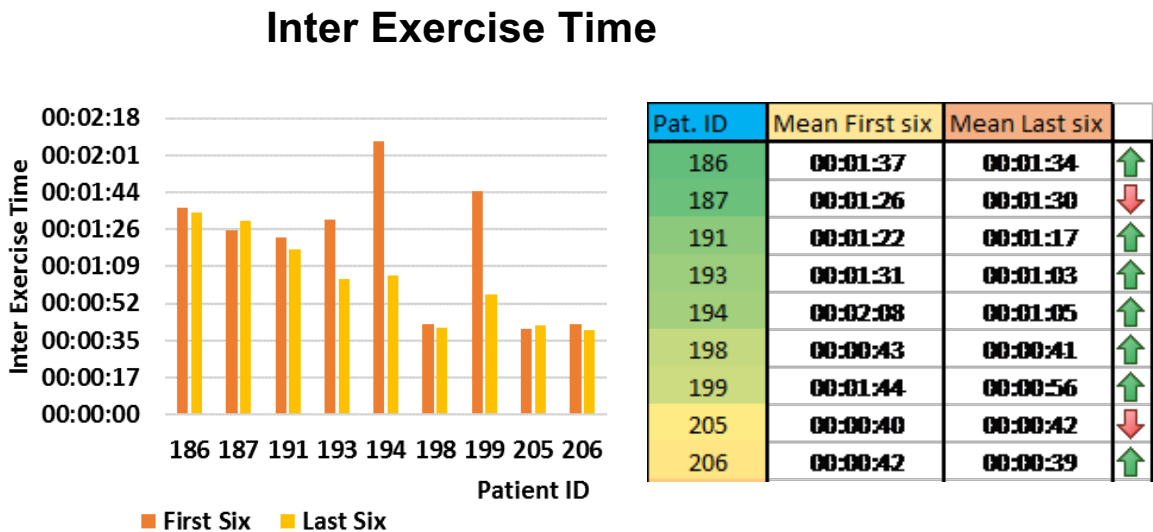


Figure 31b: On the left: Bar plot of mean inter-exercise time. Each patient's ID is shown on the x-axis, while the y-axis shows inter-exercise time expressed in hh:mm:ss. On the right: sessions subdivided into two groups with improvement assessment.

2.2. Correlation between heartbeat and exercise

With the linear regression model, we were able to obtain a clear and general summary regarding the session trend for each patient.

Figure 32 shows two examples of the linear regression computation for the score and heartbeat of patient 193.

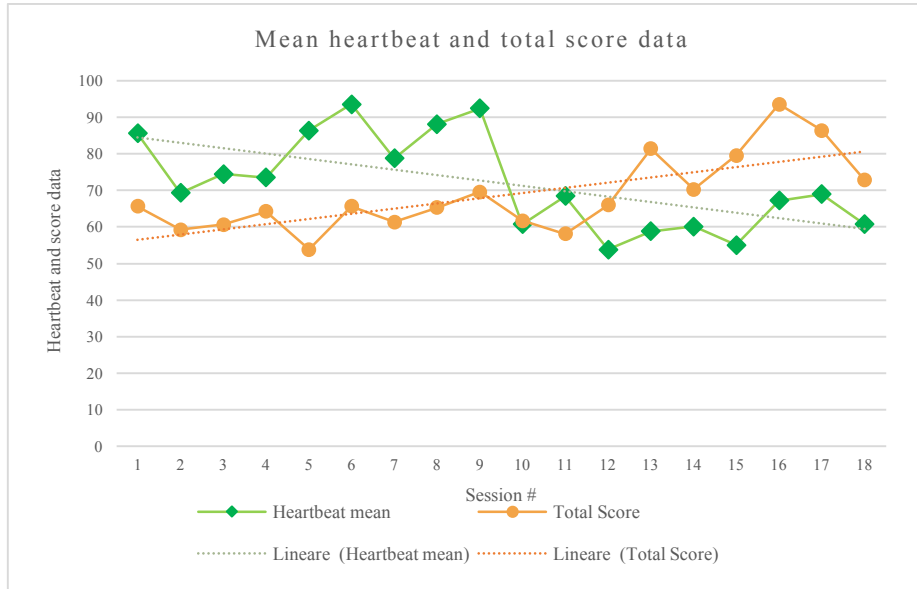


Figure 32: Example of heartbeat mean and total score representation for a single patient during the 12 rehabilitation sessions. X-axes: session number; Y-axes: score and heartbeat.

From the score and heartbeat data acquired during rehabilitation exercises, a preliminary analysis of the correlation between the normalized angular coefficients of the regression lines of the two signals was carried out. The data are represented as coordinates of a scatterplot in Figure 33.

A cluster can be observed in the second quadrant, where most of the points are located. The patients represented within the first quadrant had positive scores during the rehabilitation sessions, but they encountered difficulties, such as fatigue, stress and pain. The third and fourth quadrants show subjects who reported no improvement in rehabilitation performance regardless of the heartbeat pattern.

Within the ellipse are patients who improved with the right balance of progress, in terms of the score collected, with the physiological and psychological behaviours.

However, there are also several points scattered outside of the second quadrant, including the point for patient 199. As previously discussed, this patient exhibited improved performance during exercise C and exercise D, but, nevertheless, the patient's heartbeat continued to increase, indicating a state of fatigue and stress that was likely associated with shoulder pain. There is a consistency between the physiotherapists' report about the patients and the signals that were analysed.

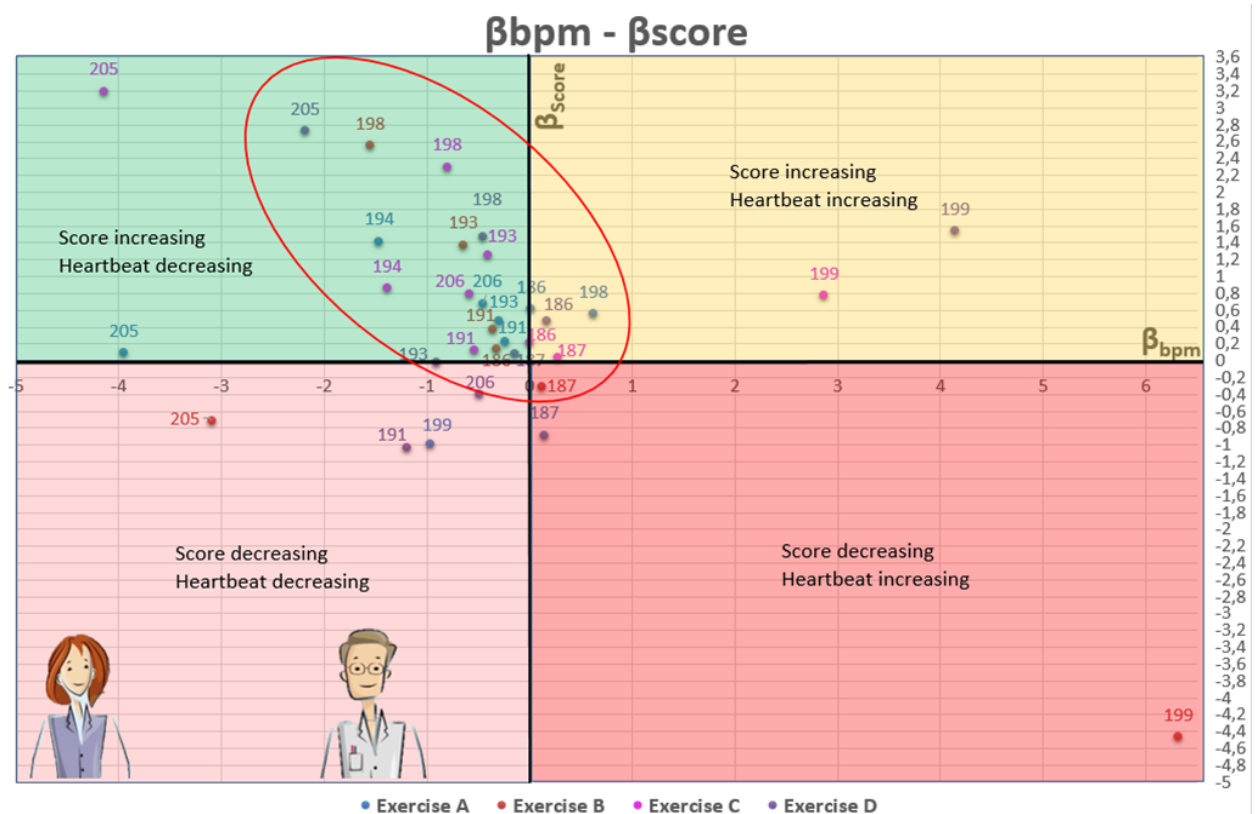


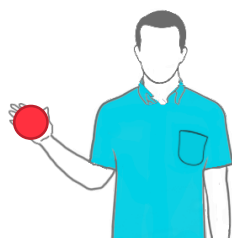
Figure 33: Scatter plot of the trend parameters of score and heartbeat during the execution of the four rehabilitative exercises. X-axis: slope of the straight line that minimizes the sum of the squared deviations of the linear regression model for the mean heartbeat. Most of the patients are concentrated in the second quadrant, which reflects the ideal situation for the best outcome in the rehabilitation program. Y-axis: slope of the total score collected for each session.

2.3. Motion

Significant examples will be shown below describing various types of implementation of the proposed exercises. The parameters extracted from the model will be reported for all the exercises, which, for this phase of study, has been obtained from the execution of the exercises by several healthy subjects. To ensure that the comparison is as realistic as possible, the next step will be creating a model from the execution of the exercises by patients, classified by pathology, who have reached the goal of the rehabilitation process: performing the exercises in the correct way.

The results of the movement indicators will be structured following the indicators shown in the method, three tables will be reported for each category, containing respectively the parameters extracted for the model, those for the patients and finally a patient-model comparison report with final indicators.

Spatial Map



As far as the analysis of the movements of the upper limb is concerned, as illustrated above, the heat map has been proposed, together with various indicators that integrate the visual information provided by the graphic instrument.

The following table shows the average values obtained from the healthy model.

Model				
Session	Score	Max Height	N movements dx	N movements sx
n	5160	63,25	30 -> 55%	25 -> 45%

The following table shows three examples of significant patients:

- The first patient examined is neglected. He/she ignores the left side of the space despite having good mobility of the upper limb, reaching all targets on the right side of the space.
- The second patient is affected from hemiplegia on the left side of the body which prevents him from reaching targets in the upper part of the space.
- The third patient is suffering from hemiplegia, following a stroke, the mobility of the right side of the body is reduced, preventing him from reaching the targets present in the upper part of the space.

As the values in the table below show, the patient with neglect did not collect a very high score, as he only reached the targets present in the right part of the space, ignoring those on the left. As indicated by the maximum height reached, the patient still has a good range of motion that allows him to reach all the targets proposed by the exercise.

The two hemiplegic patients differ mainly in the maximum height reached that for the patient number three is very small despite the range of movement on the right and left is fairly balanced.

The second patient, on the other hand, has difficulty in reaching the proposed targets in the right hem.

Patient				
Session	Score	Max Height	N movements right	N movements left
Neglect (Left)	700	61,35	66	3
Hemiplegic left	2730	32,04	14	26
Hemiplegic right	3650	11,52	32	22

The following table shows the final indicators extracted from the data in the previous tables that summarize the comments shown until now.

Report				
Session	Score	Max Height (Θ_1)	Target Right (Θ_{dx})	Target Left (Θ_{sx})
Neglect (Left)	14%	97%	96%	4%
Hemiplegic	53%	51%	35%	65%
Hemiplegic	71%	18%	59%	41%

The following chart shows the mapping of the movements extracted from the model, as can be seen the distribution of the points is homogeneous, the central part with more points concentration represents the area where the patient drags all the targets after having reached them in the various parts of the space.

The following images (Figure 34) represent the graphical output of the spatial map proposed for the therapist. This graph is the movement representation of the patient affected by neglect described in the previous tables. This tool gives a direct feedback on the spatial movements distribution, especially in cases like this reported, where a part of the space is totally ignored.

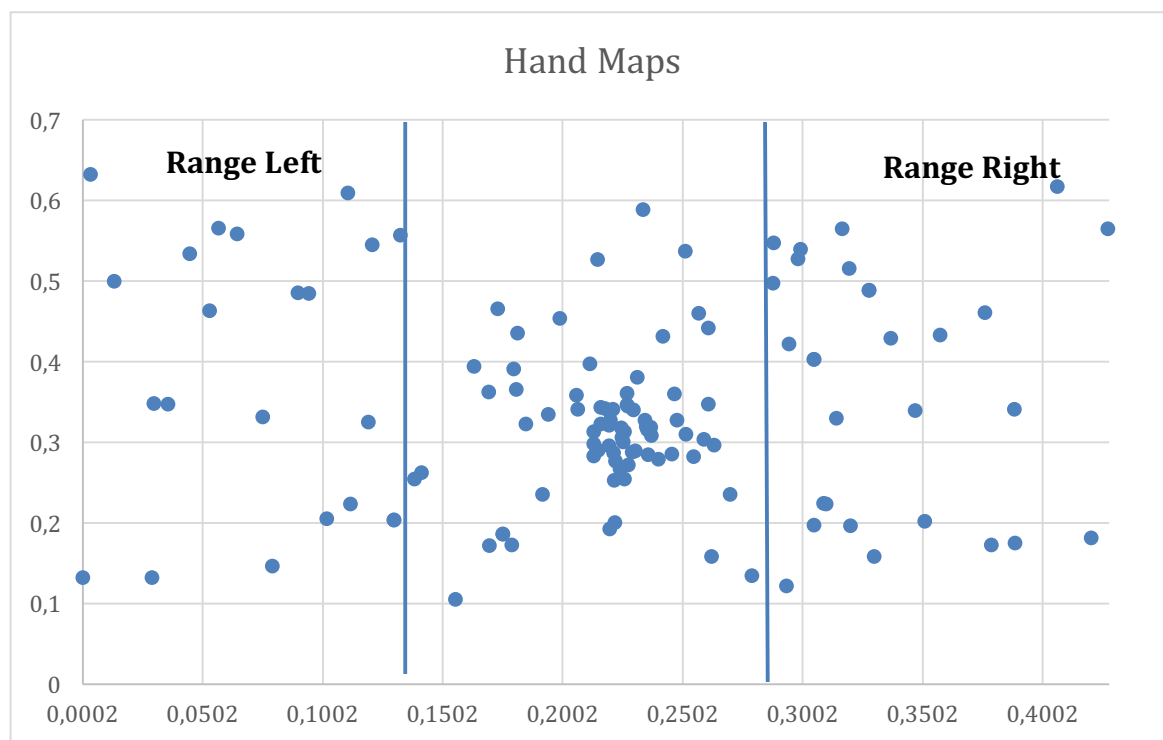
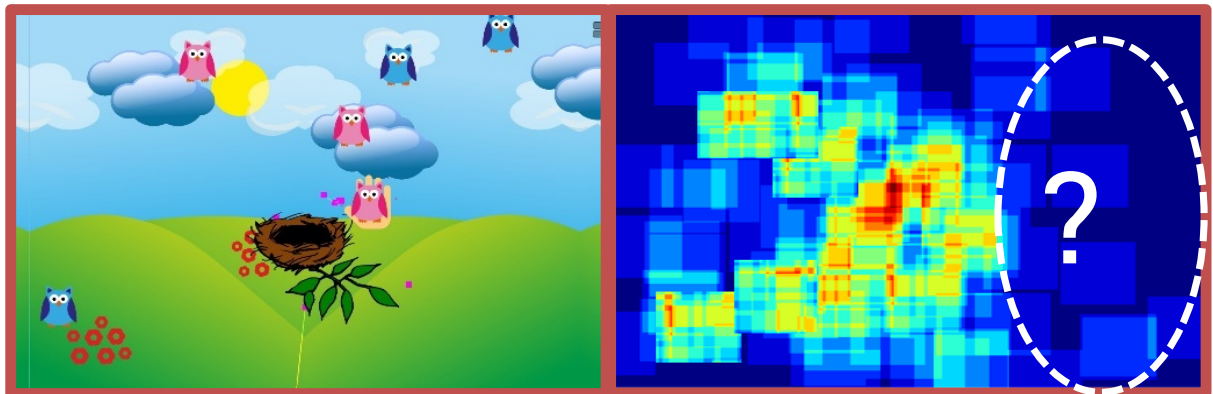
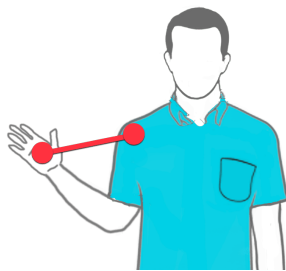


Figure 34: Spatial Map: patient's movement representation.



Hand-Shoulder distance



The exercises that involve the movement of the upper limb, can lead the patient to make a compensation strategy in reaching the targets: instead of varying the angles between the arm and forearm, and between the arm and the trunk, the whole body is moved in the direction of the target.

The angle at the elbow was then analyzed, which in case of compensation strategy will have a very low variability.

In the table below, the model reference values are shown for the results described up to now.

Model		
Session	Score	Standard deviation
n	6470	22,77

Two patients were analyzed, both with hemiplegia: the first patient reported a variability value equal to 13, index of correct execution of the movement even if not very wide. The second patient, given the low variability value, performed the movement using a compensation strategy that led him to maintain an almost constant elbow angle.

Patient		
Session	Score	Standard deviation (Θ_8)
Good	4540	13,00
Not So Good	2440	4,29

Below the percentages of comparison between the two patients under examination and the model, the first patient has collected a good score, thus reaching a satisfactory number of targets, unlike the latter. The results obtained for the score are reflected in the value of variability of the angle at the elbow compared to a healthy model that then used the entire range of movement of the elbow available.

Report		
Session	Score	Standard deviation (Θ_8)
Good	70%	57%
Not Good	38%	19%

The graph below in Figure 35 represents the trajectories of the hand extracted from the model during the execution of the "Shelf Cans" exercise, used as a reference for the analysis of the compensation strategy.

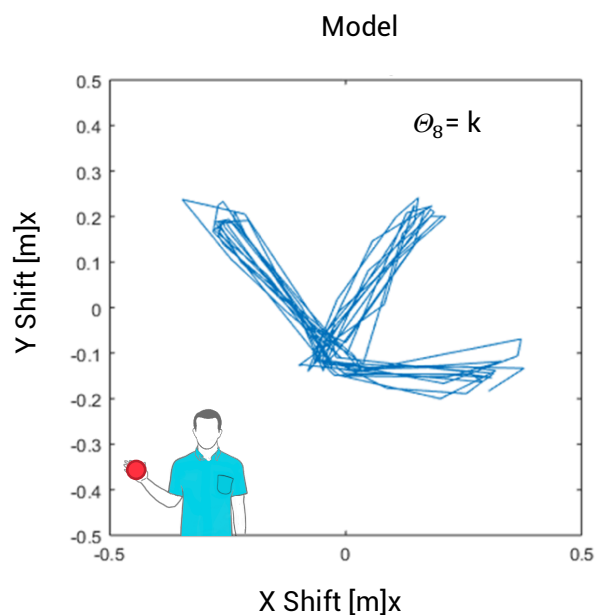


Figure 35: Hand trajectories during the execution of Shelf Cans Exercise by model.

Following in Figure 36, the trajectories carried out by the hand of the two hemiplegic patients are represented. On the left the subject who performed the exercise with a good performance, in which, as it can be seen, the trajectories are close to the model, on the right there is the second patient's chart where it can be seen how the movements are limited and rather confusing, as already indicated by the parameters previously described.

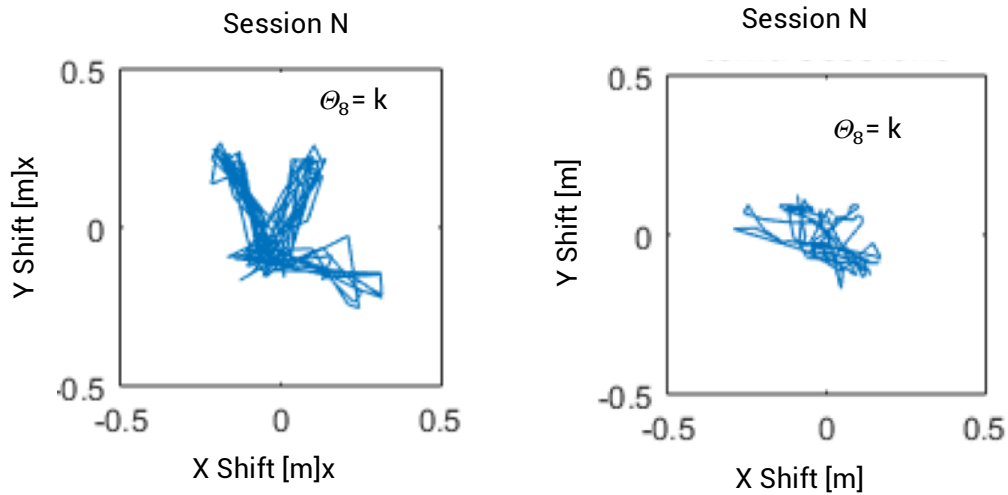
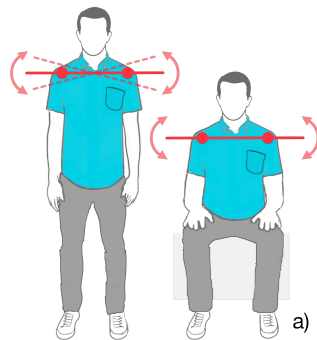


Figure 36: Hand trajectories during the execution of Shelf Cans Exercise by two hemiplegic patients.

Sit To Stand



For the analysis of this exercise two patients were chosen, representing the two main cases of the movement execution:

- The first patient underwent a hip operation for the installation of a prosthesis following a fracture. He/she performed the exercise with excellent results very close to the model.

- The second patient was hit by a stroke with consequent hemiplegia to the left side of the body. He performed the exercise, achieving good indicators, with the exception of the ROM, almost three times higher than the model.

The following table shows the average values obtained from the healthy model.

Model					
Session	Score	N repetitions	Coronal Shift [cm]	Shoulder Angle	Time [s]
n	6800	12	8	4,8°	5,1

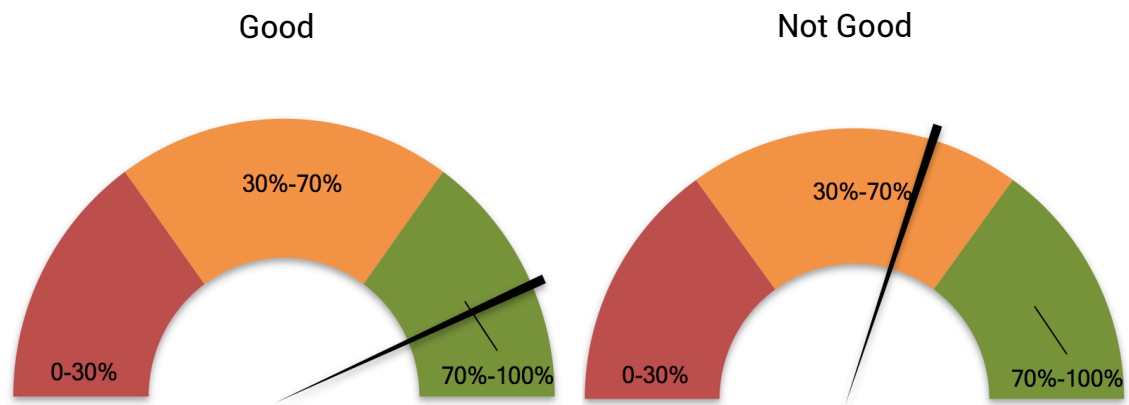
The table below shows the values obtained from the rehabilitative sessions carried out by two patients, chosen because the first performed the exercises correctly while the second found some difficulties that are reflected in the value of the Coronal Shift, representing the oscillation on the coronal plane during the transition from the sitting to the standing position and in the mean of shoulder angles.

Patient					
Session	Score	N repetitions	Coronal Shift [cm]	Sholder Angle	Time [s]
Good	6550	10	9,8	7,2°	6
Not So Good	4650	7	21	24,9	7,5

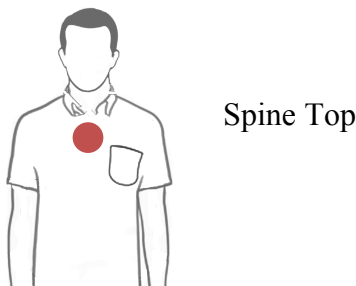
The final report that will be presented to the therapist will then contain the indicators derived from the values shown in the tables just shown, as illustrated in the Remote Biofeedback method described above. The value contained in the last column, “Final Mean”, is the mean value of all four indicators extracted.

Report					
Session	Score	Repetitions (Θ_1)	Rom (Θ_3)	Time (Θ_4)	Final Mean
Good	96,3%	83,3%	81,6%	85%	86,5%
Not Good	68,4%	66,7%	38%	67,1%	60%

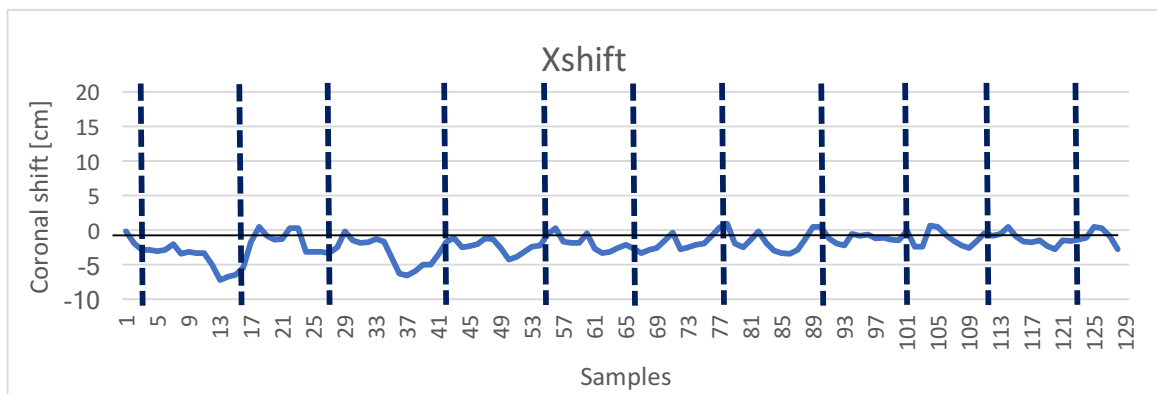
Graphically the extracted parameters can be summarized as follows:



As it can be seen, already at first glance the therapist has a general idea of how the exercise was performed by the two patients, having a quick tool to consult. The tables, on the other hand, show in detail the indicators that illustrate how the movements were performed; if the therapist needs more detailed information, he has at his disposal the graphic representations of the raw data or those elaborated by the Remote Biofeedback method. The following graph shows the shift chart of the "Spine Top" point on the coronal plane during the sit-to-stand exercise.

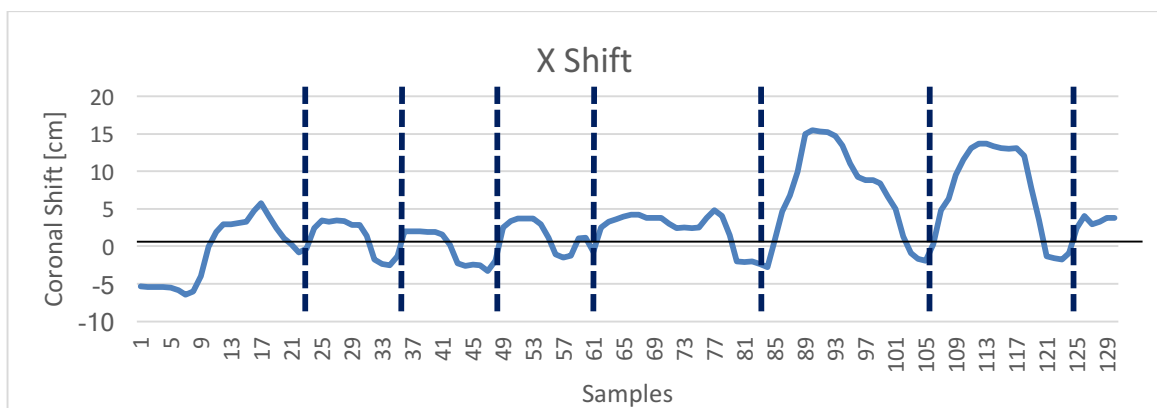


The dotted lines segment the signal isolating each phase of transition from sitting to standing position. As can be seen from the graph, the model also learns and corrects by improving his performance while keeping the movement on the coronal plane almost constant after three repetitions. It can be noted that the intervals are regular with an average of 5 seconds each.

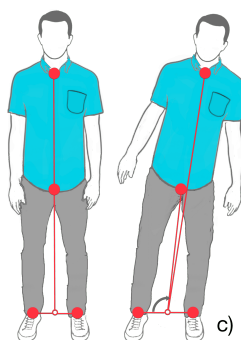


In the chart below, instead, the result of the patient who has had difficulty performing the exercise is reported.

As you can see, the intervals are irregular and increase with the progression of the session, a symptom of fatigue for the patient, the same behavior for the shift that increases a lot during the last two repetitions.



Center Of Mass



For the evaluation of the exercise that foresees the displacement of the loading on the lower limbs, two hemiplegic patients were chosen as significant, with motor deficits on the right side and on the left side of the body, respectively, following stroke.

The exercise as described above involves moving the load from the right lower limb to the left and vice versa, alternating the two directions according to the targets set by the proposed exercise.

A correctly executed movement foresees a mean value of compensations around 3 cm with a standard deviation of 2.3 cm and values of right and left range movement, which are equivalent.

The table below shows the data used as a reference extracted from the healthy model.

Model					
Session	Score	Compensation	Rom Left[cm]	Rom Right [cm]	Left-Right
n	8170	2,89 ± 2,35	36,96	37,33	0,37

The following table shows the data of the two hemiplegic patients examined.

Patient					
Session	Score	Compensation	Rom Left[cm]	Rom Right [cm]	Left-Right
Emi Right	-5300	16,19 ± 6,18	83,11	49,01	34,10
Emi Left	450	6,83 ± 3,35	31,54	42,87	11,33

Going to analyze the first patient, suffering from hemiplegia in the right side of the body, we can see how the parameter that represents the use of compensation strategy by the patient, compared to the model, takes a fairly high value, index of an improper execution of the movement. The amplitude of the movement, both left and right, is much wider than the model, indicating good mobility, but at the same time a poor load control. The collected score analyzed is very negative, in fact the patient having performed some movements that are too large not reaching the targets indicated by the exercise. Moreover, it can be seen how the deficit of the right side affects the displacement of the load on the hemiplegic side which reaches a ROM equal to 49.01 cm against the 83.11 cm of the left side.

The second patient affected by left hemiplegia, collected a sufficient score, remaining in a range of compensation closer to the model, compared to the previous patient. Also the right and left load movements have been done with good control especially on the "healthy"

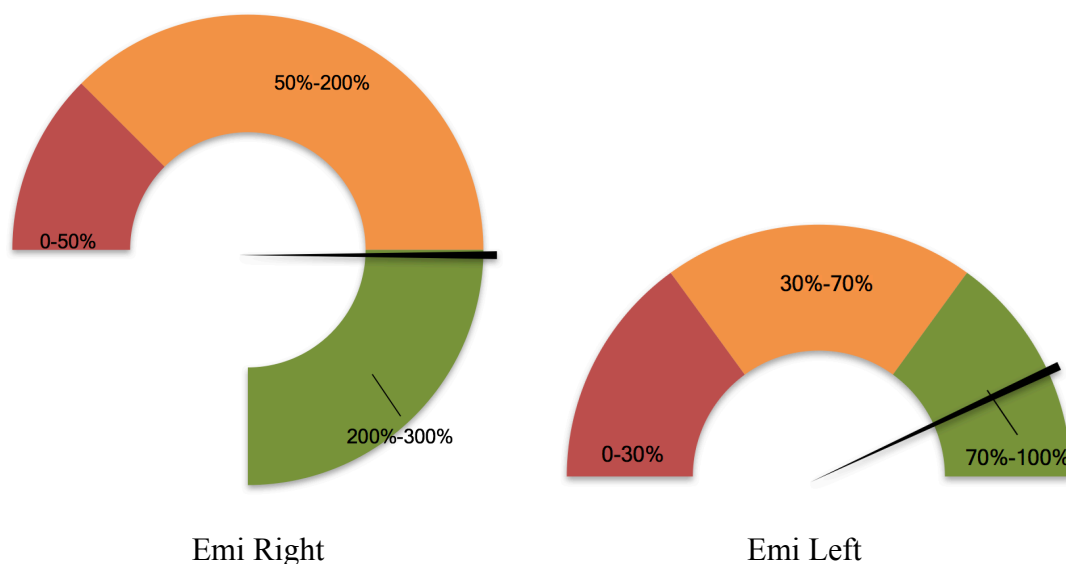
side. Also in this case, as in the previous one, the results show the greatest difficulty of movement on the part of the body to be rehabilitated (left), where the patient has reached a range of movement equal to 31.54 cm.

By analyzing the final indicators extracted from the results described above, it can be seen how the right hemiplegic patient has encountered great difficulties in the execution of the proposed exercise. The percentages reached over 100% are not in this case an index of better performance compared to the model, since despite the range of movement was twice higher than the model, this means that the exercise was not performed in the correct way, behavior confirmed by the score. The indicators must therefore always be contextualized and interpreted on the basis of the exercise in question.

The patient suffering from left hemiplegia, instead performed the exercise, maintaining greater control of his body even if using a compensation strategy with values almost double compared to the model.

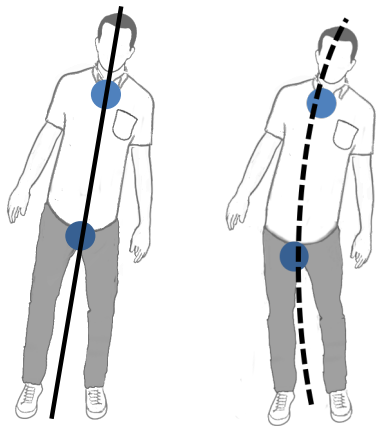
Report						
Session	Score	Compensation (Θ ₇)	Rom Left (Θ ₈)	Rom Right (Θ ₉)	Left-Right	Mean
Emi Right	-65 %	18%	208%	131%	1%	209%
Emi Left	6 %	42%	88%	116%	3%	86%

The mean values of the indicators, which summarize all the information extracted for the two patients, are shown below.



Below are depicted the graphs of the model and the of two patients examined.

In the graphs, instead, the movement data of the Spine Top and Spine Down points acquired during the execution of the movement are reported.



RIGHT

WRONG

An exercise performed correctly will result in a graph consisting of two lines almost coincident, with a limited range of movement around 70 cm, on the contrary, a poor control of the load and the use of compensation strategies lead to a graph consisting of two lines not coincident and with a wide range of movement.

As can be seen at a glance, the pattern of movements performed by patients is totally different from model's one. The path proposed by the exercise is the same in all three cases, but the resulting trend is totally different. In fact, the model presents a regular pattern and a signal that gradually increases in amplitude as the exercise progresses as shown in Figure 37.

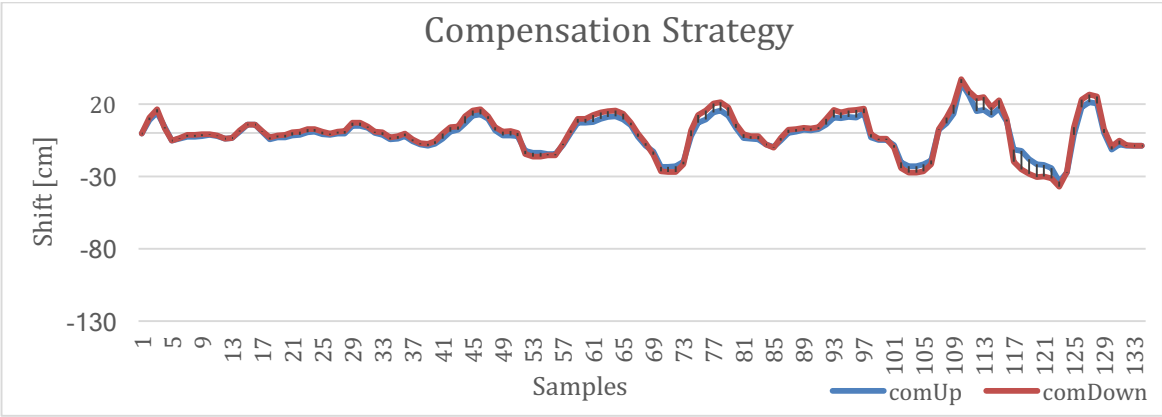


Figure 37: Spine Top and Spine Down trajectories for model.

On the other hand, the two patients present a very variable and irregular pattern that reflects a poor control of the load on the lower limbs and continuous adjustments of the balance, due to movements that are not very fluid. The trajectories of both patients are represented in Figure 38.

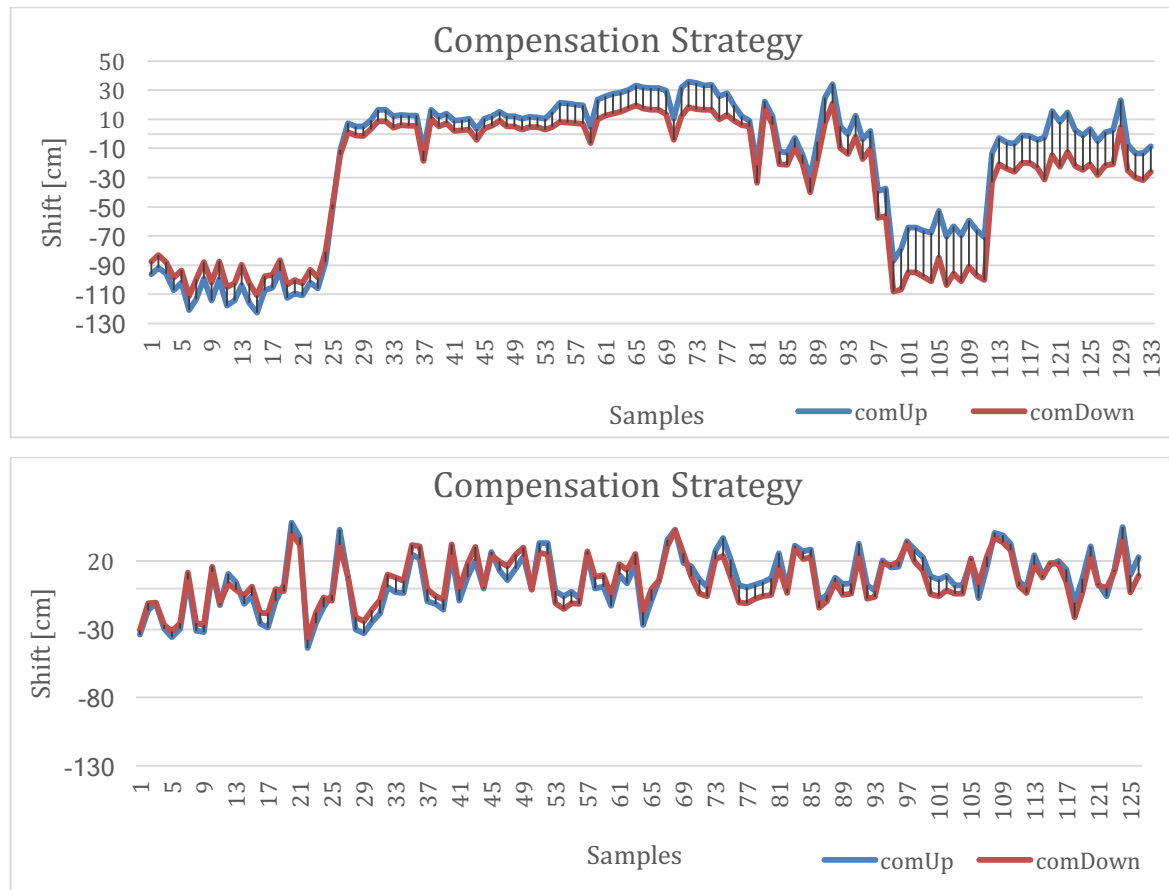
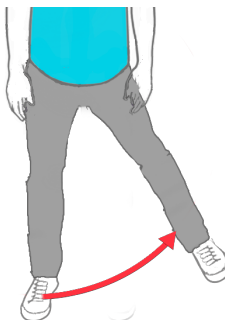


Figure 38: Spine Top and Spine Down trajectories for hemiplegic patients. On the top the Hemi right on the bottom the Hemi left.

Leg Abduction-Adduction



The following table shows or reference values extracted from the execution of the abduction and leg adduction exercise performed by a control group from which the model was extracted.

The exercise has a duration of 60 seconds so model performs the exercise keeping the foot lifted from the ground for about 50% of the duration. The maximum angle reached is about 60 ° and the score reaches almost 3000 points.

Model				
Session	Score	Max ROM	Fly Time [s]	Fly Time [%]
n	2960	58,84	31,5	53%

The two patients examined are both affected by hemiplegia, the first on the right side and the second on the left side of the body.

For the first patient, the flight time is not far from that of the model, while the second patient keeps the foot lifted for a total duration of 16 seconds. For the remaining seconds keeps the leg resting on the ground symptom of fatigue or difficulty in maintaining balance. However, they both collected a good score overcoming the obstacles proposed during the exercise by using two different strategies according to their physical faculties.

Patient			
Session	Score	Max ROM [°] (Θ ₁₂)	Fly Time [s] (Θ ₁₃)
Hemiplegic Right	2640	45,34	27,5
Hemiplegic Left	2550	37,53	16

The following table shows the percentages of execution goodness of the exercise compared to the reference model for Score and Max Height, while the Fly Time, as described in the chapter concerning the method, is calculated in relation to the patient himself, based on the duration total amount of the exercise.

Report			
Session	Score	Max ROM (Θ ₁₂)	Fly Time (Θ ₃)
Good	89%	77%	46%
Not Good	86%	64%	27%

The graphs below (Figure 39) report the movements of the leg during the execution of the exercise performed by the two patients under examination.

The first patient performs a regular movement with a variation of the wide abduction-adduction angle.

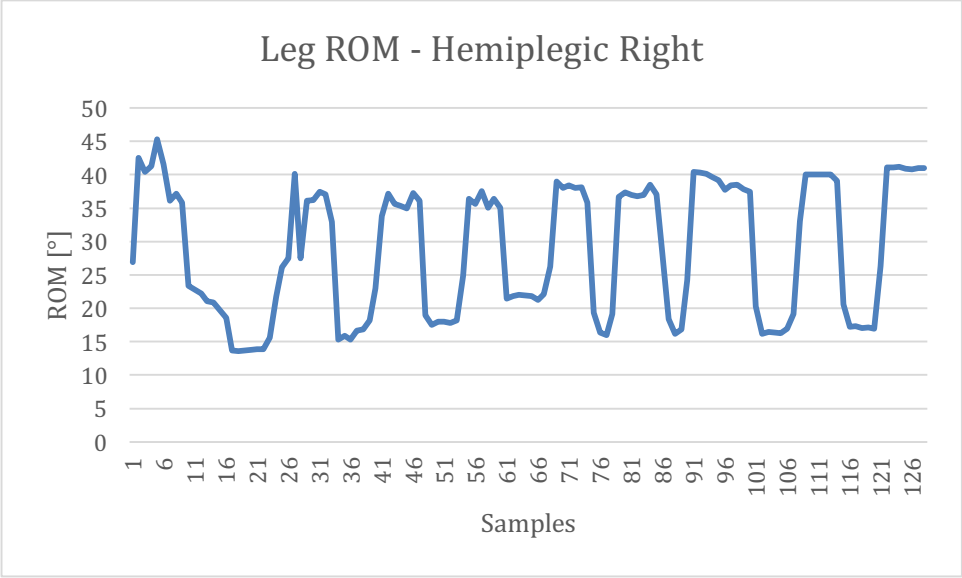


Figure 39: Leg movements during the execution of Flappy cloud exercise, Hemi right patient.

On the other hand, the second patient performs a movement that does not appear to be connected to the proposed targets that should induce the alternation of abduction and adduction. (Figure 40) The range of movement is also limited, remaining, above all in the second half, around 30°.

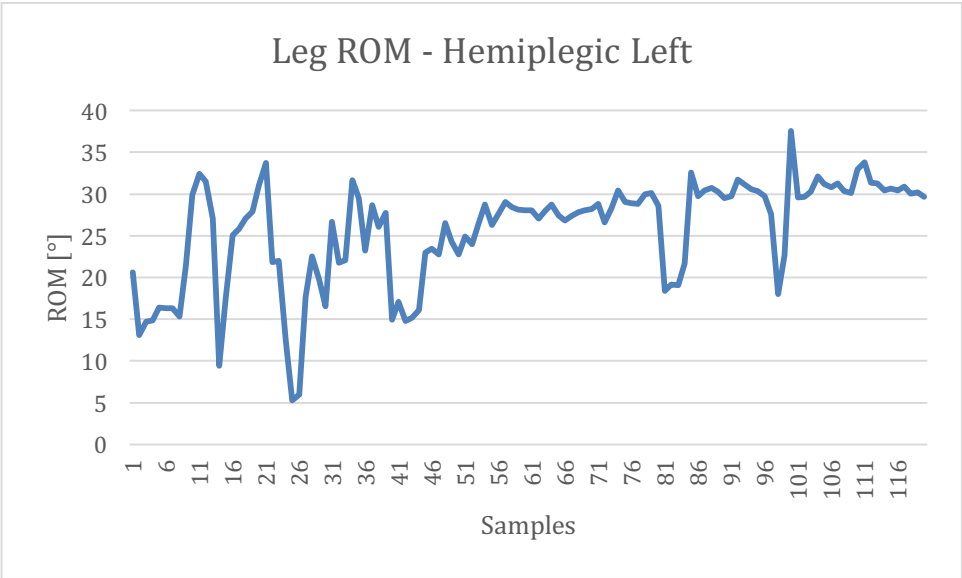


Figure 40: Leg movements during the execution of Flappy cloud exercise, Hemi left patient.

Movement Repetition

For exercises that involve repeating the same movement in the same position of the space, like to pour the contents of a bottle into a glass, both the number of repetitions and the way in which the movement is performed are evaluated. In the following table, as for the other exercises, the reference values of the model are shown.

Model				
Session	Score	N repetitions	Roll + [δ_+]	Roll - [δ_-]
n	7250	12	7,6	2,8

In the following table the evaluation parameters of the two cases, chosen as more exemplifying, are reported: a patient suffering from right hemiplegia and one from left hemiplegia.

The first patient performed well regularly and with a wide range of wrist rotation movements both clockwise and counterclockwise.

In fact, the values extracted for all four parameters are very close to the model, and in the case of the parameter δ_- he/she improves it.

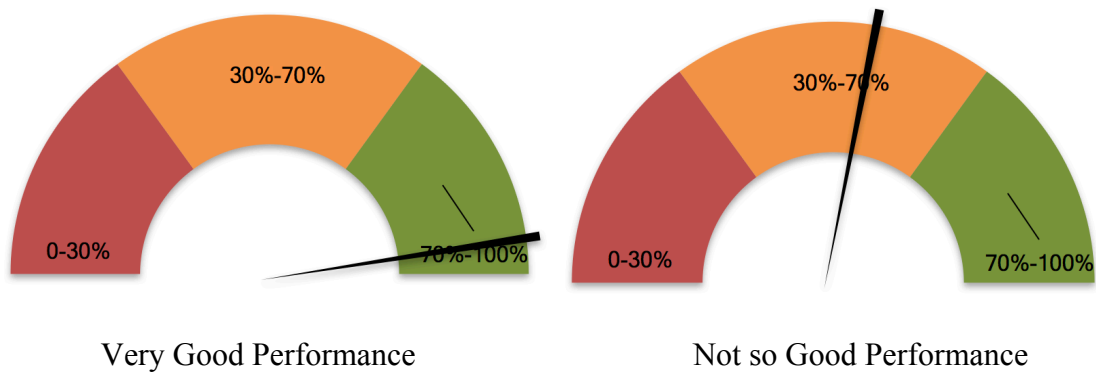
The difficulties in executing the movement, found by the second patient, have instead been reflected in irregular movements, and long times to reach the target, in this case fill the glass. The targets achieved are in fact equal to half of the reference model. The value that most deviates from the model is that of δ_- or the rotation of the wrist in a clockwise direction.

Patient				
Session	Score	N repetitions	Roll + [δ_+]	Roll - [δ_-]
Emi Right	6640	11	8,4	2,6
Emi Left	4240	6	9,6	7,6

The final indicators extracted for both cases under examination are shown in the following table.

Report					
Session	Score	N repetitions (Θ_1)	Roll + (Θ_+)	Roll - (Θ_-)	Mean
Emi Right	91,6%	91,66%	90,48%	107,69%	95%
Emi Left	58,5%	50%	79,16%	36,84%	56%

The mean values of the indicators, which summarize all the information extracted for the two patients are shown below.



The graph below shows how the movement should be performed, with regular repetitions and a pattern consisting of a series of long positive and short negative values. The positive part of the graph corresponds to a counter clockwise rotation of the wrist to fill the glass, while the negative part in the sense time, to bring back the vertical bottle and restart the required movement. A pattern therefore corresponding to a correct execution, provides in the positive part of the graph more extensive and regular curves, while in the negative part short-lived peaks, corresponding to faster movements.

Going to perform a signal analysis, it can be seen that this consists of a numerical sequence of positive and negative values grouped in quantities that are repeated over time. In particular when the pronounced supination movement is performed correctly, the roll signal must consist of a group of positive values in a number between 8 and 10 and one of negative values composed of 2 to 4 samples.

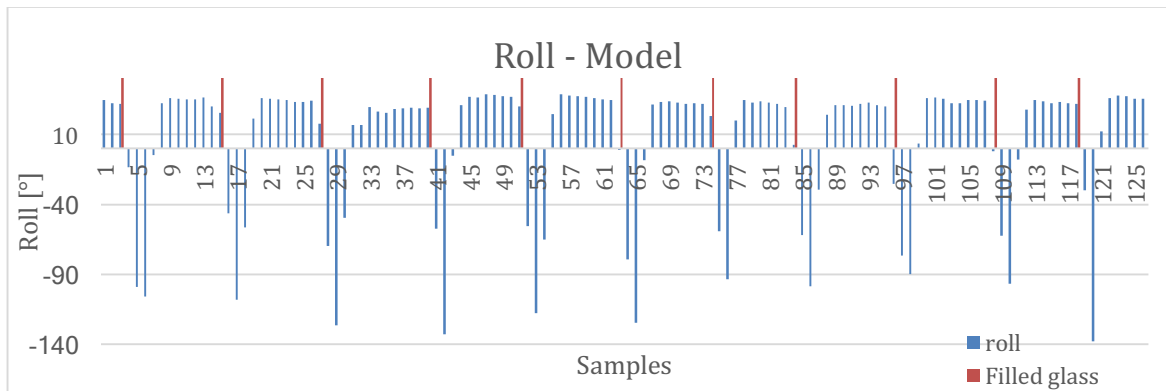


Figure 41: Roll movement during the execution of wine bottle exercise, model signal.

As can be seen from the graph below, belonging to the patient who has encountered difficulties, the movements were performed irregularly by rotating the wrist several times without reaching the target, when he/she should rotate and maintain the position until the glass is filled (moment indicated by the orange line). The intervals, marked by orange vertical lines are irregular and the number of targets reached is equal to 6, about half of those potentially executable in 60 seconds.

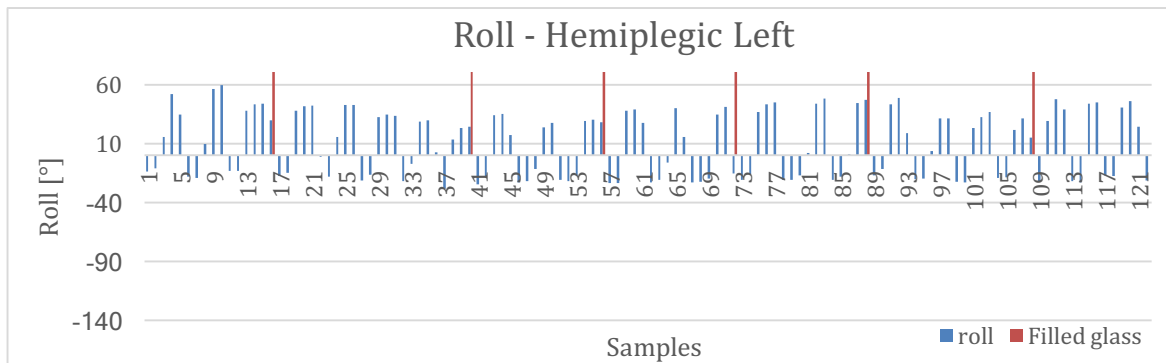


Figure 42: Roll movement during the execution of wine bottle exercise, Hemi left patient signal.

The patient suffering from right hemiplegia, instead, performed the movement very well at regular intervals and with a pattern very similar to the model as precisely described by the final indicator which is equal to 95%.

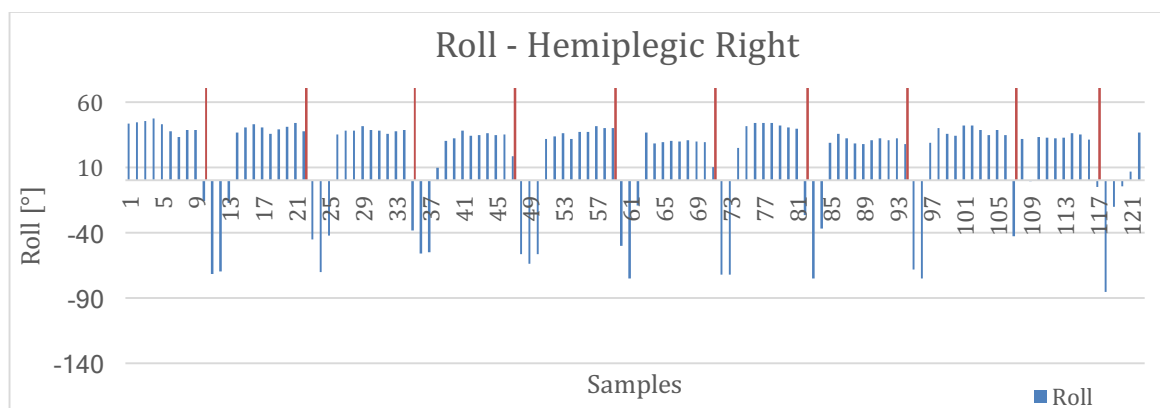


Figure 43: Roll movement during the execution of wine bottle exercise, Hemi right patient signal.

Progress Over Time

All the results shown up to now have concerned the analysis of the single session, which can help the therapist to modify or maintain the care plan assigned to his patient day by day.

To have a more long-term vision, once the appropriate treatment plan has been set, the extracted parameters are graphically represented to provide the progression of the indicators extracted from the Remote Biofeedback method over time.

Below are some examples chosen as meaningful.

The first example, reported in Figure 44, concerns the exercise of flexion and extension of the wrist in which both extension and flexion phases are characterized by a strong improvement achieved already after three rehabilitative sessions, with the difference that due to the decrease during the third session the patient has improved compared to -25° achieved during the first session, but worsened by about 15° compared to the second one.

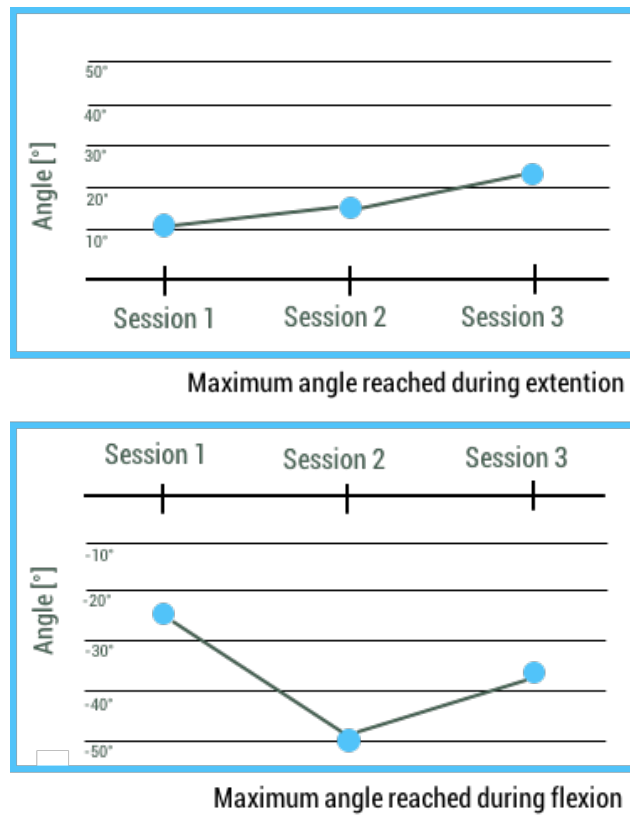


Figure 44: Maximum angle reached during wrist extension and flexion in 3 different sessions.

The second example in Figure 45 shows the score collected during 10 sessions of the "Wine Bottle" exercise, carried out by a patient affected by stroke, with motor deficits on the right side of the body. As can be seen, the patient in terms of score has improved considerably, passing from a score value just over 1000 to reach about 6500 points.

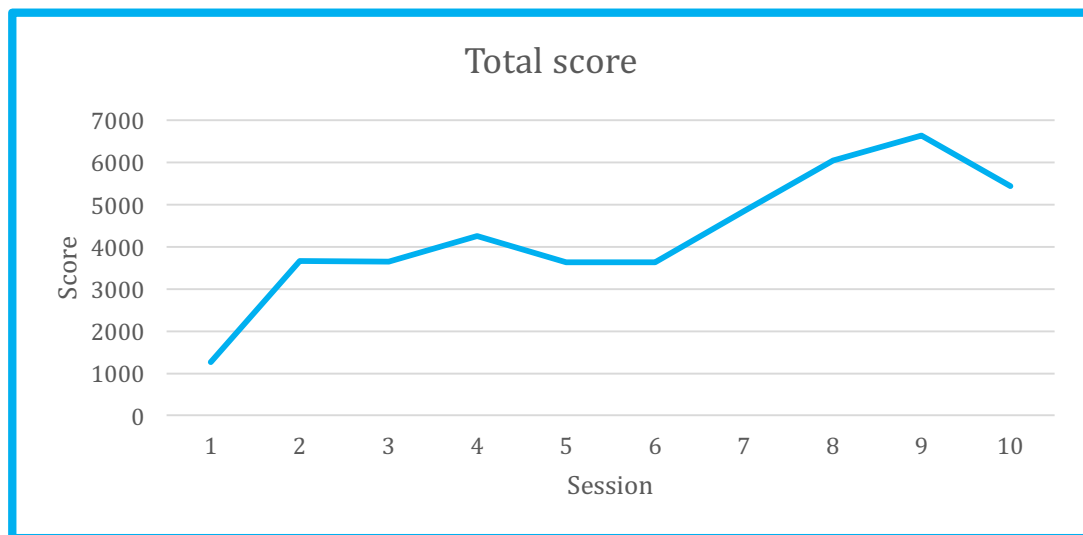


Figure 45: Score collected during 10 different sessions during the execution of wine bottle exercise.

The third example, in Figure 46, shows the number of repetitions performed during the Sit to Stand exercise. After the first three sessions, the patient continuously increased the number of repetitions from a minimum of 3 during the second session to a maximum of 11 performed during the eighth and last session.

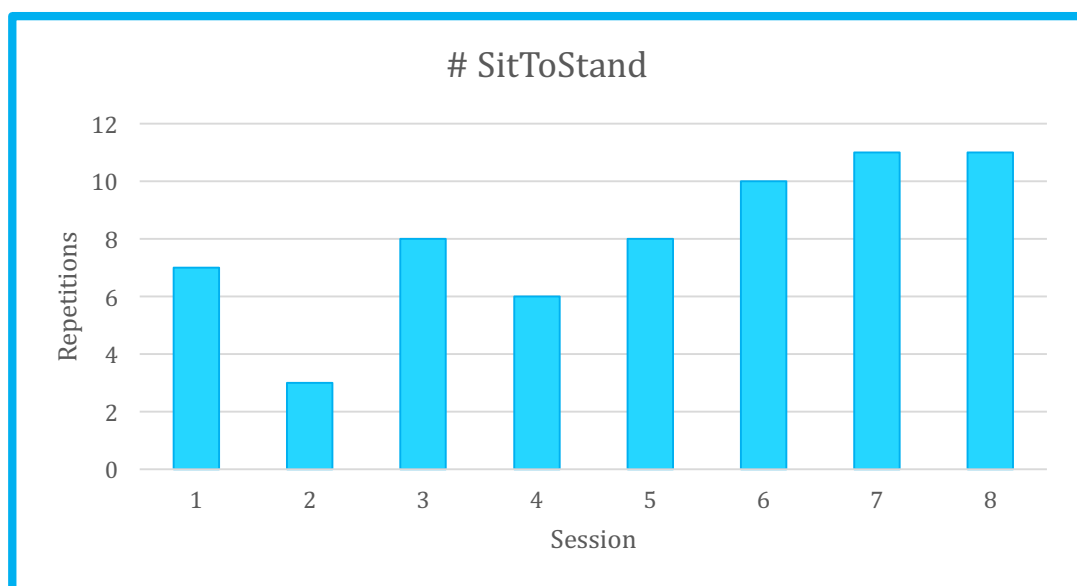


Figure 46: number of movement repetitions during 10 sessions of wine bottle exercise.

The fourth example, in Figure 47, shows the maximum height reached by a patient in the exercise "Owls in the Nest". As can be seen from the graph below, there is no clear improvement in performance, but rather a maintenance of the faculties reached through the traditional rehabilitation process daily carried out in the hospitalization facility.

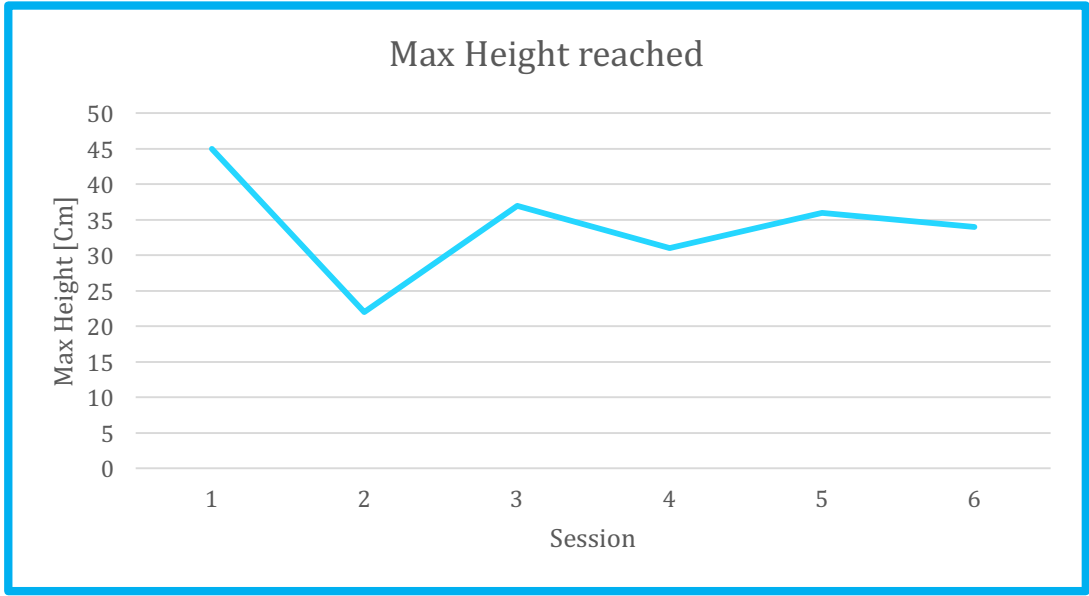


Figure 47: Max height reached during the execution of owls in the nest exercise over 6 sessions.

Chapter 7: Conclusions

The Remote Biofeedback Method has been tested for more than 700 sessions on more than 50 users with different pathologies.

The objective of this research project is not to validate the rehabilitation effectiveness of the exercises, but to understand if the indicators proposed by the biofeedback method are applicable to all the cases that are analyzed and if above all they are consistent with the actual execution of the rehabilitation session, which was given direct feedback from the therapists.

In general, the results show that the different signals, when considered individually, do not provide enough information to outline the actual rehabilitation summary of the patient; for example, improved scores do not always indicate an optimal condition.

The results of the tests on the rehabilitation system ReMoVES were presented, with a focus on the heartbeat recorded during the execution of the exercise sessions and on the motion signals.

To complete the information extracted from the heartbeat, a preliminary study was conducted on the Galvanic Skin Response with the aim of providing the therapist with information on the degree of patient involvement during the rehabilitation session.

The analysis of the signal extracted during the viewing of a video through an augmented reality viewer led to results consistent with the direct feedback of the subjects who participated in the study. In fact, the analyzed signals showed strong variations closely linked to the emotions experienced during the different segments of the video.

The same correlation was not however found during the execution of the rehabilitative exercises, in which the recorded signal did not show significant variations, thus proving not very significant to be applied in this context.

The preliminary study conducted will be used as starting point of a deeper analysis with the recruitment of a larger population in order to better investigate the results found.

The parameters analysed for the evaluation of the innovative rehabilitation system are the heartbeat, the score obtained during the execution of the task, the time interval between the execution of one exercise and the following one and all the motion signals coming from the two sensors used.

In addition to the analysis of the individual signals, a preliminary analysis of the correlation between the trend of the heart rate and the performance of the score acquired during the exercises was carried out.

An overall improvement was observed among the patients who participated in the pilot study, both in terms of their performance in carrying out the exercises and their emotional involvement during the rehabilitation session.

The feedback given at the end of the 12 rehabilitation sessions suggested that the ReMoVES system was generally well accepted by the patients.

In this study, the heartbeat was not analysed as a parameter of cardiac risk but rather as a parameter of involvement during the execution of rehabilitative exercises.

The analysis assessed the trend of the average values of the heartbeat during the 12 planned rehabilitation sessions subdivided by the type of exercise. Most patients reported a decreasing trend, symptoms of relaxation, and a feeling of motivation during the rehabilitation.

Patients who exhibited a positive trend also reported symptoms of an uncomfortable situation, which were likely due to a lack of motivation or pain. The results obtained from the physiological sensor and from the exercise corroborated these reports.

The inter-exercise time is important in order to determine whether a patient is too tired while performing an exercise and thus needs to rest before performing the next exercise.

The average inter-exercise times of the first and last six sessions were then calculated to evaluate the average improvement of the subjects. Thus, from the analysis of these parameters, we can infer that the performance of each exercise and the fluidity within the rehabilitation sessions are generally improving from session to session.

In conclusion, the parameters extracted from heartbeat, inter exercise time and score collected during the rehabilitation sessions are reliable indicators of patient status, both from a motivational and a rehabilitation point of view.

The same analysis can be applied per session in order to allow the physiotherapist to change the plan of care according to the requirements and needs of the patient, thus customizing the plan of care, which is very important for the success of the therapy.

For the motion part, the results show a very good coherence between the improvement, described by the therapist and the indicators extracted by the Remote Biofeedback Method. For the spatial map, the goal of the study has been reached, in fact the aim is to demonstrate that it will be a good instrument to investigate the neglect patients. The results obtained

shows that the neglect impairment is reflected on the spatial map recorded, giving to the therapist a visual instrument to use for the patient rehabilitation program.

The investigation of the compensation strategy for the upper limb has been conducted by analyzing the distance variation between hand and shoulder during the execution of different exercises involving the upper limb.

The results obtained for the score collected are reflected in the value of variability of the angle at the elbow compared to a healthy model that then used the entire range of movement of the elbow available. A wrong movement execution is reflected in a very low variability of the trajectories giving also in this case an immediate visual instrument for the therapist in order to understand the movement execution.

For the sit to stand exercise the parameters of interest are repetitions, execution time of each sequence and mode of execution of the movement, evaluated by analyzing the shifting on the coronal plane and the shoulder angle.

The results collected for model and the two patients analysed, demonstrate that the therapist is able to understand how the movement is executed and if the duration of the exercise is adequate for the patient.

For the evaluation of the exercise that foresees the displacement of the loading on the lower limbs, different parameters have been extracted.

From the results obtained, it can be concluded that a wide amplitude of the movement, both left and right, indicate good mobility, but at the same time a poor load control. This statement was indeed confirmed by the negative score collected, index of wrong execution of the exercise. The range of motion reflects also the impaired side of the body.

The compensation strategy was also investigated by analyzing the Top and the Down point of the Spine. The two patients analysed present a very variable and irregular pattern that reflects a poor control of the load on the lower limbs and continuous adjustments of the balance, due to movements that are not very fluid.

The leg movements have been evaluated by analyzing the fly time, in order to investigate the fatigue of the patient. A regular pattern is symptom of movement fluidity, on the contrary an irregular pattern is symptom of fatigue and difficulty in executing the exercise in a correct way.

The wrist rotation is another type of movement analysed, in particular, the number of repetitions is evaluated. A pattern therefore corresponding to a correct execution, provides

in the positive part of the graph more extensive and regular curves, while in the negative part short-lived peaks, corresponding to faster movements.

For all movements studied, the progress over time is evaluated. To have a more long-term vision, once the appropriate treatment plan has been set, the extracted parameters are graphically represented to provide the progression of the indicators extracted from the Remote Biofeedback method over time.

Finally, from the results obtained, the remote Biofeedback Method, demonstrated to be a good tool to support therapist during daily work in clinic and after the patient de-hospitalization. Without seeing directly the patient, the therapist can in fact using the indicators extracted to reconstruct the patient performance, involvement and movement, only by analysing the report presented by Remote Biofeedback Method.

The future steps will be, a creation of a model starting from patient signals, in order to have a better comparison term, and a testing phase on a larger number of patients, following a clinical protocol, subdividing subject by disease.

The Remote Biofeedback Method can be improved using automatic classification and machine learning methods in order to automate the extraction process of the parameters, useful for the therapist in order to define the accuracy of the assigned plan of care.

Appendix - Evaluation of the approach to rehabilitative technology in elderlies: a gender study

1.1. User centered systems: how gender could be considered in designing

Since technology and gender are both socially constructed and socially pervasive, we can never fully understand one without also understanding the other” (Lohan & Falulkner, 2004)

In any society, technology is a fundamental way in which gender is expressed. Domains and technical skills are divided between and within the sexes, shaping masculinities and femininities.

The personalization of a new technological system involves a process of gathering user - and process - related information during the rehabilitation, which is used to appropriately adapt process and services in order to satisfactorily enhance the user’s experience. User satisfaction is the ultimate aim of personalization. Case-based reasoning will help in further improving the rehabilitation process by either exploiting profile information of the same user or retrieving and processing information related to one or more similar users. To this end, the standard can suggest an appropriate procedure and personalization description and their application can further help conceiving such kind of systems according also to the gender and preferences of the possible users.

1.2. Preliminary studies before designing: a standard based approach

While conceiving a new technology based system, it is useful to consider a specific method.

Our approach is a standard based and user centred approach and it aims to implement international standards or part of them within a specific solution that for the moment includes a rehabilitation and biofeedback monitoring system.

In rehabilitation field, easy to use systems should help people in their common daily tasks, according to their specific needs. Many different issues should be addressed, according to the specific task the system should deliver and for that reason, stakeholders and users in particular, should be the core people in conceiving the system itself.

According to this approach, one of the applicable method is VOLERE that helps in analysing and exploiting user centred features [8], useful in building , through an adaptive method of control and re-projecting In this case the system should consider different stakeholders and then different key users.

Analysing different scenarios it is possible to understand who are the stakeholders and then users involved in a specific project.

1.3. Practical application of the standards' study

Key users involved in the rehabilitation general system can be divided into three main groups:

- **Professional Users**
 - Physicians
 - Physical Therapists
 - Rehabilitation nurses
 - Occupational and recreational therapists
 - Speech-language pathologists
 - Vocational therapist
- **Patients**
- **Family**

Physicians: they have the primary responsibility for managing and coordinating the long-term care of stroke survivors, including the decision about rehabilitation programs that will best address individual needs. They are also responsible for caring the stroke survivor's general health and providing guidance.

Physical therapists: specialized in treating disabilities related to motor and sensory impairments. They help survivors regain the use of stroke-impaired limbs, teach

compensatory strategies to reduce the effect of remaining deficits and establish ongoing exercise programs to help people retain their newly learned skills.

Rehabilitation nurses: help survivors relearn how to carry out the basic activities of daily living. They also educate survivors about routine health care and provide preventing a second stroke.

Occupational and recreational therapists: help survivors relearn skills needed for self-directed activities such as personal grooming, preparing meals and house cleaning. Occupational therapists teach people how to develop compensatory strategies and how to change things that limit activities of daily living. Recreational therapists help people to use their leisure time to enhance their health, independence and quality of life.

Speech-language pathologists: help stroke survivors with aphasia relearn how to use language or develop alternative means of communication. Exercise such as repeating the therapist's words and reading or writing exercises are the core of this rehabilitation.

Vocational therapist: perform the same function as ordinary career counsellors do. They help people with residual disabilities identify strengths and develop CVs that highlight those. They also identify potential employers and assist in specific job searches.

For this study, we focused our interest on therapist and patients and on the interaction of these two figures.

The patient gives to the therapist his remote biofeedback through the heartbeat and the game performance acquired during the rehabilitation session, and the therapist replies accordingly to a personalized plan of care.[10]

Patients' population includes all those people who are affected by an impairment of the upper limb as Stroke, Multiple Sclerosis (MS), motor impairment and Parkinson's disease.

Basic general information about a patient should include:

- **Gender**
- Age (years)
- Pathology
- Chronicity (months)
- Rehabilitation objective
- Rehabilitation therapy plan
- Gaming plan and timetable

This study has been conducted on a population of 32 patients from 32 to 82 years old, 9 men and 23 women affected by different diseases distributed as follows:

- 38% Stroke
- 35% Multiple Sclerosis
- 15% Motor Impairment
- 8% Parkinson
- 4% Cervical Myelopathy

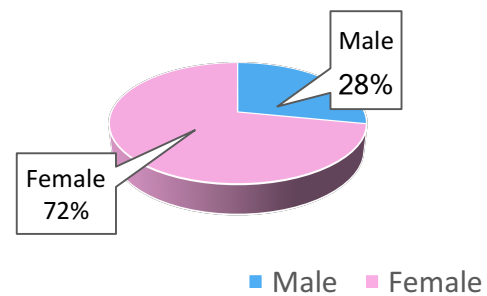


Figure 11: Study participants divided by gender

Figure 11 explain the subdivision of the population by gender, as we can see 72% are females and 28% are males. The reason of the greater percentage of women is that many participants are affected by multiple sclerosis, a pathology that affect mostly females.

1.4. Method

Human involvement and condition during rehabilitation therapy can be expressed through many channels such as gestures, facial expressions, voice, but also physiological responses like accelerations and decelerations of the heartbeat and changes in the skin conductance [4][5]. For this reason, the heart rate (HR) and the heart rate variability (HRV) were chosen as physiological signals to analyse and monitor relevant changes during different phases of a rehabilitation session [3][6].

To carry out this study it has been necessary to understand the relationship with technology by elderlies, in particular, the access to new technologies, such as serious games, focusing on the differences between males and females.

In order to achieve the desired results two main approaches were designed:

1. Use questionnaires that will be developed ad hoc during the first part of the study, in order to have direct feedback from patients.
The use of questionnaires, which will be filled out by women and men is a method for detecting gender-related preferences and attitudes.
Gender-specific related differences should already be considered during the preparation of the questionnaires.
2. Use biomedical parameters to have a remote biofeedback from the patient subjecting both genders to a protocol that provides a resting phase alternated to a game phase and extracting mean value and standard deviation of the heart beat during both phases.

Combining questionnaires and remote biofeedback the aim is to understand if heart rate is more significant in males or females as an involvement parameter.

The sensor is a classical fingertip pulse oximeter, but it has the advantage to transmit Bluetooth. So the patient is not obliged to stay near the PC or the station that received the signal. It provides oxygen saturation, pulse and inter beat value. It allows with a specific software to see the pulse signal in real time.

The subject is sitting in front of a large screen and a Microsoft Kinect for Xbox 360, far two meters from them. Before starting the rehabilitation session, he/she wears the Bluetooth pulse oximeter on the second or third finger of the hand not used for the rehabilitation, so movement artefacts do not affect the signal.

When the patient is ready, the calibration of the Kinect starts, so the range of movement for all the duration of the session is saved. [9]

From the experience of the previous pilots and tests of the system and from literature it has been chosen to not consider only the absolute value of the parameters extracted from the heart signal, but also patterns of the signals.

In particular, the indicators chosen for the analysis are pattern, dispersion analysis, absolute vs. relative value, inter-game time.

The session key rehabilitation following a well-defined protocol consists of four parts:

- I. Three minutes at rest without do anything. The signal is acquired only during the third minute.
- II. II. Three minutes of relaxation in which the patient watches a video consisting of a series of images depicting relaxing landscapes, with a music in the background that reproduces the sounds of nature.
- III. Game session: the patient plays with Kinect games as the therapist prescribed him. All games were developed trying to reproduce different daily situations, using subjects like cans flowers and eggs in environments like garden and kitchen.
- IV. Three minutes at rest without do anything.

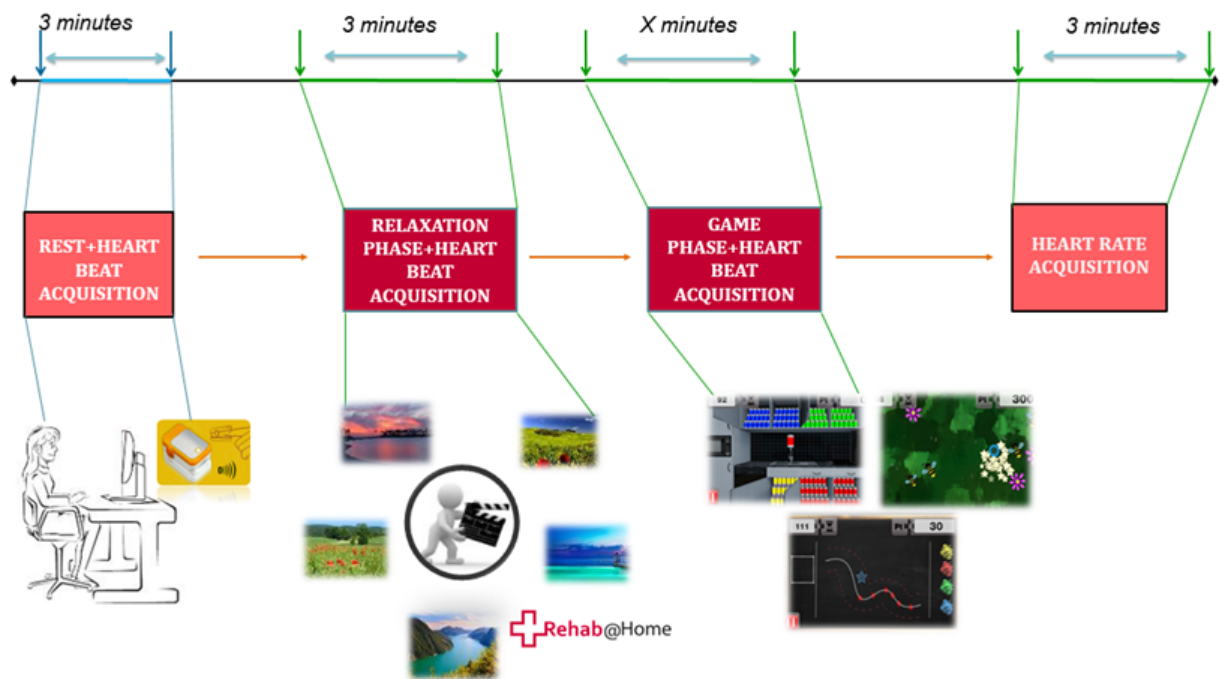


Figure 12: This figure explains the four steps of the protocol in which the rehabilitation session is divided.

1.5. Signal Analysis

From the experience of previous tests of the system and from literature has been chosen not only take into account the absolute value of the heartbeat and the parameters extracted from them, but also the pattern, the signal dispersion, the relative value of data and the time interval between two games.

Three type of scenarios were chosen:

1. A whole rehabilitation session
2. A single game session: Chart of vertical dispersion - involvement degree
3. Signal from biosensor and game score

In 1 and 2 the pattern, the timing of inter-game, by reading the game log, and the dispersion of the signal from the pulse oximeter have been studied, while in 3 the pattern of the heartbeat and score over time.

This analysis shows that the patient defined by us as "ideal" has a regular pattern with a trend "up and down" for each stage of the game, that situation does not occur in the patient stressed, whose beat is with random pattern and pretty stationary. The analysis of the dispersion confirms these behaviours different from each other bringing the dispersion values of the cardiac signal much greater in the ideal patient compared to the stressed one.

After saving a session's log, data are analyzed and processed with dedicated algorithms that extract the most important features. These data are also compared with game scores/data, to monitor the progress of the therapy and the involvement of the patient in the rehabilitation session [7].

The principal features extracted from the HR are:

- Average
- Standard deviation
- Maximum value
- Minimum value
- Difference between maximum and minimum value

To understand the gender differences of the interaction between patient and technology only average and standard deviations were chosen as discriminant parameters.

From the processing of parameters extracted from heartbeat, as known by literature, it is showed that the mean value is bigger in women in both part in which the rehabilitative session is divided. (Table 3)

The involvement during the rehabilitation therapy through serious games has been evaluated by the study of the standard deviation.

A bigger value of standard deviation (index of a bigger variability of the heartbeat) is showed from results in woman respect men during the game phase, while two values very near (2.7 and 2.9) about the relaxing phase.

	<i>Men</i>	<i>Women</i>
$\overline{Age} \pm \sigma$	59.0 \pm 17.0	69.7 \pm 20.3
$\overline{Rest\ Bpm} \pm \sigma$	71.3 \pm 14.2	80.0 \pm 13.4
$\overline{Game\ Bpm} \pm \sigma$	74.7 \pm 15.4	82.3 \pm 12.9
$\overline{\sigma Rest}$	2.7	2.9
$\overline{\sigma Game}$	1.6	3.5

Table 3: Age, Heart Beat mean and standard deviation during rest and game phase. (Mean + Dev.St.)

This behaviour is confirmed by the direct feedback given by the patients at the end of the rehabilitative session. Women were founded to be more involved than men during the game. No particular difference was found during the relaxation phase.

During the rehabilitation session women participated with more enthusiasm and involvement with a lot of comments, emotions, gesture and questions.

APPENDIX REFERENCES

- [1] Lohan, M., & Faulkner, W. (2004). Masculinities and technologies. *Men and Masculinities*, 6(4), 319-329.
- [2] Women, Science, and Technology: A Reader in Feminist Science Studies Di Mary Wyer, Mary Barbercheck, Donna Cookmeyer, Hatice Ozturk, Marta Wayne
- [3] Drachen, A., Nacke, L. E., Yannakakis, G., & Pedersen, A. L. (2010, July). Correlation between heart rate, electrodermal activity and player experience in first-person shooter games. In *Proceedings of the 5th ACM SIGGRAPH Symposium on Video Games* (pp. 49-54). ACM.
- [4] Nacke, L. E., Kalyn, M., Lough, C., & Mandryk, R. L. (2011, May). Biofeedback game design: using direct and indirect physiological control to enhance game interaction. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 103-112). ACM.
- [5] Nacke, L. E., & Lindley, C. A. (2010). Affective ludology, flow and immersion in a first-person shooter: Measurement of player experience. *arXiv preprint arXiv:1004.0248*.
- [6] S. Ponte, S. Gabrielli, J. Jonsdottir, M. Morando, SG. Dellepiane. Monitoring Game-Based Motor Rehabilitation of Patients at Home for Better Plans of Care and Quality of Life, Conference Of the IEEE Engineering in Medicine and Biology Society (EMBC), August 25-29, 2015 Milano, Italy. 978-1-4244-9270-1/15/\$31.00 ©2015 IEEE pp. 3941-3944.
- [7] Nacke, L. (2009). Affective ludology: Scientific measurement of user experience in interactive entertainment
- [8] VOLERE <http://www.volere.co.uk/>
- [9] S. Ponte, E. Ferrara, SG. Dellepiane. Home-based system for rehabilitation: improving quality of life through engineering solutions, Engineering 4 Society, Raising awareness for the societal and environmental role of engineering and (re)training engineers for participatory design. IEEE Conference June 18 and 19, 2015 Leuven, Belgium. Pp.126-130
- [10] E. Ferrara, S. Nardotto, S. Ponte, SG. Dellepiane. (2014) Infrastructure for data management and user centered rehabilitation in Rehab@Home project. PETRA'14, May 27-30, 2014, Island of Rhodes, Greece. ISBN: 978-1-4503-2746-6

Bibliography

References

- [1] Seung-Kook J, Kumar S, Xiaobo Z, et al. Automation for individualization of Kinect-based quantitative progressive exercise regimen. In: 2013 IEEE International Conference on Automation Science and Engineering (CASE). New York: IEEE; 2013: 243–248.
- [2] Fernandez-Baena A, Susin A, Lligadas X. Biomechanical validation of upper-body and lower-body joint movements of Kinect motion capture data for rehabilitation treatments. In: 2012 4th International Conference on Intelligent Networking and Collaborative Systems (INCoS). New York: IEEE; 2012: 656–661.
- [3] Brokaw EB, Lum PS, Cooper RA, et al. Using the Kinect to limit abnormal kinematics and compensation strategies during therapy with end effector robots. In: 2013 IEEE International Conference on Rehabilitation Robotics (ICORR). New York: IEEE; 2013: 1–6.
- [4] Dukes PS, Hayes A, Hodges LF, et al. Punching ducks for post-stroke neurorehabilitation: System design and initial exploratory feasibility study. In: 2013 IEEE Symposium on 3D User Interfaces (3DUI). New York: IEEE; 2013: 47–54.
- [5] Schonauer C, Pintaric T, Kaufmann H, et al. Chronic pain rehabilitation with a serious game using multimodal input. In: 2011 International Conference on Virtual Rehabilitation (ICVR). New York: IEEE; 2011: 1–8.
- [6] van Rijn RM, van Os AG, Bernsen RM, et al. What is the clinical course of acute ankle sprains: A systematic literature review. *Am J Med* 2008; 121:324–331.e7.
- [7] Crocher V, Hur P, Na Jin S. Low-cost virtual rehabilitation games: House of quality to meet patient expectations. In: 2013 International Conference on Virtual Rehabilitation (ICVR). New York: IEEE; 2013: 94–100.
- [8] Ustinova KI, Perkins J, Leonard WA, et al. Virtual reality game-based therapy for persons with TBI: A pilot study. In: 2013 International Conference on Virtual Rehabilitation (ICVR). New York: IEEE; 2013: 87–93.

- [9] Metcalf CD, Robinson R, Malpass AJ, et al. Markerless motion capture and measurement of hand kinematics: Validation and application to home-based upper limb rehabilitation. *IEEE Trans Biomed Eng* 2013; 60:2184–2192.
- [10] Roy AK, Soni Y, Dubey S. Enhancing effectiveness of motor rehabilitation using Kinect motion sensing technology. In: 2013 IEEE Global Humanitarian Technology Conference: South Asia Satellite (GHTC-SAS). New York: IEEE; 2013: 298–304.
- [11] Ertelt D, Small S, Solodkin A, et al. Action observation has a positive impact on rehabilitation of motor deficits after stroke. *Neuroimage* 2007; 36(Suppl 2): T164–T173.
- [12] Cordella F, Di Corato F, Zollo L, et al. Patient performance evaluation using Kinect and Monte Carlo-based finger tracking. In: 2012 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob). New York: IEEE; 2012: 1967–1972.
- [13] Garrido JE, Marset I, Penichet VMR, et al. Balance disorder rehabilitation through movement interaction. In: 2013 7th International Conference on Pervasive Computing Technologies for Healthcare (PervasiveHealth). New York: IEEE; 2013: 319–322.
- [14] Da Gama A, Chaves T, Figueiredo L, et al. Guidance and movement correction based on therapeutics movements for motor rehabilitation support systems. In: *IEEE Proceedings of XIV Symposium of Virtual and Augmented Reality, Niterói, 2012*. New York: IEEE; 2012: 191–200.
- [15] Anton D, Goni A, Illarramendi A, et al. KiReS: A Kinectbased telerehabilitation system. In: 2013 IEEE 15th International Conference on e-Health Networking, Applications & Services (Healthcom). New York: IEEE; 2013: 444–448.
- [16] Sadihov D, Migge B, Gassert R, et al. Prototype of a VR upper-limb rehabilitation system enhanced with motionbased tactile feedback. In: *World Haptics Conference (WHC), 2013*. New York: IEEE; 2013: 449–454.
- [17] Nixon ME, Howard AM, Yu-Ping Cheng. Quantitative evaluation of the Microsoft Kinect for use in an upper extremity virtual rehabilitation environment. In: 2013 International Conference on Virtual Rehabilitation (ICVR). New York: IEEE; 2013: 222–228.

- [18] Borghese NA, Mainetti R, Pirovano M, et al. An intelligent game engine for the at-home rehabilitation of stroke patients. In: 2013 IEEE 2nd International Conference on Serious Games and Applications for Health (SeGAH). New York: IEEE; 2013: 1–8.
- [19] Lozano-Quilis JA, Gil-Gomez H, Gil-Gomez JA, et al. Virtual reality system for multiple sclerosis rehabilitation using KINECT. In: 2013 7th International Conference on Pervasive Computing Technologies for Healthcare (PervasiveHealth). New York: IEEE; 2013: 366–369.
- [20] Woodford HJ, Price CIM. EMG biofeedback for the recovery of motor function after stroke (Review). Cochrane Library; Wiley. 2009. www.bibliotecacochrane.com/pdf/CD004585.pdf (accessed October 5, 2014).
- [21] Microsoft Corporation. Kinect for Windows. 2011. <http://kinectforwindows.org/> (accessed July 10, 2014).
- [22] S. Ponte, S. Gabrielli, J. Jonsdottir, M. Morando, and S. Dellepiane. Monitoring game-based motor rehabilitation of patients at home for better plans of care and quality of life. In Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE, pages 3941-3944. IEEE, 2015.
- [23] J. Maule and L. Chestnutt. Telemedicine in the 21st century, opportunities for citizens, society and industry. In Workshop Proceedings, 1999.
- [24] E. Ferrara, S. Nardotto, S. Ponte, and S. G. Dellepiane. Infrastructure for data management and user centered rehabilitation in rehab@ home project. In Proceedings of the 7th International Conference on Pervasive Technologies Related to Assistive Environments, page 21. ACM, 2014
- [25] Guerreiro, Sérgio. "Telemonitoring as a Core Component to Enforce Remote Biofeedback Control Systems." Ambient Assisted Living and Enhanced Living Environments: Principles, Technologies and Control (2016): 311.
- [26] R. Paradiso et al., "Wearable monitoring systems for psychological and physiological state assessment in a naturalistic environment", in 2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Boston, MA, 2011, pp. 2250-2253.

- [27] S. Ponte, E. Ferrara, SG. Dellepiane. Home-based system for rehabilitation: improving quality of life through engineering solutions, Engineering 4 Society, Raising awareness for the societal and environmental role of engineering and (re)training engineers for participatory design. IEEE Conference June 18 and 19, 2015 Leuven, Belgium. Pp.126-130
- [28] American Heart Association <http://www.heart.org>
- [29] Achten, J., & Jeukendrup, A. E. (2003). Heart rate monitoring. *Sports medicine*, 33(7), 517-538.
- [30] Lamberts, R. P., Swart, J., Capostagno, B., Noakes, T. D., & Lambert, M. I. (2010). Heart rate recovery as a guide to monitor fatigue and predict changes in performance parameters. *Scandinavian journal of medicine & science in sports*, 20(3), 449-457.
- [31] Garber, C. E., Blissmer, B., Deschenes, M. R., Franklin, B. A., Lamonte, M. J., Lee, I. M., ... & Swain, D. P. (2011). Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing exercise. *Medicine & Science in Sports & Exercise*, 43(7), 1334-1339.
- [32] Nacke, L. E., Kalyn, M., Lough, C., & Mandryk, R. L. (2011, May). Biofeedback game design: using direct and indirect physiological control to enhance game interaction. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 103-112). ACM.
- [33] Nacke, L. E., & Lindley, C. A. (2010). Affective ludology, flow and immersion in a first person shooter: Measurement of player experience. *arXiv preprint arXiv:1004.0248*.
- [34] Nacke, L. (2009). Affective ludology: Scientific measurement of user experience in interactive entertainment
- [35] Mandryk, R. L. (2008). Physiological measures for game evaluation. *Game usability: Advice from the experts for advancing the player experience*, 207-235.
- [36] Mandryk, R. L., & Atkins, M. S. (2007). A fuzzy physiological approach for continuously modeling emotion during interaction with play technologies. *International journal of human-computer studies*, 49(4), 329-347.

- [37] Martinez, H.P., Jhala, A., And Yannakakis, G. (2009). Analyzing the Impact of Camera Viewpoint on Player Psychophysiology. In Proc. of Int. Conf. on Affective Computing & Intelligent Interaction, IEEE.
- [38] Drachen, A., Nacke, L. E., Yannakakis, G., & Pedersen, A. L. (2010, July). Correlation between heart rate, electrodermal activity and player experience in first-person shooter games. In Proceedings of the 5th ACM SIGGRAPH Symposium on Video Games (pp. 49-54). ACM.
- [39] Ponte S., Gabrielli S., Jonsdottir J., Morando M., Dellepiane SG.. (2015) Monitoring Game-Based Motor Rehabilitation of Patients at Home for Better Plans of Care and Quality of Life, Conference Of the IEEE Engineering in Medicine and Biology Society (EMBC), August 25-29, 2015 Milano, Italy. 978-1-4244-9270-1/15/\$31.00 ©2015 IEEE pp. 3941-3944.
- [40] Ferrara E., Nardotto S., Ponte S., Dellepiane SG.. (2014) Infrastructure for data management and user centered rehabilitation in Rehab@Home project. PETRA'14, May 27-30, 2014, Island of Rhodes, Greece. ISBN: 978-14503-27466 doi>10.1145/2674396.26744.
- [41] Jung, C.G., “On the Psychophysical relations of the association experiment”, Journal of Abnormal psychology, 1, pp. 247-255 (Reprinted in the Collected Works, Vol. 2, chapter 12, 1907.
- [42] Abrams, S. “The polygraph in a psychiatric setting”, American Journal of Psychiatry, 130(1), pp. 94-98, 1973.
- [43] Yokota, T., Matsunaga, T., Okiyama, R., Hirose, K., Tanabe, H., Furukawa, T., & Tsukagoshi, H. (1991). Sympathetic skin response in patients with multiple sclerosis compared with patients with spinal cord transection and normal controls. Brain, 114(3), 1381-1394.
- [44] Gutrecht, J., Suarez, G. A., & Denny, B. E. (1993). Sympathetic skin response in multiple sclerosis. Journal of the neurological sciences, 118(1), 88-91.
- [45] Caminero, A. B., Perez-Jimenez, A., Barreiro, P., & Ferrer, T. (1995). Sympathetic skin response: correlation with autonomic and somatic involvement in multiple sclerosis. Electromyography and clinical neurophysiology, 35(8), 457-462.

- [46] Arafat, I. M., Ferdous, S. M. S., & Quarles, J. (2016, November). The effects of cybersickness on persons with multiple sclerosis. In Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology (pp. 51-59). ACM.
- [47] A Cappozzo, F Catani, U Della Croce, and A Leardini. Position and orientation in space of bones during movement: anatomical frame definition and determination. *Clinical Biomechanics*, 10(4):171 – 178, 1995.
- [48] [4] C Frigo, M Rabuffetti, DCKerrigan, L C Deming, and A Pedotti. Functionally oriented and clinically feasible quantitative gait analysis method. *Medical and Biological Engineering and Computing*, 36(2):179–185, 1998.
- [49] Xsens. Xsens: 3D Motion Tracking. <http://www.xsens.com/>, May 2012.
- [50] Ascension Technology Corporation. Ascension Technology Corporation. <http://www.ascension-tech.com/>, May 2012.
- [51] A Cappozzo, F Catani, A Leardini, MG Benedetti, and U Della Croce. Position and orientation in space of bones during movement: experimental artefacts. *Clinical Biomechanics*, 11(2):90 – 100, 1996.
- [52] J. Fuller, L.-J. Liu, M.C. Murphy, and R.W. Mann. A comparison of lower-extremity skeletal kinematics measured using skin- and pin-mounted markers. *Human Movement Science*, 16(2-3):219 – 242, 1997. 3-D Analysis of Human Movement - II.
- [53] S Corazza, L Mundermann, A M Chaudhari, T Demattio, C Cobelli, and T P Andriacchi. A markerless motion capture system to study musculoskeletal biomechanics: visual hull and simulated annealing approach. *Annals of Biomedical Engineering*, 34(6):1019–1029, 2006.
- [54] Ugo Della Croce, Alberto Leardini, Lorenzo Chiari, and Aurelio Cappozzo. Human movement analysis using stereophotogrammetry: Part 4: assessment of anatomical landmark misplacement and its effects on joint kinematics. *Gait & Posture*, 21(2):226 – 237, 2005.
- [55] Lorenzo Chiari, Ugo Della Croce, Alberto Leardini, and Aurelio Cappozzo. Human movement analysis using stereophotogrammetry: Part 2: Instrumental errors. *Gait & Posture*, 21(2):197 – 211, 2005.
- [56] Microsoft Xbox. Kinect. <http://www.xbox.com/kinect>, May 2012.

- [57] Jan-Henk Annema, Mathijs Verstraete, Vero Vanden Abeele, Stef Desmet, and David Geerts. Videogames in therapy: a therapist's perspective. In Proceedings of the 3rd International Conference on Fun and Games, Fun and Games '10, pages 94–98, New York, NY, USA, 2010. ACM.
- [58] J. W. Burke, M. D. J. McNeill, D. K. Charles, P. J. Morrow, J. H. Crosbie, and S. M. McDonough. Optimising engagement for stroke rehabilitation using serious games. *Vis. Comput.*, 25(12):1085–1099, October 2009.
- [59] Mónica S. Cameirão, Sergi Bermúdez I Badia, Esther Duarte Oller, and Paul F. Verschure. The rehabilitation gaming system: a review. *Studies in health technology and informatics*, 145:65–83, 2009.
- [60] Fraser Anderson, Michelle Annett, and Walter F. Bischof. Lean on Wii: Physical rehabilitation with virtual reality and Wii peripherals. *Annual Review of CyberTherapy and Telemedicine*, 8:181–184, 2010.
- [61] Christian Schonauer, Thomas Pintaric, Hannes Kaufmann, Stephanie Jansen Kosterink, and Miriam Vollenbroek-Hutten. Chronic pain rehabilitation with a serious game using multimodal input. In *Virtual Rehabilitation (ICVR)*, 2011 International Conference on, pages 1 –8, june 2011.
- [62] Mi Zhang Sebastian Koenig Phil Requejo Noom Somboon Alexander A. Sawchuk Chien-Yen Chang, Belinda Lange and Albert A. Rizzo. Towards pervasive physical rehabilitation using microsoft kinect. In *International Conference on Pervasive Computing Technologies for Healthcare (PervasiveHealth)*, San Diego, CA, USA, May 2012.
- [63] Flansbjerg UB, Holmbäck AM, Downham D, Patten C, Lexell J: Reliability of gait performance tests in men and women with hemiparesis after stroke. *Journal of Rehabilitation Medicine* 2005, 37: 75-82. PubMedGoogle Scholar
- [64] Olney SJ, Richards C: Hemiparetic gait following stroke. Part I: Characteristics. *Gait & Posture* 1996, 4: 136-148. Google Scholar
- [65] Ditunno PL, Patrick M, Stineman M, Morganti B, Townson AF, Ditunno JF: Cross-cultural differences in preference for recovery of mobility among spinal cord injury rehabilitation professionals. *Spinal cord* 2005, 44: 567-575. PubMedGoogle Scholar
- [66] Jette DU, Latham NK, Smout RJ, Gassaway J, Slavin MD, Horn SD: Physical therapy interventions for patients with stroke in inpatient

- rehabilitation facilities. *Physical therapy* 2005, 85: 238-248. PubMedGoogle Scholar
- [67] Pollock A, Baer G, Pomeroy VM, Langhorne P: Physiotherapy treatment approaches for the recovery of postural control and lower limb function following stroke. status and date: Edited (no change to conclusions), published in 2007, 21: 395-410. Google Scholar
- [68] Lennon S: The Bobath concept: a critical review of the theoretical assumptions that guide physiotherapy practice in stroke rehabilitation. *Physical therapy reviews* 1996, 1: 35-45.
- [69] Carr JH, Shepherd RB: A motor relearning programme for stroke. Butterworth-Heinemann; 1987. Google Scholar
- [70] Anderson M, Lough S: A psychological framework for neurorehabilitation. *Physiotherapy Theory and Practice* 1986, 2: 74-82. Google Scholar
- [71] Turnbull GI: Some learning theory implications in neurological physiotherapy. *Physiotherapy* 1982, 68: 38-41. PubMedGoogle Scholar
- [72] Carr JH, Shepherd RB: A motor learning model for rehabilitation of the movement-disabled. *Key Issues in Neurological Physiotherapy*. Melksham: Redwood Press Ltd 1990, 1-24. Google Scholar
- [73] Carr JH, Shepherd RB: *Neurological rehabilitation: optimizing motor performance*. Butterworth-Heinemann Medical; 1998.
- [74] Gargin, K., Pizzi, L.: Wii-HAB: Using the Wii Video Game System As An Occupational Therapy Intervention With Patients in the Hospital Setting. *Health Policy Newsletter* (March 2010)
- [75] Lange, B.S., Flynn, S.M., Rizzo, A.A.: Initial Usability Assessment of Off-the-shelf Video Game Consoles for Clinical Game-based Motor Rehabilitation. *Phys. Ther. Rev.* 14(5), 355–363 (2009)
- [76] Deutsch, J.E., Robbins, D., Morrison, J., Bowlby, P.G.: Wii-based Compared to Standard of Care Balance and Mobility Rehabilitation for Two Individuals Post-stroke. In: *Virtual Rehabilitation International Conference*, Hafia, Israel, June 29- July 2 (2009)
- [77] Sugarman, H., Weisel-Eichler, A., Burstin, A., Brown, R.: Use of the Wii Fit System For the Treatment of Balance Problems in the Elderly: A Feasibility

- Study. In: Virtual Rehabilitation International Conference, Hafia, Israel, June 29-July 2 (2009)
- [78] Nitz, J.C., Kuys, S., Isles, R., Fu, S.: Is The Wii Fit A New-generation Tool for Improving Balance. Health and Well-being? A Pilot Study. *Climacteric*, pp.1–6 (2009)
- [79] Flynn, S.M., Palma, P., Bender, A.: Feasibility of Using the Sony Playstation 2 Gaming Platform for An Individual Poststroke: A Case Report. *Journal of Neurologic Physical Therapy* 31(4), 180–189 (2007)
- [80] Lange, B.S., Flynn, S.M., Chang, C., Ahmed, A., Geng, Y., Utsav, K., Xu, M., Seok, D., Cheng, S., Rizzo, A.A.: Development of An Interactive Rehabilitation Game Using the Nintendo® Wii Fit™ Balance Board for People With Neurological Injury. In: *Proceedings of ICDVRAT*, Chile, August 31–September 2 (2010)
- [81] Gil-Gómez, J.A., Lozano, J.A., Alcañiz, M.: Nintendo Wii Balance Board for Balance Disorders. In: *Virtual Rehabilitation International Conference*, Hafia, Israel, June 29– July 2 (2009)
- [82] Billis, A.S., Konstantinidis, E.I., Mouzakidis, C., Tsolaki, M.N., Pappas, C., Bamidis, P.D.: A Game-like Interface For Training Senior's Dynamic Balance and Coordination. *Medicon IFMBE Proceedings* 29, 691–694 (2010)
- [83] WALLACE W A, COUPLAND R E 1975 „Variations in the nerves of the thumb and index finger”. *J Bone Joint Surg Br* 57-B (4): 491-494
- [84] JOHNSON S H 1998 „Cerebral organization of motor imagery”, *Contralateral control of grip selection in mentally represented prehension. Psychol Sci* 9: 219–222
- [85] NOELLE M AUSTIN 2005 „Chapter 9: The Wrist and Hand Complex“. In: *Levangie P K, Norkin C C (eds) Joint Structure and Function: A Comprehensive Analysis (4th ed.)*. F. A. Davis Company, Philadelphia. ISBN 0-8036-1191-9
- [86] SKALA KAVANAGH H, DUBRAVIĆ A, LIPIĆ T, SOVIĆ I, GRAZIO S 2011 „Computer supported thermography monitoring of hand strength evaluation by electronic dynamometer in rheumatoid arthritis – a pilot study”. *Period biol* 113(4): 433-437

- [87] OLANDERSSON S, LUNDQVIST H, BENGTTSSON M 2005 „Finger-Force Measurement-Device for hand rehabilitation“ in Rehabilitation Robotics Conf. ICORR, p 135-138
- [88] HARTOPANU S, SEREA F, POBORONIUC M, IRIMIA D, LIVINT G 2013 „Design of a Hybrid FES-Mechanical Intelligent Haptic Robotic Glove,“ in Proc. of the 17th International Conference on Systems Theory, Control and computing ICSTCC2013, Sinaia, Romania, 11-13 October, p 687-692
- [89] BROKAW E B, BLACK I, HOLLEY R, LUM P 2011 Hand Spring Operated Movement Enhancer (HandSome): A Portable Passive Hand Exoskeleton for Stroke Rehabilitation. IEEE Trans on Neural Systems and Rehabilitation Eng 19(4): 391-398
- [90] JI TING L, SHUANG W, JU W, RUOYIN Z, YURU Z, ZHONGYUAN C 2011 Development of a Hand Exoskeleton System for Index Finger Rehabilitation. Chinese Journal of Mechanical Engineering 24(5)
- [91] WEGE A, HOMMEL G 2005 „Development and control of a hand exoskeleton for rehabilitation of hand injuries.“ IEEE/RSJ International Conference on Intelligent Robots and Systems, Edmonton, Canada.
- [92] GUMMESSON C, ATROSHI I, EKDAH C 2003 The disabilities of the arm, shoulder and hand (DASH) outcome questionnaire: longitudinal construct validity and measuring self-rated health change after surgery. BMC Musculoskeletal Disorders, p 4-11
- [93] BASSILY D, GEORGOULAS C, GUETTLER J, LINNERT T, BOCK T 2014 „Intuitive and Adaptive Robotic Arm Manipulation using the Leap Motion Controller“, ISR/Robotik, 41st International Symposium on Robotics, Proceedings of, p 1-7
- [94] ZUBRYCKI I, GRANOSIK G 2014 „Using Integrated Vision Systems: Three Gears and Leap Motion, to Control a 3-finger Dexterous Gripper“, Recent Advances in Automation, Robotics and Measuring Techniques, Advances in Intelligent Systems and Computing Volume 267, p 553-564
- [95] KHADEMI M, HONDORI H M, MCKENZIE A, DODAKIAN L, VIDEIRA LOPES C, CRAMER S C 2014 „Free-hand interaction with leap motion controller for stroke rehabilitation“. CHI '14 Extended Abstracts on Human Factors in Computing Systems, p 1663-1668

- [96] WEICHERT F, BACHMANN D, RUDAK B, FISSELER D 2013 „Analysis of the Accuracy and Robustness of the Leap Motion Controller”. Sensors 13: 6380-6393
- [97] GUNA J, JAKUS G, POGAČNIK M, TOMAŽIČ S, SODNIK J 2014 „An Analysis of the Precision and Reliability of the Leap Motion Sensor and Its Suitability for Static and Dynamic Tracking”. Sensors 14(2): 3702-3720
- [98] R. Paradiso et al., “Wearable monitoring systems for psychological and physiological state assessment in a naturalistic environment”, in 2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Boston, MA, 2011, pp. 2250-2253.
- [99] Guerreiro, Sérgio. "Telemonitoring as a Core Component to Enforce Remote Biofeedback Control Systems." Ambient Assisted Living and Enhanced Living Environments: Principles, Technologies and Control (2016): 311.
- [100] <http://blog.mrtz.org/2015/12/14/adaptive-data-analysis.html>
- [101] Reeder, B., & David, A. (2016). Health at hand: A systematic review of smart watch uses for 516 health and wellness. Journal of Biomedical Informatics, 63, 269-276.
- [102] Kenney, J. F. and Keeping, E. S. (1962) "Linear Regression and Correlation." Ch. 15 in Mathematics of Statistics, Pt. 1, 3rd ed. Princeton, NJ: Van Nostrand, pp. 252-285
- [103] National Institute of Neurological Disorders and Stroke, Bethesda, MD 20824
- [104] Multiple sclerosis: a preliminary study of selected variables affecting rehabilitation outcome DW Langdon,¹ and AJ Thompson Institute of Neurology, Queen Square, London WC1N 3BG, UK.
- [105] R. A. Clark, A. L. Bryant, Y. Pua, P. McCrory, K. Bennell, and M. Hunt. Validity and reliability of the Nintendo Wii Balance Board for assessment of standing balance. Gait & posture, 31(3):307–310, 2010.
- [106] H. L. Bartlett, L. H. Ting, and J. T. Bingham. Accuracy of force and center of pressure measures of the wii balance board. Gait & posture, 39(1):224–228, 2014.
- [107] Jakob Nielsen, Usability Engineering, Morgan Kaufmann Publishers, 1994, ISBN 0-12-518406-9.

- [108] J Piskorski¹ and P Guzik². Geometry of the Poincarè plot of RR intervals and its asymmetry in healthy adults. *Physiol. Meas.* 28, 2007 287–300.
- [109] Rehab@Home European Union (FP7/2007-2013) under grant agreement n 306113.
- [110] Ulrich, R.S. View through a window may influence recovery from surgery. *Science* 1984, 224, 420-421.
- [111] Grinde, Bjørn, and Grete Grindal Patil. "Biophilia: does visual contact with nature impact on health and well-being?." *International Journal of Environmental Research and Public Health* 6.9, 2009: 2332-2343.
- [112] Hartig, T.; Kaiser, F.G.; Bowler, P.A. Psychological restoration in nature as a positive motivation for ecological behavior. *Environ. Behav.* 2001, 33, 590-607. *Int. J. Environ. Res. Public Health* 2010, 7 1045.
- [113] Maller, C.; Townsend, M.; Pryor, A.; Brown, P.; St Leger, L. Healthy nature healthy people: 'contact with nature' as an upstream health promotion intervention for populations. *Health Promot. Int.* 2006, 21, 45-54.
- [114] Parsons, R.; Tassinary, L.G.; Ulrich, R.S.; Hebl, M.R.; Grossman-Alexander, M. The view from the road: Implications for stress recovery and immunization. *J. Environ. Psychol.* 1998, 18, 113-140
- [115] Ulrich, R.S.; Simons, R.F.; Losito, B.D.; Fiorito, E.; Miles, M.A.; Zelson, M. Stress recovery during exposure to natural and urban environments. *J. Environ. Psychol.* 1991, 11, 201-230.
- [116] Van den Berg, A.E.; Hartig, T.; Staats, H. Preference for nature in urbanized societies: Stress, restoration, and the pursuit of sustainability. *J. Soc. Issues* 2007, 63, 79-96.
- [117] Kaplan, S. The restorative benefits of nature toward an integrative framework. *J. Environ. Psychol.* 1995, 15, 169-182.
- [118] Fredrickson, B.L.; Mancuso, R.A.; Branigan, C.; Tugade, M.M. The undoing effect of positive emotions. *Motiv. Emotion*, 2000, 24, 237-258.
- [119] Laumann, K.; Garling, T.; Stormark, K.M. Selective attention and heart rate responses to natural and urban environments. *J. Environ. Psychol.* 2003, 23, 125-134.

- [120] Alvarsson, Jesper J., Stefan Wiens, and Mats E. Nilsson. "Stress recovery during exposure to nature sound and environmental noise." *International Journal of Environmental Research and Public Health* 7.3. 2010, 1036-1046.
- [121] Ley, Ronald. *An introduction to the psychophysiology of breathing. Biofeedback and Self-regulation*, 1994, 19.2: 95-96.
- [122] Blumenstein, Boris, et al. *Regulation of mental states and biofeedback techniques: Effects on breathing pattern. Biofeedback and self-regulation*, 1995, 20.2: 169-183.
- [123] Tuzemen, Gokhan, et al. "Galvanic Skin Response Test: A New Quantitative Diagnostic Method for Frey Syndrome." *Journal of Craniofacial Surgery* 24.4 (2013): 1280-1284.
- [124] Villarejo, María Viqueira, Begoña García Zapirain, and Amaia Méndez Zorrilla. "A stress sensor based on Galvanic Skin Response (GSR) controlled by ZigBee." *Sensors* 12.5 (2012): 6075-6101.
- [125] Lim, Dae-Woon, et al. "Development of a magnetic resonance-compatible galvanic skin response measurement system using optic signal." *International Journal of Neuroscience* 119.9 (2009): 1337-1345.
- [126] Jankowiak, Katarzyna, and Paweł Korpala. "On Modality Effects in Bilingual Emotional Language Processing: Evidence from Galvanic Skin Response." *Journal of psycholinguistic research*(2017): 1-15.
- [127] Joshi, Anurag, Ravi Kiran, and Ash Narayan Sah. "An experimental analysis to monitor and manage stress among engineering students using Galvanic Skin Response meter." *Work* 56.3 (2017): 409-420.
- [128] Phitayakorn, Roy, et al. "Practicality of using galvanic skin response to measure intraoperative physiologic autonomic activation in operating room team members." *Surgery* 158.5 (2015): 1415-1420.