MIMICS: Multimodal Immersive Motion rehabilitation of upper and lower extremities by exploiting biocooperation principles

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Abstract— The purpose of this paper is to present the newly founded European research project MIMICS. The hypothesis of this project is that movement training for neurorehabilitation can be substantially improved through immersive and multimodal sensory feedback. The approach is real-time acquisition of behavioral and physiological data from patients and the use of this to adaptively and dynamically change the displays of an immersive virtual reality system, with the goal of maximizing patient motivation. In this project two exemplary systems are complemented for robot-assisted rehabilitation of upper and lower extremities. The systems are able to record multi-sensory data (motion, forces, voice, muscle activity, heart rate, skin conductance etc.) and process this data in real-time to infer the intention of the patient and the overall psycho-physiological state. The computed information will be used to modify immersive virtual reality systems including 3D graphics and 3D sound. Experimental tests on humans are underway with expected basic insights into the presence and motivation of humans. Furthermore, MIMICS technology is entering clinical routine so that large patient populations (e.g. stroke, spinal cord injury) can benefit.

I. HYPOTHESIS AND CONCEPT

THE main hypothesis of this project is that neurorehabilitation movement training can be substantially improved through immersive and multimodal sensory feedback in both lower and upper extremities. The Multimodal systems consist from three modalities: haptic to provide sense of touch with virtual environment, visual to provide realistic 3D visual impression and quality sound system. The fundamental feedback loop involves detecting the patient's activities within an immersive virtual environment so that the effects are experienced as meaningful and purposeful rather than just experienced as mechanical training. The second major aspect of feedback is to measure the patient's psycho-physiological state and consequently influence on the multimodal environment. Both loops together represent bicooperative principles. Thus, the technical system would be able to intelligently adapt to the state of the patient in the context of the goals defined by the specific sensory-motor deficit and the resulting interaction between the human and the robot will be more natural and safer.

The idea of this project is to apply a modular framework that is capable of recording, processing, and displaying multimodal information in such way that the patient is supported and motivated to perform the movement training with maximum intensity. The multi-sensorial acquisition of biomechanical and physiological patient information will allow the interpretation of physiological and some aspects of the psychological state of the patient, thus, enabling assessment of their level of motivation. Furthermore, feedback of the recorded information via multimodal display technologies (allowing the patient to move within a virtual environment, manipulate virtual objects, observe the effects of movements and body activity) can not only immerse the patient into a virtual environment that is experienced as realistic but also motivate him or her to perform the training with maximum effort, endurance and fun. Such a multimodal interface allows the employment of a large number of human motor and sensor channels, thus, maximizing the plastic changes in the patient's central nervous system.

A. Objectives

The overall scientific objective of MIMICS is to carry out research that will address the issue of the extent to which patient's sensory-motor rehabilitation is significantly improved through enhanced motivation and engagement arising from a biocooperative feedback.

B. State-of-the-Art and Progress Beyond

Current therapeutic interventions for patients with severe brain injury such as traumatic brain injury or stroke are based on neurofacilitatory techniques, muscle tonus controlling therapies according to Bobath, progressive strengthening, biofeedback or electrical stimulation (e.g.,

[1,2]). Several studies have demonstrated that the outcome of rehabilitation can be significantly improved by task-oriented exercises, intensive therapy, and motivation [3-6].

Although, there is strong evidence that early and intensive exercise therapy enhances functional recovery in stroke and other neurological diseases, current rehabilitation treatment programmes are often shorter and less intensive than required for gaining an optimal therapeutic outcome. The role of motivation is known to be important in the success of neurorehabilitation [7,8].

A large number of robotic platforms have been developed to support the rehabilitation of lower extremities [9-11] and upper extremities [12-15]. Availability of various hardware platforms is demanding adequate control approaches and applications. Current immersive effects are poor since cognitive abilities of patients are not adequately addressed – for example, the sense of presence is not measured or estimated.

Therefore, more and more groups apply Virtual Reality (VR) to support rehabilitation of gait and arm function this way increasing the motivation. Adjusting the level of difficulty to the individual patient's capabilities within a VR task is of crucial importance for cognitive and motor remediation. Virtual environments create a sense of presence [16-19]. The established feeling of presence can be used to motivate and engage the patient in rehabilitation.

In order to properly integrate various sensory cues (visual, acoustic, haptic) and to adequately "dose" the sense of presence to patients a sensory system for assessing the sense of presence is required. This information should be further mapped into adequate changes of haptic, visual and audio primitives. Operationally, presence may be thought of as the extent to which participants in a virtual environment respond and act realistically – as if the virtual sensory data represented real situations and events [20]. Response is considered at many levels ranging from unconscious physiological responses (such as electro dermal activity, heart rate and heart rate variability) through automatic behavioral responses, volitional behavioral responses, through to emotional and cognitive responses, including the sense of being in the scenario depicted in the virtual environment (VE).

Presence was originally defined as the sense of 'being there' in the scenario depicted by the virtual environment display – for example [17,21]. This could be defined in a more operational sense as realistic response to virtual stimuli, where 'response' is considered as multi-dimensional, ranging from low level physiological, behavioral, emotional and cognitive responses. Based on this we consider a number of variables that we would be able to monitor in real-time, each related to this operational approach to presence: arousal and stress (e.g. via electro dermal activity, heart rate, heart rate variability),

involvement, and a fourth variable that can be constructed that we refer to as 'breaks in presence' (Slater and Steed 2000). The final variable is overt behavior.

C. MIMICS Approach

The project is exploiting significant advances in the field of human-machine coordination based on implicit communication from human to machine. Implicit communication is defined as a communication where the psycho-physiological state of the person is interpreted by the machine. States such as stress, anxiety, engagement, and muscle effort are included within the domain of psycho-physiological space that can represented on arousal, valence and physical effort axis [22-27].
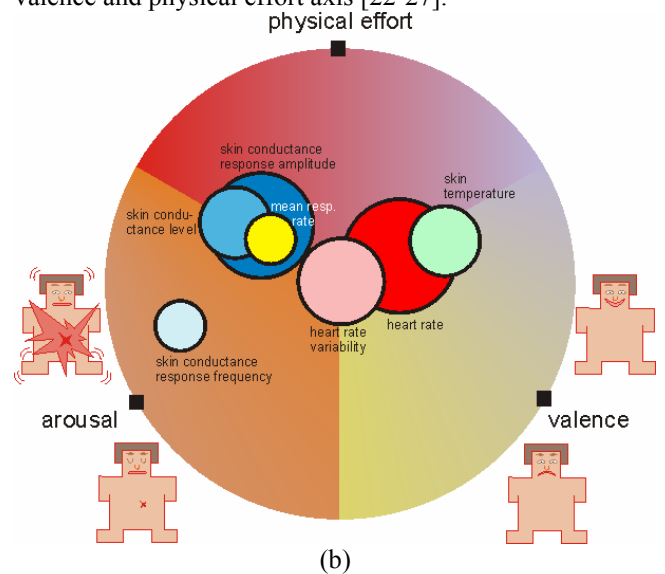

(b)

Fig. 1. The influence of arousal, valence and physical effort on various physiological parameters (circles). The distance of a circle from black square represents the effect that square has on it; the shorter the distance, the greater the effect. The radius of a circle represents variability between subjects; a larger radius means higher variability. Emotional state (arousal, valence) can be assessed through measurement and analysis of physiological parameters (MIMICS measurements).

The human is influenced by multimodal haptic, video and audio streams, causing biomechanical and psycho-physiological effects on the human. The subjects' psycho physiological state is evaluated from physiological signals including ECG via R-peaks, the times between two normal heartbeats (NN intervals), standard deviation of NN intervals as a measure of heart rate variability (HRV), the skin conductance signal is divided into two components: the skin conductance level (SCL) and skin conductance responses (SCRs). Body temperature and variations is measured as well as parameters linked to subject breathing. These measures are reflecting in arousal, valence and physical effort. What project needs to further is to modify accordingly haptic, visual and audio primitives, with this new approach placing the human into the loop (Fig. 2).
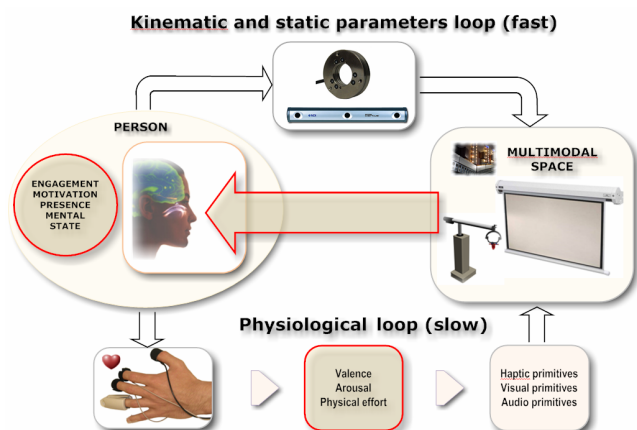
Fig. 2. Robot is enhanced with multimodal virtual environment. Multiple sensors are used to measure user's motor actions and assess his/her emotional state. Acquired data are processed in real-time and a feedback loop is established to be able to adaptively adjust task complexity and optimize the patient sense of presence.

In our approach we use existing rehabilitation robots (Lokomat and HapticMaster) as haptic interface devices. Our devices are improved in such way that they are more compliant and patient-cooperative so that they can react to the patient muscle activity. In this way, the patient will get engaged and motivated to transform visual and auditory information into forces and movements, i.e. haptic interactions executed by the robotic device. The haptic interaction is crucial for a successful motor learning and rehabilitation of the patient.

II. METHODOLOGY

A. Locomat for lower extremities

One of two robotic systems is the Lokomat, which is used for the support of gait during treadmill training (Fig. 3). The Lokomat is a bilateral robotic orthosis that is used in conjunction with a body-weight support system to control patient leg movements in the sagittal plane. The Lokomat's hip and knee joints are actuated by linear drives, which are integrated in an exoskeletal structure [28]. A passive foot lifter induces an ankle dorsiflexion during the swing phase. The legs of the patient are moved with highly repeatable predefined hip and knee joint trajectories on the basis of a position control strategy. Knee and hip joint torques can be determined from force sensors integrated inside the Lokomat.

Fig. 3. Robotic gait orthosis Lokomat including visual and auditory displays.

B. HenRiE for upper extremities

The upper extremity rehabilitation system consists of the haptic interface device HapticMaster (Moog FCS Inc.), a grasping device, a gravity compensation mechanism, a wrist connection mechanism (Fig. 4). The haptic interface allows adequately large reaching movements in three active degrees of freedom. These are coupled to a gimbal with two passive degrees of freedom to allow reorientation of the subjects's hand (hand pronation/supination is constrained). The system is upgraded with a one degree of freedom finger training subsystem (isometric, passive isokinetic) in order to provide grasping, reaching and object carrying capabilities. This results is an upper limb rehabilitation system that allows training of complex ADLs in an adaptive virtual environment.

The patient sits in a chair with his/her arm supported by an elbow orthosis suspended from the overhead frame to eliminate the effects of gravity and minimize the problem of shoulder subluxation. The wrist is placed in a wrist-orthosis connected to the haptic interface. Fingers are placed in cuffs attached to the fingers training subsystem.

Fig. 4. Subject training with HEnRiE: a grasping device is attached to the HapticMaster end-effector, a 3D projection screen is positioned in front of the subject, the elbow cuff links to the arm gravity compensation motor positioned above the subject.

C. Physiology recording system

The ECG is recorded using pre-gelled, disposable surface electrodes affixed to the chest and abdomen. Skin conductance is acquired using a g.GSR sensor (g.tec Medical Engineering GmbH). The electrodes were placed on the medial phalanxes of the second and third fingers of the non-dominant hand using Velcro™ straps. Respiratory rate was obtained using a thermistor-based SleepSense Flow sensor. This sensor is placed beneath the nose and can measure respiration both through the nose and through the mouth. Peripheral skin temperature was measured using a g.TEMP sensor (g.tec Medical Engineering GmbH) attached to the distal phalanx of the fifth finger using medical adhesive tape.

The skin conductance signal is divided into two components: the skin conductance level (SCL) and nonspecific skin conductance responses (SCRs). Mean respiratory rate is calculated in breaths per minute. Respiratory period and variability are calculated from consecutive peaks in the respiration signal. Analysis of the ECG began by extracting the R-peaks. This is leading to heart rate, heart rate variability, the standard deviation of NN intervals (SDNN), the square root of the mean squared differences of successive NN intervals (RMSSD) and the number of interval differences of successive NN intervals greater than 50 ms divided by the total number of NN intervals (pNN50) were calculated. In frequency-domain analysis is applied the power spectral density (PSD) analysis with two frequency bands of interest: the low-frequency band (LF) between 0.04 Hz and 0.15 Hz and the high-frequency band (HF) between 0.15 Hz and 0.4 Hz. Parameters include total power in the LF band, total power in the HF band and the ratio of the two (LF/HF ratio). Peripheral skin temperature is calculated as average of five seconds.

III. SAMPLE SCENARIOS

A. Lower Extremity Scenario: Walk through a City Environment

A typical sample scenario could be a stroke patient running performing treadmill training in the Lokomat. Angular positions, forces, EMG signals, and other physiological data (e.g. heart rate) are measured and transferred to the Lokomat controller and the multimodal processing unit. Model-supported data processing is applied to drive a virtual 3D audiovisual scenario based on the data recorded from the patient. On a 3D graphical display the subject sees how he walks through a virtual city environment, where he has to solve different tasks such as stepping over obstacles, kicking a ball, crossing a narrow bridge over a deep canyon, crossing a street with a traffic light, walking with increased friction through deep water or snow, walking up/down a virtual ramp etc. Realistic forces are produced in order to provide a realistic haptic feeling. Other modalities such as wind can be added to generate a highly realistic scenario leading to an increased feeling of presence.

The patient can be depicted as virtual character or he can be given an egocentric viewpoint, and see the environment and parts of his own body as in everyday life. The patient can give voice commands in order to adapt the settings to his preferences and therapy status. Sound is produced indicating, if he walks in the right speed with a physiologically correct pattern. The sound can be modulated in order to inform the patient, whether he does move in the desired way. The environment can adapt according to the overall state of the patient (degree of stress for example) as estimated from the physiological data. For example, as the patient becomes more stressed the displayed scenario can adapt to try to bring him or her back to a more relaxed state. The motivational goals of the subject will be social ones – for example, satisfying curiosity as to what a crowd of people at the end of the street are observing, or the desire to continue a conversation with an attractive character located at the end of the street.

Fig. 5. Presentation of subject walking within the city scenario.

B. *Upper Extremity Scenario: Virtual Therapist (VPT)*

The training scenario is implementation of a virtual physiotherapist. The patient sits in a chair with his hand attached to the HEnRiE end-effector. The weight of the arm is partially compensated using active gravity compensation system. The grasping device is attached to the robot end-effector and the patients is able to grasp the device with thumb on one side and index and middle fingers on the other side. A 3D projection screen is positioned approximately 1m away from the patient (across the robot from the patient). Sound speakers are positioned around the patient in order to provide audio surround.

A virtual physiotherapist is presented in 3D mode on the screen in front of the subject. Quality rendering is used to provide realistic look. Out-of-screen effect is such to enable the VPT's hand to virtually reach patient's hand attached to the robot end-effector. The robot produces the haptic feedback simulating the forces produced by the VPT on the patient's arm/hand.

The VPT (actually the robot) can passively move the patient's arm, it can provide active resistance, generate disturbances, constrain movements, guide movements, indicate directions. The VPT haptic behavior is based on a set of control primitives: preprogrammed trajectories, impedance based virtual tunnels, force fields, and force pulses for disturbances. The expected performance values are expressed as biomechanical and physiological reactions (speed of movement, range of motion, force direction and magnitude, grasp and arm movement coordination precision of movement), cognitive behavior (coordination and accuracy, planning of movements), and psychological reactions (joy/relaxation when successfully accomplishing the task).

Fig. 6. Virtual physiotherapist experimental setup - 3D projection screen (white) with a virtual physiotherapist projected in 3D, HapticMaster robot with haptic grasping device, person doing exercise with the virtual physiotherapist.

IV. CONCLUSIONS

The state of the art rehabilitation systems were designed so far in the project to positively influence the outcome of the rehabilitation period through more effective therapy especially by motivating the patient with a multimodal haptic, visual and audio display and his active involvement in the therapy.

Locomat allows for complex walking exercises and HEnRiE allows training of complex reaching and grasping movements, while the VPT scenario provides suitable platform for rehabilitation. Real-time acquisition of behavioral and physiological data from patients and processing allows to adaptively and dynamically change the displays of an immersive virtual reality system, with the goal of maximizing patient motivation. Having the system build, can in the sequence be studied the methods of psycho-physiological signal analysis in normal and patients and effects of various haptic, visual and audio primites on these measures.

The proposed automated rehabilitation system may provide one possible direction of development of future rehabilitation systems.

V. ACKNOWLEDGEMENTS

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