MIMICS: Publishable Summary II

Multimodal Immersive Motion rehabilitation with Interactive Cognitive Systems

1 Project goals and objectives

The main 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 behavioural 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 maximising patient motivation. The overall objective of MIMICS is to significantly enhance existing robot-assisted rehabilitation methods with multi-sensorial acquisitions, multimodal displays and technical cognition so that the patient's motivation, expressed by participation (physical activity) and mental engagement, can be improved leading to a more intensive training and to an improved therapeutic outcome. Following objectives were in the focus of the reporting period (2nd project year):

- Development of multi-sensorial data acquisition and integration methods based on recording of sensory-motor actions and physiological measurements.
- Development of a machine learning system to match the psycho-physiological state of the user with the ongoing action inside a virtual environment.
- Downscaling the "maximal configuration" rehabilitation systems for upper and lower extremities to "minimal configuration" systems with optimal function, usability, and maximal benefit for the patient based on experimental evaluations.
- First evaluation studies on healthy subjects and single patients to test the effect of increased motivation in terms of physical effort and mental engagement.

2 Work and results so far

2.1 WP1: System specification and hardware set up

Maximal configuration hardware setups for the upper and lower extremities were already developed in the first year and formed the basis for the proceeding steps (i.e., downscaling, use for the first experimental studies on humans). The main system components for the rehabilitation of upper extremities at UL are the HapticMaster robot, with additional axes for arm gravity compensation and training of grasping, 2D projection system, surround sound system and a system for measuring psycho-physiological signals. The complete system for therapy of the lower extremities (ETH Zurich and NKBA) consists of the robotic device Lokomat, a body weight support system, an automatic treadmill, a 2D projection system, a surround sound system and a system for measuring psycho-physiological signals. For the online detection and assessment trials of psycho-physiological activities during arm and gait training we downscaled the maximum configuration systems to simplified systems, which were comprised by the following recording functions: skin conductance, skin temperature, electrocardiogram (for recording of heart rate and heart rate variability), breathing frequency, joint angles, and interaction torques.

2.2 WP2: Multimodal immersive interactive display environments

Audiovisually rendered scenarios have been further developed for both upper and lower extremities at UL, UB, and at ETH Zurich in close collaboration with HOCOMA with challenging tasks for the participants (Figure 1).

In the lower extremity setup an avatar of the patient walks on a parcour, where he or she has to solve different motor and cognitive tasks. Two new scenarios have been developed, 1) where the subject walks within a city scenario and 2) where the subject walks along a forest trail (Figure 1, left), which also includes a narrow bridge over a canyon. The level of arousal and valence can be affected by changing the weather atmosphere (sun, rain, thunderstorm), the surrounding actions (animals appearing in the forest, dog walking on the trail), the shadow of a large creature appearing from the back, the height or width of the bridge, different background sounds and music etc.. The active participation expressed by physical activity and mental engagement, can be influenced not only by these features but also by the choice and difficulty of a task given to the subject (e.g. collecting balls by changing walking direction, jumping over moving obstacles, increasing walking speed to collect coins or decelerating gait to avoid collisions with rocks). The new scenarios were implemented in both clinical environments at Balgrist University Hospital (ETH Zurich) and the Neurological Clinic Bad Aibling (NKBA).

In the upper extremity scenario three different multimodal virtual scenarios have been developed for the HapticMaster including 1) a simple pick-and-place task, in which apples falling from a tree have to be picked up and placed into a crate, 2) a slope with a ball rolling down to be catched by the subject (Figure 1, middle), and 3) a river scenario, where the subject has to perform three different physical and mental tasks dealing with a bottle floating in the river. All the scenarios offer a variety of simple or complex tasks of physical activity (with different haptic primitives, difficulty levels, speeds, sizes of objects etc.) and psycho-physiological challenges (a variety of video, audio and quiz primitives). The scenarios offer all active haptic support options. The user can choose among different types of music (rock, pop, folk music, classical, instrumental) depending on his or her preferences and mood. UL generated a music database to be applied for the training scenarios and to investigate the effect of sound (tempo, mode, pitch, harmonics etc.) on arousal and valence.

At UB a city environment with streets and points of interest has been developed. A large scale collision detection algorithm allows a user to navigate within the city in a realistic manner with the system responding correctly if the user tries to go through a building. In order to assess whether reinforcement learning can be used to create a situation where a virtual character is able to affect the behaviour of participants, the concept of proxemics is being introduced dealing with the issue of interpersonal distances. Taking advantage of this theory, the goal was to get the participant to move 30 meters backwards from a virtual character within the city scenario. A second part of the UB activities deals with body ownership illusions, based on the rubber hand illusion and other similar paradigms. In MIMICS, the patient ultimately will not be wearing a head-mounted display, and therefore their avatar will be displayed on a screen. It is our hypothesis that there will be a stronger identification with the avatar when there is a chord connecting the person to their virtual representation (Figure 1, right). In a third experiment, UB investigates the effect of facial expressions of an avatar on the physiology of the user in the same environment. Reinforcement learning is now being applied to manipulate the emotional state of participants depending on the facial expressions of the virtual characters. The goal within MIMICS is to be able to help determine the affective state of participants, to make sure for, example, that they are not becoming too stressed in carrying out their tasks.

Figure 1 New virtual scenarios for the lower extremity training setup (ETH Zurich and Hocoma), the upper extremity training setup (UL) and the presence study setup (UB) as developed in year 2.

In December 2009, the ARMEO$^{®}$ was delivered to UL and setup by Hocoma. The river scenario has been successfully transferred to the ARMEO and thoroughly tested. Since the ARMEO does not support active haptics, no haptic feedback can be provided. All other options in the river scenario are fully functioning. The ARMEO platform will be moved to the Institute for Rehabilitation in the beginning of 2010. Another ARMEO system will be available at NKBA for the clinical investigations planned.

2.3 WP3: Multi-sensorial data processing and decision making

All algorithms for acquisition and processing of physiological and motor data have been developed and tested. Basic connections have been established between physiological data and psychological states. Mechanical and psycho-physiological sensor data of the Lokomat (ETH Zurich) and the HapticMaster (UL) platforms have been successfully obtained and processed. Algorithms for real-time acquisition and processing of physiological data have been jointly developed by UL, ETH Zurich and UB. Large differences in baseline values of several physiological parameters were found among subjects.

The following data analysing methods have been developed to be used for different investigations on humans: 1) Motor action analysis (pick and place time, work performed, power transitions, linearity and jerk of movements, applied for upper extremity experiments at UL). 2) Heart rate model for control of heart rate in the Lokomat (ETH Zurich, UL, NKBA). 3) Automatic learning systems for adaptive haptic support including adaptive discriminant analysis (UL). 4) Basic reinforcement learning library and closed-loop applications for the purpose of automatic decision making (UB and UL). 5) Statistical methods and principal component analysis (PCA) employed to extract the main features out of the physiological recordings that carry information on the psychological state of a subject (UL and ETH Zurich).

The developed methods yielded the following results: 1) Patients prefer haptic feedback to be combined with auditory feedback. 2) The heart rate model is able to differentiate between physiological and psychological changes in heart rate. It was successfully implemented in a heart rate controller for healthy subjects. 3) Automatic learning systems adjust haptic and auditory features of the virtual environment based on movement kinematics and dynamics. 4) Reinforcement learning is based on the principle of rewarding actions that achieve a predefined goal. These goals are defined by the designer of the system. The algorithm then aims to maximise the long-term reward by choosing appropriate actions. The developed algorithm can be trained before being used in experiments in order to reduce the initial learning phase. The learning can continue while the experiment is progressing, adjusting the real-time algorithm according to each individual participant. This capability of the algorithm can respond to changes in the behaviour of the user. This learning system was integrated into the HapticMaster ball-catching task developed by UL in order to create a psycho-physiological feedback loop. 5) As a result of the PCA, we were able to identify the signals, which explained most of the variance. A new classification was performed using only the physiological signals dominant in the first principal components. ETH Zurich and UL together investigated whether the PCA of psycho-physiological parameters could be adapted for use with the HapticMaster. While the principal component analysis had some success, it was very prone to overfitting, and it was decided to focus on other options for psycho-physiological analysis in the HapticMaster platform.

2.4 WP4: Experimental evaluation

With the downscaled technical systems of the Lokomat and HapticMaster platforms, first trials on healthy subjects and patients could be performed at ETH Zurich, NKBA, and UL supported by UB.

With the Lokomat setup open and closed-loop studies could be performed. In the open-loop study I, it was investigated how audiovisually generated situations with different psychological states (bored, challenged, and overchallenged) influence the recorded physiological reactions. The results were then used to control physiological states to a desired value using biomechanical and audio-visual stimuli (studies II a-d). These closed-loop studies comprised the following conditions: a) heart rate of healthy subjects and patients was controlled to desired reference values via a biomechanical stimulus treadmill speed; b) power expenditure during Lokomat walking was controlled to desired reference values via stimulus treadmill speed; c) “biofeedback” (i.e. therapeutically desired power expenditure) during Lokomat walking was controlled to desired reference values via a visual stimulus (instruction); d) heart rate during Lokomat walking was controlled to a desired reference trajectory via a visual stimulus (stimulus).

Results of the open-loop study I (17 healthy and 10 subjects with stroke and other neurological gait disorders) showed that the different difficulty levels of the virtual task caused a significant change not only in recorded physiological signals but also in self-reported measurements. The three desired psychological states could all be induced. Furthermore, it was shown that the different psycho-physiological states were significantly different from each other in at least 1 measured parameter in healthy subjects (ETH Zurich). However, measurements in severely affected patients (NKBA) revealed that the task was originally too demanding. Therefore, a second, less demanding VR scenario was developed and tested on ten healthy and ten stroke subjects. Data analysis is still in progress. The closed-loop studies II a-d were all successful, when applied to healthy subjects (tests with 5 subjects per condition). In contrast, patients showed a larger variability and, in average, smaller effect on heart rate (II a, 12 patients), so that only a fraction of about five patients could use the heart rate controller. So far, we could successfully show on healthy subjects that physical effort can be controlled by biomechanical and audiovisual stimuli. Further tests on patients are on their way.

NKBA examined the influence of medication in a typical clinical patient collective on heart rate and heart rate variability (retrospective analysis of 300, 24-hour ECG measurements). For the majority of substance classes, no significant effect could be demonstrated, implying that including patients with these medication patterns in study collectives and analyzing HRV should render accurate data. In order to evaluate the intrinsic motivation of our patients, a 24-item version of the Intrinsic Motivation Inventory (IMI) was chosen to assess effort/importance, value/usefulness, interest/enjoyment, perceived competence and pressure/tension of the performed tasks. This allowed us to test the feasibility of the setup and to modify the scenarios and better adjust the difficulty level of the gait scenarios to the stroke patients (N=15). A high level of motivation could be detected in the patients.

A large study was carried out by UL (at subcontractor Institute of Rehabilitation of the Republic of Slovenia – IR-RS) using the minimal HapticMaster configuration in order to test the effectiveness of the first haptic support system and determine whether stroke subjects exhibit useful psycho-physiological responses to the ball-catching scenario in a clinical setting. The extensive clinical trial comprised 53 subjects divided into three groups: a control group (N=23), a subacute stroke group (N=23), and a smaller chronic stroke group (N=7). All three groups performed different ball catching tasks and underwent two sessions in order to determine, whether psycho-physiological responses are repeatable. Results of psycho-physiological analyses showed that stroke patients exhibit significant responses to both cognitive and rehabilitation tasks, but that differences between patients and healthy controls do exist. This study showed that skin conductance is recommended as the most important psycho-physiological signal in rehabilitation robotics, with other signals providing supplementary information. Furthermore, stroke patients do exhibit psycho-physiological responses that are not caused only by physical workload, but also by cognitive workload. Further studies were performed at UL in order to investigate whether background sounds affect subjects' physiological state (13 healthy subjects showing no clear dependency) and to test the influence of haptic primitives on kinematics and dynamics of arm movements (12 healthy subjects, showing that a heavier ball required much more effort and resulted in more regular pick-and-place movements). In another study with seven healthy subjects, a physiological feedback loop was successfully constructed as it was possible to keep the skin conductance level within a certain range while also keeping the user's performance above a certain threshold. Last not least, it was shown with 33 healthy subjects that adaptive discriminant analysis performed successfully with either task performance, motor actions or psycho-physiological stimuli as inputs.

2.5 Dissemination, exploitation and management

Our public web site of the project (www.mimics.ethz.ch) was continuously updated and our project flyer was distributed. A scientific symposium was organised in February 2009 together with Hocoma as main organizer (www.inrs2009.com). More than 350 attendees participated and the general feedback of the symposium was tremendously good. All deliverables and achievements of milestones have been on time. One internal newsletter was distributed to the consortium within this second project year. Only within this period, eight scientific peer-reviewed journal publications, 16 conference contributions and about three media reports in newspapers and on television have been published. The work of this phase was presented in 17 invited and plenary talks. Furthermore, three patents were applied covering the technological basis of the feedback concept and systems of this project.

3 Potential impact and use

The novel systems being developed in MIMICS will autonomously assess the actual psycho-physiological state and motor actions of the user. This will be the basis to increase the patient's sense of presence, engagement and motivation, which should finally enhance rehabilitation outcome. The capability of the machine to alter its behaviour based on human physical interaction and emotional state will be a hallmark of a successful patient-centred robotic rehabilitation system that can be transferred to other areas of human-robot and human-computer interactions. Besides those scientific and technological outcomes, MIMICS will produce a large portion of novel clinical expertise and scientific results in the area of robot-assisted rehabilitation. Gait training in stroke patients is the most important task to enable the patients return to their home self-dependence. Current treatment relies heavily on manual assistance by therapists. Improvements of therapeutic outcome of rehabilitation training might be achieved by increasing the sense of self-control and effort by the patient through awareness and challenge in the training process. The proposed project analyses the contributions of this additional variables to the process of relearning gait. Unique is the approach of combining leaders in technology and neurorehabilitation medicine. Therefore, the scientific basis of locomotor training should be broadened through a combined view.

Coordinator contact details

Prof. Dr. Robert Riener
ETH Zurich & University Hospital Balgrist
Tannenstr. 1, CH-8092 Zurich, Switzerland
Tel.: +41 44 632 66 79, Fax: +41 44 632 12 11
Email: riener@mavt.ethz.ch

SEVENTH FRAMEWORK PROGRAMME