

# Emotion-Aware System for Upper Extremity Rehabilitation

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**Abstract**—Immersive and multimodal sensory feedback was implemented to improve neurorehabilitation movement training. A major aspect of feedback is to reflect back the patient’s psychophysiological state into the environment, and also to use this as a guidance mechanism as to how events within the virtual environment unfold. The virtual environment was constructed using haptic, visual and acoustic primitives (basic sets of changes applied to the multimodal virtual environment that are expected to change the psychophysiological state of the patient). State transitions between primitives are defined as a response to changes in the user’s psychological state and motor performance. The mapping of biomechanical and physiological measurements to motor performance and psychological state and then to changes in action primitives was implemented using a fuzzy-logic system.

**Keywords** - rehabilitation robotics, psychophysiology, emotion-aware system, valence-arousal model

## I. INTRODUCTION

Motor recovery after stroke or traumatic brain injury is a dynamic process that usually starts with a total incapacity to move the affected limb followed by development of some imprecise movements. These movements become more precise after some time, but sometimes stiffness and involuntary activity hamper the return to functionality. Several studies have demonstrated the efficacy of different training therapies for arm paresis in stroke patients [1, 2] and that task-oriented therapies are important to improve the function of the affected arm [3]. There is evidence that machine delivered therapies can be effective in progressing the treatment [4]. Robotic devices are capable of reaction times far in advance of any human, which opens up the breadth of possible treatments, where robotic device responds to forces generated by the patient. For people with upper limb paralysis it is possible to consider therapies where intelligent assistance from a robot is able to provide varying degrees of compensatory movements for the affected limb. At the same time evidence indicates that where patient is motivated and premeditates his movement, the recovery is more effective. Intelligent machines allow a broad scope to investigate these conditions. Various robotic devices have been constructed that enable investigation of the above mentioned rehabilitation strategies. MIT Manus robot was upgraded with wrist functionality to allow training of complex movements [5], GENTLE/S robot system based on HapticMaster device (Moog

FCS Inc.) was upgraded with device for training of reaching and grasping [6], ARMin robot was developed that allows training of complex activities of daily living (ADLs) [7]. However, though motivation and engagement have been identified as important factors for the outcome of the rehabilitation process, robotic devices still lack the intelligence required to assess and influence these parameters.

The hypothesis is that neurorehabilitation movement training can be substantially improved through immersive and multimodal sensory feedback. The fundamental feedback loop involves detecting the patient’s activities within an immersive virtual environment (VE) so that the effects are experienced as meaningful and purposeful rather than just as mechanical training. The second major aspect of feedback is to reflect back the patient’s psychophysiological state into the environment, and also to use this as a guidance mechanism as to how events within the VE unfold. 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. The resulting interaction between the human and the robot would thus be more natural. Fig. 1 summarizes the basic idea.

In such a system, the multi-sensorial acquisition of patient’s biomechanical and physiological information allows the interpretation of motor performance and some aspects of the psychological state of the patient, thus enabling assessment of their level of motivation and engagement. Furthermore,

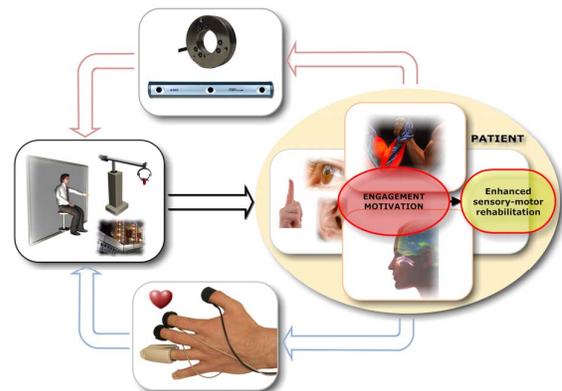


Figure 1. The robot is enhanced with an immersive multimodal virtual environment. Multiple sensors are used to measure user’s motor actions and assess his/her emotional state. Acquired data are processed in real time and a feedback loop is established to adaptively adjust task complexity and optimize the patient’s sense of presence in order to increase engagement and motivation.

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feedback of the recorded information via multimodal display technologies consisting of visual, acoustic, and haptic modalities (allowing the patient to move within a VE, manipulate virtual objects, observe the effects of movements and body activity) can not only immerse the patient into a VE that is experienced as realistic but also motivate him or her to perform the training with maximum effort, endurance and fun.

There is now a vast body of literature on the two key concepts of virtual environments, immersion and presence [8, 9, 10]. Immersion is a description of a technology that ideally delivers a real-time computer generated surrounding, stereo, high resolution, high frame-rate, low latency virtual world in multiple displays (visual, auditory, haptic), determined as a function of head-tracking and full body tracking. Such systems have a high degree of interactivity where the participant's body is paramount in the interface – for example, to pick up a virtual object from the virtual ground, the participant may bend down and reach out for it, rather than manipulate objects with a mouse [11]. Such immersive systems may give rise to presence. Operationally, presence may be thought of as the extent to which participants in a VE respond and act realistically - as if the virtual sensory data represented real situations and events [12]. Response is considered at many levels ranging from unconscious physiological responses (such as electrodermal 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 VE.

Psychophysiology, the study of physiological phenomena as they relate to behavior, relies on the assumption that information about a person's psychological state in a particular situation can be obtained from physiological processes. Psychophysiology has been used to assess responses to many types of virtual environments, especially therapeutic virtual reality (VR). Subjects' physiological responses were monitored in order to determine their engagement, their therapy progress and the similarity of VR therapy and real-world therapy. It was found that VR therapy is generally highly effective and that physiological responses can even be used to gauge the effectiveness of the therapy. For instance, skin conductance has shown quick reactions in response to phobic stimuli, but these reactions become smaller and smaller over the course of treatment as desensitization occurs [13]. Similarly, heart rate has shown differences between phobic and non-phobic subjects in response to phobic stimuli [14]. Psychophysicists have also found evidence that emotions experienced while playing computer games are reflected in physiological responses and that this could be used to determine a person's level of enjoyment or frustration while playing [15]. However, though many studies have been done to identify emotions in controlled situations, far fewer studies have actually acted upon this information. If we can identify a person's emotions while they are engaged in an artificial environment, the logical next step is to use that information to modify the environment and make the experience more pleasant for the user. For instance, if a subject is bored by a computer game, it would be possible to increase the difficulty during game play. Alternatively, if VR phobia treatment is proving too stressful for a patient, the frequency or intensity of phobic stimuli can be lowered or the

session can be terminated. With the use of psychophysiological responses, this could be done automatically, without volitional input from the subject or anyone else.

The paper focuses on estimation of users' physiological state in a rehabilitation environment through measurements of physiological responses. An adaptive virtual exercise environment is proposed where the intensity of practice can be consistently and systematically manipulated to create the most appropriate motor learning approach.

## II. METHODS

Motor improvement during movement exercise is commonly achieved by applying tasks of increasing difficulty in combination with physical or verbal guidance of the patient's actions. Thus, integrating the means to modulate the level of difficulty within a VR task is of utmost importance.

The rehabilitation system used in this study is based on the development of the GENTLE/S project [16]. A robotic device for rehabilitation of upper extremities enables simultaneous distal and proximal movement training. It consists of the haptic interface device HapticMaster (Moog FCS Inc.), a grasping device, a gravity compensation mechanism, a wrist connection mechanism, a 3D visualization system and a Dolby surround sound display. The system shown in Fig. 2 is augmented with sensors for physiological signal measurement that enable estimation of user's psychological state.

### A. Emotion model

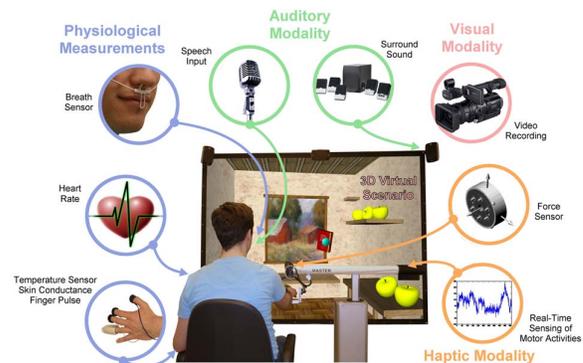


Figure 2. Experimental setup consists of a HapticMaster robot with a haptic device for training of grasping, stereoscopic projection system and surround sound system; sensing includes measurement of physical interaction between the patient and the robot (forces, positions, accelerations) and sensors for measurement of patient's physiological responses (heart rate, skin conductance, breathing).

In order to meaningfully study emotions, any psychophysiological study must decide how the observed emotions are to be categorized or structured. Two main approaches are possible: a discrete approach, claiming the existence of universal 'basic emotions' [17], and a dimensional approach, assuming the existence of two or more major dimensions which are able to describe different emotions and to distinguish between them [18]. Though attempts have been made to combine the two, there is still major controversy as to which approach best captures the structure of emotion. In the

field of human-computer interaction, the two-dimensional arousal-valence model has recently been suggested as a relatively simple, yet effective model of emotions suitable for designing emotion-aware systems [19, 20]. In this model, an emotion is represented by two independent variables. Arousal represents a person's general level of mental activity (sleepy at one extreme and focused on the other) while valence indicates whether the person's feelings are positive or negative (miserable at one extreme and happy at the other). Within a complete set of all physiological measurements, we chose a subset, which we considered relevant for rehabilitation purposes: heart rate, heart rate variability (HRV), skin conductance level, skin conductance responses (SCR), respiratory rate and skin temperature are easily recordable and provide meaningful data for assessment of valence and arousal.

However, the usefulness of emotion-aware systems decreases in situations that require physical activity (such as rehabilitation), as many physiological responses are significantly affected by it. Skin conductance level and respiratory rate are affected even by mild activity. While the frequency of nonspecific skin conductance responses does not increase significantly for mild movement, alternative psychophysiological methods have to be used for emotion-aware systems in situations that require strenuous physical activity. In order to be able to properly interpret physiological signals, keeping track of physical activity (such as force sensors or muscle electromyography) is of utmost importance. Fig. 3 shows a sketch of how arousal, valence and physical effort affect the physiological parameters in question. The sketch is a result of study that examined physiological responses of 50 subjects to an inverted pendulum balancing task performed in a VE using two different haptic interfaces [21]. The Phantom Premium (SensAble Technologies, Inc) interface required only slight movement of the lower arm while the HapticMaster (Moog FCS) interface required movement of the entire arm and actively resisted movement. Additionally, a control task was performed with both haptic interfaces where the participants moved their arm in the absence of a VE.

In order to maximize the rehabilitation outcome, the three parameters shown in Fig. 3, arousal, valence and physical effort, have to be maximized, where maximization of physical effort has to be done in accordance with specific patient's motor performance. This leads to a multiple input-multiple output system where arousal, valence and motor performance are the variables to be controlled by modifying the virtual exercise parameters. From this perspective, the output of the system is an element of a three-dimensional space. In a simplified version, the three output variables present three orthogonal axes (in reality arousal, valence and motor performance are not independent of each other).

### B. Virtual task for upper limb rehabilitation

Virtual task provides the platform to control the user's psychological state and motor performance. Thus, it must allow a varying degree of physical activity as well as interaction with the VE that influences emotions. A detectable emotional response is possible as a result of social interaction, which is therefore implemented as an integral part of the scenario.

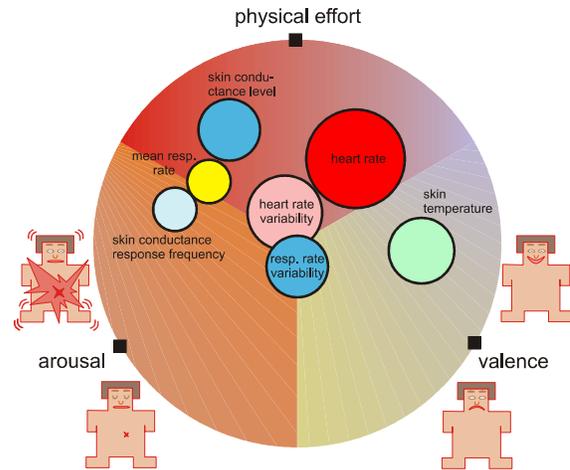


Figure 3. The influence of arousal, valence and physical effort on various physiological parameters (circles). The distance of a circle from a black square represents the effect that square has on it; the shorter the distance, the greater the effect. The radius of a circle represents variability between subjects; a larger radius means higher variability. Emotional state (arousal, valence) can be assessed through measurement and analysis of physiological parameters.

The virtual task is a combination of dynamic tracking of objects with arm movement and catching and grasping of objects. The basic scenario consists of a table with adjustable inclination and a ball that rolls from the opposite side of the table toward the patient. A more complex environment is enhanced with avatars that enable social interaction: a rival sits at the opposite end of the table, while spectators at both sides of the table cheer either for the patient or the opponent. The patient needs to catch and grasp the ball, place the ball in another location or push it back to the rival. A snapshot of the scenario is shown in Fig. 4. Various levels of robotic support are available to the patient. In order to ease lifting of objects a weight compensation is implemented. Catching of a rolling ball can be assisted by the robot, which moves the arm in the correct position with adaptable support. For patients with strong paralysis virtual tunnels are implemented, which guide the patients arm along the tunnel trajectory.

In order to control the users' psychological state and motor performance, actions are taken based on patient's estimated psychological responses and quality of physical interaction with the VE. Actions are grouped into action primitives and represent basic sets of changes applied to the multimodal VE that are expected to change the psychophysiological state of the patient. Action primitives must allow changes of psychological state and motor performance in a three-dimensional valence-arousal-motor performance space, preferably influencing each dimension independently of the other two. However, the interplay between motor performance, arousal and valence is such that completely independent influencing of each dimension is not possible.

### C. Groups of action primitives

The multimodal display shown in Fig. 2 consists of three modalities through which the subject perceives the VE: haptic, visual and acoustic. Activation of action primitives needs to reflect in changes in valence-arousal-motor performance space.



Figure 4. Snapshot of a basic game scenery (patient's view of the scene). The avatar at the opposite end of the table is the opponent. Other avatars are fans that encourage either the patient or opponent. Red cones and sphere represent the patient's end-effector.

While the visual and acoustic modalities mainly influence valence and arousal, the haptic modality influences all three dimensions through its physical interaction with the subject.

Action primitives are grouped based on the modality through which they are mediated to the user. This results in three groups of primitives: *haptic*, consisting of seven basic primitives (obligatory collisions with the environment), *visual*, consisting of five basic primitives (obligatory basic game scene), and *acoustic*, consisting of six basic primitives (obligatory basic game sounds). Basic primitives are combined into groups of action primitives. Combinations feasible from the technical and psychophysiological point of view are considered:

1. Haptic primitives are primarily linked to the patients' motor responses and their influence on the psychological state is regarded as a disturbance. This means that haptic primitives are chosen based on the assessed motor performance of the patient. The only haptic primitive not related to motor performance is the rival primitive, which requires minor changes in motor activity, but results in different emotional responses.
2. Visual and acoustic primitives are primarily linked to the user's emotional state. They do not influence motor performance directly, only through their instructional nature. In order to reduce complexity, visual primitives were chosen in such a way as to primarily influence valence, while acoustic primitives, on the other hand, mainly influence arousal.
3. Though the proposed separation of primitives and their relations to motor performance, valence and arousal are in no regard ideal, they enable basic control of psychological state and motor performance.

Combinations of haptic, visual and acoustic primitives are shown in Fig. 5, 6 and 7.

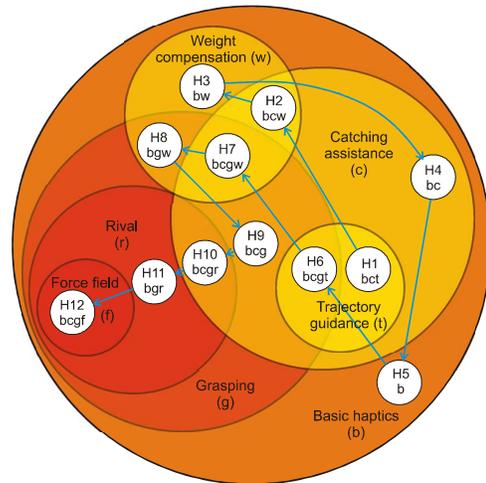


Figure 5. Haptic action primitives and their state transitions from simple to challenging: basic haptics for collisions with the environment (b), arm weight compensation (w), virtual tunnel for trajectory guidance (t), horizontal assistance for catching the ball (c), force field for disturbances (f), grasping modality for training of finger functions (g) and a rival (r), which adds a more social component to the game. Primitives indicated with yellow circles make task easier, primitives indicated with red circles make tasks more challenging. White circles indicate haptic states (combinations of primitives), blue arrows indicate state transitions from simple to challenging.

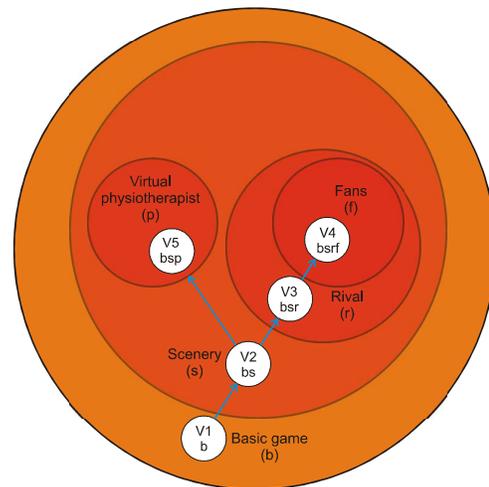


Figure 6. Visual action primitives and their state transitions in order to predominantly increase valence: basic game scenario (b), sophisticated room environment with animations (s), a rival to play against and add a social component (r), fans who support the patient or rival (f), and a virtual physiotherapist to assist the patient's movements (p). White circles indicate visual states (combinations of primitives), blue arrows indicate state transitions to increase valence.

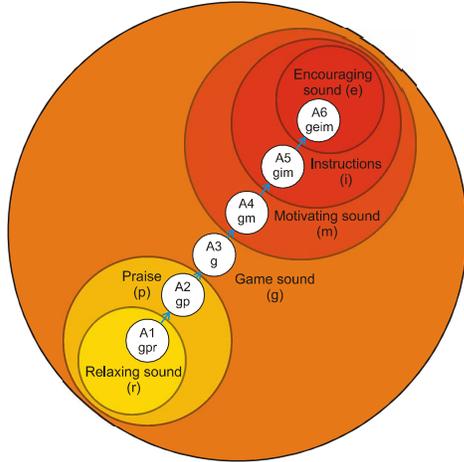


Figure 7. Acoustic action primitives and their state transitions in order to predominantly influence arousal: relaxing sound played as music (r), praising statements when subject successfully accomplishes task (p), basic game sounds (g), motivating sound in the form of music or speech (m), instructions to guide the patient (i), encouraging sound to additionally motivate the patient. White circles indicate acoustic states (combinations of primitives), blue arrows indicate state transitions to increase arousal. Primitives indicated with red circles primarily increase arousal, primitives indicated with yellow circles primarily decrease arousal.

#### D. Mapping physiological and motor signals to action primitives

The feedback loop that enables adaptive adjustment of task complexity and optimization of the patient's sense of presence as indicated in Fig. 1 requires mapping from physiological and motor signals to action primitives. The system being addressed is a multiple input-multiple output, nonlinear, time varying and non-deterministic, which makes the addressed mapping problem non-trivial. Reinforcement learning, artificial neural networks and fuzzy logic systems were considered for this task. The first two options require relatively large training sets, which were not available immediately. Therefore, a fuzzy logic system was implemented in two stages: the first stage maps physiological and motor signals to psychological state and motor performance, while the second stage maps changes in psychological state and motor performance to action primitives. A block diagram of the fuzzy system is shown in Fig. 8. Psychological state is detected as an absolute value, as well as a change of arousal and valence in a positive or negative direction. Membership functions for detection of psychological state and motor performance are too complex to be shown in the paper. Decision making in arousal, valence and motor performance estimation is accomplished by if-then rules of the form:

if ((*skin conductance freq. response* = "constant") AND (*std. deviation of respiratory rate* = "increasing")) AND (*skin temp.* = "constant") then (*valence* = "decreasing")

Changes in psychological state are required to plan transitions between states representing combinations of action primitives. In general, no change or positive change of psychological state does not require any changes in action primitives. There are two exceptions to this: 1) if the absolute

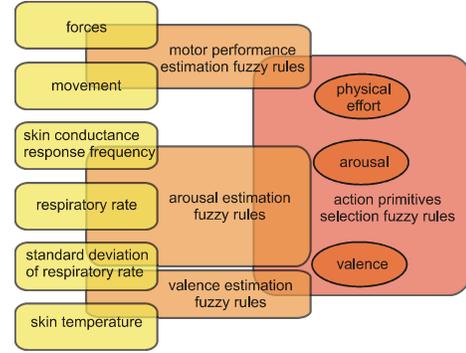


Figure 8. Two stage fuzzy logic model for mapping physiological and motor signals to action primitives.

value of arousal is too high, it must be decreased and 2) if arousal or valence are too low, they should be increased. Summary of fuzzy rules are as follows:

1. if (*motor performance* = "good") then (*action* = "next haptic state")
2. if (*motor performance* = "medium") then (*action* = "keep haptic state")
3. if (*motor performance* = "poor") then (*action* = "previous haptic state")
4. if ((*arousal* = "down") OR (*arousal* = "too low")) then (*action* = "next acoustic state")
5. if (*arousal* = "const.") then (*action* = "keep acoustic state")
6. if (*arousal* = "too high") then (*action* = "previous acoustic state")
7. if ((*valence* = "down") OR (*valence* = "too low")) then (*action* = "next visual state")
8. if (*valence* = "const.") then (*action* = "keep visual state")

### III. RESULTS AND DISCUSSION

Successful implementation of the proposed methodology relies on accurate mapping of physiological and motor signals to user's psychological state and motor performance. Once psychological state and motor performance are estimated, the mapping to action primitives is relatively straightforward. It only requires adequate state transitions. Therefore, an extensive study was conducted and its results were used for definition of fuzzy membership functions and if-then rules for the first stage of the fuzzy logic system. Since this part of the study was performed with healthy subjects, the motor performance was evaluated as averaged force acting on the robot end-effector. For patients other motor performance criteria would apply. Thirty students and staff members of the University of Ljubljana (age range: 19-46 years, mean 26.2, standard deviation 5.8) participated in the study. The aggregated results of the study (average of thirty participants) were first used to determine which physiological signals provide meaningful information regarding the user's psychological state under the conditions that require significant physical effort and how these signals relate to arousal and valence [21]. From here the block scheme on Fig. 8 was constructed and fuzzy rules were defined. However, working with aggregate data filters out

differences on the user level. Therefore, the main question was how the fuzzy logic system would perform for individual users. The results of evaluation for a typical task with low and high difficulty levels are shown in Fig. 9. Even though the fuzzy system was tuned based on the averaged results, it was still accurate in estimating valence and motor performance for all participants. The results for estimation of arousal are not conclusive since the task in general required constant arousal, but changes can be observed for both difficulty levels in Fig. 9. Oscillating arousal values were noticed also for other subjects. It is possible that these changes actually occurred, however, it is also possible that arousal estimation is too sensitive. If the first level of fuzzy logic underwent an extensive evaluation procedure, the second level and the entire closed loop for control of user's psychological state still needs verification study, as for now only case studies were performed.

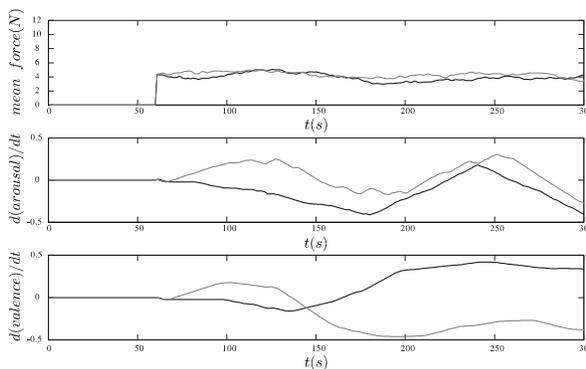


Figure 9. Estimated motor performance, valence and arousal: all variables are averaged across 60 second intervals; motor performance is given as mean absolute force on the robot end-effector, valence and arousal are given as relative changes over time. Grey lines indicate results for an extremely difficult task, black lines indicate results for medium difficulty task.

#### IV. SUMMARY AND CONCLUSIONS

A virtual exercise for training of stroke patients in a complex multi-modal environment was proposed. The exercise not only responds to the user's motor performance, but also to changes in his/her psychological state as estimated through psychophysiological measurements. In order to be able to implement a physically demanding task, we first analyzed changes in physiological signals as a response to an increased physical effort. By showing that psychophysiological measurements yield significant results even in the presence of physical load, we were able to implement a rehabilitation scenario for upper extremities. A fuzzy logic system was fine-tuned for estimation of psychological state and motor performance from physiological signals and force and kinematic measurements. The system enables precise tracking of motor performance and allows estimation of changes in user's psychological state. A second level fuzzy logic system is used to map psychological state and motor performance to haptic, visual and acoustic primitives. This level still needs extensive validation.

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