Multimodal Interfaces to Improve Therapeutic Outcomes in Robot-Assisted Rehabilitation

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***Abstract*—The paper presents the developing of a new robotic system for the administration of a highly sophisticated therapy to stroke patients. This therapy is able to maximize patient motivation and involvement in the therapy and continuously assess the progress of the recovery from the functional viewpoint. Current robotic rehabilitation systems do not include patient information on the control loop. The main novelty of the presented approach is to close patient in the loop and use multisensory data (such as pulse, skin conductance, skin temperature, position, velocity, etc.) to adaptively and dynamically change complexity of the therapy and real-time displays of a virtual reality system in accordance with specific patient requirements. First, an analysis of subject's physiological responses to different tasks is presented with the objective to select the best candidate of physiological signals to estimate the patient physiological state during the execution of a virtual rehabilitation task. Then, the design of a prototype of multimodal robotic platform is defined and developed to validate the scientific value of the proposed approach.**

***Index Terms*—Control, multimodal interfaces, physiological state, rehabilitation robotic.**

I. INTRODUCTION

According to the World Health Organization, the number of people over 65 years will increase by 73% in the industrialized countries and by 207% worldwide. By 2050, the percentage of the European population over 65 years should almost double from 12.3% to 20.6% (from 40 to 80 million). This age group is particularly prone to cerebral vascular accident, also known as stroke. The relative incidence of stroke doubles every decade for people over 55 years old. In fact, stroke is the leading cause of permanent disability in industrialized nations. Each year, over 920 000 Europeans and 700 000 North Americans have a stroke; more than a half survive, but often with severe impairments. The main symptoms are loss of muscle strength, spasticity, and lack of coordination of muscle activation [1]. Therefore, an interdisciplinary rehabilitation program to provide integrated care for people that survive a stroke is required. The use of robotic devices, as a possible rehabilitation strategy to achieve motor recovery, can be justified because of their potential impact on better therapeutic treatment and motor learning. Researchers have demonstrated the effectiveness of repetitive grasp and release exercises [2], constraint induced therapy for the paretic limb [3], [4], increased intensity or duration of therapy including external manipulation [5], biofeedback [6], bilateral movement training [7], [8], and robot-assisted therapy [9]–[12] in restoring motor function in the paretic upper limb during acute and chronic stages of stroke recovery. In any case, the therapeutic approach is well structured and repetitive in order to promote cortical reorganization after stroke [13], [14]. Recently, a scientific statement published by the American Heart Association in the Comprehensive Overview of Nursing and Interdisciplinary Rehabilitation Care of the Stroke Patient reports the best current evidences and recommendations for interdisciplinary management of post-stroke rehabilitation including robot-assisted therapy [15]. Their recommendations and levels of evidence for treatment of motor issues regarding robot-assisted therapy are Class I, Level of Evidence A for stroke care in the outpatient and chronic care settings, and Class IIa, Level of Evidence A for stroke care in the inpatient settings. [15].

It is well known that a classical robot-aided rehabilitation therapy consists of a robot guiding linked with a virtual reality system motivating the patient to accomplish a predetermined motion. On the other hand, a new trend in the development of novel rehabilitation systems is placing the patient in the control loop [16]–[20]. Furthermore, the main achievements of multimodal immersive motion rehabilitation with interactive cognitive systems research project funded by the European Commission were in the line of the development of biocooperative control systems to adapt the robotic therapy in order to maximize patient motivation.

The aim of this paper is to research on the use of physiological signals to adaptively and dynamically modify the therapy and real-time displays of a virtual reality system in accordance with the specific state of each patient. To do this, we need to address the following questions: Is it possible to use physiological responses to differentiate between different levels of physical workload and between different levels of cognitive workload? How different are subjects' physiological responses? Which physiological responses would provide the most reliable information about subjects' state in rehabilitation assisted by robotic devices? Is it possible to use physiological and motor

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signals to automatically modify an adaptive rehabilitation therapies assisted by a robotic device?

Next sections try to address these questions. The paper is organized as follows. Materials and methods of the two experiments presented are commented in Section II. First, the experiment carried out to record and process physiological signals from the subject is presented, and then the experiment to show the scientific value of the proposed multimodal robot-assisted rehabilitation system. In Section III, a discussion about the results of the experiments is commented.

II. MATERIALS AND METHODS

A. *Ethical Approval*

Before the study began, ethical approval was obtained from the Medical Ethics Committee of the Universidad Miguel Hernández of Spain.

B. *Subjects*

Fifteen students and staff members of the Bioengineering Institute of Universidad Miguel Hernández (11 males and 4 females) participated in the experiment. All were healthy, with no major cognitive or physical deficits. They were aged between 20 and 41, mean age 28 years, median age 26 years, and standard deviation 6.6 years.

C. *Subject's Physiological Responses*

In this section, the materials and methods of the experiment to record and process physiological signals from the subject is presented.

1) Hardware: The hardware configuration can be decomposed by four major blocks: signal monitoring and processing system, haptic device, virtual reality system, and control system. The haptic device used during the experiments was the PuParm, which is a force-controlled planar robot designed and developed by nbio research group at Universidad Miguel Hernández.

For PuParm robot, pneumatic swivel modules have been selected as actuators. In short, a pneumatic swivel module with angular displacement encoder (DSMI-25-270-A-B manufactured by FESTO) has been used as actuator for each two joints. The semirotative drives are being controlled by two proportional pressure valves (MPPE manufactured by FESTO) to achieve a maximum torque of 5 N·m at 6 bar and a maximum swivel angle of 270.

In Fig. 1, the setup of experiment including the PuParm robot is shown. The robotÕs end-effector is held by the user with his or her right hand, which allows the movement of the robot in two dimensions. Some physiological sensors are attached to the user's left hand and the respiration rate sensor is placed beneath the nose. The signal amplifier to sample all the physiological signals can be seen in the bottom-left corner of Fig. 1. A subfigure in the bottom-right corner of Fig. 1 shows a detail of one of the virtual tasks.

Physiological signals (pulse, skin conductance, skin temperature, and respiration rate) were sampled at 2.4 kHz using a g.US-Bamp signal amplifier from g.tec medical engineering GmbH. All signals were acquired and processed directly in MATLAB and Simulink (The Mathworks, Natick, MA).

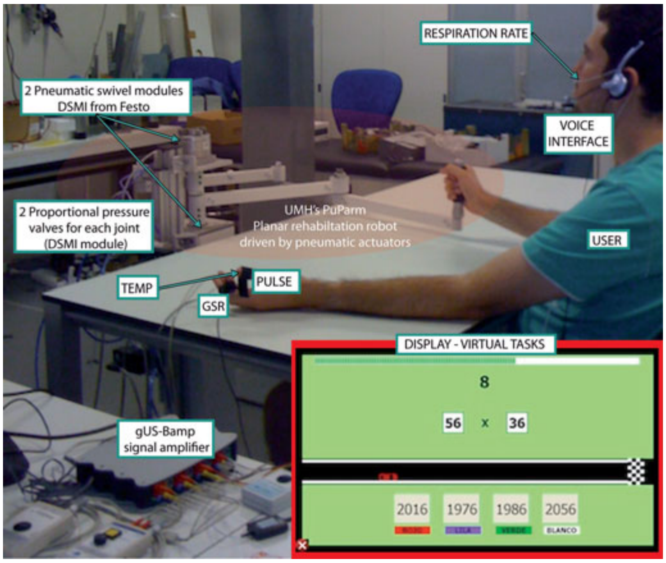


Fig. 1. Experiment: Display-virtual Task, PuParm, and Physiological signals equipment (sensors + signal amplifier).

Motor signals (position, velocity, and acceleration) were recorded from the feedback provided by the PuParm sensors. Therefore, a motor performance was computed based on these measurements.

2) Experiment Protocol: The experiments were conducted in a dedicated room at the Bioengineering Institute of Universidad Miguel Hernández, where external stimuli do not disturb the subject. Two people were present: the subject and the experiment supervisor. The experiment protocol is inspired by [21]. Before starting with the experiment, subjects were informed of the purpose and procedure of the experiment, and then the informed consent form was signed. Following the completion of the informed consent, an adaptation period of few minutes is given to the subjects before the baseline rating task. After that, the subjects remain in a relaxed state for 3 min so that baseline measurements can be obtained. Then, the subjects perform five tasks during 3 min. After each task, a computer version of self-assessment manikin (SAM) [22], [23] is presented to the subjects to measure their effective responses. Following the completion of SAM, the subjects rest for 3 min before starting a new task. The five tasks are physical/coordination tasks with or without disturbance and/or a cognitive task.

3) Tasks: Subjects were presented with different virtual tasks based on a physical/coordination task and/or a purely cognitive task.

a) Physical/coordination: This task consists in moving a little car through a straight road. If the car arrives the goal in time, the activity frame is colored green. If the car goes out the road or the time is over, the activity frame is colored red. The subject has 8 s to do the straight movement.

b) Physical/coordination with disturbance: The same as the physical/coordination, but the subject is stimulated by external forces applied by the robot/haptic device.

c) Cognitive: This task is a modified version of Montreal imaging stress task [24]. It presents the subject with two numbers that must be multiplied. These numbers are randomly generated between 0 and 99. Using a headset and ViaVoice IBM speech recognition software development kit, the subject must verbally choose the answer they believe is correct. If the subject answers correctly, their choice and the activity frame are colored green. If the subject answers incorrectly, their choice and the activity frame are colored red. The subject has 12 s to answer each question; if they fail to answer within this time, the result is identical to making an incorrect choice (except that no number turns red) [21].

d) Physical/coordination + cognitive: It is a combination of physical/coordination and cognitive tasks.

e) Physical/coordination with disturbance + cognitive: It is a combination of physical/coordination with disturbance and cognitive tasks.

4) Questionnaires: During the experiment, after each task, subjects were presented with nine-point arousal and valence scales from the SAM [22]. The SAM was developed by Lang [23] and Hodes *et al.* [25], and it is an effective measure for self-report emotion recognition. Emotions are rated on a nine-point scale by the two dimensions valence and arousal. Each dimension is represented by nine graphic figures. For valence ratings, SAM ranges from a figure with a smiling face to a sad figure. Arousal ratings are illustrated by a figure which ranges from eyes wide open to sleepy eyes.

D. Multimodal Robot-Assisted Rehabilitation

In this section, the materials and methods of the experiment to adaptively and dynamically change complexity of the therapy and multimodal feedback of a robot-assisted rehabilitation system according to the specific patient requirements is presented.

1) Hardware: The hardware setup consisted of the same parts described previously in Section II-C: signal monitoring and processing system, haptic device, virtual reality system, and control system. The virtual reality system used in this section is totally different from the one used during the evaluation of physiological responses in Section II-C; and it will be described in the following section.

2) Virtual Rehabilitation Task: A virtual reality software has been developed with adjustable level of task difficulty, which can be adjusted as a function of the evolution of the subject. The developed software creates a necessary virtual world for activities of daily living, like taking a glass, drinking and placing object on shelves, etc., and the robot creates the interaction between the real world and the virtual world through simulation of the interaction forces between patient's virtual arm and objects to be manipulated. The basic scenario consists of a table inside a virtual kitchen, a glass, and a coaster. At the beginning of the task, the glass appears on a random position over the table, the subject must grasp the glass. When the glass has been grasped, a coaster appears on a random position over the table and the subject must leave the glass over the coaster. A screen of the scenario is shown in Fig. 2. The subject has a limited time to carry out the task and it is displayed in the screen through a progress bar.

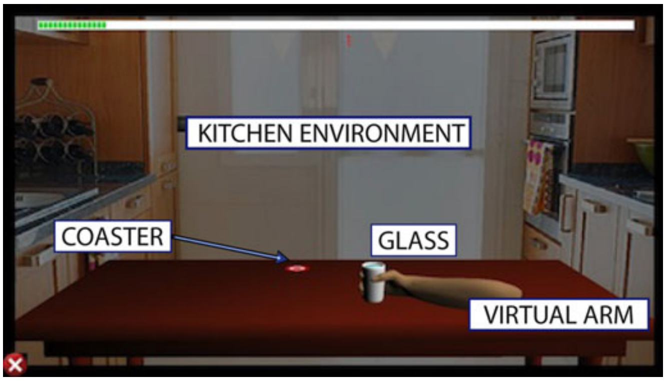


Fig. 2. Screen of the kitchen scenario used in the virtual rehabilitation task. The table, the glass, the coaster, and the virtual arm are shown.

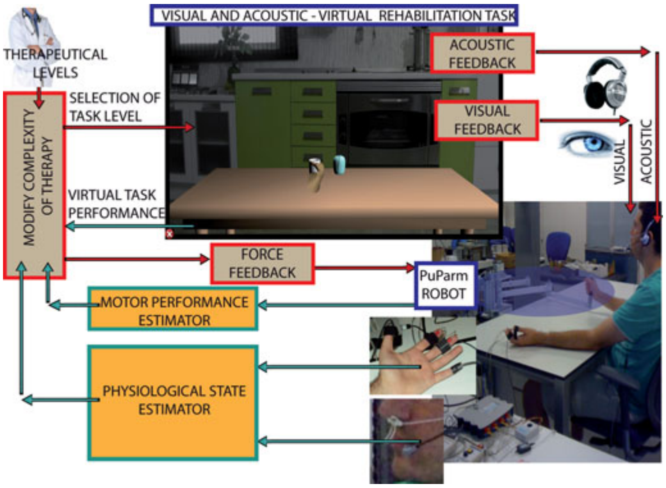


Fig. 3. Scheme of the multimodal rehabilitation system. The block "modify complexity of therapy" uses the information provided by the physiological state estimator and the measurements of motor and virtual task performance to adapt the difficulty level of therapy between the ranges indicated by the clinical staff.

Moreover, the multimodal virtual rehabilitation system has been designed to modify three modalities of multimodal feedback: visual, acoustic, and haptic (see Fig. 3). The estimation of subject's physiological state, motor, and virtual task performance will produce the changes of visual, acoustic, and haptic feedback reflected to the subject with the objective of maximizing the motivation of the subject and improving the therapeutic outcomes.

The implemented multimodal feedback modalities are as follows.

a) Haptic actions: i) basic force feedback for collision with the environment without assistance or resistance; ii) trajectory guidance through force fields; iii) damping force field related to the approaching velocity to the target; iv) force field for disturbances; and v) resistance force field related to the position error between the coaster and the current position of the glass.

b) Acoustic actions: i) relaxing sound played as music; ii) motivating sounds when subject successfully grasps the glass and/or leaves the glass over the coaster; and iii) encouraging statements to additionally motivate the subject.
c) Visual actions: i) basic game scenario without environment; ii) home scenario representing a virtual kitchen; and iii) animations to motivate the subject.

The combinations of these multimodal feedback allow us to define different task levels to be selected according to the estimation of the subject's evolution during the virtual rehabilitation task.

3) Experiment Protocol: The experiments were conducted in a room at the Bioengineering Institute of Universidad Miguel Hernández taking care of external stimuli do not disturb the subject. Two people were present: the subject and the experiment supervisor. Before starting with the experiment, subjects were informed of the purpose and procedure of the experiment, and then the informed consent form was signed. The experiment proceeds as follows: a) the subject spends a few minutes practicing tasks and rests for 3 min so that baseline measurements can be obtained; b) the first task (physical task) is performed for 3 min and after that the virtual rehabilitation task is performed for 20 min. Finally, a computer version of SAM is presented to the subjects to measure their affective responses.

III. DISCUSSION

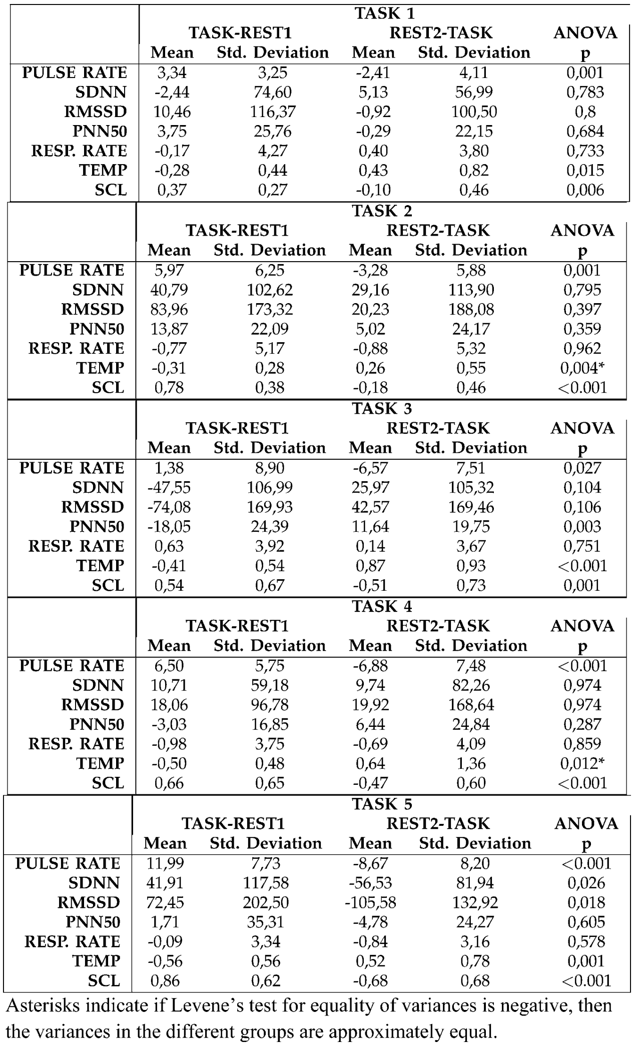
A. Psychophysiological Responses

In this section, we answer the question: Is it possible to use physiological responses to differentiate between different levels of physical workload and between different levels of cognitive workload? This is proposed as one of the objectives of this paper. To do this, a statistical data analysis was performed to know whether each task causes significant physiological changes between "rest previous to the task-task" and "task-rest posterior to the task." Table I shows the results of statistical significance analysis using one-way ANOVA. Differences were considered significant for $p < 0.05$. The Kolmogorov–Smirnov test was used to test for normality and Levene's test was used to test the homogeneity of variance. Levene's test was negative in the skin temperature data for Tasks 2 and 4, what it means that the variances in the different groups are not approximately equal. However, most physiological parameters did not show a significant difference ($p < 0.05$) between rest and task period for all the five tasks. The two exceptions were pulse and skin conductance level (SCL) (see Table I).

To better illustrate the differences in physiological signals between tasks (from Task 1 to Task 5), six physiological parameters that exhibit particularly significant differences between task types are shown as box plots in Fig. 4. On a box plot, the central line represents the median value, the bottom and top of the box represent the 25th and 75th percentiles, and the whiskers represent the minimum and maximum of all the data. A positive value represents an increase from baseline.

For all the tasks, from tasks with purely physical load to tasks with cognitive load plus physical load, pulse and SCL showed a significant difference between task with different physical load even when tasks have cognitive load as well (Tasks 4 and 5). Thus, a combination of pulse and SCL appears to be a robust method of physical and cognitive workload estimation in virtual rehabilitation that interacts with haptic robots.

TABLE I
PHYSIOLOGICAL DIFFERENCES BETWEEN DIFFERENT TASK AND REST PERIODS

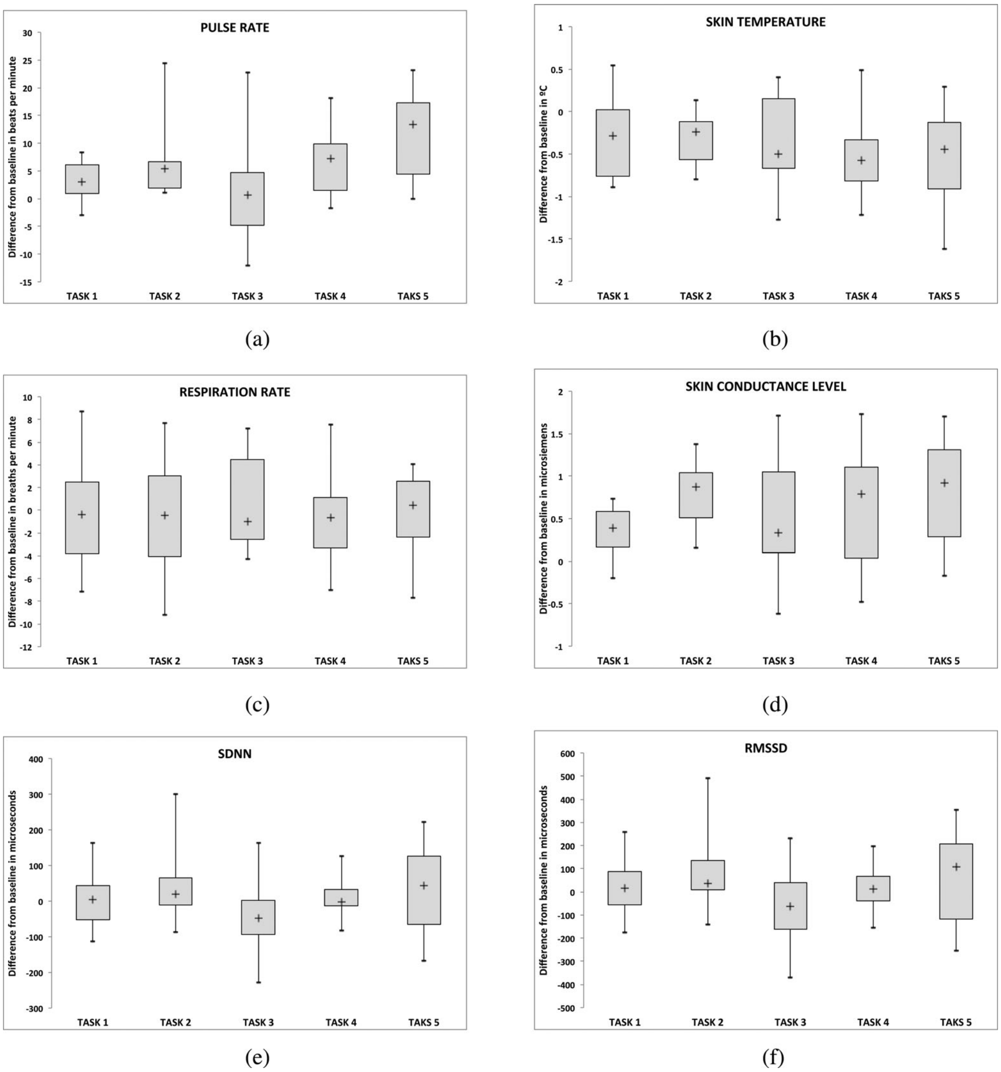


	TASK 1				
	TASK-REST1		REST2-TASK		ANOVA
	Mean	Std. Deviation	Mean	Std. Deviation	p
PULSE RATE	3,34	3,25	-2,41	4,11	0,001
SDNN	-2,44	74,60	5,13	56,99	0,783
RMSSD	10,46	116,37	-0,92	100,50	0,8
PNN50	3,75	25,76	-0,29	22,15	0,684
RESP. RATE	-0,17	4,27	0,40	3,80	0,733
TEMP	-0,28	0,44	0,43	0,82	0,015
SCL	0,37	0,27	-0,10	0,46	0,006
	TASK 2				
	TASK-REST1		**REST2-TASK**		**ANOVA**
	Mean	**Std. Deviation**	**Mean**	**Std. Deviation**	**p**
PULSE RATE	5,97	6,25	-3,28	5,88	0,001
SDNN	40,79	102,62	29,16	113,90	0,795
RMSSD	83,96	173,32	20,23	188,08	0,397
PNN50	13,87	22,09	5,02	24,17	0,359
RESP. RATE	-0,77	5,17	-0,88	5,32	0,962
TEMP	-0,31	0,28	0,26	0,55	0,004*
SCL	0,78	0,38	-0,18	0,46	<0.001
	TASK 3				
	TASK-REST1		**REST2-TASK**		**ANOVA**
	Mean	**Std. Deviation**	**Mean**	**Std. Deviation**	**p**
PULSE RATE	1,38	8,90	-6,57	7,51	0,027
SDNN	-47,55	106,99	25,97	105,32	0,104
RMSSD	-74,08	169,93	42,57	169,46	0,106
PNN50	-18,05	24,39	11,64	19,75	0,003
RESP. RATE	0,63	3,92	0,14	3,67	0,751
TEMP	-0,41	0,54	0,87	0,93	<0.001
SCL	0,54	0,67	-0,51	0,73	0,001
	TASK 4				
	TASK-REST1		**REST2-TASK**		**ANOVA**
	Mean	**Std. Deviation**	**Mean**	**Std. Deviation**	**p**
PULSE RATE	6,50	5,75	-6,88	7,48	<0.001
SDNN	10,71	59,18	9,74	82,26	0,974
RMSSD	18,06	96,78	19,92	168,64	0,974
PNN50	-3,03	16,85	6,44	24,84	0,287
RESP. RATE	-0,98	3,75	-0,69	4,09	0,859
TEMP	-0,50	0,48	0,64	1,36	0,012*
SCL	0,66	0,65	-0,47	0,60	<0.001
	TASK 5				
	TASK-REST1		**REST2-TASK**		**ANOVA**
	Mean	**Std. Deviation**	**Mean**	**Std. Deviation**	**p**
PULSE RATE	11,99	7,73	-8,67	8,20	<0.001
SDNN	41,91	117,58	-56,53	81,94	0,026
RMSSD	72,45	202,50	-105,58	132,92	0,018
PNN50	1,71	35,31	-4,78	24,27	0,605
RESP. RATE	-0,09	3,34	-0,84	3,16	0,578
TEMP	-0,56	0,56	0,52	0,78	0,001
SCL	0,86	0,62	-0,68	0,68	<0.001

Asterisks indicate if Levene's test for equality of variances is negative, then the variances in the different groups are approximately equal.

1) Subjective Evaluation: Data from the questionnaires of Section II-C4 are summarized in Table II. For purposes of analysis, the pictures were assigned numerical values from one to nine. On the arousal scale, one represented very low arousal, while nine represented high arousal. On the valence scale, one represented very negative valence, while nine represented very positive valence.

Arousal is significantly different between Task 1 and the other tasks (from Task 2 to Task 5) and is increased until 40% from Task 1 to Task 5. It is noticeable that the median value of arousal for Task 2 and Task 3 is nearly the same and we can hypothesize that a challenged physical activity and cognitive activity produces the same perceived psychological state from the arousal point of view (boredom to excitation) in our case. The valence dimension decreases monotonously with the task level [from underchallenged (Task 1) to overchallenged task (Task 5)].



(a) (b)

(c) (d)

(e) (f)

Fig. 4. Changes in physiological signals as a response to different tasks. Task 1: physical/coordination, Task 2: physical/coordination with disturbance, Task 3: cognitive, Task 4: physical/coordination + cognitive, and Task 5: physical/coordination with disturbance + cognitive. (a) Changes in mean pulse rate. (b) Changes in skin temperature. (c) Changes in mean respiration rate. (d) Changes in SCL. (e) Changes in standard deviation of NN intervals. (f) Changes in the square root of the mean squared differences of successive NN intervals.

TABLE II

RESULTS OF SELF-REPORTED QUESTIONNAIRES, SUCCESSES, AND FAILS OF THE EXPERIMENT TO EVALUATE SUBJECT'S PHYSIOLOGICAL RESPONSES

	VALENCE	AROUSAL	SUCCESS	FAIL
TASK 1	7.00±1.80	2.25±0.75	19.33±8.28	13.50±19.46
TASK 2	5.50±1.97	4.00±1.34	12.00±6.88	24.33±11.86
TASK 3	3.75±1.54	4.66±1.23	6.91±5.41	9.41±5.35
TASK 4	3.63±1.74	4.91±1.67	4.66±3.67	12.75±4.99
TASK 5	3.00±1.70	6.00±1.80	3.91±4.18	21.08±10.24

B. Multimodal Robot-Assisted Rehabilitation

The aim of the multimodal robot-assisted rehabilitation experiment was to reach a challenging and motivating, but feasible task difficulty for each subject. In the experiment, we defined four levels combining the multimodal feedback defined in Section II-D2.

1) *Level 1:* The haptic action is a basic force feedback for collision with the environment without resistance and assistance, the acoustic action is a relaxing sound played as music, and the visual action is a basic game scenario without environment.
2) *Level 2:* The haptic action is a resistance force field related to the approaching velocity to the target, the acoustic action consists of a motivating sound when subject successfully grasps the glass and/or leaves the glass over the coaster, and the visual action implemented is a home scenario representing a virtual kitchen.
3) *Level 3:* The haptic action is a force field for disturbances, the acoustic action consists of a motivating sound when subject successfully grasps the glass and/or leaves the glass over the coaster, and the visual action is a home

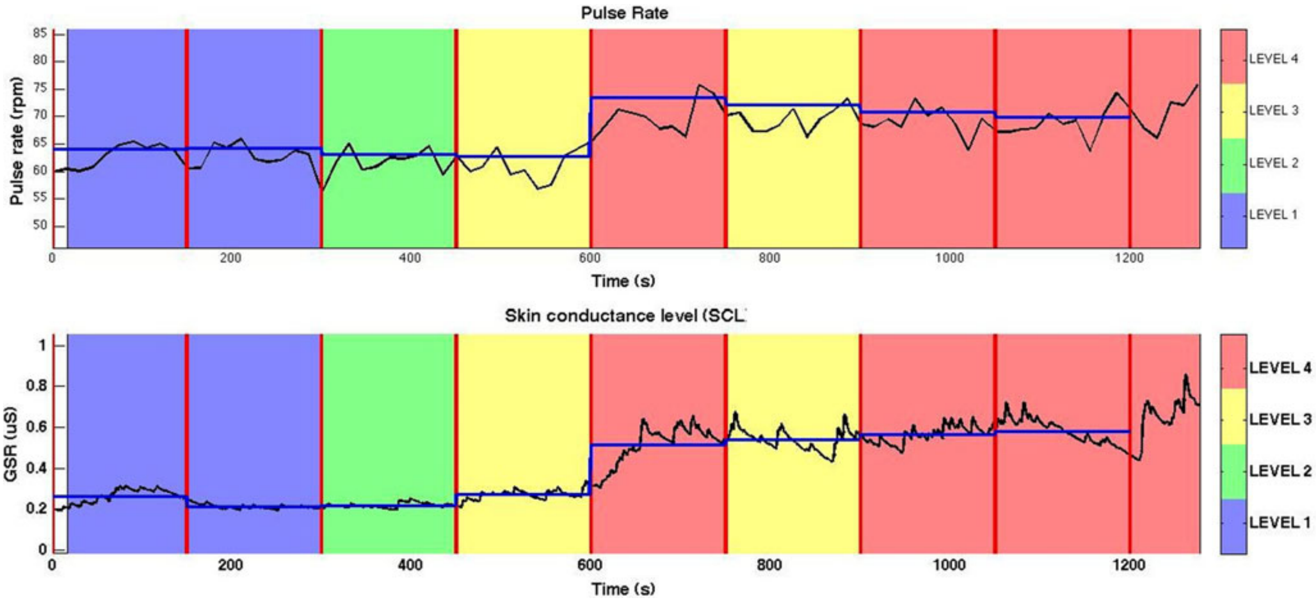


Fig. 5. Changes in rehabilitation task level in function of changes in pulse and skin conductivity level. Data extracted from a typical subject's experiment.

scenario representing a kitchen and animations to motivate the subject.

4) *Level 4:* The haptic action is a resistance force field related to the position error between the coaster and the current position of the glass, the acoustic action consists of a motivating sound when subject successfully grasps the glass and/or leaves the glass over the coaster and encourages statements to additionally motivate the subject, and the visual action is a home scenario representing a virtual kitchen.

The block "modify complexity of therapy" in Fig. 3 that enables the selection of the task level is a multiple input–multiple output, nonlinear, time varying, and nondeterministic system. To implement this block, we have selected fuzzy logic systems for two main reasons: 1) the simplicity of the implementation and 2) they do not require large training sets. The final solution implemented in this experiment is based on a fuzzy logic system in two hierarchical levels: first, the estimation of subject's physiological and motor state using the physiological signals and the measurements of motor performance, and second, the estimation of level changes using the provided information about the estimation of physiological and motor state [26]. To illustrate the performance of the proposed multimodal robot-assisted rehabilitation system, the level changes during the execution of a virtual rehabilitation task by a typical subject are shown in Fig. 5. The estimation of physiological and motor state and the evaluation of the required level changes are carried out every 150 s and they are represented as a red vertical line in Fig. 5. We used pulse and SCL as physiological feedback and their relations with the level changes are shown in Fig. 5. The level changes depend on the estimation of arousal and valence in function of the changes in physiological signals (pulse and SCL). We can see in the figure that the arousal and valence increase or decrease with the increasing/decreasing of pulse and skin conductivity level, according to the fuzzy rules implemented.

IV. CONCLUSION

Our research has two main findings. 1) It is possible to use physiological responses to estimate different subject's physiological state during a virtual task assisted by a haptic robot. Moreover, a combination of pulse and SCL seems to be a robust method of physical and cognitive workload estimation in virtual rehabilitation tasks assisted by a haptic robot. 2) It is possible to modulate the complexity of the virtual rehabilitation task using artificial intelligent techniques in order to estimate subject's performance and physiological state. From the acquired experience in this research, it seems that the use of adaptive algorithms for intelligent machine learning could be the basis for future rehabilitation devices that automatically adapt the delivered therapy to the specific needs and demands of the patient. In general terms, our approach based on fuzzy logic systems works fine, but it still needs extensive evaluation. Moreover, the evaluation and comparison of other artificial intelligent techniques would be in line with our next developments inside this topic.

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