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Robotic rehabilitation tasks and measurements of psychophysiological responses

M. Munih, *Member, IEEE,* D. Novak, J. Ziherl, A. Olenšek, J. Podobnik, T. Bajd, *Fellow, IEEE,* M. Mihelj

***Abstract*—Rehabilitation robots, together with vision and audio systems form the multimodal environment for exercising the person in a number of ways, unavoidably influencing the physiological state of the subject. This paper examines viability of measuring psycho physiological responses to different robotic tasks. The heart rate, skin conductance, respiration and peripheral skin temperature were observed to verify if physical activity obstructs useful recordings and to verify responses in stroke population. 30 healthy subjects were checked with a control task, a purely mental task and task with physical load. 23 subacute stroke persons did a control task, pick and place task (+ inverted version) and Stroop test, same as 22 healthy control subjects. Psycho physiological measurements yielded results even in the presence of physical load and can thus potentially be useful for rehabilitation robotics. Similar responses as in healthy control group were found in the stroke group. Skin conductance response frequency, respiratory rate, skin conductance and skin temperature (all changes from baseline) were confirmed as parameters signaling changes in arousal and valence of both, stroke and control groups.**

I. Introduction

A NUMBER of robotic platforms have been designed specifically for upper extremity rehabilitation. There are two types of devices: the exoskeleton and the end effector. Some examples of exoskeletons are the L-Exos tendon-driven wearable haptic interface with 5 DoF, Powered exoskeleton with 8 DoF and ARMin (I, II and III) with an interesting design that currently allows movements with 6 DoF.

Examples of end-effector upper-extremity devices include MIT Manus, Assisted Rehabilitation and Measurement (ARM) Guide, Mirror Image Motion Enabler (MIME), Bi-Manu-Track, GENTLE/S, Neurorehabiltation (NeReBot), REHAROB, Arm Coordinating Training 3-D (ACT3D), Braccio di Ferro and the NEDO project device.

Haptic rehabilitation robots can challenge the exercised person's sensory, cognitive and motor functions. When used in conjunction with Virtual Reality (VR), robots can be used as a general tool to harness brain plasticity and promote recovery at least for stroke in the long run for both subacute and chronic cases [4].

A therapy regime must be intensive [5], of long duration [6], repetitive [7] and task-oriented [8]. Based on short-term changes in Fugl-Meyer scores before and after robot-aided therapy, Prange et al. concluded that robot-aided therapy of the proximal upper limb can improve short and long-term motor control of the paretic shoulder and elbow. A comparative study by Mehrholz et al. with a total of 328 participants and 11 clinical trials could not find evidence that the use of electromechanical assistive devices in rehabilitation settings improves activities of daily living [10].

Multimodal Virtual Reality (VR) uses visual, acoustic or tactile cues as biofeedback in order to challenge or motivate patients during physical therapy exercises. For optimal integration of various sensory cues (haptic, acoustic, audio), a method of assessing the patient's psychological state is required. There are several off-line measures that can estimate psychological state, including questionnaires, motor behavior parameters or analysis of psychophysiological signals. Psychophysiological responses have previously been used to monitor patient progress in therapeutic VR (e.g. [11]). Evidence has additionally shown 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 [12]. After identifying a person's emotions with an online assessment system, the logical next step is to make a real-time closed-loop adaptive system. This system would modify the multimodal environment in order to make the experience more pleasant or more challenging for the user. In flight simulators, basic systems have already successfully shown an ability to affect the subject's attention level based on skin conductance [13].

When examining the feasibility of using biocooperative emotion-aware closed-loop systems in rehabilitation robotics [23,24], we are faced with various questions: Can psychophysiological measurements be used in situations with physical activity, or would physiological changes due to physical activity mask any physiological changes caused by psychological state? Do stroke group (e.g. acute or chronic) and control group have similar physiological responses? To answer these questions, a multi-phase study was designed. In the first phase, psychophysiological signals were recorded in a task involving large haptic robot

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All authors are with the Faculty of Electrical Engineering, University of Ljubljana, Trzaska 25, SI-1000 Slovenia. Contact : Marko Munih, phone: +386-1-4768-219; e-mail: marko.munih@robo.fe.uni-lj.si.

movements that required significant forces, simultaneously gathering psycho physiological signals. In the second phase, patients were faced with a multimodal environment for motor rehabilitation while psychophysiological signals were recorded. Same was done for healthy control group.

II. METHODS

A. Experimental tasks

Before developing a virtual environment for motor rehabilitation, the issues of interpreting psychophysiological signals in the presence of physical activity were examined in a virtual environment consisting of an unstable pole standing atop a cart. Participants had to balance the pole (inverted pendulum) by moving the cart left and right using a HapticMaster haptic interface (manufactured by Moog FCS) that also measured the force exerted (Fig. 1). The HapticMaster actively resisted movement, requiring a significant force to move. If the pole fell to a horizontal position, it was reset to a nearly vertical position.

Fig. 1. Participant performing physical activity influence task

Three difficulty levels of the pendulum task (PT) were implemented. While the medium difficulty level (PT.M) was moderately challenging and the easy level (PT.E) was only slightly easier than the medium level, the hard level (PT.H) was intended to be difficult to the point of frustration. This was done by subtly modifying the mathematical model of the cart and pole in order to make the pole much less responsive to user input. In addition to the PT, a control task (CT) was introduced in the absence of mental load. During the CT, participants moved the HapticMaster left and right at an even, moderate speed while nothing was shown on the screen.

The participants rested before the tasks for five minutes in order to obtain baseline values. All Fig. in Results section are given relative to a baseline acquired values. CT, PT.E, PT.M and PT.H were performed in random order for five minutes each. After each period, participants responded to nine-point arousal and valence self-report scales from the self-assessment manikin [14].

After completing the study of the inverted pendulum, the psychophysiological responses of subacute stroke group were examined with a pick-and-place task (PPT) performed in VR using the HapticMaster. The virtual scenario consisted of a ball rolling down a slope. Participants had to catch the ball as it was rolling, then place it in a basket suspended above the slope (Fig. 2). A second, more difficult version of the task was also designed, being more mentally demanding but approximately equally physically demanding. The difficult version had inverted left-right controls (PPT-INV). If the participant moved his or her arm to the left, the virtual hand on the screen moved right (and vice-versa).

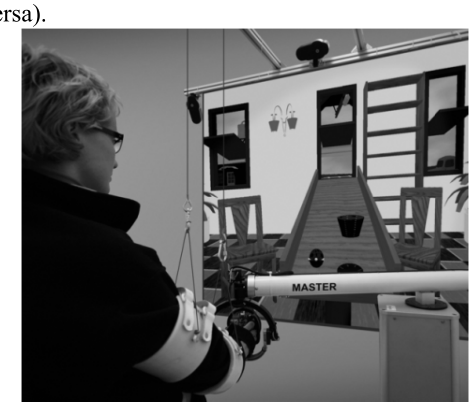

Fig. 2. A participant performing a pick-and-place task in VR

In order to gauge stroke group psychophysiological responses to a task with no physical activity, we also presented them with a variant of the classic Stroop color interference task that has been previously extensively studied by psychologists [15].

The experimental order was CT, PPT, PPT-INV and Stroop, each three minutes, with three-minute rest periods between tasks. In addition to the stroke group, the same methodology was also used with a control group of 22 healthy subjects. Again, after each period, participants responded to nine-point arousal and valence self-report scales from the self-assessment manikin [14].

B. Hardware and software

The experimental hardware consisted of three major parts: the visualization system, the haptic interface and the signal recording system. A 2 m x 1,5 m screen with back-projection was used for visualization.

For the psychological signal measurement, the electrocardiogram was recorded using surface electrodes affixed to the chest and abdomen. Skin conductance was measured using a g.GSR sensor (www.gtec.at), 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 placed beneath the nose and can measure respiration both, through the nose and through the mouth. The peripheral skin temperature was acquired with a g.TEMP sensor attached to the distal phalanx of the fifth finger using medical adhesive tape. All the signals were amplified and sampled at 2.4 kHz using a g.USBamp amplifier linked to PC via USB.

C. Physiological and biomechanical measures

After the experiment, the following physiological parameters were calculated for each time period:

- HR - mean heart rate,
- SDNN and RMSSD - two standardized measures of heart rate variability [16],
- SCL - mean skin conductance level,
- SCRF nonspecific skin conductance response frequency,
- RR - mean respiratory rate,
- RRV - respiratory rate variance and
- ST - final skin temperature.

In addition to physiological measurements, the mean absolute force exerted by participants was calculated for each time period.

D. Subjects

Thirty students and staff members of the University of Ljubljana (age: 19-46, mean 26.2, st. dev. 5.8 years) participated in the inverted pendulum balancing task. All were without any known major cognitive or physical defects.

For the pick-and-place task and Stroop task, psychophysiological responses were acquired from 23 subacute stroke persons, 16 men, 7 women, age from 23 to 69, mean 51.0, st. dev. 13,3 years. 10 had a weakened right while 13 had a weakened left arm. The following individual clinical scores were used in subsequent analysis:

- functional arm test (7 questions describing activities of daily living abilities);
- Mini Mental State [19] ;
- FIM chapter on self-care (washing, feeding, etc.) [20];
- FIM chapter on transfer (to bed, on chair, toilet, etc.);
- FIM chapter on communication and social cognition (social interaction, problem solving, memory).

The control group consisted of 22 healthy subjects, 16 men, 6 women, age 24 to 68, mean 50.5, st. dev. 12.6 years. Demographically (age, gander) were members of this selected to approximately match to the stroke group.

III. Results and Discussion

A. Acquiring physiological changes in the presence of physical activity

First, we show the results of acquiring physiological signals in the presence of physical activity, measured with healthy subjects during the inverted pendulum task. One interesting parameter was skin conductance response frequency (SCRF) (Fig. 3). Higher values were observed for higher difficulty levels. Respiratory rate (RR) was also higher during the mentally demanding pendulum task than during the control task (Fig. 4). In general, respiratory rate variability (RRV) decreases from baseline during mental activities, except in the case PT.H (Fig. 5). This could be explained with increased arousal leading to decreased RRV until the task becomes too hard for the subject to deal with, at which point RRV is again increased. Very similar trends could be shown for ST in Fig. 6.

Mean absolute force during CT was more than twice as high as during all three difficulty levels of PT ($p < 0.001$). It was also higher during PT.H than PT.E and PT.M ($p < 0.05$ for both comparisons). Thus, the change in a physiological response may not have been caused by changes in psychological state, but by the differences in physical load.

The physiological parameters that changed significantly from baseline to CT are: HR (increased by 10%, $p < 0.001$), SDNN (incr. by 17%, $p < 0.01$), RMSSD (incr. by 24%, $p < 0.01$), SCL (incr. by 1 μS, $p < 0.001$), SCRF (incr. by 236%, $p < 0.001$), RR (incr. by 17%, $p < 0.001$) and RRV (decreased by 6%, $p = 0.04$). Thus, all physiological parameters other than ST were affected by physical load.

The following physiological parameters were significantly different between CT and PT.M: HR (lower in PT.M, $p < 0.001$), RMSSD (lower in PT.M, $p < 0.001$), RR (higher in PT.M, $p = 0.006$) and RRV (lower in PT.M, $p = 0.02$). The difference in SCRF approached significance (higher in PT.M, $p = 0.07$).

Since there was no significant difference in SCL between CT and PT.M, it appeared to be primarily affected by physical load and thus not useful in physically demanding tasks. Previous studies have noted a connection between SCRF and arousal [17]. However, since the difference in SCRF between CT and PT.M was not quite significant, SCRF is apparently only a reliable indicator of arousal if little physical load is involved (Fig. 3). RR during CT was significantly higher than the baseline value, but RR during PT.M was higher still (Fig. 4). Since mean absolute force was higher during CT, the changes in RR cannot be attributed solely to changes in physical load, but must be caused by arousal. Previous studies have indeed shown respiratory rate to be connected to arousal [18]. Similarly, RRV during CT was significantly lower than the baseline value, but was even lower during PT.M (Fig. 5). Mental arousal thus apparently also decreases RRV. By far the highest increase in HR was during CT, where the exerted force was also the highest. Since there was no significant difference between difficulty levels, we can conclude that HR was mostly influenced by physical load. Similarly, though significant differences in SDNN and RMSSD were observed between CT and PT.M, none can be reliably attributed to changes in psychological state – they may have been caused by physical load.

No physiological parameters showed significant differences between PT.E and PT.M. There were two significant differences between PT.M and PT.H: RRV was lower during PT.M ($p < 0.001$) while ST was higher during PT.M ($p = 0.01$).

Differences between CT and PT.M indicated that RRV decreases as arousal increases. The difference in RRV between PT.M and PT.H suggests that RRV also increases as valence decreases (i.e. as frustration increases). Since ST significantly decreased from baseline only during PT.H and was lower during PT.H than during PT.M, it apparently decreases as valence decreases. Other studies have linked decreases in fingertip temperature to anxiety and stress [21], supporting our findings. Again, it is worth noting that ST was the only psychophysiological response not influenced by physical load.

B. Acquiring responses of subacute stroke group

The SCRF graph in Fig. 7 shows a significantly higher response in PPT task than in CT. This means that, while the physical activity in CT does slightly contribute to SCRF, SCR is measurably higher as a result of the coordinated actions required in PPT. SCRF increases the most as a result of the Stroop test.

RR is higher during any mental activity compared to the simple physical activity encountered during CT (Fig. 8). The same could be stated for SCL in Fig. 9. Attention may cause a subtle difference between PPT and PPT-INV. There is a statistical difference between PPT and PPT-INV at $p<0.02$. Skin temperature, shown in Fig. 10, differentiates very well between CT and any other activity: all mentally demanding tasks cause a decrease in skin temperature.

Correlations computed among all variables mentioned in section II.C above and self-report scales from the self-assessment manikin result in the following values: valence is correlated with temperature ($\rho = 0.54$, $p = 0.035$); arousal is correlated with SCR frequency ($\rho = 0.59$, $p = 0.019$) and RRV ($\rho = 0.40$, $p = 0.043$).

The following correlations were performed between FIM test results and task outcome.

Correlations between FIM and Stroop values:

- FIM transfer is correlated with time needed to answer ($\rho = -0.55$; $p = 0.014$);
- FIM on communication and social cognition is correlated with time needed for answer ($\rho = -0.464$; $p = 0.05$);

This correlation might be a result of the fact that patients who are capable of complex movements are also capable of faster responding to questions.

Correlations between FIM and various PPT indicators:

- the functional arm test and FIM chapters on self-care and transfer are correlated with numerous force and work parameters (details not shown here to limit the presentation space);
- functional arm test score is correlated with SCRF ($\rho = 0.49$; $p = 0.028$)
- FIM on communication and social cognition is correlated with RRV ($\rho = -0.465$, $p = 0.05$); Mini Mental State is correlated with RR variability ($\rho = -0.47$, $p = 0.041$);
- Mini Mental State is correlated with SCRL ($\rho = -0.498$; $p = 0.026$);
- FIM transfer is correlated with SCRL ($\rho = 0.545$, $p = 0.016$);
- FIM transfer is correlated with RR variability ($\rho = 0.507$, $p = 0.016$) .

C. Comparison of subacute stroke group and healthy controls

In this chapter, we present differences between the stroke and control groups during baseline measurements, during the Stroop task and the PPT. The observations for baseline measurements are:

- in self assessment, the stroke group shows a higher positive valence (stroke: 2.27; control: 3.33; $p = 0.013$ – with 1 representing very positive and 9 representing very negative valence);
- the stroke group has a higher heart rate (HR stroke: 76.5 beats/minute; control: 65.5 beats/minute; $p < 0,001$);
- the stroke group has lower heart rate variability (SDNN in stroke group is 62% of control group value; $p < 0,001$).

There are no other significant differences. Lower heart rate variability has been previously reported and described in literature [22].

Observations for the Stroop task are:

- stroke group has a lower percentage of correct answers (stroke: 93.9%; control: 97.9%; $p = 0.007$);
- stroke group needs more time for each answer (stroke: 2.85 s; control: 1.99 s; $p = 0.016$);
- control group shows a higher increase in HR (stroke: +2,6 beats/minute, control: +7.2 beats/minute; $p = 0.049$);
- the control group shows a larger, measurable decrease in peripheral skin temperature (stroke: -0.1 ^{o}C; control: -0.9 ^{o}C; $p = 0.014$).

Observations for PPT are:

- subjects in control group could catch more balls (stroke: 69%, control: 84%; $p < 0.001$);
- the control group needs less time to place the ball into the basket (stroke: 7.7 s; control: 4.8 s; $p < 0.001$);

An interesting point is that temperature is lower during PPT-INV than during PPT for the control group, but not for the stroke group. One possible explanation for this, with no proof at the moment, is that the main challenge for stroke group is generation of adequate forces for simple arm movement and the movement coordination.

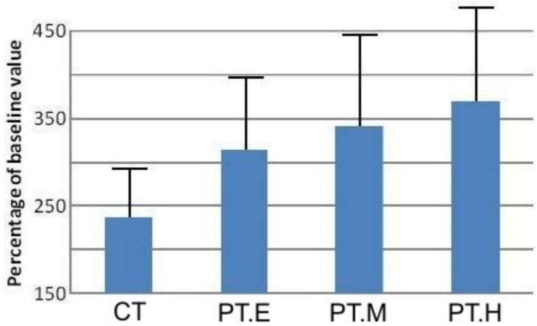

Fig. 3. Skin conductance response frequency (SCRF) change from baseline as a function of task difficulty (see Methods text for abbreviations)

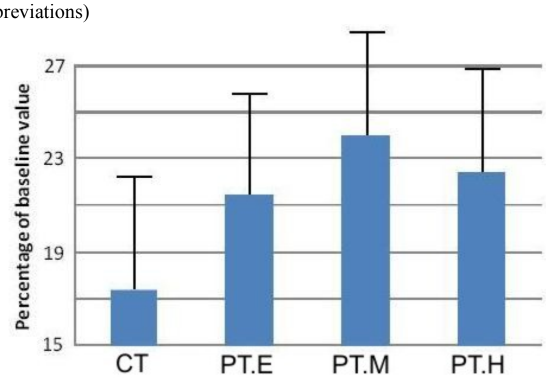

Fig. 4. Respiratory rate (RR) change from baseline as a function of task difficulty (see Methods text for abbreviations)

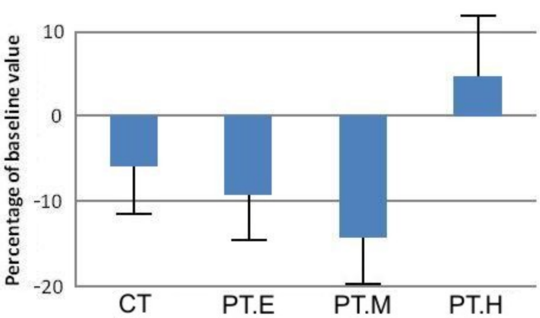

Fig. 5. Respiratory rate variability (RRV) change from baseline as a function of task difficulty (see Methods text for abbreviations)

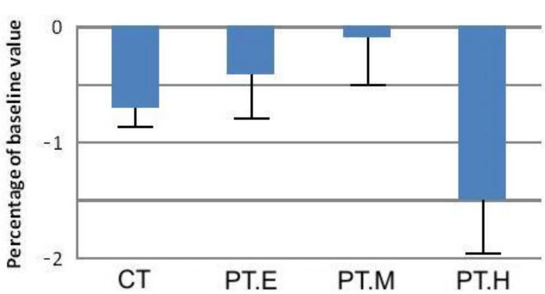

Fig. 6. Skin temperature (ST) change from baseline as a function of task difficulty (see Methods text for abbreviations)

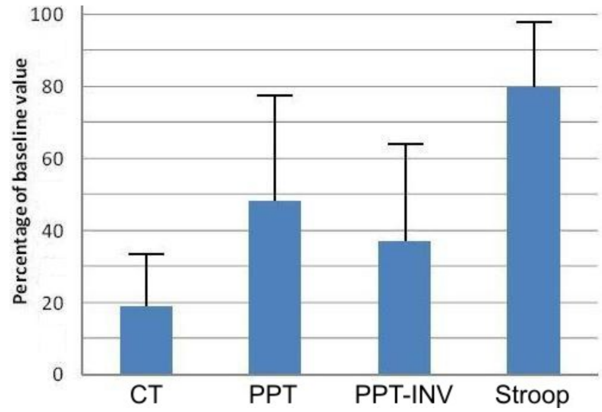

Fig. 7. Skin conductance response frequency (SCRF) change from baseline as a function of task type (see Methods text for abbreviations)

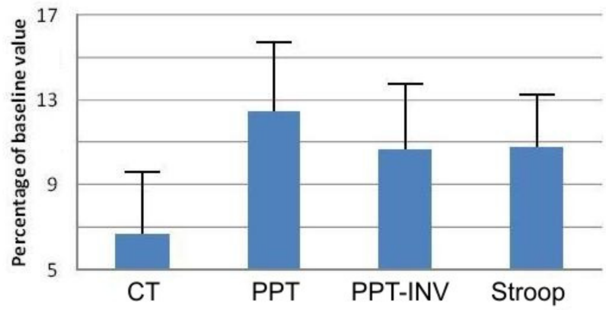

Fig. 8. Respiratory rate (RR) change from baseline as a function of task type (see Methods text for abbreviations)

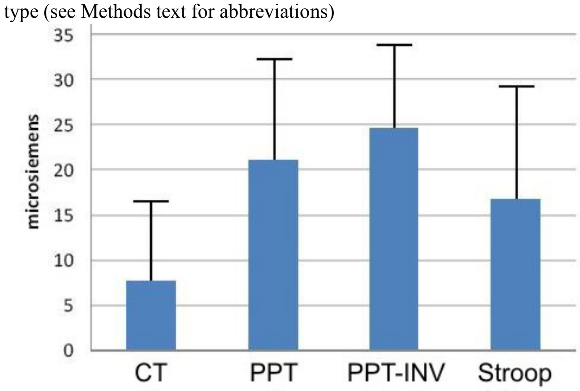

Fig. 9. Mean skin conductance level (mean SCL) change from baseline as a function of task type (see Methods text for abbreviations)

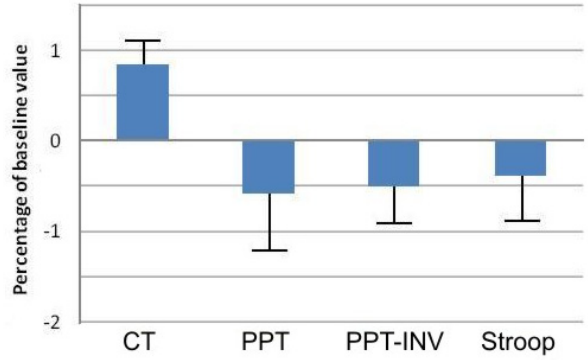

Fig. 10. Mean skin temperature (mean ST) change from baseline as a function of task type (see Methods text for abbreviations)

This is no problem for the control group, which is thus not challenged until PPT-INV. Thus, the differences between PPT and PPT-INV are more evident in the control group. Additionally, temperature often exhibits a transient response. After task initiation, ST deviates promptly from baseline, but as the person accommodates to the task, the effect decreases. Thus, if PPT-INV is not much more challenging for stroke group than PPT, ST is expected to return toward the baseline level. The control group is more occupied with PPT-INV, leading to a larger deviation of ST from baseline than during PPT.

IV. Conclusions

We were able to demonstrate a significant influence of both mental arousal and emotional valence on physiological responses even in the presence of significant physical load. Mean respiratory rate and frequency of skin conductance responses are both indicators of arousal, but also both influenced by physical activity. Changes in skin conductance level and frequency, respiratory rate variability and skin temperature were the most interesting variables in stroke and control groups. Details are shown in text.

The findings presented here have a high value for analysis of human psychophysiological responses to robotic rehabilitation tasks and could be indispensible for designing future closed-loop biocooperative systems that would adapt to user responses by adjusting haptic, visual and audio modalities.

While this work could have significant impact on biocooperative systems in rehabilitation robotics [23,24], it is unrealistic to claim that future rehabilitation outcome could be directly influenced using the emotion-aware closed-loops. Benefit for the subject could be achieved indirectly, with adequately dosed, more pleasurable, motivated, as well as intensive, of long duration, repetitive and task-oriented rehabilitation.

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