

Psychophysiological responses to robot training in different recovery phases after stroke

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Abstract— Psychophysiological responses have become a valuable tool in human-robot interaction since they provide an objective estimate of the user's psychological state. Unfortunately, their usefulness in rehabilitation robotics is uncertain since they are influenced by both physical activity and pathological conditions such as stroke. We performed psychophysiological measurements in subacute and chronic stroke patients as well as healthy controls during a reaching and grasping exercise task performed in a multimodal virtual environment. Furthermore, we evaluated the differences in kinematic and static parameters between the three groups of subjects. The results of the observed kinematic and static evaluation parameters showed significant differences when different assistive modes enabled the subject to focus on a particular function of the exercise, like reaching or grasping, or coordinated actions that combine reaching and grasping, reflecting the motor abilities of the individual. The analysis of psychophysiological responses suggests that both chronic and subacute stroke subjects have weaker psychophysiological responses than healthy subjects, though the responses of chronic patients have recovered somewhat. This certainly indicates that further studies are needed before psychophysiological responses can be used in clinical practice.

Keywords—rehabilitation robotics; psychophysiology; stroke; upper extremities

I. INTRODUCTION

Our understanding of the neurophysiological processes underlying functional recovery after stroke is evolving. Since cortical reorganization is use- or activity-dependent, modern concepts of motor learning favour repeated practice linked to incremental success at some task or goal [1]. However, participants must be motivated to practice movement over and over. There is a need for stroke rehabilitation practitioners to consider more effective ways of delivering valid interventions that make a real contribution to an individual's life, can be easily undertaken, and increase the possible therapy length.

Robotic interfaces are becoming increasingly common in motor rehabilitation [2, 3] since they enable more intensive therapy and offer an objective estimation of the patient's motor performance and functional improvement [4]. As the patient's cognitive activities further enhance motor relearning, robots are commonly combined with virtual reality [5-7]. The key concepts of such systems are repetition, feedback and

motivation by allowing exercise in interesting, varied virtual environments.

While rehabilitation robots can provide objective information about the patient's motor performance, they do not offer insight into his or her psychological state: mood, motivation, engagement, etc. Thus, a quantitative method of measuring patients' psychological states during rehabilitation would be very useful.

Psychophysiological responses have become a valuable tool in human-robot interaction since they provide an objective estimate of the user's psychological state. The most commonly used psychophysiological responses are those of the autonomic nervous system: heart rate, skin conductance, respiration and skin temperature. It was shown that heart rate increases and heart rate variability decreases as a response to cognitive workload [8-10]. Skin conductance increases with general psychological arousal and cognitive workload [9, 11, 12]. Respiratory rate also increases with arousal and cognitive workload [8] while respiratory variability decreases during mentally demanding tasks [13]. Skin temperature decreases as a result of cognitive workload [14] as well as a result of tension or anxiety [15].

Unfortunately, autonomic nervous system responses are not only influenced by a person's psychological state, but also by any physical activity. Additionally, the disease/injury itself can change the activity of the autonomic nervous system. Stroke patients, for instance, show long-lasting abnormalities in sweating and heart rate variability [16]. Furthermore, many patients receive medications (e.g. beta blockers) that affect the autonomic nervous system.

One of the concerns of our study was whether psychophysiological responses to physically demanding virtual environments differ in different recovery phases after stroke and from those of the healthy subjects. For this purpose, we performed psychophysiological measurements in subacute and chronic stroke patients as well as healthy controls during a reaching and grasping exercise task performed in a multimodal virtual environment. Furthermore, we analyzed kinematic and static parameters and evaluated the differences in these parameters between the three groups of subjects. This allowed us to gauge the movement abilities and task performance of the different groups.

II. MATERIALS AND METHODS

A. Study groups

Three different groups of subjects participated in the experiment: a subacute stroke group, a chronic stroke group and a control (healthy) group. All stroke patients had to have at least some voluntary control of the shoulder, elbow and wrist of the affected arm. The main subject characteristics are listed in Table I. Due to low availability of subjects, the chronic stroke group was smaller than the other two. A day before the session, subjects in the stroke groups were tested with both the mini-mental state examination (MMSE) [17] and the Functional Independence Measure (FIM) [18]. Score on the FIM is shown in Table I and Fig. 1. All but three subjects scored at least 26 out of a possible 30 on the MMSE and can thus be considered without greater cognitive deficits. The remaining three were interviewed by a clinical expert and approved for participation in the study. The control group had no major physical or cognitive defects.

TABLE I. SUBJECT CHARACTERISTICS. N = NUMBER OF SUBJECTS. LEFT/RIGHT PARESIS = NUMBER OF SUBJECTS WITH HEMIPARESIS OF THE LEFT / RIGHT SIDE OF THE BODY. FIM = FUNCTIONAL INDEPENDENCE MEASURE. DIAGNOSES: SH = SUBARACHNOID HEMORRHAGE, IH = INTRACEREBRAL HEMORRHAGE, CI = CEREBRAL INFARCTION.

group	subacute	chronic	control
N	23	10	23
gender	16 M, 7 F	8 M, 2 F	16 M, 7 F
age (years)	51.0 ± 13.3	44.0 ± 14.9	50.5 ± 12.6
age range	23-69	29-66	24-68
time since stroke	154 ± 79 days	74 ± 48 months	N/A
diagnosis	4 SH, 9 IH, 10 CI	6 IH, 4 CI	N/A
paretic limb	13 left, 10 right	5 left, 5 right	N/A
FIM	101 ± 13	112 ± 6	N/A

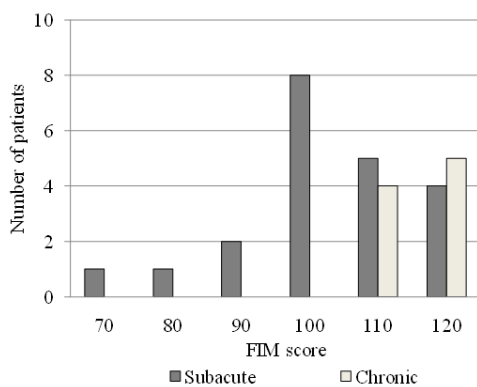


Figure 1. Histogram of Functional Independence Measure scores for subacute and chronic stroke groups.

B. Hardware

The HapticMaster robot [19], developed by Moog FCS, was used as the haptic interface. Its end-point was equipped with a two-axis gimbal and a passive grasping module. The subject's arm was supported by two cuffs fastened above and below the elbow. These cuffs were connected to a motorized pulley which applied a constant pulling force in order to compensate for the gravity acting on the subject's arm. A 1.4

m x 1.4 m screen was used to display visual data. Subjects sat approximately 1.25 m in front of the screen, with the robot situated between the subject and screen.

Physiological signals were sampled at 2.4 kHz using a g.USBamp signal amplifier (g.tec Medical Engineering GmbH). The electrocardiogram (ECG) was recorded using four disposable surface electrodes placed on the torso. Skin conductance was measured using a g.GSR sensor (g.tec) whose electrodes were placed on the medial phalanges of the second and third fingers of the unaffected hand. Respiratory rate was obtained using a thermistor-based SleepSense Flow sensor placed beneath the nose. Peripheral skin temperature was measured using a g.TEMP sensor (g.tec) attached to the distal phalanx of the fifth finger of the unaffected hand.

C. Virtual rehabilitation task

Our virtual rehabilitation (VR) task combines reaching and grasping exercise. In the centre of the screen, there is a table sloped toward the subject. At the beginning of the task, a ball appears at the top of the slope and starts rolling downward. The subject's goal is to catch the ball before it reaches the lower end of the table. Once the ball is grasped, a basket appears above the table. The subject must then hold the ball and place it in the basket. Once the ball is dropped into the basket or falls off the table, another ball appears at the top of the table, the basket disappears and the task continues. The robot allows the subject to feel each virtual item. More detailed information about the task is available in [20].

The robot offers various modes of support. If a patient is unable to perform any or all of the following, the robot will actively guide his or her arm in order to move left or right in order to catch the ball, squeeze the grasping device in order to grasp the ball, and/or lift the ball into the basket. Four subjects in the subacute stroke group required reaching support, seven required grasping support, and eight required lifting support (with some requiring multiple types of support). One subject in the chronic stroke group required reaching support, six required grasping support, and three required lifting support (with some requiring multiple types of support). The control group did not receive any support from the robot.

A second, harder version of the task (henceforth referred to as the harder VR task) was also designed. Meant to be more mentally demanding but equally physically demanding, the harder VR task had inverted left-right controls. If the subject moved his or her arm to the left, the virtual hand on the screen moved right (and vice-versa).

D. Questionnaires

During the experiment, subjects were periodically presented with nine-point *arousal* and *valence* scales from the Self-Assessment Manikin (SAM) [21]. These scales allow subjects to rate their level of emotional valence and arousal graphically by choosing the picture that best represents their current mood.

Valence (sometimes also called pleasure) is defined as positive versus negative affective states (e.g., humiliation, disinterest, and anger at one end versus excitement, relaxation, and tranquility at the other end) while *arousal* is defined in terms of mental alertness and physical activity (e.g., sleep, inactivity, boredom, and relaxation at the lower end versus wakefulness, tension, exercise, and concentration at the higher end).

The purpose of the questionnaires was to perform Spearman correlations with psychophysiological features (section G) and determine whether any significant correlations between psychological factors and physiological measurements can be found in rehabilitation.

E. Study protocol

The experiment was conducted in a dedicated room at the University Rehabilitation Institute of the Republic of Slovenia. Three people were present: the subject, experiment supervisor and occupational therapist. Upon arrival, subjects were informed of the purpose and procedure of the experiment, then signed an informed consent form. Then, they were seated in front of the robot. The affected arm was strapped into the cuffs and grasping device, and the physiological sensors were attached. The normal VR task was demonstrated, and subjects were allowed to practice it briefly. Each subject practiced for at least two minutes, and more time was given to any subject who had not yet attained a basic level of proficiency. During practice, the three modes of support (section II.C) were set manually for each subject based on his/her observed functional ability. Then, subjects went through the following procedure: rest period, normal VR task, harder VR task.

Each task and rest period lasted three minutes, and the SAM was presented on the screen after each period. Subjects verbally made a selection for both arousal and valence scales. Subjects remained quiet during rest, which served as a baseline period for physiological measurements.

F. Kinematic and static data extraction

The positions of the robot and the forces were sampled at 100 Hz. To analyze performance of the subjects, we observed the following features:

Efficiency. The catching efficiency (CE) is the percentage of caught balls divided by the number of all balls. The placing efficiency (PE) is the percentage of balls successfully placed in the basket divided by the number of caught balls.

Mean Reaching forces. The mean reaching forces (MF) at the end-effector sensor can provide information about the direction of the intended movement. The positive sign represents the force toward the ball, while the negative sign represents the force away from the ball. Only the horizontal component of the force was observed since this component represents the left-right movement of the subject's arm.

Pick-and-place time (PT). This is the duration of the pick to place movement from the time the ball was caught to release time.

Deviation Error (DE). This is the percentage of the maximal deviation of the measured movement trajectory from a reference line normalized by the reference line length. The reference line is the trajectory measured in healthy subjects [22].

Rise and fall time of the grasp force. Rise time (RT) is the time required for the grasping force to change from 10% value to 90% value. Fall time (FT) is defined as the time required for the grasping force to change from 90% value to 10% value.

Each feature was calculated only for subjects who did not receive robotic support that would render the feature irrelevant (e.g. grasp rise and fall time only for those who did not receive grasping support, as subjects with grasping support do not grasp objects).

G. Psychophysiological feature extraction

Each subject's physiological signals were recorded during the experiment. They were analyzed offline and several features were extracted for each three-minute period. From the ECG, *mean heart rate* as well as two measures of heart rate variability (HRV) were calculated: the standard deviation of NN intervals (*SDNN*) and the square root of the mean squared differences of successive NN intervals (*RMSSD*) [23]. The NN interval is the time between two normal R-peaks in the ECG.

The skin conductance signal can be divided into two components: the skin conductance level (SCL) and skin conductance responses (SCRs). The SCL is the baseline level of skin conductance in the absence of any discrete environmental event. *Mean SCL* was calculated. A SCR is a transient increase in skin conductance whose amplitude exceeds 0.05 μS and its peak occurs less than five seconds after the beginning of the increase. *SCR frequency* and *mean SCR amplitude* were calculated.

From the respiration signal, *mean respiratory rate* and *respiratory rate variability* were estimated.

Final skin temperature was calculated as the mean temperature during the last five seconds of each period.

H. Statistical analysis

The normal and hard VR task were analyzed separately. For each feature, differences between groups were analyzed with a one-way ANOVA, or a one-way ANOVA on ranks in cases of violations of normality. The Kolmogorov-Smirnov test with Lilliefors' modification was used to test for normality. The threshold for significance was set at $p = 0.05$, with the Sidak correction for multiple comparisons in all post-hoc tests. Spearman correlations were calculated between the SAM scales and psychophysiological features since SAM data is ordinal.

III. RESULTS

A. Clinical observations

The tested subacute stroke group was on average 7 years older and had lower total FIM scores than the chronic stroke group (average total FIM score of 101 (68 - 123) vs. average total FIM score of 112 (102-121)). Subacute stroke patients had significantly more cases of hypertension (17/23 vs. 3/10), 9 out of 23 subacute patients had at least two co-morbidities compared only 2 out of 10 chronic patients. Consequently, the chronic group received much fewer medications. Six subacute patients were treated with carvedilol or bisoprolol (beta blockers) while none of the chronic patients were. Five patients in the subacute group received antidepressants, 9 sleeping drugs, 3 low doses of antiepileptics, medication that can cause sedation or fatigue and hinder patients while performing the required tasks.

B. Kinematic and static data results

Comparison of the three groups (subacute, chronic, controls) during the VR task revealed significant differences in both catching efficiency and mean reaching forces (Table II). For catching efficiency, post-hoc tests found that the control group caught more balls than the subacute group ($p < 0.001$) while the difference between the control and chronic groups was not significant. For mean reaching forces, controls applied lower forces than both the subacute ($p = 0.004$) and control ($p = 0.003$) groups.

Comparison of the three groups revealed significant differences in pick-and-place efficiency and deviation error (Table II). Post-hoc tests found that the control group performed pick-and-place movements more successfully than both the subacute and chronic groups ($p < 0.001$ in both cases). The chronic group had a lower deviation error than both the subacute and control groups ($p < 0.001$ in all cases). There was no significant difference between the subacute and chronic groups in pick-and-place time. The control group had shorter pick-and-place times than the subacute ($p < 0.001$) and chronic ($p=0.037$) groups.

There was a difference in grasping rise time between the subacute and control groups ($p = 0.004$). The rise time of the grasping force was longer in the chronic group than in the control ($p < 0.001$) or subacute group ($p < 0.001$). These relationships were similar for the fall time of the grasping force. There were no significant differences between subacute and control groups while the chronic group had a longer fall time compared to subacute ($p < 0.001$) and control ($p < 0.001$) groups.

TABLE II. THE RESULTS OF OBSERVED CATCHING EFFICIENCY (CE), MEAN FORCES (MF), PLACING EFFICIENCY (PE), PICK-AND-PLACE TIME (PT), DEVIATION ERROR (DE), RISE TIME (RT) AND FALL TIME (FT) OF THE GRASPING FORCE (FT) DURING TRAINING. N IS THE NUMBER OF SUBJECTS IN EACH GROUP.

	Subacute (n=18)	Chronic (n=9)	Control (n=23)
CE [%]	63±17	66±21	86±13
MF [N]	0.26±0.26	0.07±0.14	0.03±0.07
	(n=16)	(n=7)	(n=23)
PE [%]	79±14	81±15	91±9
PT [s]	8.51±2.24	6.41±2.47	4.54±1.63
DE [%]	37.9±16.4	31.5±9.1	39.4±26.8
	(n=16)	(n=4)	(n=23)
RT [s]	0.14±0.45	0.40±0.15	0.17±0.34
FT [s]	0.33±0.30	0.48±0.34	0.29±0.39

C. Psychophysiological feature results and questionnaire correlations

The control group had a lower resting mean heart rate (measured during the baseline period) than the subacute stroke group ($p < 0.001$). Resting mean heart rate for the chronic group was somewhere between the other two groups (Fig. 2), though significance could not be achieved due to a low number of subjects. Similarly, the control group had a significantly higher SDNN than the subacute stroke group ($p < 0.001$), with the chronic stroke group being somewhere in the middle. There were no other differences in baseline values.

An analysis of physiological differences between baseline and task found that the control group exhibited significantly larger increases in mean SCR amplitude than both the subacute and chronic stroke groups during the VR and hard VR tasks ($p < 0.05$ in all cases). Additionally, the control group exhibited significantly larger decreases in final skin temperature during the hard VR task than the subacute group ($p < 0.001$). The decrease in final skin temperature for the chronic group was somewhere between the decreases of the control and subacute groups, though no significant differences were found due to the small group size (Fig. 3).

Finally, correlations between self-report questionnaires and psychophysiological features found one correlation that was present in all three groups: the correlation coefficient (Spearman's rho) between SCR frequency and self-reported arousal in the VR task was 0.59 for subacute stroke, 0.60 for chronic stroke and 0.60 for controls. The chronic stroke group exhibited no other significant correlations. The control group showed a significant correlation between valence and SCR frequency in the VR task ($\rho = 0.44$, $p = 0.046$) while the subacute stroke group showed a significant correlation between valence and final skin temperature ($\rho = 0.62$, $p = 0.017$) in the VR task.

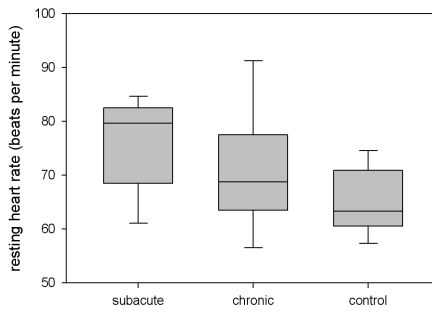


Figure 2. Resting mean heart rate for subacute stroke, chronic stroke and control groups.

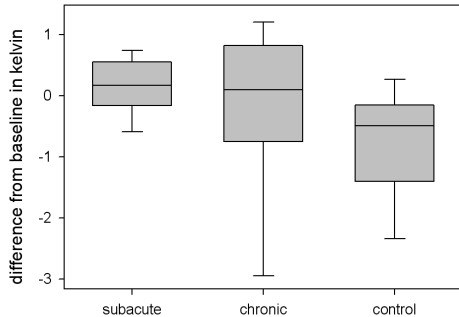


Figure 3. Differences in final skin temperature from baseline to task in the hard virtual rehabilitation task for subacute stroke, chronic stroke and control groups.

IV. DISCUSSION

A. Clinical observations

One of the limitations of the study is that it was aimed toward proof-of-concept testing so only a limited number of patients were included in the clinical evaluation. The patients exhibited large intersubject variability due to type and localization of the lesion as well as impairments of cognitive and motor abilities. We should be particularly cautious in interpretation of the results because of the differences between the two groups of stroke survivors. The patients in the subacute group were older with more comorbid conditions. More patients in the subacute stroke group received medication that may have affected psychophysiological responses. For example, beta blockers might influence heart rate while sedatives have been shown to affect skin conductance [24]. Antiepileptics, sleeping drugs and antidepressants may have also had an effect. However, the effect of various medications cannot be avoided in stroke rehabilitation and should be taken as inherent in that subset of population.

B. Kinematic and static data

As expected, results showed that the stroke subjects had lower catching and placing efficiency than the control group. However, the stroke subjects are able to complete the task. The reason why control subjects had such low mean forces is that they usually reached the right spot in short times, while the

greater mean forces in subacute and chronic subjects are the consequence of lower motor control of the arm.

The control, subacute, and chronic subjects chose the movements that strayed far away from the reference trajectory [22]. The deviation of the DE parameter is the greatest in control group. This can be explained with the shorter time of the pick-to-place movement. The stroke subject needed more time to reach the final posture.

The main difference among stroke subjects exists in rise and fall time. The grasping ability of subacute subjects is similar to those of control subjects, while the chronic subjects have lower grasping ability as seen in rise and fall time. However, no concrete conclusions can be made with regard to grasping ability due to the low number of chronic subjects that performed the task without grasping assistance.

C. Psychophysiological features

Several differences between control and stroke groups were found. Most notable among them are higher mean heart rate and lower heart rate variability, which have also been noted in previous studies [25], as well as decreased responsiveness in final skin temperature and mean SCR amplitude. This indicates that psychophysiological responses of stroke subjects during rehabilitation are weakened compared to healthy subjects. Though the size of the chronic group is too small to enable statistical significance, our limited results indicate that psychophysiological responses recover at least partially with time. Nonetheless, certain useful psychophysiological similarities do remain, such as the similar correlation coefficients between SCR frequency and arousal.

The principal limitation that should be mentioned is that we cannot with certainty say that the differences in psychophysiological responses are caused by the stroke directly. Rather, they may be caused by the poorer task performance, which is also an effect of stroke (though not a physiological one).

V. CONCLUSIONS

Rehabilitation robots provide objective performance information with their measurement possibilities. The results of the observed kinematic and static evaluation parameters in two groups of stroke patients and in healthy controls showed significant differences when different assistive modes enabled the subject to focus on a particular function of the exercise, like reaching or grasping, or coordinated actions that combine reaching and grasping, reflecting the motor abilities of the individual. A key concept in clinical environments is to appropriately set the difficulty level in a way that meets a particular patient's performance capabilities.

The analysis of psychophysiological responses suggests that both chronic and subacute stroke subjects have weaker psychophysiological responses than healthy subjects, though the responses of chronic patients have recovered somewhat. Despite improvement over time, one should take in consideration not only long-lasting abnormalities of the

autonomic nervous system but also other factors that can influence psychophysiological measurements (e.g. comorbidity and medication). Thus, appropriate psychophysiological measurements should be selected for multimodal sensory feedback in rehabilitation robots. Correlations between self-report questionnaires and psychophysiological features found only one correlation that was present in stroke patients in different phases of post-stroke recovery and in healthy controls: the correlation between SCR frequency and arousal. This certainly indicates that further studies are needed before psychophysiological responses can be used in clinical practice.

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