Physiological Responses during Performance within a Virtual Scenario for the Rehabilitation of Motor Deficits

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Abstract

Real-time physiological feedback can be used to modulate a virtual reality (VR) experience. It is not obvious, however, which parameters are most effective in achieving this such as heart rate variability and or the electrodermal response. Here we address this question by assessing the impact of the events generated by a VR based rehabilitation system on the affective state of human users. We show how the Rehabilitation Gaming System (RGS), a tool developed for the rehabilitation of motor deficits following stroke, can be enhanced using the online monitoring of bodily changes that are not under direct voluntary control. We show specific effects of the RGS on the autonomic nervous system and we propose how to use these for the modulation of the emotional state of the subject and performance.

1. Introduction

Several injuries and disorders of the nervous system lead to motor deficits that strongly affect instrumental activities of daily living. In terms of burden of disease, stroke is the main cause of adult disability with about 60% of the survivors experiencing long-lasting impairments throughout life [1]. These effects lead to a loss of productivity, with a strong impact on active and social life. Following stroke, lost functions can only be recovered by means of neuronal reorganization, as it has been shown that the brain remains plastic throughout life [2]. Indeed, effort has been made during the last few years in developing therapy methods that are based on the understanding of the neural mechanisms of recovery [3]. One of these approaches consists in using virtual reality (VR) technology combined with specific training scenarios, with special emphasis in brain injury [4]. Concerning upper limbs, different paradigms and therapy concepts for stroke rehabilitation have been coupled with VR systems, e.g.: training and intense practicing of skilled hand and finger movements [5], training of reaching tasks by means of a virtual tutor [6, 7], or training of upper limb movements by mental rehearsal and imitation of the non-paretic limb [8].

VR based rehabilitation systems have the advantage of enclosing several properties that are considered fundamental for an ‘optimal’ rehabilitation program. Ideally, therapy should be intense [9], with skilled movement practice and repetition [10] that is directed towards specific deficits [11] and rewarded through feedback on performance [12]. VR allows merging all these features.

While discussing performance within a virtual environment, a question that always arises is the role of presence and its influence on performance. Regarding motor rehabilitation, this should be connected with the ability of task completion within the scenario. Although no clear correlation has been established between presence and task performance [13], it seems reasonable to assume that the aptitude of performing within a virtual environment has an effect on presence. This might be relevant with respect to the rehabilitation of motor deficits following stroke as it may provide ways to enhance training intensity.

One way to measure presence can be derived from the evaluation of physiological responses of the autonomic nervous system during the exposure to the virtual scenario [14]. This means analyzing how events of the virtual world lead to bodily changes that are not under direct voluntary control. There is a strong relationship between the affective state of humans and somatic changes controlled by the autonomic nervous system such as the electrodermal response, heart rate, respiration, and blood volume pulse [15]. The usefulness of these measures for the study of human computer interaction has been recognized, e.g. [16]. Heart rate variability has been described as reflecting the emotional significance or valence of stimuli. Negative stimuli have been shown to slow down the heart rate while positive stimuli have the opposite effect [17] and the changes due to negative valence are longer lasting than those induced by positive valence [18]. The conductive changes of the skin due to the activity of the sweat glands often referred to as the Galvanic Skin Response (GSR) or Electrodermal Response (EDR) have been recognized as a direct measure of stress and arousal [19]. Therefore, these measures can be used to assess how events within a virtual scenario influence the affective state of the subjects.

We developed a VR based system, the Rehabilitation Gaming System (RGS), which was designed for the therapy of the upper extremities following brain injury [20]. In the RGS, a virtual scenario is presented where the user interacts through virtual arms that mimic the movements of the user’s arms. In order to assess engagement and effort during the game, we measured the heart rate and the electrodermal response of healthy subjects while performing the task. We investigate how the events triggered in our rehabilitation system lead to changes in the affective state of the user. The obtained information will allow us to understand how we can integrate real-time non-invasive physiology during therapy, in order to optimize the rehabilitation scenario, the presence of the user and the impact of training.

2. Methods

The experimental setup makes use of the RGS for the virtual task and the capture of the position of the arm. For the physiologic measures (heart rate and galvanic skin response) we used the g.MOBIlab device (www.gtec.at), a portable acquisition and analysis system that allows the recording of multimodal biosignal data on a standard notebook.

2.1. Rehabilitation Gaming System

The system integrates different elements. For the development of the virtual scenarios we used the Torque Gaming Engine (www.garagegames.com), which is versatile allowing easy adaptation to other rehabilitation scenarios. To capture arm movements, a vision based motion capture system (AnTS) detects color patches located in specific points of the real arms, i.e., wrist and elbow (Figure 1). For this application, the joint angles of both arms are computed from the position of the tracked patches. The computation of 8 joint angles from a single camera requires a perspective correction system plus a physical model of a skeleton in order to prevent the motion capture system to deliver unrealistic joint angles.

Figure 1 The Rehabilitation Gaming System. The subject faces a screen; on the display, two virtual arms mimic the movements of the user's arms that are tracked by means of a vision based motion capture system. Data gloves are used to capture finger movement.

The captured real arm movements are reconstructed onto the movements of virtual arms, embedded within the virtual scenario. The subject wears data gloves equipped with bend sensors to measure finger flexure, allowing for a complete and realistic capture of the subject's movements. Detailed position data of the limbs is recorded for subsequent analysis.

2.2. Physiologic measures

The g.MOBIlab blockset was used to perform online signal visualization, data logging and biosignal processing. The physiological data was analyzed using the gBSanalyze biosignal analysis software.

We acquired single channel ECG with a frequency of 256 Hz. For acquiring the electrodermal response, electrodes were placed on the neck of the subjects as we could not use them on the fingers (due to the noise induced by motion), and connected to the g.GSRsensor (www.gtec.at). From the readings, the Skin Conductance Level (SCL) (the baseline of the skin conductance) and the Galvanic Skin Response (GSR) (evoked changes in skin conductance) are extracted.

2.3. Task

A small group of healthy subjects (N=5), 4 males and 1 female, average age 29.6±3.6, performed the proposed task in single trials with a duration of 5 minutes.

The subject sits on a chair, facing a computer screen. The movements of the arms are made on a table surface. In a virtual scenario, the subject sees a landscape where spheres move towards virtual arms that mimic the motion of the arms of the subject. The spheres have to be intercepted, and every time there is a successful intercept, the sphere bounces back and points are accumulated for a final score. The difficulty of the task is defined by: speed of the moving spheres, time interval between consecutive sphere appearance, left/right range of dispersion and radius of the spheres.

Every 10 seconds a single sphere is delivered with high speed towards the subject to a random position of the screen. From the point of delivery, the sphere takes ~2 seconds to reach the subject. A resting period of 15 seconds precedes the start of the task. In total, the experiment has a duration of 320 seconds (Figure 2) and 31 spheres are delivered.

3. Results

Our rehabilitation setup allows real time synchronized online recordings of hand position, game related data (sphere speed, size and position, touched and missed events, etc) and physiological measures (heart rate and electrodermal response) (Figure 2). This integration of physiological measures with a VR environment has a number of possibilities for the rehabilitation of motor deficits and the manipulation of presence. By monitoring the physiological state of the patient during the game, we can assess the engagement, stress level, performance and the exact influence that the different rehabilitation paradigms or tasks have on the patient.

The system provides us with accurate performance data, precision and movement information that is used to quantify the improvements over different sessions. Moreover, we investigated how both heart rate and electrodermal response can be used as a biofeedback system and to modify the parameters of the game to adapt to the needs of the patients.

The ECG data analysis requires as a first step the detection of the QRS complexes in the raw time series (Figure 2, bottom panel). The QRS complexes define the time distance between consecutive heart contractions (RR interval). The variations in the RR-intervals, known as heart rate variability (HRV), are a good candidate to detect relevant information about the physiological state and the influence of the RGS on the patient. Only time domain measures were considered.

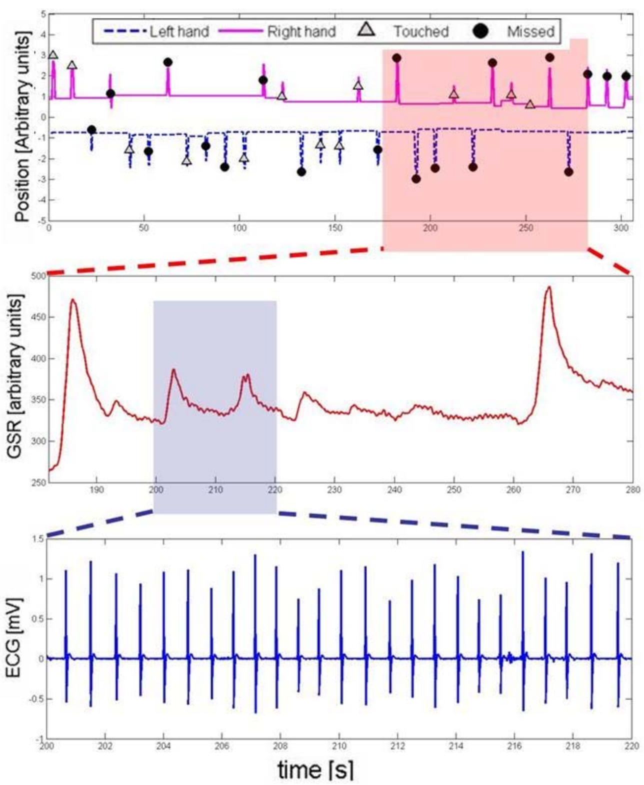

Figure 2 The different modalities of data acquired by the Rehabilitation Gaming System. Top panel: plot of the left hand (dashed line) and right hand (solid line) position over time and game related events (touched or missed spheres). Middle panel: sample of the electrodermal response during the task. Bottom panel: Electrocardiogram during the task.

The experiments aim at finding the relevant heart rate measures that contain information about the impact of the task specific training delivered by RGS. Thus, we compared a set of measures in two controlled conditions for the 5 subjects. The first one consists of a VR experience of 15 seconds where the subject can interact with its environment but no task is proposed (control condition). The second experimental condition corresponds to the first 15 seconds of the hitting task (see 2.3).

The comparison of the main time domain HRV measures (mean RR, mean HR, mean squared difference of successive RR intervals, etc) for both conditions showed that the overall state of the subject was not significantly influenced by the task itself. This could be due to the fact that results are computed from a small sample size and that the changes in the physiological responses are mainly caused by the sparse game events, and that those do not lead to long lasting effects. Therefore, it seems reasonable to assume that modulations of the physiological responses can be detected by comparing them before and after each of the events, rather than over longer periods of time.

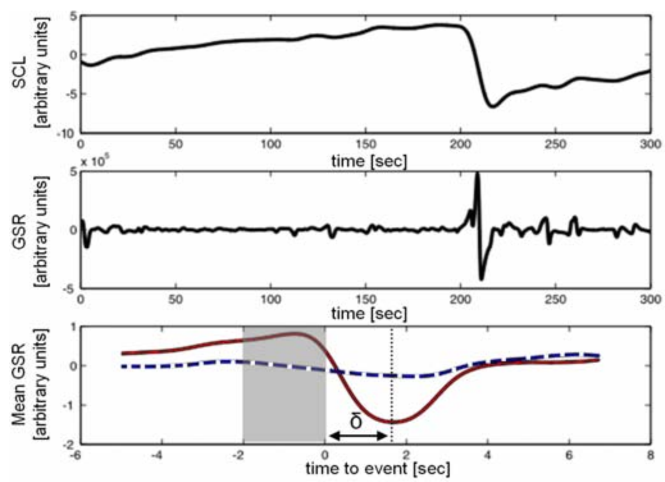

Figure 3 Electrodermal response analysis. Top panel: skin conductance level (SCL) during a trial. Middle panel: galvanic skin response (GSR) during the same trial. Bottom panel: average event centered GSR mean response for missed (solid line) and touched (dashed line) spheres. The gray area indicates when a sphere is approaching, 0 is the time of the event and δ the time between the event and the minimum of the GSR signal.

The electrodermal response is known to contain information about how discrete events affect the level of arousal. Therefore, we classified all game events (touched and missed spheres) and analyzed the effect that each of them has on the GSR during a training session. Although the effect on the 5 subjects was not equal, 3 of them showed a clear prototypical response pattern for the missed spheres (Figure 3, lower panel). This consisted of an arousal (increased GSR) during the approach of the sphere, and a faster decay after the sphere is missed, and followed by a return to the baseline position. The minimum of the decay occurred between 0.78 and 2.3 seconds after the event in case a sphere was missed. In contrast, the GSR signal during touch events was largely unaffected. In 2 of the 3 subjects that displayed the same GSR response pattern, there was a significant difference between GSR response for touched and missed spheres after the event occurred (p-value < 0.05, t-test). If true, taken into account this prototypical behavior of the GSR curve, we can try to predict when a sphere is going to be missed, given the early arousal detectable in the GSR signal before the intercept occurs, and consequently change the game parameters to keep the difficulty at an optimal level. Nevertheless, a study with larger populations is required to confirm these preliminary results.

Conclusions

We presented the Rehabilitation Gaming System that integrates a motion capture system, a VR based environment and a real-time physiology system. We build on an existing rehabilitation system that has already been tested with stroke patients with promising results [21]. This novel approach serves two purposes: on the one hand, a monitoring system that allows a more detailed control of the state of the patient during therapy; and on the other hand, it can be used as a biofeedback system that can tune the game parameters to both, the training requirements and the capabilities of the patients. In this way we can further manipulate the emotional state of the user in the task.

We examined the effect of our system on heart rate using standard time domain analysis. Surprisingly, we observed that the effects of our system can not be effectively measured by comparing conditions over a long period of time. This is due to the sparseness and short term effects of the game events, being more adequate a pre- and post-event comparison. However, we have shown that the GSR displays a prototypical evolution with respect to the interaction events (touched or missed spheres). Interestingly enough the response in relation to failures already deviates from that correlating to success before an object is intercepted. Hence, although these measures may contain a noise component induced by the motor activity, they seem to be good candidates for an online biofeedback system that will control the game parameters and the state of the user. For instance, we will be able to assess online if the patient is too stressed (or too relaxed), and adjust the difficulty of the game accordingly.

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