33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Cortical response to psycho-physiological changes in auto-adaptive robot assisted gait training

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Abstract— **Robot-assisted treadmill training improves motor function and walking ability in neurologically impaired patients. However, despite attention having been shown to play a role in training success, psychological responsiveness to task difficulty and motivational levels at task onset have not been measured. Seven healthy subjects participated in a robot-assist treadmill training task. Subjects engaged in a virtual task with varying difficulty levels that was shown to induce a feeling of being bored, excited and over-stressed. The participants' mental engagement was measured using the ECG-based heart rate variability in real time, during gait training as a proxy for EEG and psychological test batteries. Heart rate variability (HRV), which has been shown to reflect cortical engagement for both cognitive and physical tasks, was measured using nonlinear measures obtained from the Poincaré plot. We show that the cortical response to the task measured with HRV varies in relation to the level of mental engagement in response to the difficulty level of the virtual task. From these results we propose that nonlinear measures quantify cortical response / motivational level to robot-assist motor learning tasks and that the adaptation to the task is dependent on the level of motivation.**

I. INTRODUCTION

TREADMILL training is an established treatment for gait rehabilitation [1]. To improve rehabilitation outcome robot-assist devices are becoming increasingly available for automated gait training [2-4]. Active mental engagement [5] and responsiveness is important for successful training outcomes. Heart rate variability (HRV) has been shown to correlate well with EEG measures of cognitive involvement as well as to motivation levels determined using a psychological test battery [6]. The degree of adaptation to a new task with increasing level of physical and mental difficulty has not been studied previously. The goal of this research was to determine adaptation to task difficulty by a group of healthy subjects with respect to the level of mental and physical challenge to determine the optimal level of task difficulty to maximize the outcome of the training, allowing real-time adjustment of task difficulty to successfully reach set targets during training. Motor learning rate is maximal at a task difficulty level that positively challenges and excites subjects whilst not being too stressful or boring [7]. In this context challenging tasks in virtual environments were shown to have a positive, motivating effect during rehabilitation [8]. Measuring cognitive function or mental engagement whilst strapped into a robot-assist device however is difficult and we therefore used a model that is sensitive to central nervous system functioning but has a peripheral output. Heart rate variability (HRV) was shown to be an indicator of physical as well as mental load when physiological function is recorded during a virtual task with a goal [9]. Higher order processing, especially from prefrontal cortex is connected to the parasympathetic part of the autonomic nervous system, which drives efficient functioning [10]. Thus physiological and psychological function both influence heart rate inter-beat interval variability (HRV), decreasing with increasing physical challenge [11] and psychological stress [12].

II. MATERIAL AND METHODS

A. Gait Data

Seven healthy subjects (mean age 24.1 ± 2.0 years) with no neurological and physiological impairment participated in the study. Data was obtained at the Spinal Cord Injury Center Balgrist, Zurich, Switzerland. Ethics approval was obtained from the local ethics committee.

B. Training environment and virtual task

The driven gait orthosis (DGO) Lokomat (Hocoma, Switzerland) was used for the locomotion training. The DGO is an exoskeleton with drives on hip and knee joints. The device allows assisted locomotion on a treadmill at 2km/h by guiding the subject's legs along a predefined trajectory. Subjects were fixed into the DGO with a harness around the hip and cuffs around the legs and connected to a body weight support system set at 30%. Cadence was adjusted to the individual leg length of the subjects. The virtual environment was projected on to a 3x2 m back projection screen with surround sound and included a simultaneous biomechanical task and a cognitive task. Subjects were challenged to differing degrees to navigate through the virtual environment. The mechanical task was to pick up items by walking to them and the cognitive task was to jump over barrels, which rolled towards them by clicking

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a computer mouse button. Following the training session, subjects completed five experimental conditions. Standing with harness, walking with harness and three levels of difficulty/challenge whilst walking. These were related to the distance between barrels and the speed they were moving at [13]. In the under-challenged condition, all objects were easily collected without major changes in the walking direction (100%). During the challenged condition the distance settings between items and their distribution led to a maximum of 80-90% of objects to be collected. In the over-challenged condition, the objects were distributed to reduce the possible score to less than 10% of the possible maximal score. These three challenge levels correlated with three levels of mental engagement and cortical response in that under-challenge is equal to boring, correctly challenged is equivalent to excitement and over-challenged synonymous with the feeling of being over-stressed.

C. Physiological recordings

The different levels of cortical responsiveness leading to a certain degree of mental engagement were estimated by recording of ECG traces and determining heart rate variability. The ECG was recorded using a Lead II configuration at 512 samples/second. R wave peaks were determined using the algorithm first suggested by Tomkins [14]. Inter-beat variation and complexity was determined from the ECG by time domain (RMSSD, frequency domain (HFn) [15], and Poincaré plots (SD1) as well as the complex correlation measure (CCM) [16].

1) Poincaré Plot

The Poincaré plot of HRV signal is constructed by plotting consecutive points of RR interval time series (i.e., lag-1 plot). An ellipse is fitted to the Poincaré plot and the dispersion along the major and minor axis of the ellipse measured. SD1 (short axis) provides a numeric expression of the parasympathetic, that is short-term correlation between inter-beat intervals, whereas SD2 describes the sympatho-vagal function [17].

2) Complex Correlation Method

The Complex Correlation Measure (CCM) measures the variability in the temporal structure of Poincaré plot, which can characterize or distinguish plots with similar shapes. The CCM measures the point-to-point variation of the signal rather than the gross description of the Poincaré plot. It is computed in a windowed manner, which embeds the temporal information of the signal. A moving window of three consecutive points from the Poincaré plot are considered and the temporal variation of the points are measured. CCM is more sensitive than SD1 and SD2 to changes of parasympathetic activity [16].

The parasympathetic nervous system output is regulated centrally from the prefrontal cortex via the brainstem and therefore both SD1 and CCM, which provide information on heart rate variability provide information on the level of cortical engagement. That is a change in cortical responsiveness and engagement, as is expected, when novel tasks are presented to a subject will change parasympathetic output and HRV.

The main focus of our experiments was to establish whether the level of psycho-physical challenge is reflected by different levels of cortical responsiveness at the transition points from the steady state of the previous task to the first minute of the next task (e.g. walking to under-challenged). We expected to see a difference in this ‘change’ depending on the level of the challenge.

D. Statistical analysis

Using descriptive statistics, we investigated the change in HRV over the recording period for each condition to determine the adaptation differences to the three different conditions. All conditions were tested using the Friedman test followed by a Wilcoxon test for paired comparison. Bonferroni correction corrected multiple errors caused by the paired comparison. The significance level was set at $p < 0.05$.

III. RESULTS AND DISCUSSION

A. Results

Figure 1 provides information of how the HRV for two of the subjects changes for every minute during the five tasks using RMSSD. Subject 3 indicates a high degree of variance over the recording period with peaks still discernable when the task changed. However the second recording is more characteristic of the change in HRV over the recording period for the remainder of the subjects with peaks at each of the transition stages and HRV returning to a baseline level.

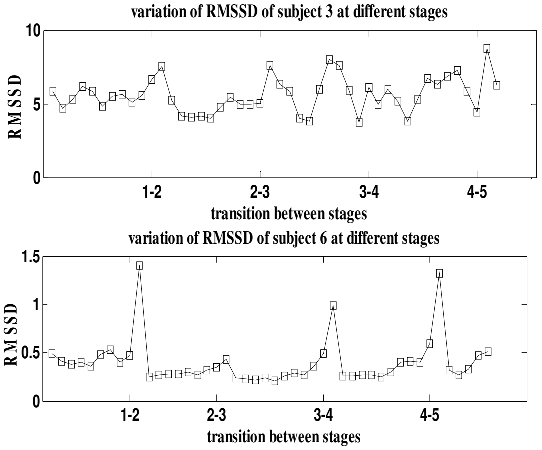

Figure 1: Variation of RMSSD of two subjects whilst engaged in the five tasks.

The variance as shown for subject 3 was more pronounced for all subjects when using frequency domain measures. This may explain why no significant differences could be found when comparing the steady state levels between the tasks for frequency domain measures in previous work by AK [13].

Table I. Investigating the level of adaptation, which is an important component in task performance we found that only the nonlinear measures, SD1 and CCM differentiated between the level of adaptation. Specifically only transition 1 and transition 3 were significant, which is found from calculating the gradient of changes for those parameters (table I) and reflected in Figure 2 and 3.

TABLE I

GRADIENT OF CHANGES OF DIFFERENT HRV PARAMETERS

stages	SDNN*	RMSSD	HFn	SD1	CCM
Transition 1#	0.40± 0.07	0.57± 0.12	0.5± 0.05	0.24± 0.08**	0.71± 0.12**
Transition 2	0.44± 0.07	0.51± 0.13	0.57± 0.08	0.27± 0.08	0.70± 0.09
Transition 3	0.59± 0.07	0.56 ±0.08	0.67± 0.1	0.39± 0.10**	0.81± 0.07**
Transition 4	0.46± 0.06	0.61± 0.09	0.49± 0.09	0.37± 0.09	0.74± 0.13

All values are mean ±standard error

Transition 1 – standing to walking; Transition 2 – walking to under-challenged; Transition 3 – under-challenged to challenged; Transition 4 – challenged to over-challenged. **Transitions between standing to walking and under-challenged to challenged show significant difference at $p < 0.05$.

Changes in the environment require a mental and physical response of the organism. This is shown in Figure 2 and Figure 3.

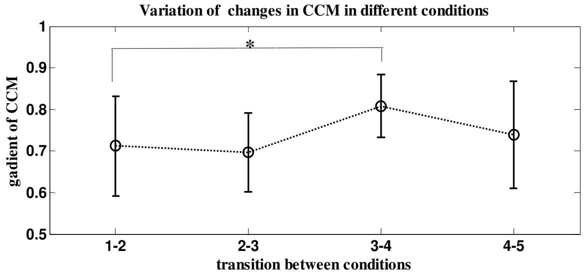

Fig 2: Variation of the gradient of CCM for the different conditions.
* indicates gradient changes of CCM is significant in transition 1 and 3

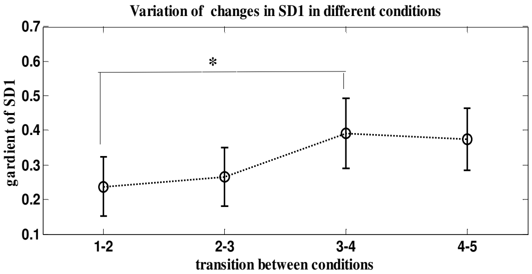

Fig 3: Variation of the gradient of SD1 for the different conditions.
* indicates gradient changes of SD1 is significant in transition 1 and 3

The maximum and statistically significant adaptation responses were between standing to walking (transition 1 to 2) and the under-challenged to challenged (transition 3 to 4) for both SD1 and CCM (Table 1) with $p < 0.05$.

B. Discussion

Robot-assisted training is an important component of neural rehabilitation and requires motivation and mental engagement for optimal task execution. Our research has focused on a group of healthy subjects that were subjected to five levels of task challenges that included three levels of motivation whilst walking: bored, excited and over-stressed in addition to the baseline conditions of standing and walking. In a previous report of ours, we show that healthy subjects differ in their steady-state outcome to different levels of physical-mental stimulation tasks as measured by heart rate variability, respiration rate and skin conductance level when steady state was reached for each of the three levels of challenge [13].

This study focused on the level of cortical responsiveness and engagement as indicated by the level of heart rate variability in people with no neurological disorders to obtain baseline data using HRV as a measure of mental engagement and avoid confounding effects [18, 19]. There is anatomical and physiological evidence for a connection between cortical structures, the brainstem and ANS output The prefrontal cortex, amygdala and hypothalamus are connected with the nucleus solitaries, dorsal nucleus of the Vagus and nucleus ambiguous that have connections to the ANS.[20, 21]

Appropriate cortical activity is an important component of neurophysiological and neuropsychological rehabilitation as the adaptive phase of mental and physical exertion when a novel task is presented provides more accurate information on the capacity of the system, which is hidden in part when the system reaches steady state. The advantages of using Poincaré plot and its SD1 measure and CCM is that these variables are robust against non-stationarity, respiration and ectopics of the ECG signal [16, 22]. Short-term heart rate variability is a function of the level of parasympathetic input, which for instance decreases when physical exercise is undertaken or an external or internal stressor is present. Stress decreases function in certain parts of the cortex linked to parasympathetic function [23]. The decrease in parasympathetic input leads to sympathetic dominance and a decrease in HRV [24]. Changes in sympathetic output were not measured as these are considered to be outside the response time for the task. Importantly we found that the level of challenge is important in how the cortex responds (Fig 2 and 3). Standing to walking and under-challenged to challenged transitions brought about the largest cortical response. Initial conditions of inactivity prior to the exercise session might be partially responsible for the large adaptation observed in the standing to walking transition. Similarly the transition from under-challenged to challenged increases motivation and cortical activity and therefore the heart rate variability. Further the level of adaptation dropped for challenged to over-challenged for both SD1 and CCM back towards the walking to under-challenged transition level. This may be due to physical or cognitive stress. Both of which would results in a parasympathetic withdrawal and therefore a lower HRV.

Heart rate variability is linked to cortical as well as brainstem modulation with the prefrontal cortex having an inhibitory influence on brainstem nuclei, which in turn inhibit parasympathetic output and therefore the level of HRV [19]. The decrease in SD1 and CCM when the over-challenged condition commenced indicates a withdrawal of the frontal cortex and emotional positive output. Therefore the inhibitory output to the brainstem is reduced leading to an increased inhibition of the parasympathetic output and therefore a balance towards sympathetic drive and a decrease in HRV.

IV. CONCLUSION

The key result of this study is the ECG assessment of cortical responsiveness when psycho-physical conditions change whilst using a robot-assist device. The algorithms used here are more robust against non-stationarity of the ECG signal and ectopic beats/noise, as no significant differences were observed using time and frequency domain measures.

ACKNOWLEDGMENT

This work was supported by the Swiss National Science Foundation NCCR on Neural Plasticity and Repair under Project P8 Rehabilitation Technology Matrix & EU Project MIMICS funded by the European Community's Seventh Framework Program (FP7/2007-2013) under grant agreement nr. 215756. Katherine Grace August is funded by the Whitaker Foundation.

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