

A Review on Bio-Cooperative Control in Gait Rehabilitation

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Abstract—While gait rehabilitation robots have become increasingly common to automate treadmill training, their efficacy is still controversial. Current robots lack the ability to react compliantly to the user’s voluntary effort and cognitive intention. Bio-cooperative control concepts allow integrating the patient into the control loop as part of the plant rather than seeing him as a source of disturbance. Closed loop control is thereby performed on a physiological and psychological level. In this paper, we review the concept of bio-cooperative control implemented with neurological patients during robot-assisted gait rehabilitation. We highlight its clinical importance and review our work on control strategies that allow bio-cooperative control. We finish by discussing the future potential of bio-cooperative control in rehabilitation robotics.

I. INTRODUCTION

Damages of the CNS, such as stroke or spinal cord injury, are amongst the leading causes of disabilities, severely limit the quality of living of affected people and their possibility to actively contribute to society [1]. Recent studies estimate the incidence of stroke to at least 101 - 285 in men and 47 - 198 in women per 100.000 subjects in Europe [2], [3]. Thus, stroke affects about 1 million people in Europe each year. Spinal Cord Injury (SCI) is reported to affect 14-20 subjects per million in Europe [4] and 14-40 subjects per million worldwide [5].

Robots have become increasingly common to automate rehabilitative treadmill training, as they allow for longer training duration and higher training intensity [6]. Two general design approaches have been pursued: end-effector based robots such as the gait trainer Gaittrainer [7], or the Haptic Walker [8] and exoskeleton robots such as the Lokomat [9]–[11], the Lopes [12], the Autoambulator (www.healthsouth.com) or the Walk Trainer [13].

Despite their advantages, their effectiveness is still controversial [14], [15]. The Lokomat, as the most studied amongst all available gait robots, was found to be superior to manual therapy [16], [17], equally efficient as manual therapy [18] or inferior to manual therapy [19], [20].

Novel control strategies allow so called bio-cooperative behavior, which is defined as the ability of the robot to react

compliantly to the user’s voluntary effort or cognitive load [10], [21], [22], thereby integrating the human into the control loop instead of treating the human as a source of disturbance. We thereby define cognitive load as the amount of focus and concentration the patient has to invest to still be able to fulfill the rehabilitation task.

The lack of bio-cooperativity in current gait robots might explain why gait robots are not clearly superior to compared to manual therapy. In the following, we will review the definition of bio-cooperative control, exemplify possible implementations and highlight its clinical relevance for rehabilitation outcome. The methods and results presented in this paper are a summary of previously published material [23]–[27].

II. BIO-COOPERATIVE CONTROL

Bio-cooperative control of a gait rehabilitation robot is possible on two key levels of integration: a physiological and a psychological level (Fig. 1). On the physiological level, the robot has to take the physiology of the patient into account and needs to react adaptively to changing demands in physical effort. On the psychological level, the robot has to interact with the patient on a cognitive level and take the patient’s current mental engagement or cognitive load into account [21], [22].

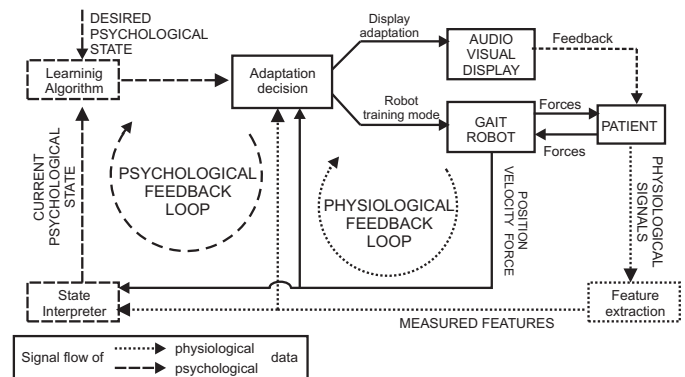


Fig. 1. The Human-in-the-loop control scheme. The gait robot and the patient exchange interaction forces, an audiovisual display allows projection of feedback on the current gait performance or to display a virtual task. The current physiological or psychological state is determined in real-time via physiological recordings. The human is therefore part of a closed loop control of physiology and psychology.

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A. Controlling physiological states

Active physical participation of the patients in rehabilitation training and high training intensities were shown to substantially improve motor learning [28] and rehabilitation outcome [29]–[32]. In addition, coordinative gait training plays a major role in rehabilitation of stroke survivors [33]. Finally, intense cardiovascular exercise was shown to improve sensorimotor functions, decrease cardiovascular risk factors and improve the medical risk management of stroke survivors [34].

The combination of coordinative gait training with cardiovascular training can therefore be regarded as key to improvement of neurological rehabilitation. Particularly non-ambulatory patients cannot exercise on treadmills, but must use stationary bicycles, where the problems of coordination and balance during walking do not need to be taken into consideration. Gait robots are strong enough to move the patient's legs along a predefined walking trajectory and can support learned passiveness of the patient.

In healthy subjects, treadmill based heart rate (HR) control has been successfully demonstrated using PID or H_{inf} control [35]–[37]. Pennycott et al. [38] controlled oxygen uptake during Lokomat walking, however only in healthy subjects and with the drawback, that the method needed an initialization time for parameter identification, which would shorten the duration available for actual cardiovascular training in patients.

B. Controlling psychological states

1) *Clinical relevance:* Active cognitive participation and motivating training sessions were shown to be key requirements for the success of motor learning in general [28], [32] and in rehabilitation [39], [40]. The learning rate of a motor task is maximal at a task difficulty level that positively challenges and excites subjects while not being too stressful or boring [41].

Research in healthy subjects suggests that motor learning decreases in the presence of a distracting cognitive task, which presents a cognitively over-challenging situation [42], [43]. A task which is too easy for the subject will be perceived as boring, a task which is too difficult will overstress the subject, while an optimally challenging task should induce maximal motivation and cognitive participation.

Therefore, controlling cognitive load has the potential to enhance motor learning and, thus, further increase the rehabilitation outcome, as it is known that task with difficult but feasible cognitive load will lead to higher motivation and active participation [32].

2) *Detecting psychological states:* Detecting the psychological state is generally done via questionnaires such as the "Intrinsic Motivation Inventory" [44] which is used to obtain subjective information, but only at discrete time-points after training has ceased. Questionnaires can therefore not be used in real time. Specifically in gait rehabilitation, neurological patients with severe cognitive deficits or aphasia might not be able to understand and respond appropriately to the questions.

Psychophysiological measurements can provide real-time information on the cognitive load of subjects [45], [46],

as physiological processes were shown to reflect behavioral, cognitive, emotional and social interaction [47]. Signals from the Central Nervous System such as the Electroencephalogram (EEG) or Near Infrared Spectroscopy (NIRS) can be used to infer to the psychological state of subjects; however, these signals are difficult to record from patients during walking. We therefore focused on signals from the autonomic nervous system (ANS) that reflected the psychological state of a human; the detectable states find primarily reflection in signals that respond to mental stress or relaxation [45]; in addition, signals from the ANS are easy to record in real-time during robot assisted gait training.

From the ECG, HR and heart rate variability (HRV) can be computed. When recorded during a virtual task, HR was shown to be an indicator of physical as well as mental load [48]. Physiological effort and psychological stress have an influence on the short-term variation of HR. In addition to psychological processes, physical effort, such as walking on a treadmill, can influence the psychophysiological measurements. HRV was shown to decrease during physical effort [49], mental stress [50] and negative emotions [51]. Galvanic skin response (GSR) is used as a direct measure for arousal [52], [53] and was found to increase during demanding tasks compared to a rest period [54]. From the galvanic skin response, skin conductance responses (SCR) measured as a number, and the skin conductance level (SCL) are computed. The number of SCR is a sensitive indicator for emotional strain [55]. In recent research, SCL was found to increase during demanding tasks compared to a rest period [54]. The breathing frequency was found to increase during stress [56], negative emotions [57] and mental effort [58] and also during physical activity [59].

However, not all physiological signals that provide information on cognitive load are unambiguous. HR was found to increase due to stress or negative emotions [45], [60], but decreased in reaction to unpleasant stimuli [61]–[63]. Skin temperature decreased during mental work stress in a study by Ohsuga [64] but increased with physical activity [65]. Other physiological recordings from the peripheral nervous system have been used as indicators of the psychophysiological state of a subject. Amongst these were facial EMG recordings as indicators for emotional responses to pleasant or unpleasant stimuli [66], [67].

3) *Modulating psychological states:* During robot-assisted gait rehabilitation, control over the psychological states of subjects is made possible via virtual environments, which have been used to motivate and challenge patients to longer training duration and cadence [40] and to modulate patient participation [68]–[70]. The patient can obtain intuitive and easy to understand information on his or her performance during the training [71]. These virtual environments can be therapeutically superior to real scenarios [68], [72]. Virtually enriched environments as well as functional and task-oriented exercise environments were shown to improve motor re-learning and recovery after stroke [73]. Virtual reality can be used to test different motor training strategies, different types of feedback provided, and different practice schedules

for comparative effectiveness in improving motor function in patients. Virtual reality technology thereby provides a convenient mechanism for manipulating these factors, setting up automatic training schedules and for training, testing, and recording participants' motor responses.

In patients, a study by Bruetsch showed that virtual reality had the potential to increase active participation of children with cerebral palsy [70] compared to gait therapy alone. Participation was thereby quantified by EMG measurements. Mirelman showed in a randomized control study that the use of VR increased the usage of a home-based ankle rehabilitation system in after stroke [69]. In return, the increased exercise time improved the functional recovery measured as gait speed and distance walked of stroke patients significantly compared to patients that exercised without VR.

4) *Previous closed loop control on psychological states:* Previously, closed loop control of psychological states in healthy subjects has been implemented to adjust the difficulty level or level of assistance in virtual tasks. Haarmann et al. [74] performed a study in 48 healthy subjects and combined GSR with HRV measurement to control the difficulty level of a flight simulation task. Also in an aviation task, Wilson et al. [75] adapted the level adaptive assistance depending on a psychophysiological estimation of a subject's workload. Rani et al. [76] estimated stress from HRV using a Fuzzy classifier and controlled stress to a desired level. Liu et al. [77] used physiological signals to adapt computer game difficulty in real-time.

III. EXEMPLARY IMPLEMENTATIONS FOR ROBOT-ASSISTED GAIT TRAINING

A. Controlling physiological patient states

Any control of physiological patient states must take the biomechanical and cognitive impairments into account that resulted from the neurological injury. In order to serve both, the severely impaired as well as the mildly impaired patients, a "one fits all" system is unlikely going to be realizable. We will first review the work on patients with mild or no cognitive impairments that were able to understand instructions delivered via visual feedback. We will then summarize on control approaches that also allowed control of HR in patients with severe cognitive impairments (Fig. 2). Details on the technological methods, study protocol and comprehensive results can be found in [23], [27]

1) *Heart rate control via visual feedback:* Patients that were cognitively capable of understanding a virtual task and producing voluntary force were provided with real time feedback on their current activity using visual displays [23]. HR of five stroke patients was exemplary controlled to a desired temporal profile (Fig. 3, gray line). With voluntary physical pushing effort, the patient had to match the current effort to a desired effort displayed on a screen. In this case, the control loop was closed via a visual feedback loop, as the instructions to the patient were given visually. The virtual stimulus was designed to be as easy and intuitive as possible such that patients with cognitive impairments were able to understand and perform

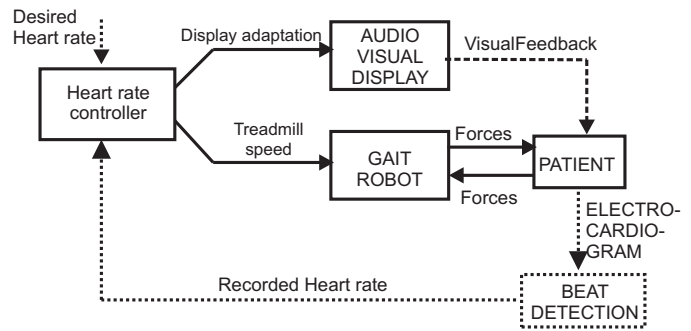


Fig. 2. Implementation of heart rate control during robot assisted gait rehabilitation. Depending on the cognitive and physical abilities of the patient, heart rate can either be controlled via treadmill speed or via visual feedback

the task. All action in the virtual environment took place on a straight path in the middle of the screen such that patients with partial neglect of the visual field could use the virtual environment. Results of an exemplary patient (71 years old, right ischemic stroke) are shown in Fig. 3.

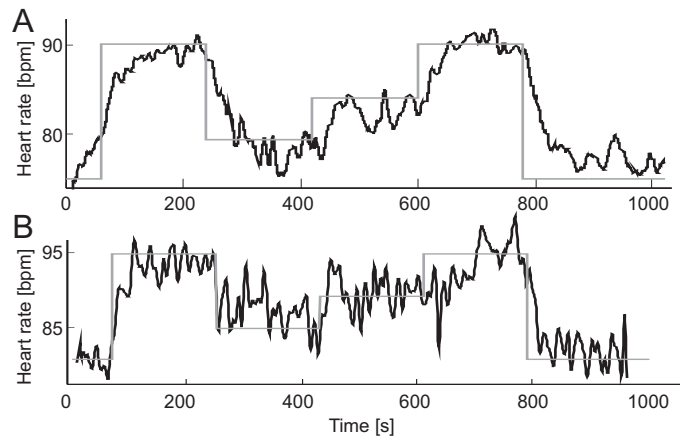


Fig. 3. Exemplary plots of heart rate control in one patient. A: using visual feedback, B: using adaptation of treadmill speed. Desired HR is plotted in gray, recorded HR in black. Recorded HR was filtered with a 4th order Butterworth lowpass filter, cut-off at 1 Hz.

2) *Heart rate control via treadmill speed adaptation:* Subjects, whose biomechanical or cognitive impairments prevented the use of virtual environments, underwent HR control via treadmill speed adaptations during walking. In this approach, HR of five stroke patient was successfully controlled to a desired temporal profile by controlling their gait speed with a PI controller. Patients were forced to change walking speed, regardless of their voluntary physical effort [23], [27]. This approach was designed for patients that were cognitively not capable of understanding visual feedback, or physically not capable of exerting enough voluntary physical effort to control the virtual task. We imposed a higher physical load on the patient by increasing gait speed such that the patient was forced into a walking movement, which required increased activity. Conversely, lower gait speeds demanded less physical activity of the patient. In studies on healthy subjects [35]–[37], HR increases of 30 beats per minute (bpm) were demonstrated;

in our experiments, we only reached an average HR increase of 12 bpm using treadmill speed as control signal. This seems to be a very small increase compared to the results obtained in healthy subjects. However, previous approaches to HR control of healthy subjects were performed at walking speeds starting at 3.6 km/h [35]–[37], which are not feasible for most patients.

B. Controlling psychological patient states

We first established real-time estimation of cognitive load during robot-assisted gait training in healthy subjects [24], [26] and stroke patients [25], [26] and then controlled cognitive load to a desired value [25]. A virtual task (Figure 4) with adaptable difficulty level was used to modulate cognitive load to three distinct levels (under-challenged, challenged, over-challenged). The task involved a biomechanical challenge (collect and avoid task) and a cognitive task (answering questions) and could be controlled by the patient by modulating the gait effort in the Lokomat. The three levels of cognitive load were then automatically classified by real-time processing of ECG, breathing frequency, skin temperature, GSR, forces applied to the robot by the user and success rate of the virtual task. Questionnaires on cognitive load were used for comparison with the results of the classifier. The questions in the scenario were selected and categorized into three difficulty levels by an expert psychologist.

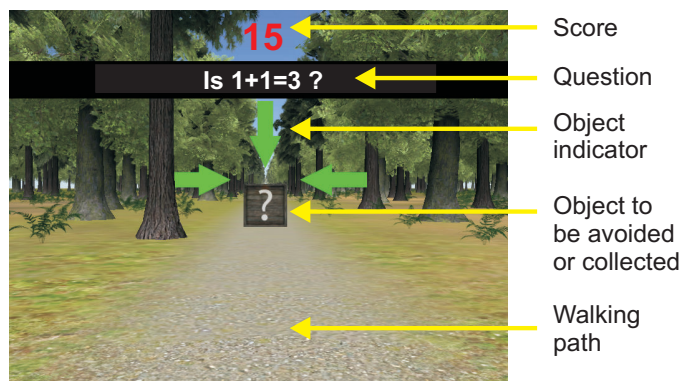


Fig. 4. Virtual environment used in control of psychological states. The question (with adaptable difficulty level) slowly disappeared in front of the subject. The subject has to accelerate (collect the object) to answer with 'yes' before it disappeared, or decelerate (avoid the object) to answer with 'no'. Object indicators were introduced to make recognition of the object easier for patients with vision problems or mild cognitive deficits.

1) *Estimating cognitive load:* We trained a neural network and a Kalman adaptive linear discriminant analysis classifier (KALDA) [78], [79] using physiological and biomechanical data. Results were verified by asking subjects questionnaires. In average, the neural network was able to correctly predict the cognitive load of healthy subjects with less than 2 % error [26]. However, it needed to be trained for each subject anew and did not generalize to classify the data of new subjects with a probability higher than chance. The KALDA reached 88 ± 9 % and 75 ± 26 % correct prediction for healthy subjects and stroke patients respectively [25], but operated auto-adaptively, as long as the initial training data allowed an initial guess of the

current cognitive load (which was the case for all recordings). Due to the inability of reidentifying the neural network for each patient in a clinical setting, we decided to continue experiments with the KALDA.

2) *Controlling cognitive load:* We performed closed loop control of cognitive load in five healthy subjects and five stroke patients [25]. Subjects started at a condition, in which the virtual task presented an under-challenging or over-challenging situation. Within ten adaptation steps, the KALDA modified the task difficulty such that subjects could exercise at a task level difficulty that was challenging, but feasible. In healthy subjects, a 87 ± 8 % match could be achieved between the classifiers estimated cognitive load and the questionnaire answers of subjects. In patients, the system could only reach 53 ± 33 % correct classification. This was expected, as stroke patients often suffer from cognitive deficits which decrease their self-assessment capabilities. Beside the patient, the experimenter also rated the patients performance objectively by filling out the questionnaires. When comparing the experimenter rating with the decision of the classifier, we were able to obtain a match of 80 ± 8 %.

IV. CONCLUSION

Bio-cooperative control during gait rehabilitation can integrate control over physiological as well as psychological aspects of the human, who then represents the plant within the control system.

In neurorehabilitation, active biomechanical participation was shown to increase motor learning [32]. The positive effect of active physical participation on rehabilitation was confirmed by Gordon et al. [34], who connect cardiovascular training with a positive effect on the recovery after neurological injury. We implemented HR control into Lokomat training and can now provide cardiovascular training to non-ambulatory patients. Besides closed loop control of physiological patient states, the role of motivation is known to be important in the progress on neurological rehabilitation [80], [81]. The bio-cooperative control structure puts the human in the loop and allows to optimize cognitive load of the subject, thus, increasing motivation. Controlling cognitive load in neurorehabilitation, therefore, has the potential to increase motor learning and thereby the training efficiency and therapeutic outcome of neurological rehabilitation [28], [39].

Detection and control of physiological and psychological states is thereby neither limited to a particular gait orthosis, nor to rehabilitation of the lower limbs, but can equally be extended to arm rehabilitation, as performed with the ARMin [82], the HapticMaster [83] or the MIT Manus [84]. In the HapticMaster, physiological signals were already shown to reliably reflect psychological states [85].

It can be concluded that closed loop control of physiological and psychological states has the potential to improve robot-assisted rehabilitation by enabling clinicians to provide patient-centered rehabilitation therapy. In the future, bio-cooperative control strategies have the potential to replace the classical

master-slave paradigm that requires the user to adapt to the rehabilitation environment.

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