Guest Editorial Special Section on Rehabilitation via Bio-Cooperative Control

THE use of conventional rehabilitation devices can be unsatisfactory, because an efficient interaction between the technical system and the patient is often limited or impossible. Many advanced rehabilitation systems that include novel actuation and digital processing capabilities work in a "master–slave" relationship, thus, tending to force the user only to follow predetermined reference trajectories without taking into account individual properties, spontaneous intentions, or voluntary efforts of that particular person. For instance, many actuated orthoses imply the patient's legs to follow a predetermined motion pattern, but do not react to the patient's voluntary effort.

A common problem of these conventional mechatronic solutions is that they are applied in an open-loop manner not incorporating the human in a natural way. The patient or therapist just presses a button or moves a joystick, and a primitive "if–then" algorithm executes a predefined unidirectional (unilateral) action on the human. This action can be the simple execution of a fixed reference movement with the support of a machine, e.g., an orthosis or wheelchair. The patient remains passive and his or her intentions and needs are ignored rather than involving the patient's complete sensorimotor system in an orchestrated manner. This action can also involve the display of other modalities, e.g., the presentation of visual or auditory instructions without taking into account the person-specific or task-specific context. During such unidirectional communication, biomechanical and psycho-physiological effects on the human are usually not taken into account. Thus, the loop is not closed via the human, in order to fit the device to the biomechanical or physiological state of the human, the human's behavior or intention and environmental factors. The possibilities of the user to intervene are reduced to "initiation" and "perturbation."

In contrast, novel rehabilitation technologies offer a new approach by placing the human into the loop, where the human is more than just a sender of the command to a device or the passive receiver of a device action. The human closes the loop by feeding back the biomechanical and physiological information to a processing unit. The interaction becomes bi-directional and the technical rehabilitation system takes into account the user's properties, intentions and actions, as well as environmental factors. For example, an actuated orthosis should be able to detect the patient's effort and engagement in order to optimize participation and support the patient only as little as needed; or the signals generated by any audiovisual display of a training system should adjust to the alertness of the patient in order to optimize engagement and maximize motivation.

Integrating the human into the loop can be considered from biomechanical, physiological and even psychological viewpoints (see Fig. 1). Biomechanical integration makes the rehabilitation system safe, ergonomically acceptable, and "user-cooperative." Thus, with respect to rehabilitation robotics, the robot assists the human in a compliant way, with just as much force as needed so that the patient can contribute to the movement with own voluntary effort. Psycho-physiological integration involves recording and controlling the patient's physiological reactions so that the patient receives appropriate stimuli and is challenged in a moderate, but engaging and motivating way without causing undue stress or harm. Including physiological or psychological interpretations into the loop makes the system "Bio-Cooperative."

In this special section of the IEEE TRANSACTIONS ON NEURAL SYSTEMS AND REHABILITATION ENGINEERING, the idea of Bio-Cooperative control has been applied to different kinds of rehabilitation devices (e.g., exoskeletal robots, end-effector robots, wheelchairs) used for the training of gait or arm movements or for the assessment of entire body activity of healthy subjects and patients with stroke and other neurological disorders.

As the established rehabilitation practice involves a human therapist who observes and adjusts different tasks to the patient's abilities, also future rehabilitation engineering aids might do the same. In the beginning of this special section, the mechanical aspects of Bio-Cooperation are considered by Ueda *et al.* Their computational algorithm suggests the force direction that needs to be applied by the subject equipped with a wearable upper limb exoskeleton, in order to efficiently conduct neuromuscular function tests on target arm muscles. When the subject follows the suggested force it results to a specific muscle activation pattern.

Bio-Cooperation is the future goal of the paper by Novak *et al.*, where rehabilitation robotic exercises are performed with an end-effector based robot for upper limb and grasping motions. The main focus deals with the dilemma if stroke persons show distinctive psychophysiological responses despite damage to the autonomic nervous system. 23 subacute and the same number of control subjects were tested with various task complexities to determine that the psychophysiological parameters derived from skin conductance offer the greatest potential to be used as a psychological state indicator, with other measures providing supplementary information.

Human in the loop Bio-Cooperation design is also shown by Grychtol *et al.* In this paper, the subjects are seated in a user-cooperative environment in front of an immersive VR system. The effect of user engagement is studied under different modalities of feedback on the performance of the BCI. The enhancement in the classification performance of the S-BCI method is

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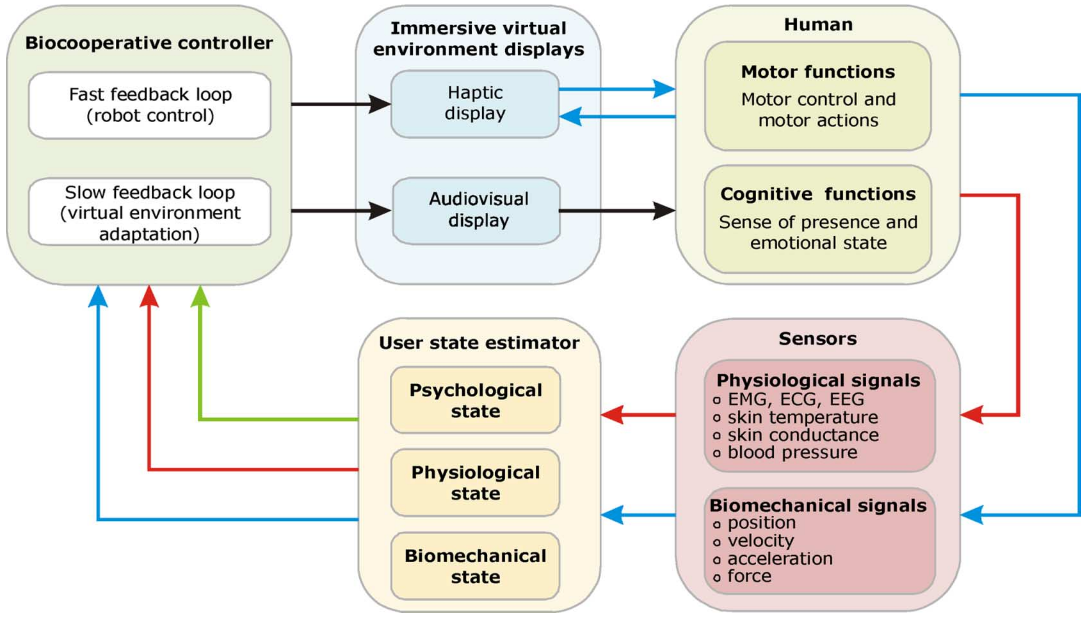

Fig. 1. Human is in the loop with respect to biomechanical, physiological, and psychological aspects.

demonstrated with the human voluntary behavioral modification brought into the loop.

Detection of mechanical and physiological signals for future Bio-Cooperation is covered in Li *et al.* Different physical activities, such as walking and lying of healthy subjects are studied with the aim to improve recognition performance. This is realized by fusion of the multimodal signals of ECG and accelerometer, as well as multidomain fusion within time domain support vector machine and cepstral domain Gaussian mixture models. Although this has not been demonstrated to work in real-time and in a closed-loop manner, the signal merging is an advanced and novel method. As it focuses on both domains together, it exceeds the state of the art of current recognition systems.

Chavarriaga *et al.* puts the human within a cognitive monitoring loop via visual feedback based on a monitor and a moving cursor. In contrast to traditional BCI systems, in this approach the user does not provide commands continuously, but rather monitors the autonomous agent's performance. Using their BCI paradigm, the authors show that error-related potentials decoded during human–machine interaction can be used to infer optimal behavior of the agent according to the user's intention.

Bio-Cooperation on a biomechanical level has been applied by Jarrasse *et al.* They are using specific performance indicators that are based on offline analysis of interaction kinematics and torques in order to determine the interaction of an exoskeleton with the body. The issues of comfort, and also terms of transparency caused by various systems may greatly effect different interaction sensations of the user. These user aspect topics were not covered so far and might influence rehabilitation robotics in the future.

Urdiales *et al.* are using the method based on cardio signals for Bio-Cooperative control of an assistive wheelchair. Medical experts report that an excess of assistance may lead to loss of residual skills. This is suggesting provision of just the right amount of assistance when needed. Key idea and main novelty are that user and robot commands are judged on the three factors smoothness, directness and safety, and then combined in a continuous way. Bio-Cooperative control is achieved by taking into account measures derived from ECG recordings. If the heart rate frequency is high, the user seems to be too active and robot decisions become more effective.

We hope that the reader will become aware of numerous opportunities that are opened with Bio-Cooperative rehabilitation robotics establishing a new taste of biomechanics and psychophysiology. These features may well affect our daily living and optimize some of the health issues in a similar manner as information technology has penetrated our social life, and influenced even our emotional attitudes.

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