Guest Editorial
Special Issue on Rehabilitation Robotics

I. Introduction

REHABILITATION robotics aims at developing novel solutions for assisted therapy and objective functional assessment of patients with reduced motor and/or cognitive abilities. These solutions augment existing therapeutic systems to improve a patient's achievable functional recovery. They are intended as therapeutic tools for temporary use (i.e., serving only the duration of the therapy at home or at the clinic), and are designed to maximize the objective clinical effectiveness of the therapy and the efficiency of the entire clinical process. It is worth noting here that this definition does not cover the field of assistive robotics, which aims at developing robotic solutions devised for promoting independent living of disabled and elderly citizens. Assistive robots are devised to be usable in a lifelong perspective in real-life scenarios, and thus, they need to take into deeper account the end-user subjective preferences in order to maximize their overall acceptability.

Current clinical evidence in physical medicine and rehabilitation clearly demonstrates that there is an important and increasing demand for innovative therapeutic solutions to address a wide variety of pathologies; for instance, patients experiencing severe stroke events have a high probability, in most cases higher than 50%, to retain severe disabilities for the rest of their lives. The positive correlation of the prevalence of many neuromotor diseases with age can give an idea of the social relevance of this research area. Novel, cost-effective solutions able to significantly improve the outcome of the rehabilitation process or assist in coping with residual abilities after the rehabilitation process are needed urgently in the many industrialized countries facing the challenges posed by their "ageing society." Such societies predict that in the near future, 20%–35% of their population will be over the age of 65 and in need of rehabilitation support.

But how can robots be actually useful to support the functional recovery process? What is the rationale for their introduction in the rehabilitation arena?

To answer these basic questions, at least four main fundamental issues should be considered, which are as follows.

1) *The technological evolution of machines for physical exercise and cognitive training:* Modern fitness and rehabilitation gyms are more and more populated with machines equipped with a variety of proprioceptive and exteroceptive sensors for recording multimodal data on the performance of the user as well as on his/her psychophysiological conditions. In some cases, these machines also embed one or more actuators and simple feedback control systems, like in the case of automatic treadmills or continuous passive motion systems. At the same time, the concept of "brain training" by means of interactive exercise/games is gaining a rapid popularity. No doubt, this trend is paving the way for a massive introduction of real robotics technology in the area of rehabilitation medicine also, just like in diagnostics and surgery.
2) *Evidence-based rehabilitation:* Modern medicine is based on objective evaluation and quantitative comparative analysis of the impact of different therapeutic approaches. Robotics technology provides accurate, precise, and very sensible tools for assessing and modeling human behavior, well beyond the capability of a human observer. This is of paramount importance for enabling appropriate initial diagnosis, early adoption of corrective clinical strategies, and for identifying verifiable milestones as well as prognostic indicators of the recovery process.
3) *Rehabilitation therapy is a time-consuming and intensive activity for healthcare operators:* Typically, one or more therapists should operate at the same time to deliver rehabilitation therapy to a single patient. In some cases, the role of the therapist is physically very demanding, involving physical activities that can lead to professional pathologies, such as low back pain and strain. This is particularly true in the case of severely disabled patients that need direct physical assistance even for performing very simple exercises. Proper introduction of robotics and automation technologies in this scenario can produce a dramatic reorganization of the working procedures within the rehabilitation process. Machines can take over most of unpleasant and physically demanding tasks, thus leaving to the healthcare operators the possibility to mainly concentrate on the quality of the therapy that is delivered. The most effective *triadic* interaction, among the patient, the machine, and the healthcare operator, should be identified in each application scenario, so that significant improvements of productivity and cost-effectiveness can be generated. The existence of these robots creates relief and opportunity. On one hand, the problem of the shortage of specialized personnel is mitigated by the possibility that a single operator can effectively supervise multiple patients, locally or even remotely (i.e., in telerehabilitation). On the other hand, patients' access to rehabilitation is improved by the opportunity to increase the duration and the frequency of their therapy experience, with limitations depending on clinical considerations and not on other organizational or economical limitations imposed by the healthcare system.
4) *Empowerment of the patient:* Recent findings on neural reorganization phenomena (neuroplasticity) related to functional recovery clearly demonstrate that patients

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suffering from neuromotor diseases can greatly benefit from activity-dependent rehabilitation therapies, which typically require the execution of goal-directed, repetitive exercises dominated by temporal and spatial constraints. During the exercise, the patient is supposed to play an active role, so that the whole sensorimotor coordination system is solicited and trained, including high-level brain functionality, such as imagination, planning, and anticipation of motor actions. In this perspective, rehabilitation robots can represent an ideal solution to implement training environments where this technology is able to continuously provide the patient with the minimal level of physical and/or cognitive support needed to repetitively initiate, execute, and complete a given exercise, while accurately complying with predefined spatial and temporal constraints.

Based on this analysis, the main functional requirements that rehabilitation robots should meet to properly address the targeted application domain can be derived.

Rehabilitation robots are among the very few robotic systems that are typically devised to operate in continuous physical interaction with the human body. The main challenge is to harmonize their behavior in constrained motion with the patient residual abilities, which are unpredictable in nature and dynamically varying, even within the same single therapeutic session. In many cases, the robot should implement assist-as-needed strategies, so that the whole set of sensorimotor control functionalities underlying the execution of the motor task is adequately stimulated and trained. Typical working conditions often require the robot to challenge the patient by using haptic interaction (e.g., spatially varying force fields) for opposing or favoring motion in predefined directions. In other situations, e.g., during evaluation sessions, the robot could be required to become fully *transparent* to the patient, so as to assess human motion parameters without introducing any perturbations on the physiological system. When purely cognitive diseases are the main focus, robotic agents acting as social mediators, like mechatronic toys or pet robots, have been successfully used; these solutions typically require a lower level of physical interactivity but a higher level of autonomy of operation than those needed in robots for motor therapy. More recently, *contactless* rehabilitation robots have also been proposed, e.g., mobile robots that, without any physical interaction with the patient, can effectively play the role of trainers, supervisors, observers, or motivational agents during a therapeutic session.

These requirements, and especially the key issue of enabling an active role of the patient to reach a real physical and/or cognitive symbiosis with the machine, pose major technical challenges for designing dependable, flexible, and effective robotic platforms. Typical main technical requirements include high back-drivability, easy adaptation of the mechanical structure to different anthropometric parameters, adaptive schemes for physical human–robot interaction control, friendly human–machine interfaces for involving and motivating the patient, and for allowing customization of the robot performance, especially in terms of the level of assistance and feedback provided to the patient during the exercise.

Robotic solutions proposed for application to rehabilitation therapy can be classified into two main categories.

1) *Operational rehabilitation robots:* For these machines, the trajectories of the robot end-effector and the human end-effector in the operational space are physically coupled. In the joint space, instead, the trajectories of the robot joints and the human joints can be significantly different, so that kinematic schemes can also be selected based on only the specific requirements of the target application scenario. Patients using these robots are supposed to exploit their own motor synergies for producing the proper configurations of the affected limb(s), so that application to severely disabled subjects could be limited.
2) *Wearable rehabilitation robots:* In these machines, a large portion of the human body (typically the whole affected limb) is in continuous physical contact with the robot. In most cases, a biomimetic exoskeleton kinematic structure is selected. Therefore, not only the trajectories of the robot end-effector and the human end-effector are the same in the operational space, but also the trajectories of the robot joints approximate those of the human joints in the joint space. While using these robots, the configuration of the affected human limb(s) is finely controlled at each joint, so that missing motor synergies can now be compensated for severely disabled patients. These systems require advanced biomechatronic design approaches in order to mimic human-like joints motion, while minimizing invasiveness for the patient in terms of weight, dimensions, etc. To overcome these challenging problems, nonbiomimetic wearable robots are also currently under investigation in a few pilot research projects recently launched in Europe and U.S.

From a historical perspective, some visionary roboticists in the mid-1980s pioneered the introduction of robotics technology into the rehabilitation scenario. The precursors of such systems were used to carry out basic neuroscience experiments on motor learning and motor control in healthy human subjects and primates. The first prototypes of rehabilitation robotic systems, mainly developed around commercial industrial robots, were successfully used to provide an initial proof of concept. Subsequent deployment of this idea to real clinical application was based on the design and fabrication of original robotic solutions, which are purposively devised for this specific application domain. The first patents in this domain were filed in the mid-1990s and shortly after systematic clinical trials were initiated.

That time onward, this area dramatically evolved into one of the most promising field of robotics research. The number, quality, and dimensions of the research groups attracted by this topic worldwide have been steadily increasing, with an important acceleration in the last decade. Several sessions on rehabilitation robotics are typically included in the programs of the most important robotics conferences, such as the International Conference on Robotics and Automation (ICRA) and the International Conference on Intelligent Robots and Systems (IROS), and two successful conferences, both held biannually in an alternate fashion, are mainly focusing on this area, namely the *IEEE Robotics and Automation Society (RAS)/Engineering* *in Medicine and Biology Society (EMBS) International Conference on Rehabilitation Robotics (ICORR)* and the *IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics (BIOROB)*.

The increasing importance of this area is also clearly pointed out by the high number of papers submitted to this Special Issue, the first focused on this topic in the history of the IEEE TRANSACTIONS ON ROBOTICS AND AUTOMATION (TRA) and the IEEE TRANSACTIONS ON ROBOTICS (TRO). The RAS Technical Committee on Rehabilitation and Assistive Robotics has sponsored this current Special Issue.

There are several companies already sending to the market a significant number of rehabilitation robotics products. Also, clinical applications of these systems are rapidly increasing; to date, robots are reported to have been used for implementing experimental rehabilitation programs for the treatment of a huge variety of pathologies, such as stroke, traumatic brain injuries, spinal cord injuries, multiple sclerosis, Parkinson's disease, Huntington's Corea, cerebellar ataxia, autism spectrum disorders, cerebral palsy, age-related mild motor or cognitive disorders, etc.

Nowadays, rehabilitation robotics can be considered a very fertile multidisciplinary research area, where robotics technology plays a pivotal role for enabling translational application of most advanced findings in neuroscience and human biology to clinical rehabilitation. The experience gained by the on-field application of the first generation of products is now becoming mature enough to let engineers and healthcare operators jointly conceive new generations of rehabilitation robotics systems that could have the potential to really generate disruptive innovation in this medical field.

II. GUIDE TO THE SPECIAL ISSUE

The papers of this Special Issue have been logically organized into four different groups.

The *first* group of papers presents enabling technologies for rehabilitation robotics. The paper by Dellon and Matsouka presents the mechanisms, kinematics, and dynamics of a life-size brake-actuated manipulator (BAM) designed to address the issue of safe training of activities of daily living tasks requiring large interaction forces. The data presented support its potential use in robot-assisted therapy. To demonstrate the importance of coping with intrinsic constraints of neural origin, Campolo *et al.* evaluate a state-of-the-art back-drivable wrist that can be moved by the user with low perceived mechanical impedance. They show that despite back-drivability, the robot still perturbs the voluntary movements of a subject. On the other hand, the paper by Bu *et al.* proposes a novel technique for developing human–robot interfaces based on a Bayesian predictive task model for motion prediction that is used to improve robustness and reliability of electromyography (EMG) based motion classification. Experiments on robot manipulation prove the feasibility and effectiveness of the proposed method. The paper by Kong *et al.* presents a novel control system for a wearable robot, Sogang University Biomedical Assistive Robot (SUBAR), that can provide assistive forces. The controller relies on the use of a flexible algorithm to overcome undesirable forces, such as resistive forces caused by the friction, the damping, and the inertia in actuators. The success of the system is demonstrated. Finally, in this group, the paper by Steinen *et al.* presents a method for designing exoskeleton robot systems for therapy that decouples joint rotations from the joint translations so that any joint misalignment occurring during therapy can be managed by the system and not by the patients' musculoskeletal system, body, or the soft tissue between their arm and the exoskeleton. Its effectiveness within the context of two systems is shown.

The *second* group of papers of this Special Issues presents two robotic systems used for assisted diagnosis of pathologies of interest in the rehabilitation domain. Koizumi *et al*. propose a master–slave type remote medical system for the diagnosis of shoulder diseases, such as dialysis-related amyloid arthropathy by ultrasonographic images. The system features impedance control capability for positions of the master and slave manipulators, and has continuous path control capability for the orientation of the slave manipulator in order to realize smooth and accurate motion of the ultrasound probe in any working conditions. Directed at a more specific pathology, the paper by Sulzer *et al.* presents a novel device based on a Series Elastic Remote Knee Actuator that is meant to diagnose and quantitatively assess stiff-knee gait (SKG), which is a gait disability that affects a significant percentage of stroke survivors.

The *third* group of papers of this Special Issue presents different robotic systems applied to assisted physical rehabilitation. Ellis *et al.* present clinical results after using the robotic system (ACT_{3D}) for therapy and quantitative measurement of abnormal joint torque coupling in chronic stroke survivors. The data obtained after testing eight subjects suggest that targeting the abnormal joint torque coupling impairment through progressive shoulder abduction loading is an effective strategy for improving reaching work area following hemiparetic stroke. The paper by Choi *et al.* discusses the design and development of a robotic therapy environment for real task practice system called Adaptive and Automatic Presentation of Tasks (ADAPT). The system was designed to enhance the recovery of upper extremity functions in patients with stroke, specifically reaching and grasping.

For the lower limb poststroke, Roy *et al.* present the design and characterization of a novel ankle robot developed at Massachusetts Institute of Technology (MIT) for assisted therapy for stroke patients. They present data to demonstrate the potential of this device as a clinical measurement tool to estimate changes in intrinsic ankle properties, such as stiffness, as a result of therapy. The paper by Saint-Bauzel *et al.* presents clinical results from the use of a reactive robotized interface for lower limb rehabilitation of patients suffering from cerebellar disease. The proposed method was validated on experiments with patients in a hospital.

Dealing with a pathology other than stroke, the paper by Jiang *et al.* presents a simple and low-cost system capable of measuring force vectors at the fingertips of the impaired hand of a multiple sclerosis patient with asymmetric impairment, which computes the force imbalance among the fingers and provides corresponding haptic signals to the fingers of the opposite hand, so to enhance grasp force control during manipulation rehabilitative tasks.

Finally, the paper by Lee *et al.* discusses a general virtual design environment that can permit therapists to evaluate and customize rehabilitation programs for their patients. The system leverages tools from musculoskeletal analysis and simulation-based design and demonstrates its effectiveness using two tasks: parametric bicep-curling and motor rehabilitative simulated driving.

The *fourth* group of papers of this Special Issues presents robotic systems used for assisted psychophysiological rehabilitation. The paper by Marti *et al.* outlines the use of modular robotics to encourage and facilitate nonverbal communication during therapeutic intervention in dementia care. Experimental results showed that elderly with dementia coordinated their behaviors with the therapist, and imitated the same interaction patterns generated by the therapist. Iturrate *et al.* describe a noninvasive brain-actuated wheelchair that relies on a P300 neurophysiological protocol and automated navigation. The paper reports a technical evaluation of the device and all functionalities, a users' behavior study, and a variability study. Finally, Miyake established a new cooperative walking system between a walking human and a walking robot by assuming "mutual entrainment" as an interpersonal synchronization mechanism. By applying the method to provide walking support for Parkinson's disease and hemiplegia patients, its effectiveness in stabilizing the walking of the patient was shown.

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