Human-Centered Rehabilitation Robotics

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Abstract—This paper presents new human-centered robotic approaches applied to the rehabilitation of gait and upper-extremity functions in patients with movement disorders. So-called “patient-cooperative” strategies can take into account the patient's intention and efforts rather than imposing any predefined movement. It is hypothesized that such human-centered robotic approaches can improve the therapeutic outcome compared to classical rehabilitation strategies.

I. INTRODUCTION

A. Human-centered robotics

Within the last 10 to 15 years robots have become more and more common in non-industrial environments such as private homes, hospitals and service areas. These robots are often called “human-centered” or “human-friendly” systems [1][2], because the robot involves the close interaction between robotic manipulation systems and human beings. This close interaction can include a contact-free sharing of a common workspace, or a direct mechanical human-machine contact.

In comparison to the traditional metrics of performance, human–centered robot interaction implies a totally different set of requirements than for industrial robots that are operated in structured environments [1]. Such requirements include safety, flexibility and mechanical compliance of the robot, gentleness and adaptability towards the user, ease of use, communicative skills of the robot, humanoid appearance and behavior, etc.

Several groups claimed that human-centered robots must be autonomous and easy to use, and are able to provide a high level of comfort, functionality and pleasure [3]. Heinzmann and Zelinsky [4] added that human-centered robots should also have natural communication channels including not only language but also facial gestures and expressions.

Incorporation of particular user-cooperative control strategies is highly challenging, when human and robot are in direct (mechanical) contact with each other. Then, in many applications it is the goal to let the robot detect the user movement intention and follow him/her rather than imposing the user with a predefined movement. One well-known solution to this problem is the application of impedance control laws that allow the user to deviate from any predefined reference trajectory [5]. Other researchers introduced adaptive control methods to adjust the robot behavior to the user and, thus, make the technical components more flexible [6], and easier to use. Ikeura et al. [7] developed human-friendly robotic approaches, where the robot copies the human characteristics while helping the user to carry an object. Lum [8] developed a similar system, where a robotic apparatus supports a paralyzed hand of a stroke patient in order to correct the orientation of an object carried by the patient (e.g. a cafeteria tray).

The application of human-centered and human-friendly robots in rehabilitation is not new. Stefanov and Bien [3] define human-friendly rehabilitation robots to be able to perform their functions without disturbing the user and without causing him/her any pain, inconvenience, or movement restriction. However, in the field of rehabilitation, most human-friendly robot applications are limited to home-assistance tasks of bed-ridden or elderly subjects [3].

The objective of this work is to apply basic human-centered principles to robot-aided movement rehabilitation. We will present some principles that allow the robot to behave patient-cooperative while being in direct contact with the patient.

B. Rationale for Movement Therapy

Task-oriented repetitive movements can improve muscular strength and movement coordination in patients with impairments due to neurological or orthopaedic problems. A typical repetitive movement is the human gait. Treadmill training has been shown to improve gait and lower limb motor function in patients with locomotor disorders. Manually assisted treadmill training was first used approximately 15 years ago as a regular therapy for patients with spinal cord injury (SCI) or stroke. Numerous clinical studies support the effectiveness of the training, particularly in SCI and stroke patients [9-11].

Similarly, arm therapy is used for patients with paralysed upper extremities after stroke or SCI. Several studies prove that arm therapy has positive effects on the rehabilitation progress of stroke patients [12]. Besides recovering of motor function and improving movement coordination, arm therapy serves also to learn new motion strategies, so called “trick movements” or “compensation strategies” to cope with activities of daily living (ADL).

Lower and upper extremity movement therapy serves also to prevent secondary complications such as muscle atrophy, osteoporosis, and spasticity.

It was observed that more and longer training sessions per week and longer total training periods have a positive effect on the motor function. In a meta-analysis comprising nine controlled studies with 1051 stroke patients Kwakkel et al. [13] showed that increased training intensity yields...
positive effects on neuromuscular function and ADL. This study did not distinguish between upper and lower extremities. The finding that the rehabilitation progress depends on the training intensity motivates the application of robot-aided arm therapy.

C. Rationale for Robot-Aided Training

Manually assisted movement training has several major limitations. The training is labor-intensive, and, therefore, training duration is usually limited by personnel shortage and fatigue of the therapist, not by that of the patient. The disadvantageous consequence is that the training sessions are shorter than required to gain an optimal therapeutic outcome. Finally, manually-assisted movement training lacks repeatability and objective measures of patient performance and progress.

In contrast, with automated, i.e. robot-assisted gait and arm training the duration and number of training sessions can be increased, while reducing the number of therapists required per patient. Long-term automated therapy appears to be a promising way to make intensive movement training affordable for clinical use. One therapist may be able to train two or more patients in the future. Thus, personnel costs can be significantly reduced. Furthermore, the robot provides quantitative measures, thus, allowing the observation and evaluation of the rehabilitation process.

D. Rehabilitation Robots: Short Overview

Most famous robotic systems available for gait training are the “Gait Trainer” from the German company “Reha-Stim” [14], the ARThuR and PAM devices from the Reinkensmeyer group in California [15], [16], and the Lokomot from our group [17], [18].

Several robotic devices have been developed to support therapy of the upper extremities. Examples are the arm trainer from Hesse et al. [19], the arm robot from Cozens [20], the haptic display of the European project GENTLE/s [21], which is based on the FCS Haptic Master [22], the MIT-Manus [23], [24], or the MIME (Mirror Image Movement Enhancer) arm therapy robot [25]. ARMin is another rehabilitation robot system currently being developed for upper extremity treatments (Fig. 1) [26].

II. COOPERATIVE CONTROL METHODS

A. Rationale of Patient-Cooperative Controllers

Most of the above-mentioned automated movement trainers do not adapt their movement to the activity of the patient. Even if the patient is passive, i.e. unable to intervene, she/he will be moved by the device along a predefined fixed trajectory.

Future projects and studies will focus on so-called “patient-cooperative” or “subject-centered” strategies that will recognize the patient’s movement intention and motor abilities in terms of muscular efforts and adapt the robotic assistance to the patient’s contribution. The best control strategy will do the same as a qualified human therapist – it will assist the patient’s movement only as much as necessary. This will allow the patient to actively learn the spatiotemporal patterns of muscle activation associated with normal gait and arm/hand function.

The term cooperativity comprises the meanings of compliant, because the robot behaves soft and gentle and reacts to the patient’s muscular effort, adaptive, because the robot adapts to the patient’s remaining motor abilities, interactive, because there is bi-directional exchange of energy and information between robot and patient, and supportive, because the robot helps the patient and does not impose a predefined movement or behavior.

It is expected that patient-cooperative strategies will stimulate active participation by the patient. They also have the potential to increase the motivation of the patient, because changes in muscle activation will be reflected in the walking pattern, consistently causing a feeling of success. It is assumed that patient-cooperative strategies will maximize the therapeutic outcome.

In the following subsections some patient-cooperative strategies are presented that detect the patient’s movement efforts in order to make the robot behavior flexible and adaptive. The concepts are currently being applied to the gait-robot Lokomat as well as to the upper extremity robot ARMin.

B. Impedance Control

Impedance controllers are well established in the field of robotics and human-system interaction. They were first introduced by N. Hogan about 20 years ago [5]. The basic idea of the impedance control strategy applied to robot-aided treadmill training is to allow a variable deviation from a given leg trajectory rather than imposing a rigid gait pattern. The deviation depends on the patient’s effort and behavior. An adjustable moment is applied at each joint in order to
keep the leg within a defined range along the trajectory. The
moment can be described as a zero order (stiffness), or
higher order (usually first or second order) function of
angular position and its derivatives. This moment is more
generally called mechanical impedance. Fig. 2 depicts a
block diagram of a general impedance controller. Similar
behavior can be achieved by admittance and combined
architectures [27].

C. Adaptive Control

The main disadvantage of the control strategy presented
above is that they are based on a fixed reference trajectory.
Any individual adjustments of the gait trajectory are difficult
to perform. It can only be manually modified based on some
qualitative observations made by the therapist.

Jezernik et al. [6], [28] developed several control
algorithms that automatically adapt the reference trajectory
of different reference-based controllers and/or the impedance
magnitude of an impedance controller to the desired motion
of the individual patient. Hereby, the human represents a
component of the entire control system, which influences the
overall system behavior (i.e., motion). Because the
involvement of human control necessarily leads to promoted
patient activity during the exercise and to increased patient
motivation, it is expected that the outcome of the movement
training with adaptive control of human-robot interaction
should result in a better outcome of the rehabilitation
therapy.

D. Patient-Driven Motion Reinforcement (PDMR)

The idea of Patient-Driven Motion Reinforcement
(PDMR) control was first presented by Riener and Fuhr [29]
for the control of FES-supported, patient-induced standing-
up and sitting-down movements. Here, the actual patient
movement is recorded and fed into a inverse dynamic
model of the patient in order to determine the robot moment
contribution that maintains the movement induced by the
patient (Fig. 3). This means that the patient has to apply
some own voluntary efforts in order to obtain a movement
supported by the robot. A scaling factor $K$ can be introduced
in order to vary the supporting moment.

The impedance controller was tested on several healthy
subjects and one incomplete paraplegic subject. Prior to the
impedance control mode the subjects were walking in a
position control loop. Angular deviations increased with
increasing robot compliance, as the robot applied a smaller
amount of force to guide the human legs along a given
trajectory. Therefore, the position controller produced a
remarkably higher amount of joint moment than the
impedance controller. Joint moment ranges during zero
impedance control were significantly greater than zero. For
the impedance controller, it has to be noticed that the patient
has to apply force in order to achieve a deviation from the
pre-programmed fixed trajectory. Thus, patients with severe
paraplegia are more or less restricted to the given trajectory
and do have only limited possibilities to change the gait
pattern. On the other hand, undeliberate muscle contractions
such as produced by high muscle tone, spasms, or reflexes,
can affect the movement and may yield a physiologically
incorrect gait pattern, depending on the magnitude of the
impedance chosen.

Experimental results were also obtained via an on-line
adaptation of the reference trajectories with an incomplete
SCI individual. The patient has followed the pre-specified
Lokomat motion until the 60th step. Afterwards he produced
voluntary efforts that yielded a change of the reference
trajectory in such way that a modified (his preferred)
trajectory was obtained. The adaptation of particular gait
parameters resulted in a considerable change of the hip
reference trajectory. The adaptation algorithms demonstrated
that a subject-driven training is possible (see also [6], [28]).

The PDMR controller enabled a healthy subject to walk
with his own walking speed and pattern. The Lokomat as
well as the treadmill speed adapts to the subject’s efforts and
supports the movement of the subject’s leg, e.g. by
compensating for the gravity and velocity dependent effects.
Prerequisite for this controller is that the subject has enough
voluntary force to induce the robot movement.

IV. DISCUSSION AND CONCLUSION

The key achievement common to all concepts presented
here is that they behave cooperatively with the patient,
behaving compliant to the patient (impedance control),
adapting the reference trajectory to the patient (adaptive
control), or supporting the movement initiated by the patient
(PDMR). The aim of these strategies is to consider voluntary
efforts and exploit remaining natural control capabilities of
the central nervous system after damage of brain or spinal
cord. As the subject is put into the center of the therapy, the
concepts are also called subject-centered strategies.
Important technical component of these strategies are the
force sensors that detect the patient’s remaining muscular
efforts reflected in the hip and knee joint moments. The
force information is used to adapt the robotic assistance to
the patient’s motor abilities enabling the patient to contribute
as much as possible to the movement. At the same time,
force and movement recordings serve to evaluate the long
term results of the movement therapy.

The effects of the cooperative strategies on the patient
can be compared to the behavior of a qualified human

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III. RESULTS

Different robot setups are presented that can support
the movement therapy of gait and upper limb function. Three
subject-centered strategies were introduced that detect the
patient’s movement efforts in order to make the robot
behave cooperative with the patient. First experimental
results were obtained by applying the presented controllers
to the gait-robot Lokomat.
therapist, who moves the patient’s limbs with some amount of compliance. The key aspect of the adaptive controllers is that the patient can become accommodated to a more individual, appropriate, and convenient gait pattern. Even if the patient remains passive, the legs will be moved, although the reference trajectory will then “deform” to an non-physiological gait pattern. In comparison, with the impedance control strategies the therapist (or patient) can decide how much the robot should support the movement. The lower the impedance value, the more is the patient forced to contribute to the movement. However, spasms or reflexes can disturb the movement in such a way that the patient stumbles, which might lead to ankle or foot injuries. The outstanding property of the PDMR strategy is that the patient has maximum freedom to define his/her own walking pattern and even speed. However, it must be noted that the patient has to be able to generate his/her own voluntary efforts.

One open question is still, how much individuality of movement pattern should be allowed by the rehabilitation robots when applied in a cooperative manner. The main goal should always be to bring the patient into a physiological movement condition rather than supporting or even training an unphysiological but “individual” gait pattern.

Under this condition, it is expected that patient-cooperative strategies will stimulate active participation by the patient. They also have the potential to increase the motivation of the patient, because changes in muscle activation will be reflected in the walking pattern, consistently causing a feeling of success. It is assumed that patient-cooperative strategies will maximize the therapeutic outcome in terms of reduced therapy duration and an improved gait quality. A broad clinical evaluation will follow in a subsequent study in order to proof the positive therapeutic effects of patient cooperative approaches.

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REFERENCES
