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Hybrid impedance control of a robot manipulator for wrist and forearm rehabilitation: Performance analysis and clinical results☆

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ABSTRACT

Therapeutic exercises play an important role in the physical therapy and the rehabilitation. The exercises that can be assisted by a physiotherapist are increasingly being performed by the rehabilitation robots partially or fully due to their various merits. This study aims to develop a complete rehabilitation system, which consists of a rehabilitation robot, an HMI and a hybrid impedance controller that can model all the therapeutic exercises for an upper limb rehabilitation. The 3-DOF upper limb rehabilitation robot is able to perform the movements of flexion–extension and ulnar–radial deviation for the wrist, and the movement of pronation–supination for the forearm. The experimental studies were conducted with healthy subjects and patients. First, the experiments were done with the healthy subjects to prove the control performance of the robotic system. The results showed that the hybrid impedance controlled robot can perform the therapeutic exercises very successfully. Then, the experimental studies were carried out with the real patients in a clinical environment. At the end of the treatment process, remarkable improvements were observed in terms of the limb force in all of the patients.

1. Introduction

Rehabilitation is a treatment process to bring an individual with a physical disability, which might be congenital or happen due to an illness, injury, or accident, to the best condition medically, socially and vocationally, and to reduce the negative results of permanent diseases to minimum [1]. A limb, which is injured due to the age-associated muscle disabilities, work or traffic accidents, wars and chronic diseases, needs rehabilitation to refunction fully or partially. Making a limb functional and increasing the force of a muscle are crucial problems. The return of those people to their social life is also highly important for themselves, their families, and the society they live in.

One of the elements of the rehabilitation is the refunction of the limbs, such as arms and legs. The therapeutic exercises play a crucial role in the process of refunction. A physiotherapist can make the patient perform the therapeutic exercises, which consist of the passive and active exercises, or the patient can perform by himself or herself depending on his or her physical condition. Especially, in populous countries, where the number of physiotherapists per patient is not enough (to set an example, in Turkey, physiotherapists are allowed to accept 16 patients in a day [2]), the transportation problems of patients, the cost of the rehabilitation process, and the constraints in the existing devices and equipments of the therapeutic exercises are the main problems of the rehabilitation process. For these reasons, the researches on the use of robots in the rehabilitation process have increased in the last 15 years [3]. The robots make a significant contribution to the rehabilitation process in terms of the cost, the duration of therapy, the objective evaluation, the remote control, and enabling home care. The rehabilitation robots can be classified in four groups [4]:

- “The assistive robots” supporting the movements of disabled people in the activities of their daily lives,
- “The prostheses” fulfilling the functions of the severed limb for amputees,
- The robots used for the gait rehabilitation,
- “The therapeutic exercise robots” help patients perform passive, active and resistive exercises.

The system of interest in this research, which aims the therapeutic exercises, is for the rehabilitation of the wrist and the forearm and belongs to the class of the therapeutic exercise robots.

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The rehabilitation robots developed for the upper-limb rehabilitation can be compared in terms of the capacity of the movement and exercise, the mechanical properties, and the control methods. The systems in the literature are capable of performing one or some of the following exercises: The passive, the active assisted, and the resistive. The mechanical parts of the systems were mostly developed by either using already available robotic manipulators or designing robotic manipulators or exoskeletons from scratch. The widely used control approaches in the rehabilitation are as follows: The convential control methods, such as PID or PD, the direct torque control, the admittance control, and the impedance control.

The most well-known robotic system of the upper-limb rehabilitation studies is the MIT-MANUS (Massachusetts Institute of Technology-MANUS) developed by Krebs et al. [5,6]. The robot was developed for the rehabilitation of the shoulder and the elbow and has 3-DOF. The system can perform the passive, the active assisted, and the resistive exercises. It can reteach the limb the motion limits of the limb and can implement applications based on target trajectory. The impedance control method was used in the control of the system. In their study, Reinkensmeyer et al. designed a 4-DOF mechanism, called ARM-Guide (Assisted Rehabilitation and Measurement), for the rehabilitation of the shoulder and the elbow [7]. The system can perform the passive, active assisted, and resistive exercises. The PD position control and the direct torque control methods were used in the control of the system. The REHAROB by Toth et al. was designed by using a 6-DOF industrial robot for the rehabilitation of the shoulder, the elbow, and the forearm [8]. The system has the capacity of performing passive exercises for decreasing the spasticity. The robot is taught the movements by a physiotherapist through the direct teaching method using an artificial intelligence based control algorithm.

An exoskeleton robot called ARMin was developed by Riener et al. for the rehabilitation of the shoulder and the elbow [9]. The robot has 6-DOF (four active and two passive) and can perform passive and active assisted exercises. The system can implement applications based on target trajectory, can feed the audio and visual information back, and has the ability of gravity compensation. The admittance and impedance control approaches were used in the control of the system. The use of such exoskeleton robots in the rehabilitation have generated an immense interest and many studies using the aforementioned control approaches reported in the literature [10–22].

Lum et al. designed a system, MIME (Mirror Image Movement Enabler), by using PUMA 360 robot for the rehabilitation of the shoulder and the wrist [23]. This system has 4-DOF and uses “mirror therapy” method in implementing the passive, active assisted, and resistive exercises. Additionally, the system can regain the limb the limits of the range of motion (ROM) and implement the mirror therapy and the applications based on the target trajectory. The PID position control and the direct torque control methods were used in the control of the system. A similar study using the mirror therapy method was presented by Lewis et al. [24]. In their study, the system was controlled by using EMG (electromyography) - based admittance control method. One of the control approaches fitting well to the control of interaction between the robot and the human is the admittance control and it plays an important role in the rehabilitation [25–27]. In the admittance control, the robot adjusts the desired motion based on the measurements of the interaction forces.

The hybrid impedance control method was developed by Anderson and Spong [28]. In this technique, the strategies of “the impedance control” and “the hybrid force-position control” are combined in a framework. By doing so, both the position and the impedance-based force controls are implemented within a single control structure. Researchers have used the hybrid impedance control in various applications. Wang et al. developed a hybrid impedance controlled 3-DOF system by using the PUMA 562 robot [29]. The robot has a tactile sensor on its end-effector and designed for massaging. Selection of the desired impedance value allows massaging in certain levels of the stiffness. Another system designed for localizing tumours in the body has 7-DOF and is controlled by a hybrid impedance control approach [30]. A 3-DOF system using both the impedance control and the hybrid impedance control for the rehabilitation of the wrist, the forearm, and the shoulder was developed by Wang et al. [31]. The system was designed for the motor recovery in the stroke patients by training the upper-limb through the predetermined tasks.

Akdogan and his colleagues were developed a 3-DOF system, which uses the impedance control in the therapeutic exercises, for the rehabilitation of the lower-limb [32,33]. In this system, to establish the therapeutic exercise modes, the PID control was used for the position-based exercises, and the impedance control was used for the force-based exercises [34]. These two techniques were used by switching between each other in the exercises requiring both the position control and the impedance control (active assistive exercises). Two disadvantages appeared in this point. One is that having the trajectory of force by using the position-based impedance model is not possible, since the trajectory of force changes depending on the impedance parameters. In the exercises requiring the PID and impedance control, the numbers of parameters are three for the impedance control (the coefficients of inertia, stiffness, and damping) and three for the PID control. The six parameters in total must be set properly. Another disadvantage is the occurrence of instability due to the disturbances, such as the noise, in the process of decision to perform switching. Thus, the control of the system affected unfavorably. For this reason, the hybrid impedance control method is highly suitable to perform the control of the required position and force as well as the desired mechanical impedance for the therapeutic exercises.

Some preliminary studies having more direct relation with this study should be cited: [35–37]. Mainly, the concept of the discussed system in this work and some experimental results with healthy subjects are explained in [35] and [36]. These works do not include clinical results and detailed system identification studies.

There are some commercial therapeutic exercise machines available in the market, such as Biodex, Cybex and Kincom. These devices are passive machines and they cannot change the applied position and force to a patient during the exercise. They are single degree of freedom. For different type movement, additional apparatus are needed. Therefore, the higher degree of freedom intelligent robotic systems which can change the exercise procedure according to patient's situation are appear to be more useful than passive exercise machines.

In this study, the hybrid impedance control of this robot manipulator was implemented for the rehabilitation of the wrist and the forearm. First, the performance of the system was shown by the experimental studies carried out with healthy subjects. The results indicated that the hybrid impedance control based robotic system can perform the passive, the active assistive, and the resistive exercises very accurately. Then, the experimental studies were carried out with real patients in a clinical environment. At the end of the treatment process, improvements were observed in terms of limb force in all of the patients. The results are presented in terms of the ROM (Range of Motion), the limb force, etc.

The contribution of this study into the literature is that the therapeutic exercises (passive, active assistive, resistive) were performed under a single control structure using hybrid impedance control and the effectiveness of this control method was shown by clinical experiments. In the literature, any study using hybrid impedance control in modeling all the therapeutic exercises does not exist. Also, another contribution is the development of an intelligent human–machine interface (HMI). This powerful HMI was developed by combining knowledge- and rule-based intelligent techniques and a conventional control technique.

2. System description

The developed rehabilitation support system consists of a physiotherapist, a patient, a robot manipulator, and an HMI. The block