Guided Physical Therapy Through the Use of the Barrett WAM Robotic Arm

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***Abstract*—Physical therapy is a crucial part of the rehabilitation process during recovery from an injury that has resulted in motor function loss. Newly introduced technologies can enhance traditional physical therapy, first, by complementing the expert's work, and second, by providing a platform for rich data collection and analysis. In this work, we present a prototype adaptive rehabilitation instrument, based on the use of robotic arm, which can be dynamically controlled to guide the exercise motion of the upper extremities, in patients with motor disabilities. Our proposed method, enables simultaneous active and passive control of the robotic arm, to produce adaptive force feedback for motion guidance, and allow for data collection, for patient motor function assessment.**

I. Introduction

A traffic accident, a battlefield injury, or a stroke can lead to brain or musculoskeletal injuries that impact motor and cognitive functions and drastically change a person's life. In such situations, rehabilitation plays a critical role in the ability of the patient to partly or fully regain motor function. In recent years, a number of different approaches have been proposed, aiming to assist and enhance the traditional rehabilitation paradigm, by complementing the patient-therapist interaction with assistive technologies, such as computer games, virtual reality, and robot-based rehabilitation systems.

In this work, we present an instrument for rehabilitation and physical therapy, which is based on the use of a highly adaptive robotic arm (WAM Arm - developed by Barrett Technology, Inc. – Fig. 1). The arm utilizes back-driveable, torque-controlled actuators with 7 degrees-of-freedom, using a patented cable-driven method to facilitate kinematic motion when used as a manipulator or active resistance when used as a haptic device. The device was developed such that safety for the user is guaranteed in both modes, whether the user is in proximity of the device or interacting through direct contact. The maximum amount of torque applied for each degree of freedom is independently controllable (along with joint positions, speeds, etc.), which allows the robotic arm to be easily customized to match user ability while ensuring safety for all users through maximum allowable limits. The arm is accompanied by an active-torque gimbals end effector, which provides a point of contact for a human hand. A force-torque sensor is also applied to the wrist to provide an additional real-time measurement when used as an active-resistance haptic device.

Fig. 1. Photo of Barrett WAM robotic arm with gimbals.

We introduce a new mode of robot-assisted rehabilitation, where the therapist initially teaches the robotic arm, with a set of exercises that a patient needs to perform. The correct trajectories and ranges of motion are captured by the system, as executed by the therapist. Subsequently, the patient attempts to perform the same exercise. The system then compares the trajectory of the patient's motion with the one previously executed by the therapist, and in cases where the patient cannot correctly perform the exercise, either because of lack of strength or motor function control, or simply because of lack of understanding, the robotic arm exerts an amount of force in order to correct the trajectory of motion.

Previous efforts for the use haptic robotic devices in physical therapy, employ either passive or active motion control for the robotic arm, which means that either the patient fully controls the motion and the robotic arm acts as a sensor to collect trajectory data (possibly applying some constant resistance), or the robotic arm controls the motion and the patient just follows along. In this work, we present a novel hybrid approach, where the robotic arm acts as a passive sensor when the patient follows the prescribed exercise trajectory correctly, whereas it intervenes to correct that trajectory, applying dynamically variable levels of force towards the right direction, when the trajectory is not followed correctly, either in space or in time. This is achieved through the use of a combination of PID controller and a space-time trajectory alignment algorithm.

In the following sections, we summarize the related work in robot-assisted physical therapy, and subsequently we present our approach and methodology for adaptive physical therapy using the robotic arm as haptic device that can guide the exercise execution.

II. Related Work

The use of robots to enhance rehabilitation has been previously reported in the literature [1], [2], [3]. Robots have been used to test how the nervous system models its external dynamic environment. The nervous system builds internal models and uses them in combination with feedback control strategies. Robots are being used for repetitive movement exercises after a brain injury and can haptically assess sensorimotor performance, quantify training, thus eventually enhancing motor learning and rehabilitation beyond the levels possible with conventional training [4].

Exercise delivered by robotic devices helped stroke patient reduce impairment and increase motor power [2]. Patients with early sensorimotor robotic training after stroke were compared to patients with standard poststroke rehabilitation and found to show greater improvements in functional abilities [1], [5]. Matarić et al. [6], proposed in-home robot-interaction-based therapy and further examined upper limb recovery after hemiparesis, combining the intensity of task-specific training and the engagement and self-management of goal-directed actions. Another mechanical orthosis device, SaeboFlex [7] has supported the weakened wrist, hand, and fingers of patients. A haptic robot, Wrist-RoboHab [8], utilized hand movement therapy for treatment and evaluation of forearm, wrist ulnar, and radial motor disabilities. Finally, in [9], the authors describe the design and modes of operation of a robot-based neurorehabilitation framework that enables artificial support of the sensorimotor feedback loop for patients with severe motor impairment due to cerebrovascular brain damage (e.g., stroke) and other neurological conditions.

A strong motivator for the use of robotic devices in rehabilitation, is that they record and measure the kinematics and kinetics of human movements (speed, position and force) with high resolution, and facilitate clinical assessment. In [10], a closed-loop, position-tracking controller is presented to drive the robot stably and smoothly stretch the impaired limb of the patient to move along the predefined trajectory with a supervisory controller in patients suffering stroke or spinal cord injury (SCI). In [11] the authors model the arm dynamics of a post-stroke patient, as an impedance model, and propose an adaptive control scheme which consists of an adaptive proportional-integral-derivative (PID) control algorithm and a damp control algorithm to control the rehabilitation robot moving along predefined trajectories in a stable and smooth manner.

Our work takes advantage of the advanced capabilities of the Barrett Arm in dynamic adaptation, force-feedback, and torque sensing, in order to deliver a safe, computer-guided physical therapy regimen. In this paper, we focus mostly on the utilization of the robotic arm and in (PID) full trajectory tracking controller during the combined active-passive patient training, however, this work is part of a bigger effort, to create an adaptive computer-aided rehabilitation instrument that also incorporates a number of other factors, such as specific user profiles, historical data, multi-sensory assessment of the patient's condition, etc.

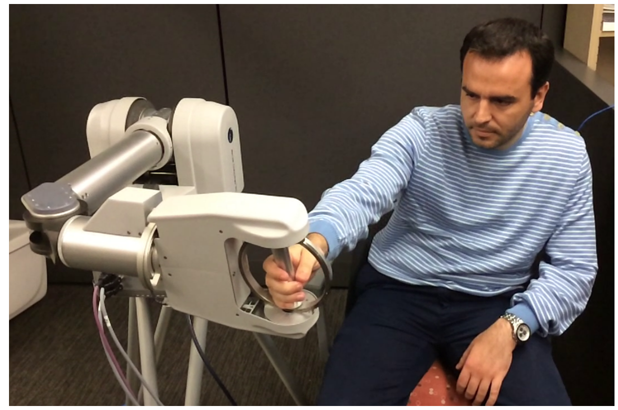

Fig. 2. A user performing a physical therapy exercise with the help of the Barrett Arm. The user is holding onto the active gimbals attached to the free end of the robotic arm.

III. Approach

A. Overview

We develop a system that can guide a physically handicapped patient on performing physical therapy exercises that focus mainly on their moving and controlling their arms. Fig. 2 shows an example of user performing a rehabilitation exercise with the help of the robotic arm. With a highly back-drivable robotic arm, a patient can be led through performing an exercise as presented to them from a computer display. The robotic arm can help guide the patient to follow a precise trajectory as dictated by previously recorded exercises done by a physical therapist. The patient can attempt to perform the prescribed exercise, and whenever they deviate from the prescribed trajectory, an appropriate correctional force is applied by the robotic arm to guide them back onto the correct trajectory. This correctional force is applied in a manner where the current error, the sum of the errors, and the rate of the change of error are accounted for in Cartesian 3D space.

Fig. 3 shows a comparison of the trajectory of the motion, as performed by the therapist, with the one performed by the patient, in 3D Cartesian coordinates. The two trajectories are directly captured by the robotic arm. As one can see, there is difference between the two trajectories. A small difference is naturally expected, as it is impossible, even for the same user, to perform an exercise twice following exactly the same trajectory. However, when the deviation exceeds a specific threshold, it may be a sign of inability of the patient to perform the exercise correctly, due to lack of strength or lack of control of their arm. In such cases a correctional force is applied to assist the patient, which is guided by a control algorithm, and it is proportional to the deviation from the correct trajectory.

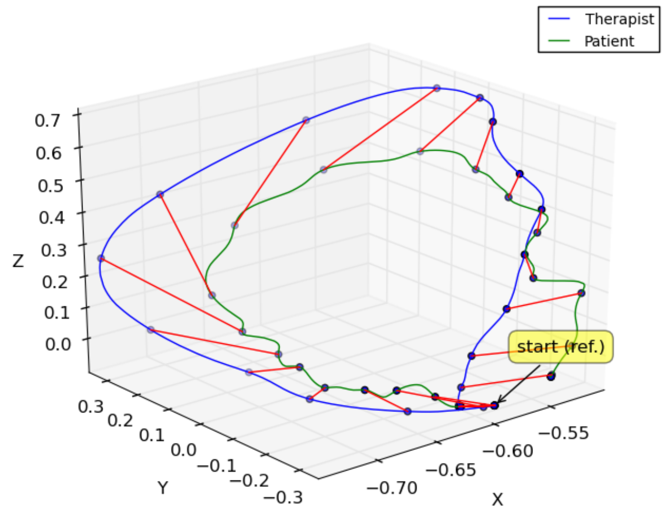

Fig. 3. 3D plot of the trajectory of motion of the hand position of a therapist and a patient performing one repetition of an exercise. The blue continuous line represents the therapist's trajectory, which is used as the reference trajectory, whereas the green line represents the trajectory of motion of the patient's hand. The red lines show the distance of the therapist and patient hand positions at the corresponding key-points.

Besides spatial, the deviation can also be temporal, i.e. the patient performs the exercise much slower or much faster than the therapist. When either of the two deviation types occurs, an error-correction force is applied to bring the patient's hand position closer to the prescribed trajectory. The force vector is calculated dynamically, in discrete time intervals, defined as key-points. At each key-point the direction of the force vector is calculated to point towards the corresponding key-point of the reference trajectory. The force amount to be applied towards that direction, is proportional to the distance of patient hand position at the current key-point, from the corresponding therapist hand position at the corresponding key-point. The red lines in Fig. 3, show the distances of a sample comparison between therapist and patient trajectories for a singe repetition.

The control algorithm used is the PID controller [12] which is implemented for each 3D axis of each active force under position and orientation. The resulting PID gains (eq. 4) are then reduced to where the positional control is not too strict or stiff, allowing the patient some freedom in deviating off the path, otherwise moving the robotic arm along a strict 3D path would be difficult due to the tangential forces received along curvatures of the path. This is due to the difficulty, for any person not expertly familiarized with moving his or her limbs through an exact 3D trajectory, to correspond to that exact path.

The PID, proportional-integral-differential, controller is described by the following equations:

$$P = \hat{e}(t) \tag{1}$$

$$I = \int_0^t \hat{e}(t)dt \tag{2}$$

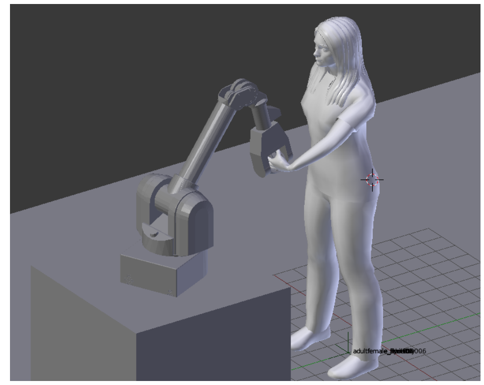

Fig. 4. Simulated 3D rendering of the robotic arm and an animated human avatar. The 3D simulation clip is used to demonstrate the correct way of exercise execution to the patients.

$$D = \frac{d(\hat{e}(t))}{dt} \tag{3}$$

$$u(t) = K_P * P + K_I * I + K_D * D \tag{4}$$

Where t is the time at which the PID controller computes its correctional effects. K_P, K_I, and K_D are usually constant gains, which are tweaked for the specific application and it's operating environment. Equation 4 is the resultant combination of the individual PID components and $\hat{e}$ is the error vector of the robotic arm's end effector (i.e. the patient's hand) off of the reference trajectory. The result is used to adjust the robotic arm's driving motor forces. For the tasks of aiding a patient complete a physical therapy exercise, these gains would be modified to allow for a certain amount of deviation from the reference path. For example, the resulting PID controller could limit the patient's deviation at 1 foot maximum off course before it applies significant correctional motor forces and makes it very difficult to deviate any further.

B. Physical Therapy Procedure

The procedure starts with a physical therapy specialist performing the exercises with the robotic arm for the system to record into its database. When the patient is ready to start the physical therapy session, he or she would view the playback of the reference trajectory, in a simulated 3D environment showing the robotic arm and a virtual human animated character (avatar), as shown in Fig. 4, in order to learn how to perform the maneuvers for the exercise. The exercises are shown to the patient one at a time, along with instructions regarding the required number of repetitions, etc.

When performing the exercise, their position along the trajectory is displayed on screen to provide visual guidance. During each exercise that the patient performs on the robotic arm, the actual trajectory is recorded along with any influences the robotic arm had to apply to correct the patient's movements. This data is later used by the therapist for evaluation of the patient's performance.

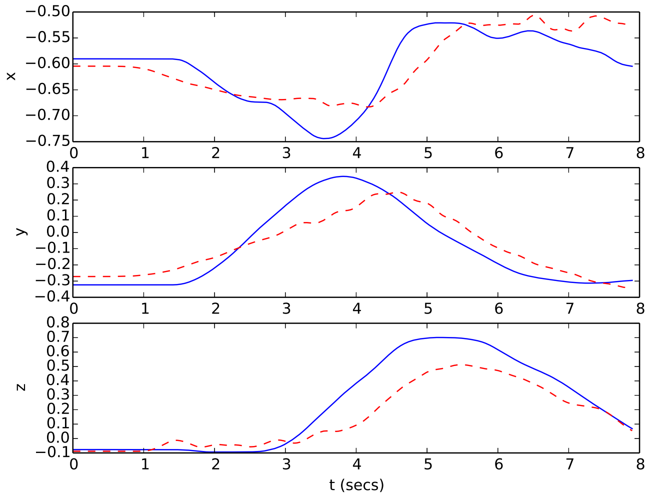

Fig. 5. Comparison between the reference (therapist) trajectory (blue continuous line) and the patient trajectory (red dashed line) in the 3 axes of the Cartesian coordinates.

C. Trajectory Error Quantification

The goal of the system is to have a patient perform certain rehabilitation exercises following the protocol prescribed by the therapist as closely as possible. The protocol may often require the robotic arm to apply resistance against the direction of motion, or assistance, depending on the capabilities of the patient.

In cases where the patient's trajectory of motion deviates from the prescribed one, the system intervenes to correct that trajectory. This correction serves multiple purposes:

1) maintains the range-of-motion of the patient's joints within acceptable levels to avoid possible strain injuries;
2) actively teaches the patient of the correct range of motion to be followed;
3) collects data that can be used by the therapist to assess the patient's motor deficiencies and monitor progress over time.

The trajectory deviation is quantified as error in space (3-axes (x, y, z)) and in time. Fig. 5 shows the differences in trajectories, in the three axes, of a real measurement taken from two different users performing one repetition of a given exercise, whereas Fig. 6 shows the respective absolute errors, of the same measurement, in the three axes, assuming that the two trajectories are temporally aligned (using key-points). Assuming temporal alignment, the three errors can be calculated as follows:

$$e_x(t) = x_{therapist}(t) - x_{patient}(t) \tag{5}$$

$$e_y(t) = y_{therapist}(t) - y_{patient}(t) \tag{6}$$

$$e_z(t) = z_{therapist}(t) - z_{patient}(t) \tag{7}$$

In the general case, temporal deviations are also considered as errors, which we try to eliminate by applying some force parallel to the trajectory tangent, either in the direction of motion (to speed up the motion) or opposite to the direction of motion (to slow down the motion). If we want to allow

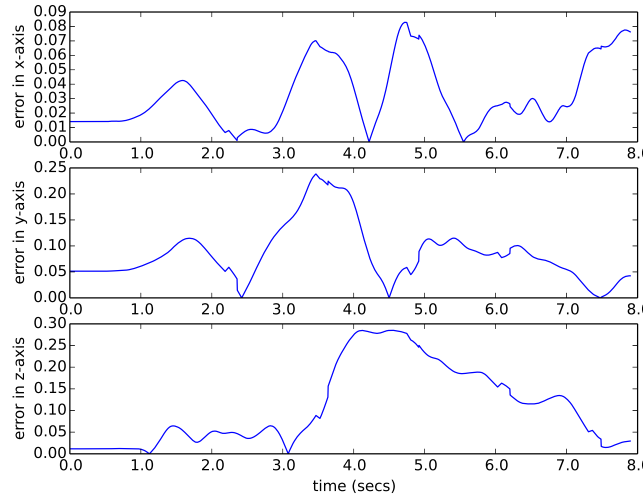

Fig. 6. Quantification of the deviation of the patient's trajectory compared to the reference trajectory, measured as error in the 3 axes of the Cartesian coordinates.

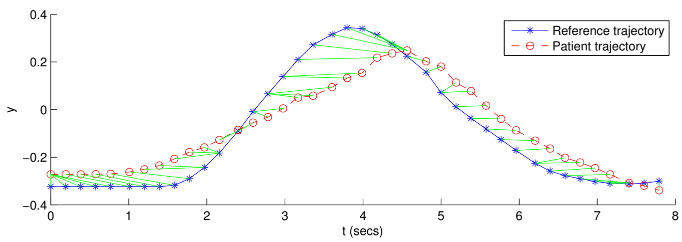

Fig. 7. Temporal trajectory alignment on axis y using the DTW algorithm.

temporal deviations, and focus only on spatial trajectory error, then a more sophisticated method for trajectory alignment is required. In such situations, a one-to-one matching of points in the three axes would not yield meaningful results, since the main error measured, would be attributed to the temporal deviations. To eliminate that problem, we employ Dynamic Time Warping (DTW) [13] to fist align the sequences temporally and then measure the spatial deviation error. DTW has been successfully used in the past for the optimal alignment between two given (time-dependent) sequences. Fig. 7 shows the corresponding alignment of the y axis (of the same measurement as in Fig. 5), using DTW. As one can note, the algorithm is trying to achieve an optimal temporal alignment of the two trajectories, by matching corresponding frames in order to minimize the overall spatial error. At each time point, the length of the green line that connects a point in the reference trajectory (blue) with the patient trajectory (red), measures the temporal deviation. Given that temporal alignment, the spatial error can be measured by taking the absolute difference, $|y_{patient} - y_{reference}|$, between each pair of matched frames.

IV. Conclusion and Future Work

In this work, we have presented an innovative physical therapy system, based on the use of robotic arm, to guide exercise execution. The system is able to record the therapist exercise trajectory and help the patient to execute the same trajectory using passive and active training modes. Even though our current work lacks qualitative evaluation of the effects of the proposed system on the rehabilitation progress of real patients, the proposed methods have been successfully evaluated in the lab, in experiments with healthy subjects. The system will be evaluated in clinical studies in the near future, as part of a bigger system that incorporates multimodal sensor data analysis in order to better assess the condition of the user at each moment and adapt accordingly.

One problem with having different users performing the same exercise trajectory is that they could have different physical characteristics such as body height and arm length. To combat this, a camera system could be used to transform the trajectory against the users physical characteristics to make the exercise more effective for them. To make things straightforward, were are currently experimenting with a Kinect depth sensor and its OpenNI library, to capture the user's pose and physical characteristics, using the built in skeleton tracker.

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