Turk J Elec Eng & Comp Sci, Vol.19, No.5, 2011, © TÜBİTAK
doi:10.3906/elk-1007-585

A multi-lateral rehabilitation system

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Received: 13.07.2010

Abstract

This paper proposes a multi-lateral shared control concept for robot assisted rehabilitation. In particular, a dual-user force-feedback teleoperation control architecture is implemented on a forearm-wrist rehabilitation system consisting of two kinematically dissimilar robotic devices. The multi-lateral rehabilitation system allows for patients to train with on-line virtual dynamic tasks in collaboration with a therapist. Different control authority can be assigned to each agent so that therapists can guide or evaluate movements of patients, or share the control with them. The collaboration is implemented using a dual-user force-feedback teleoperation control architecture, in which a dominance factor determines the authority of each agent in commanding the virtual task. The effectiveness of the controller and regulation of the dominance for each agent is experimentally verified.

Key Words: *Robot-assisted rehabilitation, physical therapy for forearm and wrist, multi-lateral control architecture, wrist exoskeleton*

1. Introduction

Neurological injuries are the leading cause of serious, long-term disability in developed countries according to statistics by World Health Organization. Studies have shown that physical rehabilitation therapy is responsible for most of the recovery experienced by patients with disabilities secondary to neurological injuries. Using robotic devices in repetitive and physically involved rehabilitation exercises helps eliminate the physical burden of movement therapy for the therapists, and enables safe and versatile training with increased intensity. Robotic devices allow quantitative measurements of patient progress while enforcing, measuring, and evaluating patient movements. Furthermore, with the addition of virtual environments and haptic feedback, rehabilitation robots can be used to realize new treatment protocols.

Despite the benefits of the robotic technologies on rehabilitation, human involvement is still critical for high level decision making. Therapies need the supervision of the therapists as well as their active guidance and their expertise in evaluations. In this paper, a multi-lateral control architecture is proposed in order that human experience and judgement capabilities can be included in robot assisted therapy. The proposed approach

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is applied to a forearm-wrist rehabilitation system with virtual reality integration. With the proposed controller in place the rehabilitation system is capable of providing passive, assistive, resistive, and bilateral therapy modes and features virtual reality integration and force-feedback teleoperated use by multiple agents.

Successful results gained by application of rehabilitation robots to shoulder and elbow motions motivated the extension of robotic devices to target distal parts of the upper extremities. To target wrist therapies several devices have been developed. Rehabilitation systems are generally classified according to their coupling with the patient as task space based and exoskeleton type devices. Task space based devices that target forearm and wrist motions include *MIT-Manus* wrist extension [1], *RoboTherapist* full arm therapy robot [2] and *Haptic Knob* rehabilitation device [3]. Exoskeleton type robots can be further categorized based on their kinematic structure. In particular, *ArmIn* [4] and *IntelliArm* [5] represent kinematically serial exoskeletons, while 3U$\underline{\text{P}}$S-S[1] mechanism [6] and 3R$\underline{\text{P}}$S-$\underline{\text{R}}$ *RiceWrist* [7] are the kinematically parallel exoskeletons, which support forearm and wrist movements. Task space devices are simple and low cost. However, these devices suffer from the limitation that only coupled joint movements can be imposed and measured, since the human interaction with these devices are only at the end effector. Exoskeletons are more complex but these robots can robustly and faithfully impose/measure individual joint motions. Exoskeletons with serial kinematics possess large workspace; however, coinciding human joint axes with robotic joints is not trivial for such devices. On the other hand, kinematically parallel exoskeletons can ensure joint alignment satisfying the ergonomic constraints. Advantages of parallel kinematic structures include high position and force bandwidths, that are crucial for high fidelity force feedback. Moreover, devices with such kinematics inherit higher precision as measurement devices, since joint level errors are not superimposed.

Rehabilitation devices can be position and force (impedance/admittance) controlled to implement passive, assistive and resistive therapy modes. Some alternative control methods have also been implemented for wrist rehabilitation. For instance, Song et al. have adjusted the intensity of the assistance provided to palmar/dorsal flexion motions using EMG signals collected at the wrist [8]. Although not designed for wrist rehabilitation, *MIME* system has implemented the mirror image therapies, in which the movement of the injured limb mirrored the motion of the healthy limb [9]. Hesse et al. have implemented bimanual therapy exercises and specifically targeted wrist rotations [10]. Bimanual therapies have also been delivered using *SEAT*, a motorized steering wheel [11].

This paper proposes a multi-lateral shared control algorithm for robot assisted rehabilitation systems. In particular, forearm-wrist therapies are targeted and the algorithm is implemented on a physical setup consisting of two kinematically dissimilar robotic devices. The multi-lateral shared control architecture allows for multiple agents (patients and therapists) to simultaneously interact while performing a (virtual) therapeutic task. Through a dominance factor, different control authority can be assigned to each agent such that therapists can guide or evaluate movements of patients, or share the control with them. Remote and group therapies, as well as remote assessments, can be realized using the proposed control architecture.

The paper is organized as follows: In Section 2, forearm-wrist rehabilitation system is explained. Local controllers and the multi-lateral shared control architecture are introduced in Section 3. Section 4 presents and discusses the experimental results. Section 5 concludes the paper.

[1]Parallel mechanisms are commonly denoted by using symbols U, R, S, and P, which stand for universal, revolute, spherical, and prismatic joint. Symbols corresponding to actuated joints are underlined in this notation.

2. Forearm-wrist rehabilitation system

Figure 1 presents the forearm-wrist rehabilitation system consisting of three major components: the forearm-wrist exoskeleton attached to the patient, the force-feedback joystick coupled to the therapist and the virtual environment driven by dynamics based simulation.

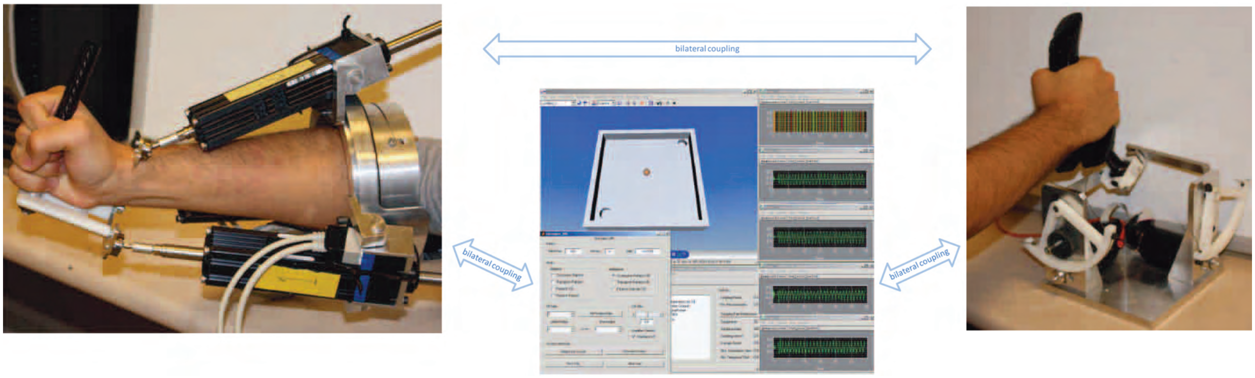

Figure 1. The multi-lateral forearm-wrist rehabilitation system.

On the patient side, a 3RPS-R exoskeleton with four degree of freedom (DoF) is utilized. An exoskeleton with parallel kinematics is selected for interaction with the patient since such a device can ensure alignment of the axes of rotation of human joints with the controlled degrees of freedom (DoF) of the device and enables decoupled actuation and measurement of human joint rotations. Additionally, the device can span a large portion of the natural human wrist and forearm workspace. The 3RPS-R exoskeleton is actuated with three direct drive linear actuators and a direct drive motor coupled to a 1:12 capstan transmission. On the therapist side, a simple task space device with RRRRR parallel kinematic is used. This force-feedback joystick is actuated with two direct drive motors coupled to a 1:9 capstan transmission. The virtual environment is modeled in VRML for visual feedback and is driven by dynamics based simulation of a ball, rolling on a table without slipping under the action of gravity.

The virtual task is composed of a ball that is intended to be successively placed on the holes situated on at the diagonals of the square table by controlling the orientation of the table. During the task the virtual table is coupled to 3RPS-R exoskeleton as well as the force feedback joystick; the patient and the therapist can simultaneously affect the orientation of the table. The dynamics of the moving ball, calculated according to the position and weight of the ball, is force-fed to both users.

3. Control architecture of the forearm-wrist exoskeleton

The goal of the multilateral control architecture is to allow multiple agents (therapists and patients) to work collaboratively to achieve certain therapeutic tasks; in this case, to perform manipulation tasks in a dynamic virtual environment. Since the patient is deprived of the necessary neuromuscular activity to overcome even a resistive task; let alone a dynamic one, the therapist should start as the dominant factor in the collaborative task. As recovery of the patient takes place, the power distribution should gradually revert and the patient should be able to cope with the task individually at the later phases of therapy. During such therapy mode, the patient places the injured arm in the 3RPS-R exoskeleton, while the therapist utilizes the joystick to help the patient with the task.

As the first priority, the controllers should guarantee stability (through passivity) rather than rendering perfect transparency of forces. Since all of the controllers are implemented and run on the same computer, stability deterioration due to time delays introduced by the communication channels can be kept negligibly small. The general architecture of the controller is depicted in Figure 2. In this multi-lateral control architecture the control authority can be gradually shifted from the therapist to the patient by tuning the gain α.

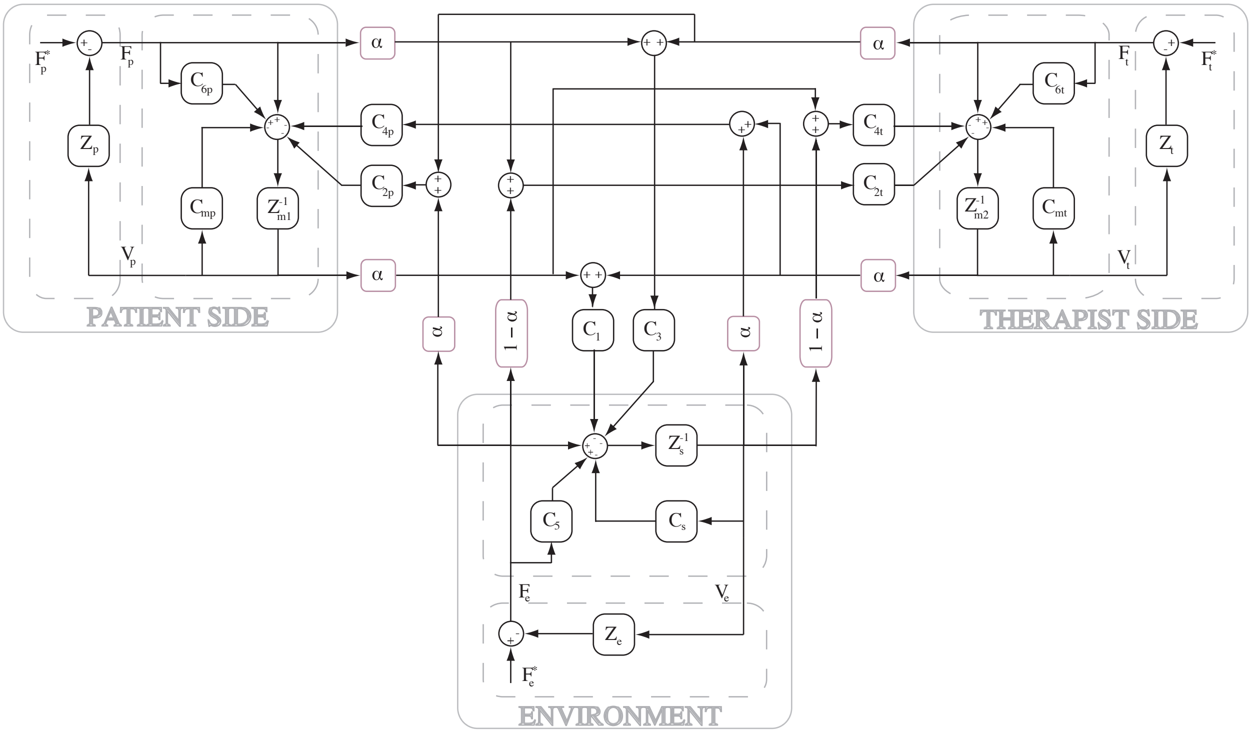

Figure 2. Block diagram of the multi-lateral teleoperation controller.

3.1. Local controllers

The control scheme involves two distinct local controllers, commanding two kinematically dissimilar robots. Both of these robots are backdriveable impedance-type haptic interfaces with low effective inertia. Furthermore, both robots are well-characterized dynamically, rendering model based control and partial dynamics cancelation feasible. Once the highly nonlinear robot dynamics are canceled, desired linear dynamics are imposed using impedance controllers.

Figure 3(a) presents the block diagram of the local controllers. In the block diagram, x, q and $\dot{x}$ and $\dot{q}$ denote task and joint space positions and velocities, respectively. M, C and G matrices represent the inertia, Coriolis and gravity terms of the plant, while J is the Jacobian matrix. $\hat{C}$ and $\hat{G}$ represent modeled estimates of Coriolis and gravity terms. F_{int} denotes the interaction force with the environment, F_s is the force readings from the sensor and F_d is the desired force value. ξ_f, ξ_q and $\xi_{\dot{q}}$ signify measurement and quantization noise on F_{int}, q and $\dot{q}$, respectively.

The impedance controllers are designed to work in the task space, since assigning impedances in joint space is rather non-intuitive. To faithfully assign desired decoupled impedance Z_d along each separate DoF

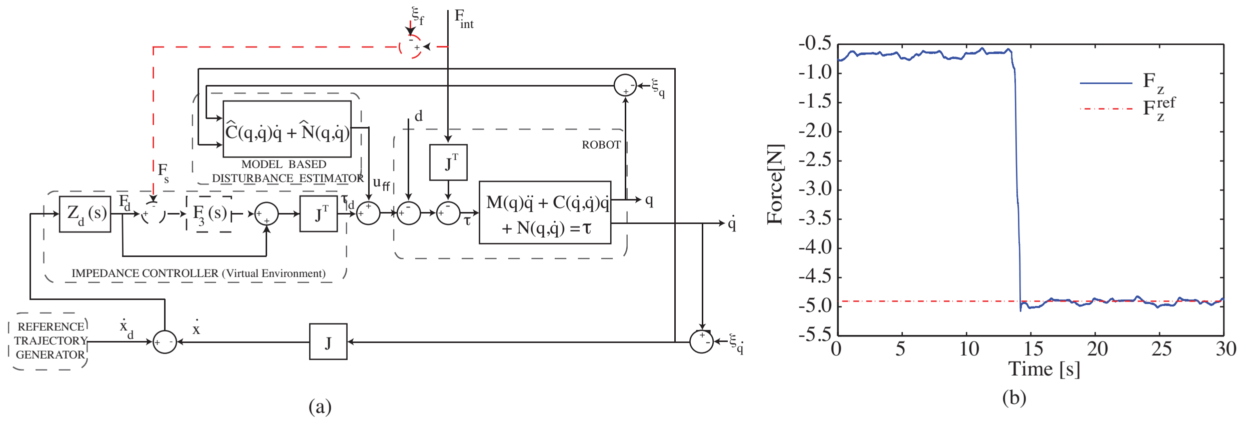

Figure 3. (a) Block diagram of the impedance control algorithm, (b) Experimental results for the impedance control of 3RPS-R .

of the device, model-based dynamics cancelation is utilized. The equations of motion of both mechanisms are derived using Kane's method. The Coriolis/centripetal and gravity terms are evaluated using the nominal plant parameters and these dynamics subtracted from the system dynamics to feedback linearize the system (see Figure 3(a)). Once the desired impedances along each DoF are multiplied by the corresponding position/velocity error, the desired end effector forces/torques are obtained. The error between the desired and the actual force to implement the force control scheme is only possible with force sensors; however, these sensors are expensive and relatively hard to integrate in rehabilitation applications. As a result, open-loop impedance control is implemented and the force controller term $F_3(s)$ is set to zero.

Experimental verification of the impedance control of the 3RPS-R exoskeleton is presented in Figure 3(b). In this experiment, the stiffness along the z-direction was commanded as 2000 N/m. Then, a force of 4.9N was applied along this direction and the motion of the end effector was observed to be 2.5 mm, verifying the fidelity of the rendered impedance. The parameter uncertainties in the plant model are the source of small steady state errors observed in the result.

As far as the implementation details are concerned, the forward and inverse kinematics of the 3RPS-R mechanism are solved numerically. Since, the encoders situated on the actuators are only capable of position measurement, angular velocities are estimated using Euler approximation with adaptive windowing technique, in an effort to reduce the numerical noise. The controllers are programmed in C and implemented in real-time at 1 kHz utilizing a PC running the RTX real-time operating system. The PC-based control architecture compromises of a workstation simultaneously running RTX real-time operating system and Windows XP SP2; and a Quanser Q8 HIL I/O card. To minimize the torque ripple, all actuators are driven via high-bandwidth linear current amplifiers.

3.2. Multi-lateral controller for dual-user bilateral teleoperation

The dual-user bilateral teleoperation concept [12] extends upon the traditional bilateral teleoperation techniques, in that, it uses a distribution parameter α, so called the dominance factor, that dictates the degree of contribution of each master over the slave. In agreement with the literature, small signal linearization is implemented and the operators and the environment are modeled to possess linear and time-invariant dynamics about the equilibrium configurations. The operators and the environment are also assumed to be passive. The stability of the overall system is guaranteed ensuring passivity of the controllers, since the observability conditions are satisfied.

In the discussion to follow, the subscripts p and t represent the patient and the therapist, respectively. The slave environment is denoted by the subscript e. Following relations hold for the system

$$F_p = F_p^* - Z_p V_p \tag{1}$$

$$F_t = F_t^* - Z_t V_t \tag{2}$$

$$F_e = F_e^* + Z_e V_e \tag{3}$$

where F_p^*, F_t^*, and F_e^* denote the external inputs from the two operators and the slave, respectively. The external slave input will be taken to be zero, as rehabilitation task is a passive dynamic simulation. The symbols Z_p, Z_t, and Z_e denote the impedances of the masters, the slave and the virtual environment, following the LTI model convention. Similarly, Z_{m_1}, Z_{m_2}, and Z_s denote the impedances of the master devices at the therapist side, patient side, and the slave device rendered at the environment, respectively. Utilizing the local controller introduced in the previous section, the masters are bestown linear dynamics which can be modeled with the control inputs F_{ctrl}, a combination of the local impedance controllers (C_s, C_{m_p}, C_{m_t}), the local force controllers (C_5, C_{6_p}, C_{6_t}) and the communication channel controllers (C_1, C_{2_p}, C_{2_t}, C_3, C_{4_p}, C_{4_t}) given in Figure 2

$$M_p \dot{V}_p = F_p + F_{ctrl}^p \qquad F_{ctrl}^p = -C_{m_p} V_p + C_{6_p} F_p - C_{4_p} V_p^d - C_{2_p} F_p^d \tag{4}$$

$$M_t \dot{V}_t = F_t + F_{ctrl}^t \qquad F_{ctrl}^t = -C_{m_t} V_t + C_{6_t} F_t - C_{4_t} V_t^d - C_{2_t} F_t^d \tag{5}$$

$$M_s \dot{V}_e = -F_e + F_{ctrl}^e \qquad F_{ctrl}^s = -C_s V_e + C_5 F_e + C_1 V_e^d + C_3 F_e^d \tag{6}$$

where the superscript, d denotes the corresponding desired signal. Local controllers C_{mp}, C_{mt}, C_s are the impedance controllers without the inertial terms, since it is not practical to obtain noise-free acceleration signals without introducing additional sensors. To achieve good transparency the communication channel gains are selected as $C_1 = C_s$, $C_{4_p} = -C_{m_p}$, and $C_{4_t} = -C_{m_t}$.

The effect of the dominance factor α is obviated with the following velocity and force definitions:

$$V_p^d = \alpha V_e + (1-\alpha) V_t \qquad F_p^d = \alpha F_e + (1-\alpha) F_t \tag{7}$$

$$V_t^d = (1-\alpha) V_e + \alpha V_p \qquad F_t^d = (1-\alpha) F_e + \alpha F_p \tag{8}$$

$$V_e^d = \alpha V_p + (1-\alpha) V_t \qquad F_e^d = \alpha F_p + (1-\alpha) F_t \tag{9}$$

To elucidate the primary aim of the application, consider what is expected to happen when the dominance factor α is zero. Then $V_t^d = V_e$, $F_t^d = F_e$ and $V_e^d = V_t$, $F_e^d = F_t$. Assuming the second operator to be the therapist, the resistance offered by the environment is overcome solely by the therapist in this case. Similarly, when $\alpha = 1$, all the effort is burdened on the patient. In between the two values, the load is split between the therapist and the patient. The lower the dominance factor, the lower the effort exerted by the patient.

4. Experimental results

An experiment is conducted using the rehabilitation system depicted in Figure 1. The virtual task is to direct a ball into the two holes diagonally placed at the two corners of the table. The task is to be fulfilled collaboratively by the patient and the therapist. The therapist uses the two DoF force-feedback joystick whose axes are made to coincide with those of 3R<u>P</u>S-<u>R</u> and the table in the virtual environment. The joystick is locally impedance controlled and coupled to the virtual task and the therapist through the multi-lateral control architecture. The arm of the patient is placed in the 3R<u>P</u>S-<u>R</u> exoskeleton whose two relevant DoF are coupled to the joystick and the virtual environment, while the remaining two DoF are set-point position controlled to restrict undesired movements. In particular, the medial axis rotation of the forearm is constrained by the motor, while the linear motion along the z-axis is first adjusted according to the arm length of the user, and is then constrained by the linear actuators. The rest of the DoF are locally impedance controlled and are coupled to the virtual task and the therapist through the multi-lateral control architecture.

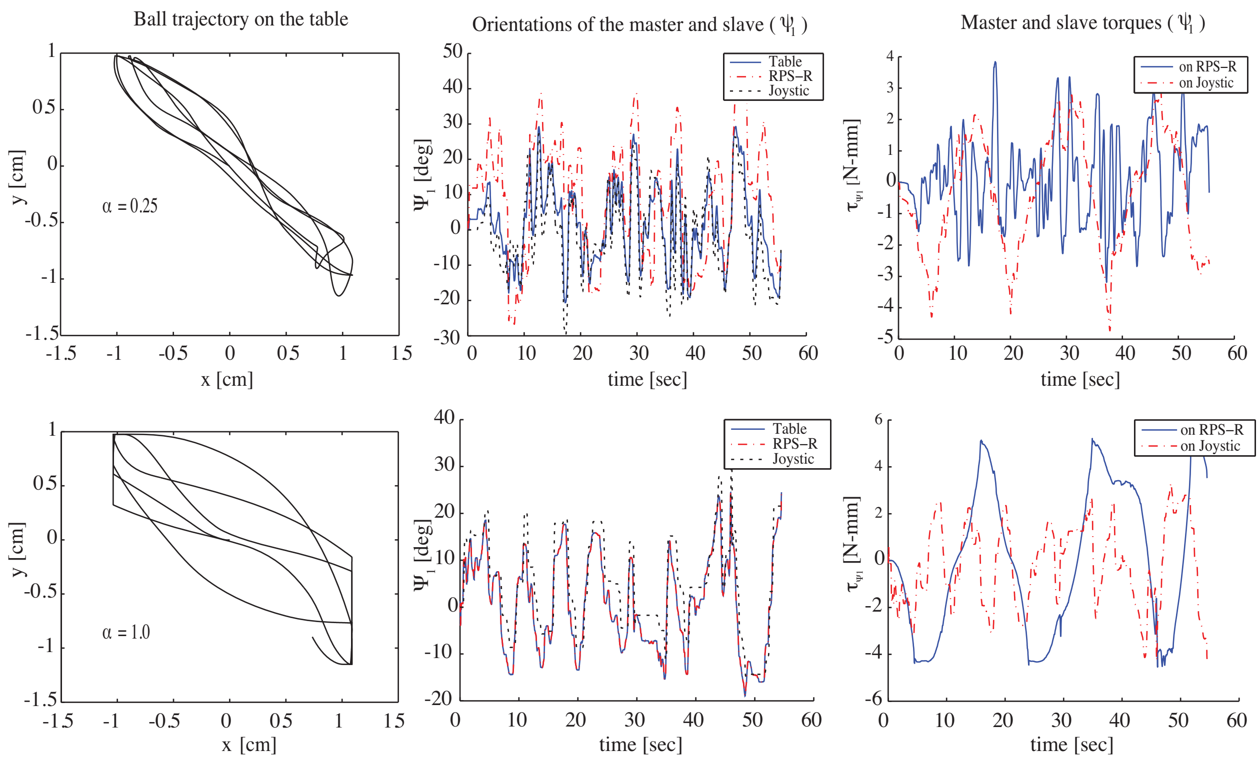

Figure 4. The top row and bottom row present the experimental results for $\alpha = 0.25$ and $\alpha = 1.0$, respectively. The first column depicts the trajectory of the ball on the table. The second column presents the orientation of the table, 3R<u>P</u>S-<u>R</u> , and the joystick about their first axes. The last column depicts total torques applied on the 3R<u>P</u>S-<u>R</u> and the joystick about their first axes.

In Figure 4, the top row and bottom row present the experimental results for $\alpha = 0.25$ and $\alpha = 1.0$, respectively. The first column of figures depicts the trajectory of the ball on the table. From these plots, it can be observed that $\alpha = 1.0$ produces a smoother ball movement than that of $\alpha = 0.25$. The reason is that when α is not 0 or 1, commands given by the patient and the therapist may conflict resulting in such hesitant ball trajectories.

The second column of figures presents the orientation of the table, 3RPS-R , and the joystick about their first axis. Observe that when $\alpha = 1.0$, the table exactly follows 3RPS-R . The joystick, being coupled to these two systems, follows this trajectory imposed by the patient with some error. This distinction is not so clear when $\alpha = 0.25$, since both the therapist and the patient can command their own trajectories. However, observe that since $\alpha = 0.25$ implies that the therapist is thrice more dominant than the patient, and the table follows the joystick more closely than the 3RPS-R .

The last column of figures presents total torques applied on the 3RPS-R and the joystick about the first axis. The increased frequency of the oscillations when $\alpha = 0.25$ is in parallel with the non-smoothness of the ball trajectories shown in the top figures. This is due to the fact that both users are able to affect the orientation of the table and may impose motions conflicting each other, leading to more frequent changes of applied torque direction to compensate for errors with respect to their desired ball trajectories. When $\alpha = 1.0$, there remains only one master, who can command the ball without experiencing any coupling forces from the other master, and as a result no such high frequency torque fluctuations are observed.

5. Conclusion

The design and implementation of a dual-user force-feedback teleoperation control architecture is implemented on a forearm-wrist rehabilitation system. The patient's injured arm is placed in the 3RPS-R exoskeleton, while the therapist commands a joystick to help the patient with a virtual task, that is driven by dynamic simulation. Experimental results of multi-lateral control architecture have been presented with interpretations of the dominance factor α. The experiments demonstrate the feasibility and effectiveness of assigning different control authorities to each agent.

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