Implementation of a Robot Assisted Framework for Rehabilitation Practices

Giorgia Chiriatti, Luca Carbonari, Daniele Costa and Giacomo Palmieri

Abstract The possibility to use collaborative robots in close cooperation scenarios is probably their most interesting characteristics. In industry, this allows the implementation of human in the loop workflows. However, this feature can also be exploited in different fields, such as healthcare. In this paper a rehabilitation framework for upper limbs of neurological patients is presented, consisting of a collaborative robot helping the users in performing a given three-dimensional trajectory. Such practice is aimed at improving patients' coordination by driving their motions along a preferred direction. The mechatronic set up is shown in the following, together with a preliminary experimental set of results.

1 Introduction

As well known, the use of *Collaborative Robots* (*cobots*) in industry is spreading due to their great flexibility. Their success, in fact, is mostly given by the possibility to implement workflows where humans and robots safely cooperate in a shared environment [1–3]. This feature is recently being exploited also in fields of applications different from bare production. Healthcare, for example, is a widely investigated scenario towards which the efforts of many researchers have focused, since it provides an extremely wide range of challenges and applications [4].

Robotics has been a first level player in assistance since years, and also the use of collaborative robots is not a novelty. Among others, Yin and Yushenko [5] used a collaborative robot in surgery; Colucci et al. [6] developed a mobile service robot exploiting a Kinova light weighted cobot; Mišeikis et al. [7] tested

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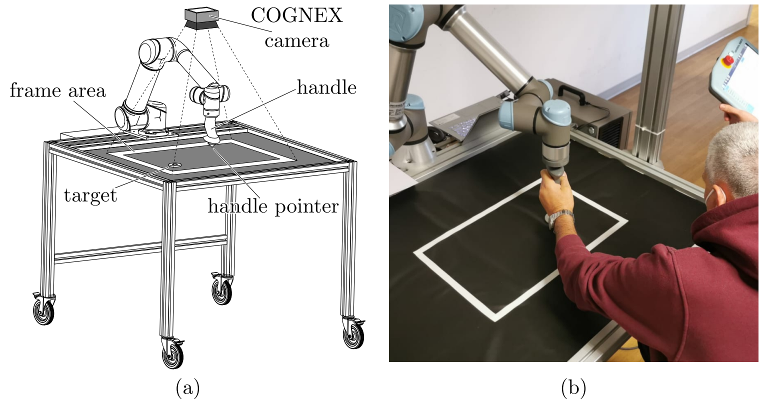

Fig. 1 (a) CAD model of the rehabilitation device; (b) patient exercising during a preliminary experimental test

the prototype of assistive mobile collaborative manipulator in retirement facilities. Research have been further pushed by the COVID-19 pandemic [8], which made even more evident the lack of healthcare operators, and stressed on the importance of human-human distancing in certain environments (e.g., hospitals and geriatric yards). Many applications also involved rehabilitation [9, 10]. For example, Kajopoulos et al. [11] designed a robot-assisted training protocol based on response to joint attention for children with autism. Kyrkjebø et al. [12] analysed the chances given by the collabortive robot UR5 by Universal Robot for rehabilitation of stroke patients. Gherman et al. [13] also envisaged the use of a cobot for rehabilitation of upper limbs, while Prendergast et al. [14] focused on shoulders diseases.

In this crowded scenario, this paper follows up the analyses performed in 2020 by authors [15] by proposing a mechatronic implementation of a platform for rehabilitation practices. The test-bench has been developed with a specific focus on the enhancement of stroke patients ability to follow specific trajectories with their upper limbs. Such directions have been constrained by a collaborative robot (namely a UR5e by Universal Robots), able to teach the help the user in performing the wanted motions by preventing different directions of movement by means of an impedance control law. The target of the movement is dynamically modifiable by the exercise supervisor in order to optimize the result. The remainder of the paper describes in detail the framework (which is shown in Fig. 1), and presents a preliminary experimental set of data.

2 Rehabilitation Framework Description

As mentioned, the main target pursued by the rehabilitation framework is to train the ability of neurological patients to follow a given trajectory, chosen by the caregiver.

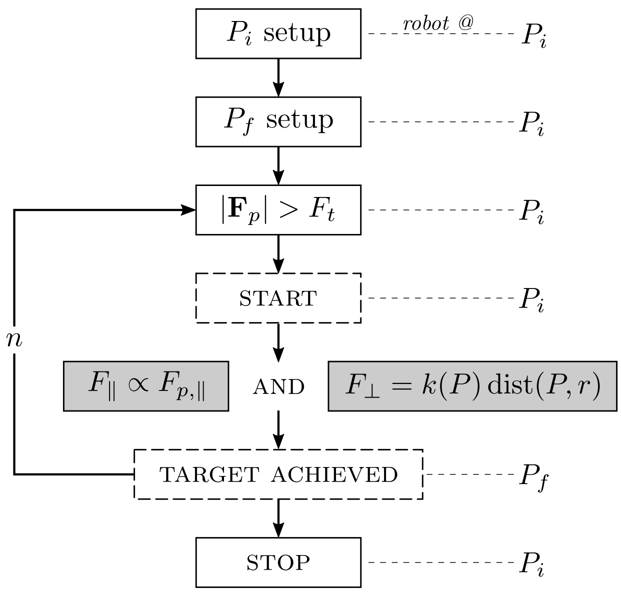

Fig. 2 main phases of the rehabilitation exercise

To such aim, a collaborative robot UR5e by Universal Robots has been provided with a handle specifically designed to be manipulated by both people unable to exert a grasping force and by subjects suffering from spasticity, who cannot easily open their fingers to grasp. The patients are then asked to move the handle, which is provided with a pointer, towards an object (which serves as a target) whose position is dynamically recorded by a COGNEX camera and transmitted to the UR5e controller by TCP communication. A specific program has been developed to make the robot accomplish two basic tasks: to help the patient running the linear trajectory towards the target, and to hinder possible deviations from that path by means of an elastic pull-back force.

2.1 Exercise Phases

The phases of which the exercise is composed are shown in Fig. 2. Briefly, they can be described as it follows:

1. The caregiver (or the patient, if able to) sets the starting point P_i of the trajectory by positioning the handle (i.e., the UR5e end-effector, *EE*) in front of the subject, so that it can be grabbed comfortably.

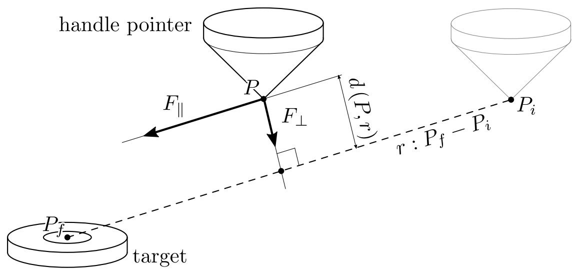

Fig. 3 force components of the UR5e robot thrust

2. The caregiver chose a final point P_f for the trajectory just moving the ring target on the plane of the bench. The COGNEX camera frames the target coordinates and communicate them to the robot.
3. The EE is maintained steady at P_i until the patient exerts a force $\mathbf{F}_p$ greater in module than a pre-defined (eventually customized on patient's characteristics) threshold value F_t:
$$\left|\mathbf{F}_p\right| > F_t \tag{1}$$
Since that moment on, the actual exercise starts and the robot moves according to a control law detailed later in the text.
4. During the exercise, which is cycled for a number n of times decided a priori, the robot exerts a force which depends on the patient interaction and on the EE tip point position (called P) with respect to the line $r : P_f - P_i$. In particular, two components of force are depicted: a component parallel $F_{\|}$ to the line r and proportional to the force exerted by the user in the same direction ($F_{p,\|}$, measured by means of the on-board force sensor), and a component $F_{\perp}$ perpendicular to r configured as a variable stiffness elastic force.
5. The exercise repetition is considered completed when the EE tip reaches the target position P_f. When this happens, the UR5e moves the handle to P_i driving back the patient's hand to the starting point.
6. Once the subject completed the n repetitions, the exercise is up and the patients hand is moved back to P_i where the caregiver decides if a further set of repetitions has to be done with identical or modified force parameters.

2.2 Control Law

As above mentioned, the three components of force to be exerted by the UR5e are computed to pursue two different aims: to help the motion along the line r, and to contrast any deviation from such trajectory. To this purpose, the force has been broke down into two components, parallel and perpendicular to r (see Fig. 3).

The component $F_{\|}$ has been chosen to be proportional to the component of the force applied by the patient to the handle ($\mathbf{F}_p$) parallel to r, called here $F_{p,\|}$. To provide the exercise with a further degree of customization, the proportionality can be selected by the caregiver according to three different level of intensity:

- EASY $\rightarrow F_{\|} = cF_{p,\|}$: the robot applies a force towards the target, actively helping the patient to reach the target. The constant c was chosen equal to 0.5 following the suggestions of professional caregivers after personally testing the device.
- MEDIUM $\rightarrow F_{\|} = 0$: the robot does not apply any force in the direction of the target. Therefore, the patient must apply the force necessary to move the handle as if the robot is set in *free-drive* in such direction.
- DIFFICULT $\rightarrow F_{\|} = -cF_{p,\|}$: the robot contrasts the patient providing a force in the direction opposite with respect to the target.

It is worth remarking that a proper set of safety protocols and force thresholds has been implemented to avoid the robot to push on the patient's hand in an uncontrolled manner. Such programming details are not specified here for the sake of conciseness.

The perpendicular component of force is determined by a variable stiffness to provide a smooth reaction of the robot, especially across the line r. Also, according to the suggestions of professionals, it is useful for patients to have a superior compliance when the handle pointer is far away from the target, while it shall became harder to deviate from the trajectory while approaching P_f. To achieve this purpose, a variable stiffness k has been implemented, as graphically presented in Fig. 4. In few words, a conic transition space has been defined around the line r. Within such space, the stiffness follows a cubic trend going from 0 (when $P \in r$, i.e., when the patient is exactly following the trajectory) to a maximum value k_{max} on the surface of the cone. The apex of the cone coincides with P_i, while its aperture is given by the maximum radius ρ_{max} reached at P_f. For simplicity, ρ_{max} was set proportionally to the distance $\left|P_f - P_i\right|$. The constant σ which rules the proportionality is for this manuscript $\sigma = 1/3$. In formulas, it is:

$$k : \begin{cases} \text{dist}(P,r) \leq d\sigma \Rightarrow k = \frac{k_{max}\text{dist}(P,r)^2}{(d\sigma)^2}\,(3 - 2\,\text{dist}(P,r)) \\ \text{dist}(P,r) > d\sigma \Rightarrow k_{max} \end{cases} \tag{2}$$

where d is the distance among the handle pointer P and the target P_f projected on the line r, as shown in Fig. 4. The maximum stiffness k_{max} was set at 20 N/mm. It should be remarked that the maximum force that the robot is able to exert is quite limited (50 N), providing an intrinsic force saturation which ensure the overall safety of the application.

3 Preliminary Experimental Results

In this section a set of experimental results is discussed, obtained in the preliminary set-up phase of the framework. The subject, which is suffering from no disorder, was

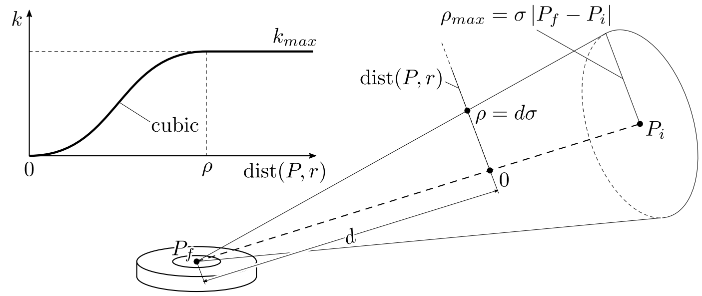

Fig. 4 force components of the UR5e robot thrust

asked to perform 3 repetitions of the exercise (i.e., repeating 3 times the passages from phase 3 to 5 as enumerated in section 2.1). The resulting trajectories are shown in Fig. 5 together with the recorded values of $F_\perp$ and $F_\parallel$. For space reasons, the forces are shown only for an execution in EASY mode. The two forces are shown in a normalized time abscissa, in order to make the three repetitions comparable. The actual times required for the three executions have been 6.64 s, $5.22S$ and 4.96 s (mean 5.61 s).

As visible, a small deviation from the line $P_f - P_i$ is present although the patient is affected by no neurological disorder. Such offset is higher next to point P_i, at the beginning of the exercise and it is probably due to the force threshold that the subject is asked to overcome in order to start the motion (phase 3 of the exercise). Despite such higher deviation, the perpendicular force $F_\perp$ in this region of space is extremely low since the EE is provided with a great compliance. On the contrary, the robot strictly drives the subject hand next to P_f where the transition among null stiffness and k_{max} is pretty fast. The parallel force $F_\parallel$ remains, in all the three repetitions, almost low steady at an average value of 2.94 N (respectively, for the three repetitions mean values of 3.02 N, 2.73 N, 3.08 N). Actually, a peak of 10.97 N was recorded for first repetition, but in general the force overcomes the value of 10 N for a negligible amount of time. In general, the average value of absolute force required to the user to perform the exercise (which is $1/c$ times that exerted by the robot) is $\sim$ 6 N. It is worth reminding that the value of the rehabilitation does not lie in the muscular effort but on the coordination required to achieve the goal of following a trajectory.

4 Conclusions

In this manuscript a novel framework for robot-assisted rehabilitation practices is presented. The framework is targeted at neurological patients to train their capacity of following simple trajectories (e.g., lines) towards a target without deviating from the shortest path. To this aim a collaborative UR5e robot has been provided with a specifically designed handle. The phases of the exercise, which have been refined together with professional caregivers, have been presented together with the control law of the robot. Such law has been developed to reach a double goal of helping the motion along the linear trajectory and contrasting any deviation from it. The task has been accomplished using a force proportional to that exerted by patients along the trajectory, and an elastic pull-back in the perpendicular direction. The development of the framework permitted to perform experimental tests on non-sick volunteer and on some neurological patients. With the aim of simply presenting the framework, the paper only discuss data of the first type, although a comparative analysis of the two sets is undergoing. In conclusion, the experiments showed that the control law provided the expected results and, according to the opinion of the non-sick volunteer, the exercise is sufficiently simple and non-stressing. Obviously, a further assessment

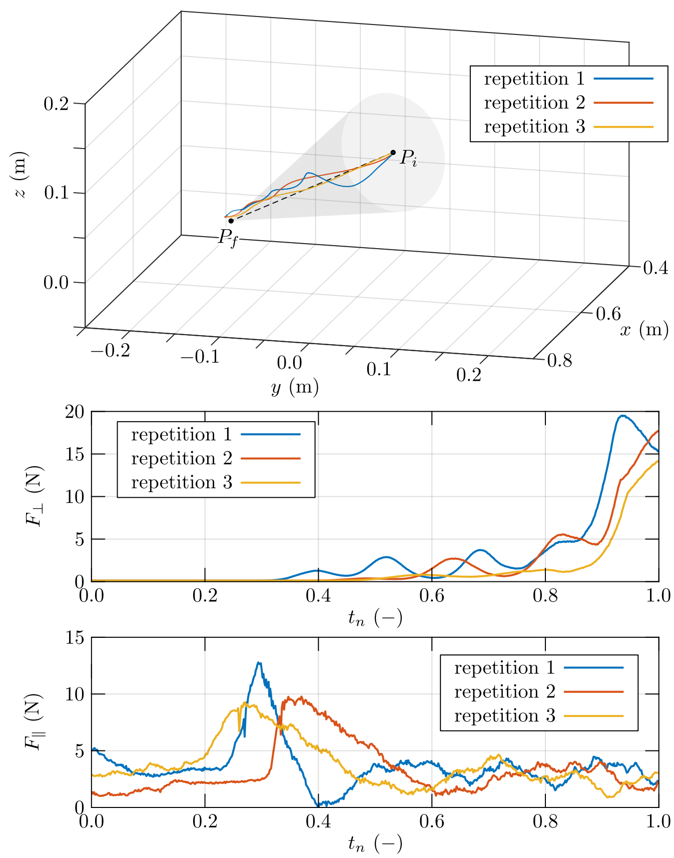

Fig. 5 results of a preliminary experimental test on non-sick subject in terms of executed trajectories and forces ($F_\perp$ and $F_\parallel$) executed by the robot

is mandatory when a significant set of neurological patients will get involved in experiments.

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