

Feasibility of the UR5 Industrial Robot for Robotic Rehabilitation of the Upper Limbs After Stroke

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Abstract—Robot-assisted therapy is an emerging form of rehabilitation treatment for motor recovery of the upper limbs after neurological injuries such as stroke or spinal cord injury. Robotic rehabilitation devices have the potential to reduce the physical strain put on therapists due to the high-effort one-to-one interactions between the therapist and patient involving repetitive high-intensity movements to restore arm and hand functions. Numerous custom robotic devices have been developed in recent years to aid in physical rehabilitation of stroke patients, but most commercially available systems are high-cost devices because of low production volumes and high development costs. In this paper, we analyse the safety and functionality of the UR5 collaborative industrial robot from Universal Robots equipped with an external force/torque sensor in a real-time control system for typical rehabilitation exercises. The aim of the paper is to show that a new class of general-purpose industrial robots designed for human-robot collaboration may prove a viable alternative to custom designs. Experiments show that robotic rehabilitation of the upper limbs using a standard industrial robot manipulator UR5 may be feasible. Results have the potential to make robotic rehabilitation more available as a high-quality therapeutic treatment for more patients.

I. INTRODUCTION

A stroke or traumatic brain injury may cause partial destruction of cortical brain tissue, disturb the generation and integration of neural commands, and may lead to impaired arm and hand motor functions. Restoration of arm and hand motor functions is essential for patients to independently perform activities of daily living (ADL) [1], and current conventional treatments (CT) are high-effort one-to-one interactions between the therapist and patient using repetitive high-intensity and task-specific upper-limb movements that involve significant efforts for therapists. For economic reasons, the duration of primary rehabilitation is becoming shorter and shorter [2].

Robot-assisted therapy (RT) is an emerging form of rehabilitation treatment for motor recovery after neurological injuries such as stroke and spinal cord injury, and has the potential to improve cost-benefit profiles by reducing therapist supervision [2], [3]. Recent systematic reviews of trials comparing CT with RT suggest that the latter leads to similar levels of motor function recovery and motor control [4], [5], [6]. Also, supplementing regular CT with sessions

of RT has been shown to be even more beneficial to motor recovery than CT alone [1]. RT enables patients to train more independently and with less supervision from therapists, and more complex motor tasks can be controlled more precisely with RT than with CT [4], and some rehabilitation therapy modes such as adaptive training or highly repetitive complex movements cannot easily be accomplished with CT [7]. In addition, RT allows for more performance-based rehabilitation strategies because of the robot's abilities to measure upper-limb function and monitor patient progress [8], [9], and may increase somatosensory stimulation and enhance positive feedback from patient efforts [10].

Robotic devices can help patients achieve the high-intensity, repetitive, task-specific, and interactive practice needed to stimulate neural recovery. Recently, more effort has been put into task-specific robot rehabilitation where training for individual patients is focused on acquiring skills necessary to perform everyday functional tasks. Task-specific training should be context-relevant [11], [12], consist of a large number of tasks in a variety of contexts, and involve manipulation of real and functional objects [9]. Also, training should be progressively adjusted to maintain the level of difficulty as task performance improves. Recent results also suggest that reaching against gravity have an additive effect on motor recovery [10], [13]. Motor learning is also amplified when task variability is introduced and when patients experience errors [14].

An extensive survey of robotic devices available for upper-limb rehabilitation can be found in [8], and almost all current robotic rehabilitation systems use custom-designed devices to assist or manipulate the upper limb. The popular ArmeoPower from Hocoma and the InMotionARM from Bionik are well-known commercial examples of end-effector systems. Only a few efforts have been made to employ six-degrees-of-freedom (6-DOF) industrial manipulators for rehabilitation. The REHAROB rehabilitation system [15] uses the IRB 140 and the IRB 1400H from ABB Ltd. in a two-robot concept, and the MIME system [16] uses a PUMA 560 industrial robot in a single-robot setup. In [17] and later publications, the Mitsubishi Pa10-7 is used to assess upper-limb motor control and functional ability, and to investigate the effect of passive RT on upper-limb function using pre-defined reaching and hand-to-mouth movements. All these robots are from a class of industrial robots which are not specifically designed for physical human-robot interaction (pHRI), and [18] warns that such robots should not be used in close physical contact with patients because they have significantly higher impedance than the human upper limbs.

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A new class of collaborative industrial robots is now emerging, consisting of robots designed to work together with humans and to minimise the risk of pinching and high-speed impacts or injuries from collisions. One of the first attempts to use a collaborative robot for robot rehabilitation was made by [19] with a Universal Robots UR5 industrial robot to provide a range of challenging grasping and reaching tasks. In [20], the UR5 was used to replicate the rehabilitation training of two simple 1-DOF training robots, and later in [21] with more advanced dynamic motion primitives as training exercises for robot rehabilitation. However, neither the safety nor the functionality of 6-DOF rehabilitation training with the UR5 have been thoroughly analysed in these previous works, and thus the feasibility of using standard industrial collaborative robots as generic robotic rehabilitation training devices still remains an open question.

In this paper, we investigate safety and control aspects to determine the feasibility of using a standard industrial collaborative robot UR5 for robot rehabilitation. We first present the new class of industrial collaborative robots and the features of the UR5 robot in particular in Sec. II, and then propose safety and control strategies in Sec. III. In Sec. IV we assess the safety and functionality of the UR5 for robot rehabilitation in an experimental study, and discuss the findings in Sec. V.

II. ROBOTIC REHABILITATION SYSTEM

A new class of industrial robot manipulators has been designed for working together with humans, including such robots as the KUKA LBR iiwa, the Universal Robots UR (3, 5 and 10) robots, the Baxter and Sawyer robots from Rethink Robotics, the ABB Yumi, and the Green Fanuc CR-35iA, and others [22]. These robots are purposefully designed to minimise injury in collisions between the human and the robot, and are also equipped with force-sensing and force-limiting features. Some even have sensors on the manipulator's body to allow the robot to identify which link is in contact with the human. Although different in the number of axes, built-in force-sensing features, and physical design, all these robots have the potential for close pHRI because of their lightweight design and their active and/or passive high compliance [23].

In this paper, we will use the UR5 from Universal Robots to investigate the functionality and safety of one of these collaborative robots for robotic rehabilitation. The UR5 is an affordable lightweight six-axis industrial manipulator with a reach of 850 mm and a maximum payload of 5 kg. The UR5 complies with point 5.10.5 of the EN ISO 10218-1:2006 standard, implying that the UR5 robot can operate in close proximity to humans, and have several built-in safety mechanisms such as a protective stop that triggers if an external force that exceeds 150 N is applied to the robot. The highest servo update rate is 125 Hz. The UR5 robot monitors large force/torque (F/T) changes for safety, but in the present study, the robot is augmented with a 6-DOF external F/T sensor Mini45 from ATI Industrial Automation to provide

more accurate F/T feedback to the control system during human-robot interaction.

III. ROBOT SAFETY AND CONTROL

In this paper, we propose safety and control strategies for the UR5 industrial collaborative robot manipulator to make it a feasible device for robot rehabilitation training. Firstly, we propose a set of external safety limitations imposed on the robot through a low-level controller, and propose a cylindrical virtual workspace to limit the potential for crush injuries and singularities. Secondly, we propose a set of generic robot control strategies that can form the basis for robot rehabilitation training exercises. Thirdly, we propose two functional ADL tasks for testing feasibility of the proposed robot rehabilitation control strategies when applied to a UR5 collaborative robot.

A. Robot safety strategies

Safe interactions between stroke patients and the robot system are crucial for allowing a robotic device to aid in rehabilitation training. The UR5 robot has an internal controller safety mechanisms that stops all movements of the manipulator within 500 ms if the force acting on the tool-centre-point (TCP) exceeds 150 N, or if the momentum of the robot arm exceeds 25 Kg·m/s [24].

In addition, we propose to impose a set of external safety limitations on the robot through a low-level external robot controller. Data from the force/torque sensor are set to trigger an emergency shutdown if they exceed a safety limit (experimentally set to 50 N and 8 Nm, respectively). The safety limits can be linked to the patients' residual functional abilities if desirable. In addition, all new reference values are introduced with a gentle step-up or step-down in magnitude to prevent sudden movements of the manipulator, and the controller outputs are limited for both forces and torques. Also, we propose a virtual workspace to limit the workspace of the UR5 manipulator within a cylindrical band defined by inner and outer cylinders centred 40 mm above the base frame and having a (height, radius) of (520, 350) mm and (520, 700) mm, respectively. This virtual workspace limits the potential for crush injuries, singularities at the edge of the UR5 workspace, and oscillations from any unstable inverse-Jacobian calculations.

B. Robot rehabilitation control strategies

Robot rehabilitation control strategies can be divided into high-level control algorithms designed to induce motor learning, and low-level algorithms designed to control positions, velocities, forces, and torques [8]. The only purpose of the low-level compliance control strategy is to follow any movement of the patient in all six DOF, and it is implemented directly in the tool frame to encourage natural interactions between the end-effector and patients.

Three generic high-level control strategies are proposed in this paper to simulate components of standard robot rehabilitation training exercises: one assistive strategy aiding the

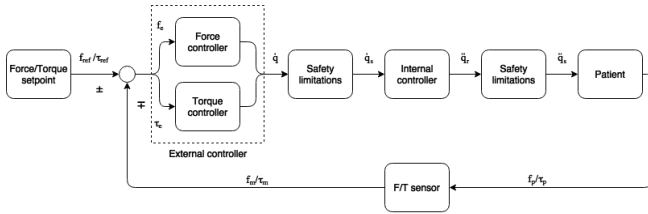


Fig. 1. Controller design, where f_i/τ_i denotes F/T, and q , \dot{q}_i and \ddot{q}_i denote joint positions, velocities, and accelerations, respectively.

patient and two challenge-based strategies resisting patient movement to increase the effort and attention by the patient.

Buoyancy mode is an assistive training strategy aimed at helping the patient to perform movements or tasks in all six DOF by reducing the perceived weight of the afflicted arm. The amount of force the manipulator applies to counteract the weight of the stroke patient’s arm can be defined up to a maximum allowed compensation force of 25 N.

Resistance mode is a challenge-based training strategy that applies a resistance to movements generated by the patient in all six DOF. The goal is to assist stroke patients who master basic hand-eye coordination to improve muscle strength.

Random mode is a challenge-based training strategy to challenge all patients having basic upper-limb functionality. The control strategy generates random vectors at a magnitude of up to ± 15 N in random directions using a gentle step-up and for a random time interval between 2 and 4 seconds.

These high-level control objectives are realised by modifying the F/T reference values of the standard low-level compliance controller shown in Fig. 1. Note that the internal controller block in Fig. 1 is the built-in joint servo controllers of the UR5. The proposed high-level control strategies are not intended as complete robot rehabilitation training modes, but rather as basic components and functionalities that could form the basis for a robotic rehabilitation put together by a therapist. As they are proposed here, they are also more suited for patients with mild to moderate impairments after stroke. Note also that the maximum allowed compensation force and the magnitude of random vectors are chosen for testing purposes only, and should be set more carefully based on the advice from therapists in a rehabilitation setting.

C. Functional ADL tasks

The proposed high-level rehabilitation training strategies will be tested using two functional ADL tasks to demonstrate the feasibility of the UR5 robot as a functional robot rehabilitation training device. The *functional reach* test consists of an abduction movement and an adduction movement by the upper limb in the sagittal, frontal, or transverse planes. These movements are the foundation for almost all ADL tasks. The *drinking test* mimicks the motion of a patient when drinking from a cup. This motion is part of the early goal of eating without assistance in rehabilitation therapy, and is a motivating activity that greatly improves the feeling of independence and the quality of life for stroke patients. The drinking test also allows the patient to perform task-specific rehabilitation exercises with real and functional objects [9].

The two proposed functional tasks are in many respects similar to the reaching movement and hand-to-mouth movement proposed for assessing upper-limb functionality in [25].

The two functional ADL tasks are designed to test the ability of the UR5 robot to perform task-specific rehabilitation training while focusing on skill acquisition in accordance with the findings in [26] and [11]. The two challenge-based high-level control strategies of resistance mode and random mode both require the patient to be an active participant where the challenge may be progressively adjusted, and random mode in particular introduces variability and errors to the training exercise as suggested by [14].

IV. FEASIBILITY STUDY

In this section, we assess the safety and functionality of the UR5 robot for robot rehabilitation training by experimentally testing the safety strategies in III-A, and the high-level control strategies of Sec. III-B using the two functional ADL tasks of Sec. III-C.

A. Experimental setup

The experimental analysis is done using the UR5 robot running on the maximum 125 Hz update frequency, the Mini45 F/T sensor with a sampling frequency of 250 Hz and a low-pass filter with a 5 Hz cut-off frequency, and using a custom end-effector designed to comfortably - but rigidly and safely - fix the patient’s hand to the UR5 robot. The system controller is implemented in URScript on an external computer running Ubuntu 14.04, using the GNU Scientific Library, and written in C++. A software bias and dead-band filters are introduced to compensate for the mounting bias due to the gravity of the custom end-effector. The dead-band filters do not increase system delays, but reduce system sensitivity. The low-level external control scheme is implemented as force and torque P-controllers with gain parameters $K_p = 0.005$ and $K_{p,T} = 0.4$, respectively. Note that the robot manipulator is acting as a natural integrator in the control loop since the control inputs available through URScript are the joint velocity \dot{q}_i , and that the effect is equivalent to implementing a PI-controller on the joint position q_i .

B. Experimental analysis of safety strategies

The emergency shutdown procedures of Sec. III-A were tested by applying an increasing F/T in each DOF, and by verifying that the shutdown is triggered when the controller detects forces or torques exceeding 50 N and 8 Nm, respectively.

The virtual workspace safety strategy of Sec. III-A was tested by trying to penetrate the soft boundary and hold the position three times during a 30 second test period. The virtual workspace verification test results are presented in Fig. 2. The force readings turn red when the TCP is outside the soft boundaries, and the TCP trajectory highlights the relevant radius or height correction vectors applied by the external controller to guide the TCP back inside the virtual workspace. All TCP trajectories located outside the virtual

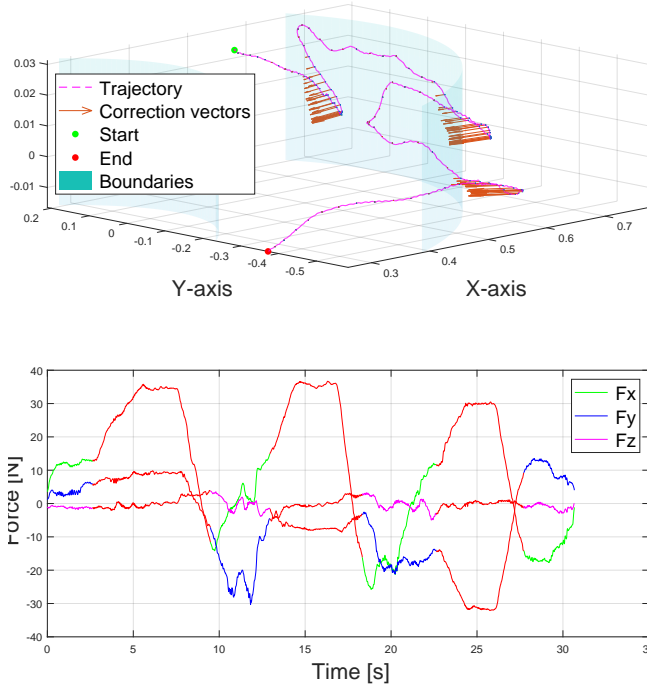


Fig. 2. Experimental test of the outer boundary in the virtual workspace.

workspace show correction vectors that are pointed back towards the virtual workspace with a magnitude that is scaled according to the distance from the relevant soft boundary.

C. Experimental analysis of rehabilitation strategies

The three high-level rehabilitation strategies of Sec. III-B were experimentally tested using the ADL *functional reach* and *drinking test*. Only one of the functional ADL tests of III-C is shown per rehabilitation control strategy because of space limitations; for a complete set of experimental tests, see [27]. Note that force readings in the plots turn red if the TCP is outside the virtual workspace.

Buoyancy mode is shown in Fig. 3 for the functional reach test with a constant buoyancy vector of 15 N upwards. The operator twists the third wrist joint $\Delta q_6 > 90^\circ$ before initiating a multidirectional functional reach test of four consecutive functional reaches: horizontally in the transverse plane, diagonally upwards in the sagittal plane, vertically in the frontal plane, and horizontally in the transverse plane. The first three functional reaches are contained within the virtual workspace, while the fourth functional reach in the XY plane crosses the outer cylindrical soft boundary at the peak of the trajectory. The trajectory shows yellow buoyancy vectors consistently pointed upwards in a vertical direction and shows outer radius correction vectors in red at the peak of the fourth functional-reach trajectory in the lower left corner of Fig. 3. The force plot shows complex force readings in the approximate time interval [0s–3s], which is consistent

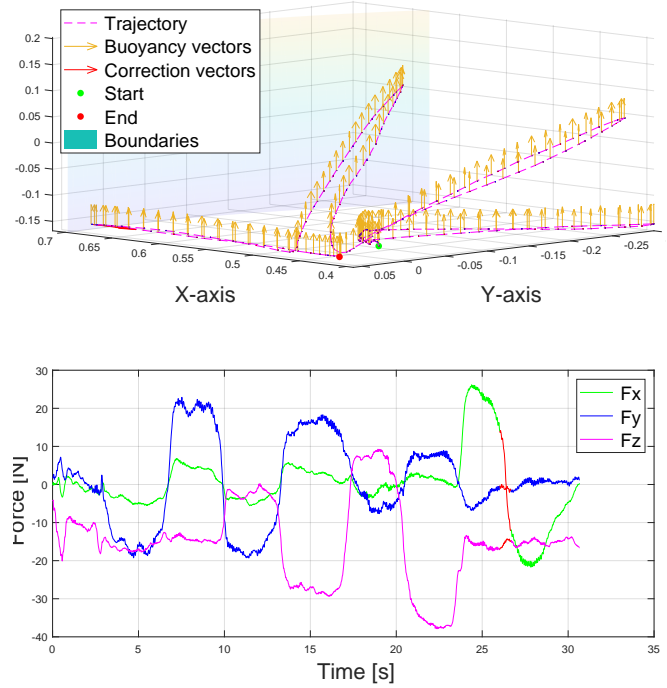


Fig. 3. Experimental test of functional reaches in buoyancy mode.

with the third wrist joint being twisted. Observe that the difference in the F_z magnitude during the third functional reach in the YZ plane from [17.5s–23.5s] is consistent with the upper-limb abduction and adduction movements being aided and resisted by the buoyancy vectors. The result from the drinking test in buoyancy mode was consistent with these results [27].

Resistance mode is shown in Fig. 4 for the drinking test with 50% of maximum resistance (100% is equivalent to full stop) to movement in all six DOF. In the drinking test, the objective is to reach with an open hand for a cup placed on the table, firmly grasp the handle, move the cup to the mouth, take a small drink, return the cup to its original position, and return the hand to the starting pose.

The results show the complex movements associated with the drinking task. The initial functional reach towards the cup moves slightly outside the virtual workspace at the lowest part of the trajectory. The functional reach towards the mouth is followed by a pause while the operator is drinking. The cup is placed back on the table with a functional reach that is barely contained inside the virtual workspace. The hand is retracted towards its initial pose by a functional reach where it is stationary for the remainder of the drinking test. The trajectory shows force vectors consistently pointing along the TCP trajectory, with a small exception at the lower parts of the TCP trajectory where an additional height correction vector is present. Observe the small force vibrations during the drinking movement and the lack of a stationary force

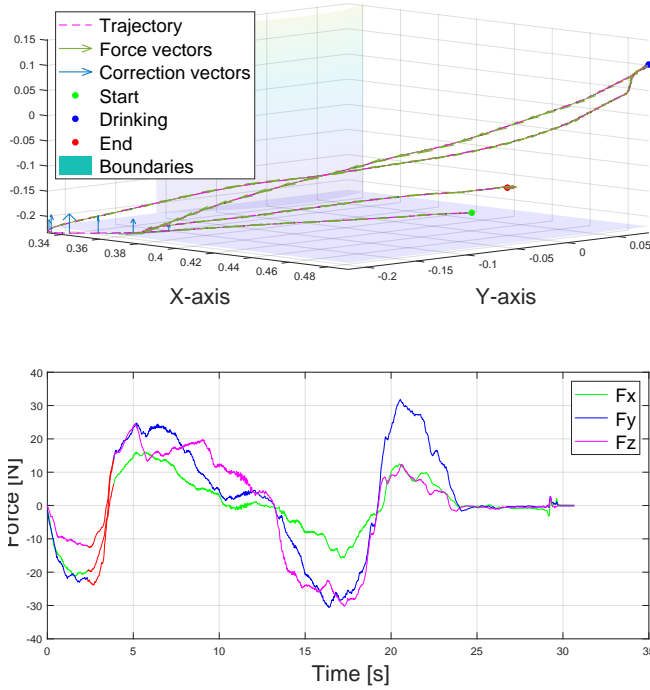


Fig. 4. Experimental test of a drinking task in resistance mode

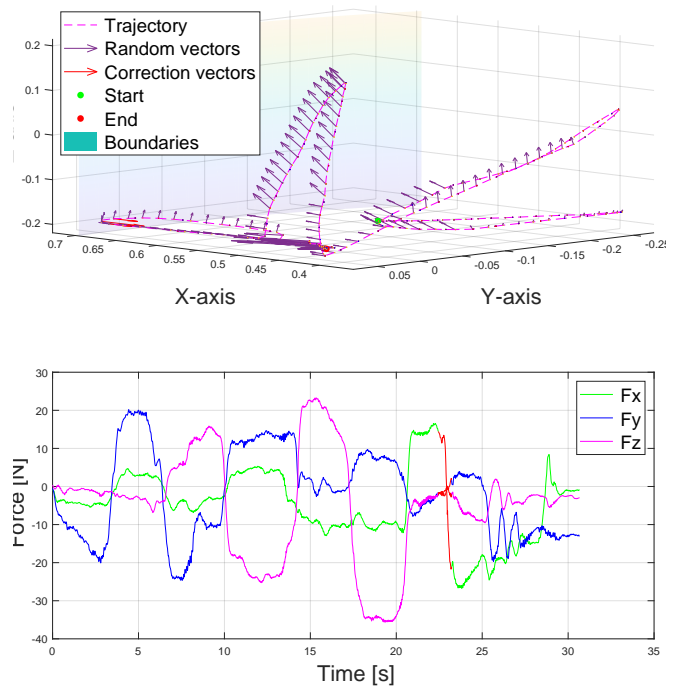


Fig. 5. Experimental test of functional reaches in random mode

deviation in F_z in the waiting period. The result from the functional reach test in resistance mode was consistent with these results [27].

Random mode is shown in Fig. 5 for the functional reach test with a random force vector of 100% of maximum magnitude in all three transitional DOF. The implementation was identical to the procedure established for the functional reach test in buoyancy mode. The results show four functional reaches predominantly located in the XY plane, XYZ space, XYZ space and XY plane, respectively. Observe the inability to contain the third functional reach to the YZ plane because of the random force vector. The first three functional reaches are contained within the virtual workspace, while the fourth functional reach in the XY plane barely crosses the outer cylindrical soft boundary at the peak of the trajectory. The trajectory shows purple random vectors pointed randomly along the TCP trajectory and outer radius correction vectors at the peak of the fourth functional reach trajectory. The force readings show four dominating force readings that are consistent with the four functional reaches. Observe the fluctuations in the force readings during the waiting period from [25.5s–30s]. The results from other tests in random mode were consistent with these results [27].

V. DISCUSSION

In this paper, we have investigated safety and control aspects to determine the feasibility of using a standard industrial collaborative robot UR5 for robot rehabilitation.

We have proposed additional safety strategies to supplement the built-in safety mechanisms of the manipulator, and have proposed three high-level control strategies as examples of robot rehabilitation strategies. All three have been tested using the UR5 robot for two functional ADL tasks.

The experimental testing in Sec.IV-B has shown that the proposed external safety limitations are working as intended so that forces and torques outside the permitted range instantly trigger a full stop of the robot. Also, the proposed virtual workspace with soft boundaries actively generates forces that push the patient back towards the desirable workspace firmly but gently. The three high-level control strategies tested using the two ADL tasks show that using a UR5 robot and the proposed control strategies can provide both assistive and challenging functional rehabilitation training exercises. Both the proposed safety limitations and rehabilitation strategies give a predictable and proportional response to patient inputs, an important aspect to increase patient trust in the robotic rehabilitation system. The proposed assistive- and challenge-based control strategies form a good basis for implementing a large variety of ADL rehabilitation training tasks.

The safety and control strategies are implemented on the UR5 robot with a maximum update frequency of 125 Hz, while others [17] have used customised industrial robots capable of an update rate up to 750 Hz. In the low-speed experiments performed in the feasibility analysis, we have not encountered situations where the servo update frequency

has been limiting for safety or control performance. The relatively low servo update frequency is also to some extent justified by the limited motion frequencies of potential patients from voluntary motions or spasticity or trembles. This matter should however be more carefully addressed for more high-speed rehabilitation exercises.

The maximum payload of the UR5 robot is 5 kg, which could potentially limit some patient training exercises. However, the proposed safety and control strategies of the feasibility study presented in this paper should also be valid for the UR10 robot if more power is needed.

The work presented in this paper shows that it may be feasible to use the standard 6-DOF industrial collaborative robot manipulator UR5 combined with accurate F/T measurements in robot rehabilitation training of the upper limbs after stroke. The results allow customising a wide range of movements and control strategies for robotic rehabilitation using a standard industrial robot manipulator. Further work will focus on evaluating the feasibility of the UR5 robot using clinical rehabilitation techniques in close cooperation with therapists, and on clinical trials with patients to evaluate the rehabilitation outcomes of the proposed system.

VI. AUTHORS' CONTRIBUTIONS

EK introduced the concept, performed the literature review, and drafted the paper. MJL designed, implemented, and performed the experiments. ØS contributed to the concept and to the paper's structure. All authors revised and approved the manuscript.

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