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On the robotic-assisted rehabilitation of the upper limb using collaborative robots

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Abstract. The paper focuses on the development of an intuitive human-robot interface for the robotic-assisted rehabilitation of the upper limb, using commercially available collaborative robots. Initially developed for various industrial processes, where the human-robot collaboration within the workflow is required, the collaborative robots' utility can be extended towards medical applications, especially due to their innate safety functions. A task-oriented training exercise is defined based on specific patient requirements using two-dimensional (2D) and three-dimensional (3D) defined trajectories. To illustrate such possibilities, two use-cases have been proposed: a user-defined, training-based maze as a task-oriented approach for the 2D trajectory, and a point-to-point dynamically defined rehabilitation exercise for the 3D trajectory. Validation tests in laboratory conditions using healthy subjects have been performed to validate the proposed robotic-assisted rehabilitation architecture for the upper limb.

Keywords: robotic-assisted rehabilitation, collaborative robot, image processing, tracking device, human-robot interaction.

1. Introduction

Neuromotor disorders represent a medical condition which usually affects motion abilities, posture and finally the life quality. Causes which lead to such impairments have various natures, such as: congenital, where genetics play an important role (e.g. muscular dystrophy or hereditary spastic paraplegia) or acquired through traumatic injuries, infections or neurologic diseases [1]. Nevertheless, most of the times neuromotor disorders are caused by damage at the

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level of the central nervous system, mostly represented by stroke. 15 million people suffer a stroke every year, worldwide [2]. About a third die, while the stroke survivors are almost always disabled in various degrees, which leads to a burden placed on their families, friends and finally the society at large.
The treatment varies according to the disability level and comorbidities for each patient, but it usually encompasses a combination of medication, rehabilitation therapies or assistive technology, accompanied by psychological services [3-5]. Physical rehabilitation plays a very important role in restoring the limb's lost functions, aiming to improve mobility and ultimately the life quality of the patients, [4]. Robotic-assisted rehabilitation integrates robotic systems into the rehabilitation process, leading to a more precise, highly repetitive and intense training, with proven efficiency. Besides the obvious positive outcomes of the patients, the use of robots also leads to a reduced therapist workload, allowing them to focus on other complex aspects within the rehabilitation process [6-10].
Collaborative robots have increasingly been used in industry due to their great flexibility, being used in workflows which require a close human-robot collaboration to perform the required tasks [11]. Their key characteristics, i.e. safety features, ease of use, flexibility, precision and consistency, contributed to their use in other application fields, different from the traditional industrial field, such an example being healthcare. A mobile robot based on the Kinova lightweight robot has been developed in [12], while in [13] the authors have tested an assistive mobile collaborative robot to be used in retirement facilities. In [14-16] the authors have tested different collaborative robots for the rehabilitation process of the upper limb. These studies certainly prove the ability to use collaborative robots for various rehabilitation training exercises.
Based on this introduction paper is structure as follows: section 2, Materials and methods, present a brief description of the UR5e robot and the equipment's used for define 2D and 3D rehabilitations trajectories; section 3, Results and discussions presents the obtained results, and some explanations and section 4 contain some conclusion and future direction about this work.

2. Materials and methods

2.1. The Universal Robots UR5e collaborative robot

The UR5e robot developed by Universal Robots is a serial arm with 6 degrees of freedom (DOF) and is part of the e-Series, which comes with several improvements over the UR5 version. These improvements include the integration of force and torque sensors in the motor axes, an enhanced graphical interface and touchscreen, improved software for faster and easier configuration compared to the previous version, better repeatability (±0.03 mm compared to ±0.1 mm), 5kg payload and reduced setup and configuration time [17]. The collaborative feature of the UR5e robot is due to the inclusion of force and torque sensors in each motor axis, which can detect even the smallest collisions with the external environment. This feature facilitates working with human operators without the need for protective fences or other auxiliary safety equipment to prevent accidents during the robot's operation. At the same time, the UR5e complies with ISO/TS 15066, ISO 10218-1, and ISO 10218-2 standards [18, 19], which define safety and security conditions when integrating robots into work with human operators [20]. The increased flexibility of the system, its rapid programming and integration into various applications, whether industrial or medical, are key advantages that define this system. These features have encouraged the current research by integrating such a system into the medical rehabilitation of the upper limb [20, 21]. Based on the previous description, the UR5e robot is used in this paper to carry out the necessary operations for upper limb rehabilitation, using two ways for defining motion trajectories. The first approach uses image processing to generate a planar motion trajectory defined in the two-dimensional (2D) space, while the second focuses on capturing the motion of a pre-defined rigid body using the OptiTrack motion monitoring system [22] to generate the three-dimensional (3D) motion trajectory. A detailed description of the two approaches is provided in subsections 2.2 and 2.3.

2.2. Customized rehabilitation robotic trajectory definition in two-dimensional space

The materials used for defining the motion trajectory in a 2D plane with the UR5e robot are divided into two categories: hardware and software. The hardware components used for this stage include the UR5e robot with its control unit and teach pendant, a Full HD webcam (Trust Tyrol), physical layout paper, and a 3D-printed patient hand support device that attaches to the robot flange. The software components used in this stage are Visual Studio Code, Python, URSim, and Open Source Computer Vision (OpenCV). A simplified diagram of the connections between the hardware and software components is presented in Figure 1.

According to Figure 1, the input data sent to the UR5e robot is generated from the image captured by the webcam positioned above the sheet of paper where the layout is defined, and this image is processed using the OpenCV software program. Thus, the image recorded by the webcam is sent to the OpenCV program, where it is processed by applying various filters to convert the image from RGB (1) to Grayscale (2). This conversion makes it easier to detect the white area from the area where the contour is defined. The program then labels the desired contour in white, replacing the rest of the sheet with a black background (3). The obtained image overlaps with the image resulting from applying the filters, thus obtaining the contour along which the robot must move. The obtained image (4) is labeled using green dots for the area outside the contour and red dots for the area inside the contour (5). This labeling is optimized by removing the green dots and maintaining the red dots only in the corners where the contour changes direction (6). These labeling and optimization operations were carried out in Python by writing the sequences of code that perform these tasks. The results of processing the image recorded by the webcam are illustrated in Figure 2.

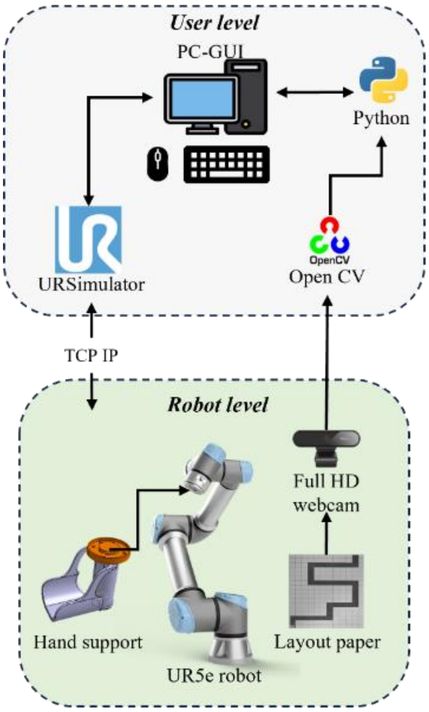

Fig. 1. Communication diagram between hardware and software equipment used to perform the 2D rehabilitation trajectory definition.

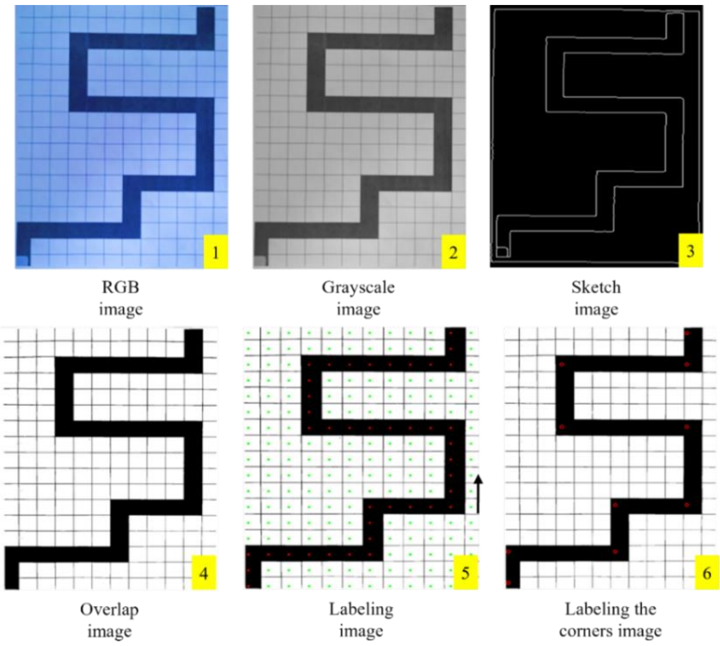

Fig. 2. The stages of image processing performed by the webcam.

Based on the generated image (6), the local coordinates are converted into the robot's global coordinates through a Python software program using a function called *process_tuningPoint*. Three parameters have been used: local coordinates, robot coordinates and direction (the default is from left to right). Then, a reference point is selected (which is the first point in the list of the coordinate points) and is located 17.5 millimeters away from the surface of the paper on which the path is drawn is set. The other coordinates of the reference are $\left(ref_x, ref_y\right)$. To normalize the local coordinates relative to the reference point, the transformation below is used. Thus, if the direction is from left to right:

$$\begin{cases} local_x = x - ref_x \\ local_y = -\left(y - ref_y\right) \end{cases} \tag{1}$$

and if the direction is from right to left:

$$\begin{cases} local_x = -\left(x - ref_x\right) \\ local_y = y - ref_y \end{cases} \tag{2}$$

The next step is to transform the local coordinates into global coordinates, which is performed using (3), where $robot_x$ and $robot_y$ are the global coordinates of the robot's end-effector. The *z* coordinate and the orientation remain constant.

$$\begin{cases} global_x = local_x + robot_x \\ global_y = local_y + robot_y \end{cases} \tag{3}$$

The data (the global coordinates and the orientation) is transmitted to the robot through the URSimulator program using the TCP-IP (Transmission Control Protocol/Internal Protocol). To facilitate the interaction between the physical therapist and the UR5e robotic system, an interactive graphical user interface (GUI) was defined and developed in the Python software program using the *tkinter* library. The resulting GUI is illustrated in Figure 3.

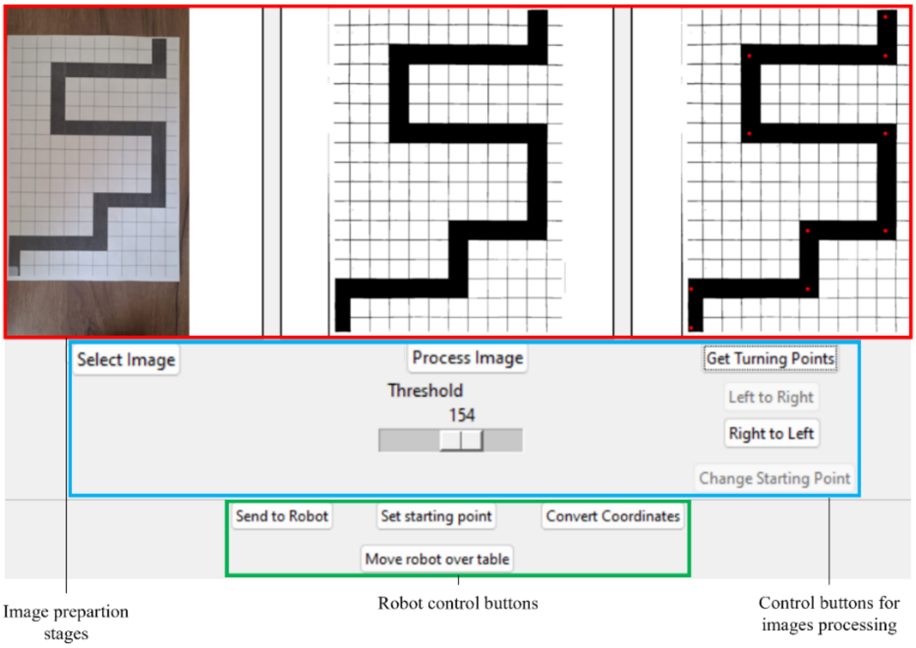

Fig. 3. The graphical user interface developed for the 2D rehabilitation trajectory definition.

2.3. Customized rehabilitation robotic trajectory definition in three-dimensional space

The 3D trajectory of the rehabilitation motion has been defined using of the OptiTrack motion tracking system [16], which is used to record the movements performed by the physical therapist during the medical rehabilitation procedure for the patient's upper limb. For the experimental setup, the UR5e robot was used, equipped with a 3D-printed and designed device in which the patient attaches their hand, the OptiTrack camera system composed of a control unit and six Prime 41 cameras, calibration equipment for the OptiTrack system, and a rigid body on which three markers were placed to capture the data generated from the therapist's hand movements. The conversion of inputs transmitted by the physical therapist through the OptiTrack system cameras to the robot's end-effector was carried out using Matlab and Python software programs. A flowchart showing how the data is captured from the physical therapist and transmitted to the robot's end effector is presented in Figure 4.

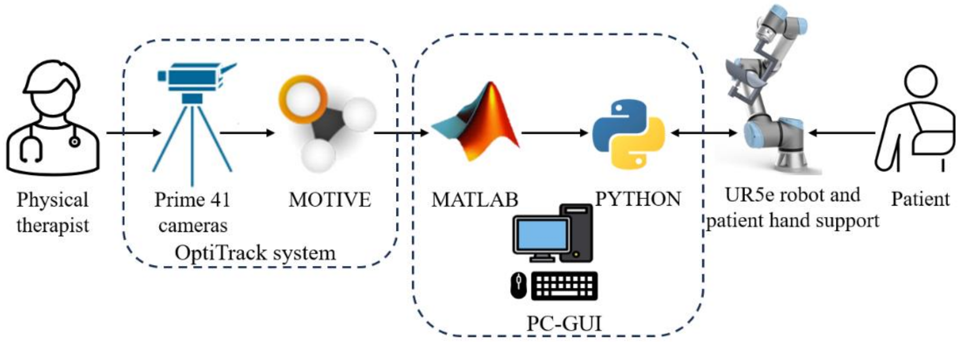

Fig. 4. Data transfer flowchart from the physical therapist to the patient.

To achieve good data transmission using the OptiTrack camera system, it is mandatory to calibrate the system. These steps include:

- Securing the cameras and connecting them to the system's control unit (using the TCP-IP communication protocol);
- Selecting the marker size for the application (markers used in this step have a diameter of 6.3 mm);
- Calibrating the system using the CWM-125 support;
- Recording over 1000 points per camera;
- Generating each camera's workspace and the total system workspace based on the recorded points (this process is done using the Motive software);
- Verifying and saving the obtained results.

A detailed view of the workspace obtained from the previously described steps, as well as the data obtained from the calibration, is illustrated in Figure 5.

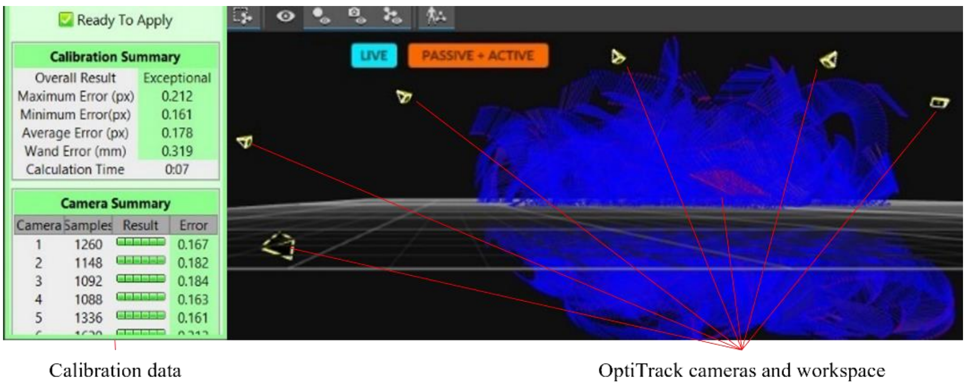

Fig. 5. The workspace of the OptiTrack system cameras.

The following step is to define a rigid body used to transmit data from the OptiTrack system to the UR5e robot. For defining this rigid body in Motive, the three markers were placed on a 3D printed plastic support, which will be manipulated by the physical therapist. Based on these three markers attached to the

3D-printed support, the virtual rigid body was automatically generated using Motive software. The result of the virtual body and the 3D-printed plastic support is illustrated in Figure 6. The Cartesian coordinates (*OX*, *OY*, *OZ*) of the virtual body center of mass (VBC) will be recorded by Motive and processed by MATLAB, thus generating the inputs that will be sent to the UR5e robot.

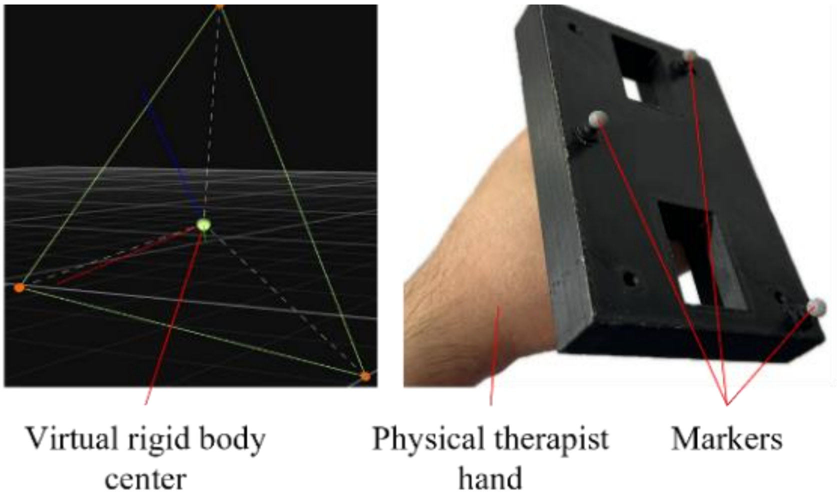

Fig. 6. Virtual and real body used for recording the input data for the proposal method.

To convert the data recorded by OptiTrack, Motive software was used. This program forwards the VBC coordinates to MATLAB, thus facilitating their conversion and scaling from the global camera system to the global robot system. As a result of this conversion, the data from the first reading of the camera system coincides with the data of the UR5e robot's end effector. The data is then forwarded from MATLAB to Python. The Python program directly connects with the robot via the URSimulator software, with the data being transmitted using the TCP-IP protocol. Based on these connections established between the OptiTrack camera system and the UR5e robot, the data transmitted by the physical therapist using the 3D-printed rigid body is converted by MATLAB and sent to Python as global end effector coordinates, where the patient's hand is fixed. The robot thus replicates the physical therapist's movements on a real scale by adjusting these coordinates according to the transmitted data. A simplified diagram of the data transmission process is illustrated in Figure 7.

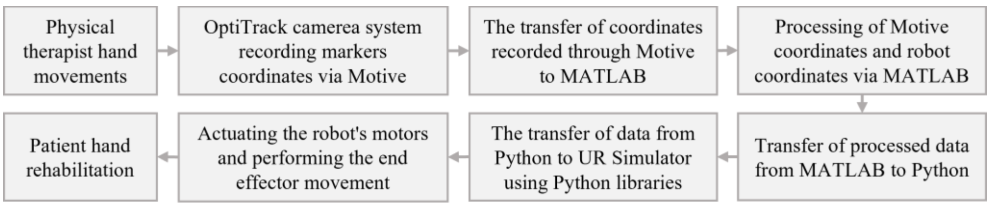

Fig. 7. The simplified diagram of the data transmission process.

3. Results and discussions

Using the two-dimensional trajectory presented in Figure 2, an experimental test in laboratory conditions has been performed. A healthy subject acting as a patient was asked to perform a rehabilitation exercise using the UR5e collaborative robot using the proposed trajectory. The human-robot interaction was passive, meaning that the robot performed the motion, while the patient The integrated Force/Torque sensor was used to measure the forces acting upon the robot end-effector while it drives the patient's hand. The patient was asked to resist the motion, thus acting with a certain degree of spasticity. The results are presented in Figure 8 and represent the time history diagram of the recorded forces projections on the three axes of the robot base coordinate system while performing the proposed exercise.

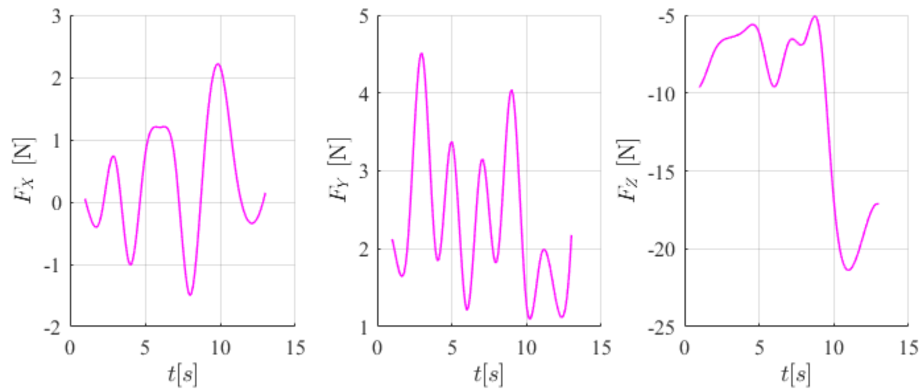

Fig. 8. Time history diagram of the recorded forces while performing a two-dimensional trajectory rehabilitation exercise.

Peak recorded forces on the *OX* and *OY* axes are around 2.2 and 4.5 N, respectively, below the safety barrier which was set at 7 N for these axes. The forces on the *OZ* axis had higher values, but no safety barrier was set here, since the proposed trajectory was two-dimensional. Nevertheless, this doesn't mean that patients may not apply forces on the OZ axis while performing the exercise, but just that large variations along this axis is not as dangerous as for the other two axes.

The second experimental test included a trajectory generated in three-dimensional space using the OptiTrack system, Figure 9. Figure 10 presents the time history diagram of the trajectory in the fixed coordinate system (the UR5e base coordinate system), and the end-effector trajectory in the same coordinate system performed by the robot. The calculated RMSE error is: 0.02, 0.023, 0.034 for the *OX*, *OY* and *OZ* axes, respectively, which validates the proposed approach for generating upper limb rehabilitation trajectories.

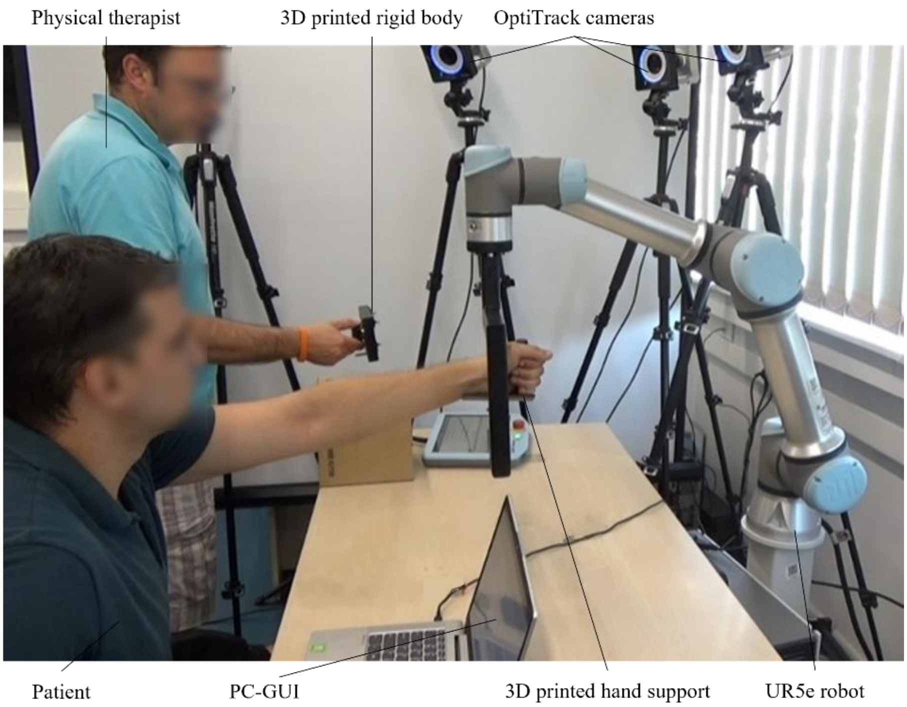

Fig. 9. Experimental setup for the rehabilitation of the upper limb using the OptiTrack system as input for the UR5e collaborative robot.

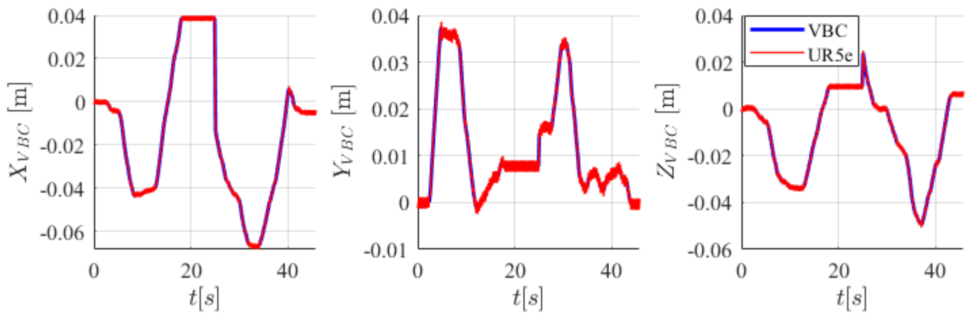

Fig. 10. Comparative displacements time history diagram of the VBC and the UR5e end-effector for a three-dimensional training exercise trajectory.

4. Conclusions

The paper presents two different approaches for defining motion trajectories in the two- and three-dimensional space for upper limb rehabilitation using a commercially available collaborative robot. In the first approach, the integration of image processing and the transfer of coordinates based on image processing to the collaborative robot is presented, with the robot following the generated trajectory without leaving the contour created by the image processing. This approach has several advantages: the dynamic definition of different planar trajectories based on the patient's treatment requirements, range of motion, anthropometric dimensions, providing a high degree of versatility and flexibility for the upper limb rehabilitation. The second approach involves generating a 3D motion trajectory using a tracking system (OptiTrack) that captures data from markers fixed on a rigid body held by the physician/therapist and transfers it to the robot's end effector, which replicates the therapist's movements using a pre-defined scale. In addition to the previous approach, this one adds another dimension, which means that the trajectories can be more complex. Both approaches provide a very user-friendly interface with the robot, eliminating the need for in-depth knowledge regarding the operation of collaborative industrial robots. The physician has now the possibility of teaching the robot to perform the required rehabilitation training exercising by simply printing different layouts of a maze or naturally moving the hand and mimicking a rehabilitation exercise. The utility of these applications can be easily extended towards other fields, where a high dynamic is required in the trajectory's generation.

Future developments will focus on the mechanical design of upper limb attaching devices that allow for adjustments and provide optimal ergonomics. Additionally, there will be an expansion of tests with healthy subjects under laboratory conditions, combining the three modes of medical rehabilitation: active, passive, and assistive.

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