Workspace Placement of Motion Trajectories by Manipulability Index for Optimal Design of Cobot Assisted Rehabilitation Solutions

Marco Caramaschi[1], Dario Onfiani[1], Fabio Pini[1], Luigi Biagiotti[1] and Francesco Leali[1]

[1]"Enzo Ferrari" Dept. of Engineering, University of Modena and Reggio Emilia, {marco.caramaschi, dario.onfiani, luigi.biagiotti, fabio.pini, francesco.leali}@unimore.it

Corresponding author: Marco Caramaschi, marco.caramaschi@unimore.it

Abstract. Nowadays the rehabilitation process involves the patient and the therapist, that must interact to recover the motion of limbs and the strength of related muscles to restore the initial functionalities. The therapy relies on the experience and sensitivity of the therapist that identifies the rehabilitation exercises which are necessary to recover the expected ability. To prevent inappropriate practices an interesting aid may come by mixing collaborative robots, namely Cobots, and additive manufacturing technologies. The proper integration of a Cobot assistant and custom-printed training objects enables a significant improvement in the effectiveness of the therapy action and the related user experience since the programmed trajectories can mimic the movements related to activities of daily living. To this aim, this work describes an integrated approach to support the design of Cobot assisted rehabilitative solutions. The object selected by the patient and therapist, the motion pattern, the clamping area, and loads on the limb represents the design requirements. The motion trajectories defining the specific training tasks are the starting point to the optimal placement within the Cobot workspace. Specifically, manipulability maps can provide an objective evaluation of the locations where the exercises are performed at the best of workspace and configuration of the Cobot. A simple upper limb rehabilitation exercise based on a demonstrative handle has been selected to prove the effectiveness of the proposed approach. The results confirm that the manipulability index can be adopted to drive the preliminary design of the Cobotic solution toward a feasible configuration.

Keywords: Occupational Therapy, Assisted Rehabilitation, Cobot, Integrated Design, Manipulability Index.
DOI: https://doi.org/10.14733/cadaps.2023.S6.1-12

1 INTRODUCTION

The recent advances in robot technologies are opening new development pathways that are of great interest to the medical sector, especially for palliative and supportive care [15] as well as for rehabilitation actions [4, 6]. Mainly two solutions of rehabilitative robots are well established in clinical applications, namely grounded exoskeletons and grounded end-effector devices [8]. The former control individual joints while the latter focus the control on selected joints or limb segments. Examples of exoskeletons are ARMIN [14], Rupert [22] and NESM [5], among many others. These devices empower perfect repeatability of the movement for each joint. Nevertheless, they need a complex design of the parts aimed to execute a specified exercise with a scarce possibility to adapt it to perform other types of exercises. Furthermore, the complex anatomical structure of human limbs generates additional torques and forces during rehabilitation training. Conversely, some examples of end-effector solutions are MIT-MANUS [10], GENTLE/S [12], REHAROB [23], PUParm [2] and EULRR [25]. The end-effector solutions objectify the mobility of the limb and define both the path and the effort to perform the exercises. The effort required by the patient is related to the resistance or the help that the robot can apply along the path of the rehabilitation exercise. So, the higher the resistance, the greater the forces that must be able to be applied to the end-effector. Also, in this case, the mechanisms used for end-effector robot solutions still focus on motion trajectories for tailored exercises with limited customization.

The intrinsically safe collaborative robots, namely Cobots, applied as rehabilitative mates for post-operative therapies represent an interesting advance from the aforementioned devices that enables more effective approaches. Research activities demonstrate the feasibility of the Cobot mate to recover the mobility of upper and lower limbs [11, 24] and available commercial solutions reinforce this achievement, such as the system ROBERT® by Life Science Robotics [20]. A recent survey expresses positive feedback about the adoption of collaborative interaction with robots for assisted training on upper limb function [18]. The main benefit of the adoption of Cobots is the integrated sensing system for a controlled force exchange with human beings, that can be configured for specific tasks. Repetitive high-quality movements can be produced, enabling an increased intensity of the rehabilitation action. The internal sensors of the Cobot can be also exploited to return objective data to evaluate the progress of the patient's mobility, which itself can change the interaction by altering the control parameters of robot motion [17]. Consequently, the monitored interaction between the Cobot and the patient's limb improves the efficiency of the therapeutic action [1, 13]. Through tailored end-effectors attached to Cobot extremal flange and programmed paths, a large variety of exercises can be designed for the therapist to choose from. Additive manufacturing technology can help to this aim by shaping the end-effector like the object to be manipulated by the patient in everyday life. Thus, the exercise assumes tangible significance over the physical action by further motivating the execution of rehabilitative action. Therefore, the use of Cobots and customized end-effectors strengthen the two main actors of the rehabilitative action; the therapist gathers objective data to evaluate residual mobility and thus define the exercises necessary for expected recovery; the patient performs exercises tailored to the mobility to be restored thanks to the integration of tailored objects to mimic the everyday action to retrieve. Nevertheless, dedicated approaches are required to design the proper rehabilitative setup. Interesting proposals arise from the literature [4, 6] but general design procedures that support the engineer with the definition of Cobot based layouts and the integration with other technologies are still missing. By choosing a Cobot to perform rehabilitation tasks, the main issues are related to their limited payload and the low stiffness, which change within the workspace. Consequently, the actual upper bound for the interaction forces is strictly related to the joint configuration. So, there are areas of the space in which the patient can apply a higher force during the rehab training and areas in which for the same level of the external forces, the joint torques overcome the safety thresholds. This issue leads to the need of optimizing the Cobot/patient layout in order to identify the best areas of the operative space where the exercise can be performed and drives the design of end-effector to be mounted on the terminal flange according to the specific rehabilitation task.

With this work, the Authors suggested an integrated design approach to identify the best configuration for Cobot assisted rehabilitation settings. More in detail, the topic of workspace design is addressed. As suggested by the work of Chiriatti et al. [3], the manipulability index can be used to evaluate and design the best limb/Cobot configuration. Here the manipulability index is adopted to return an objective assessment of i) best configuration of Cobot from wrist flange orientation; ii) manipulability of the whole trajectory to identify the best location within the workplace. To validate the theoretical results of the optimization process the proposed methodology is applied to a reference trajectory required for a representative exercise, that has been located in different areas within the operative space of the Cobot. To present the first achievements of this study the next sections of the paper are organized as follows. The design methodology and the tools used for the implementation are presented in section 2. The use case for the validation of the method is presented in section 3 while the related results are collected in section 4. Conclusive remarks close the paper.

2 DESIGN METHODOLOGY

The effective adoption of Cobotic solutions for rehabilitation purposes needs a dedicated approach to drive the design according to the needs from the therapist and the patient. Therapist needs are for a tool that should be easily reconfigurable for different exercises with a limited effort and knowledge to manage Cobot technologies. The patient should feel comfortable and motivated by adopting objects of daily use while using the Cobot system. To translate these needs into technical specifications to drive the selection of components and arrangement of Cobot workspace, the design approach embodies the steps linked as the flow presented in Fig. 1.

The first step, namely *"Exercise constraints"*, identifies the design boundaries related to the exercise conceived by the therapist. By focusing on the activity to reinforce and related object to handle, the type of grip and the posture of the patient are identified as well as the characteristics of the trajectory that limb should travel, such as shape and width. These geometrical characteristics bring to the second step *"Technical specification"* that is related to identification of the technical requirements that the robot environment should satisfy, such as the dimension of the volume requested to execute the trajectory and a first approximation of the interaction forces; for example, the type of grip and type of trajectory respectively identify the direction along which the patient will constrain the Cobot end and the sub-zone where the trajectory lies on. These data drive the selection of the Cobot that has a large enough workspace and the appropriate payload, which is the third step *"Cobot choice"*. Merging the input from steps 1 and 3 it is possible to develop the step *"Preliminary layout"* to get an evaluation of the overall dimensions of the area for the Cobot and the relative position of the patient while executing the exercises.

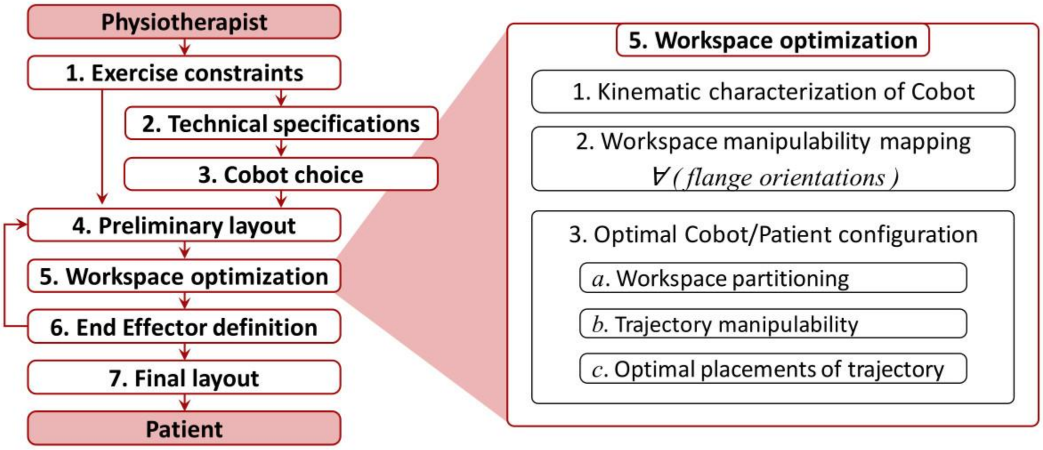


Figure 1: Design methodology for Cobot assisted rehabilitation solution.

This phase enables the subsequent *"Workspace optimization"* where to assess the performances of the Cobot selected and identify the configuration that optimizes the assisted rehabilitation. A novel approach here is proposed by the author based on manipulability ellipsoids to derive indexes to map this property along the Cobot workspace as well as for the trajectory selected in the first step. As a result, it is possible to automate the identification of workspace optimal areas in which the interaction forces at the robot terminal are the highest within the Cobot range. Subsequently, given the flange orientation and the direction of the grip, the *"End Effector definition"* phase, step 6, receive the constraints to shape the structure to connect the Cobot end, the flange, to the object to manipulate. The advantages of Additive Manufacturing enable the adoption of Topology Optimization to identify the shape with the lowest weight and expected strength. Now, experimental tests with the user can provide a realistic assessment of the usability of the proposed solution. In the case of drawbacks, the preliminary layout can be adjusted by evaluating again the placing of the Cobot. Conversely, *"Final layout"* step returns the setup of the collaborative solution for the rehabilitation.

2.1 Workspace Placement of Motion Trajectories

In the initial stages of the rehabilitation, the patient barely manages to maintain his arm up in a certain position. So, the Cobot must sustain all the weight of its limb almost by itself. Moreover, depending on the anatomical characteristics of the patient, the Cobot should also be able to apply a higher or lower force at the end-effector without reaching its torque limits. Nevertheless, to comply with limited energy exchanges in case of unexpected contact the Cobots have a limited payload. Moreover, the same load applied to the Cobot end flange returns different forces and torques as the joints configuration change. Consequently, the design process should identify those areas of the workspace and the configuration in which the interaction forces are far from the limits of the Cobot, to exploit all the range of payload available to withstand changing behaviour by the progress of the rehabilitative program. Within the *"Workspace optimization"* step for the proposed methodology, for the selected Cobot the kinematic chain is represented through the Denavit-Hartenberg (DH) parameters.

The coordinate systems of each link are related to the serial structure by means of these parameters. Specific to this approach, the adoption of DH modified method [19] identifies, in a systematic way, the coordinate frames of each link and calculate the homogeneous transformation matrices between two consecutive frames. By multiplying the homogeneous transformation matrices from the base frame to the tool frame, the pose of the end-effector with respect to the base frame is calculated. In this way the expression of the direct kinematic of the Cobot is firstly addressed by the step *"Kinematic characterization of Cobot"*. The subsequent *"Workspace manipulability mapping"* returns the robot capabilities in the task space to exert forces.

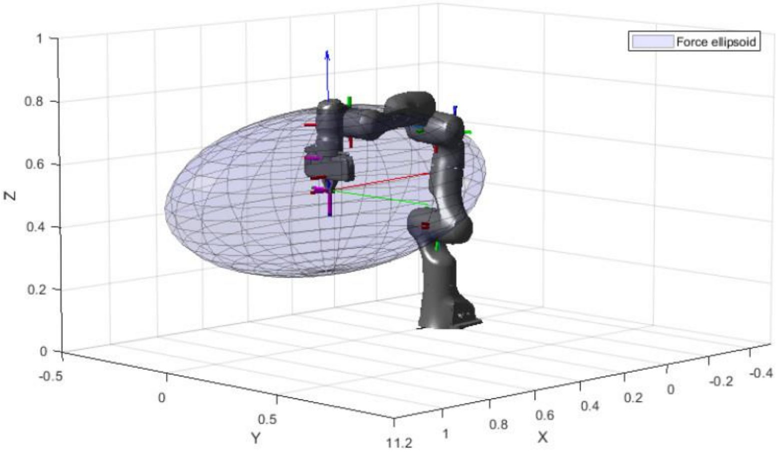


Figure 2: Graphical representation of force manipulability ellipsoid.

This method adopts different scalar indices related to the concept of force manipulability ellipsoid [21] that provides a graphical indication about the direction along which the interaction force can be higher (Fig. 2). The more the ellipsoid is close to a sphere, the more manipulator will respond in an isotropic way to the external forces. Force ellipsoids can be easily computed, and they make it possible to define manipulability measures related to robot volume [25]. The index used to evaluate ellipsoids is the manipulability index, m, defined as:

$$m(\vartheta) = \sqrt{\det\left(J(\vartheta)J^T(\vartheta)\right)} \tag{2.1}$$

Given its definition, m depends on the configuration of the robot joints (ϑ) and its geometric Jacobian (J). It is a scalar value useful to map the workspace, that assume always positive values except for the case in which the manipulator is in a singular configuration ($m = 0$). Physically it represents the distance from singularity positions in which high forces cannot be applied at the end flange because the joint torques increase too much causing the robot to stop during the interaction. Consequently, the workspace can be discretized with a finite number of points. For each of them, ϑ is calculated by means of the inverse kinematic. Subsequently, the related J is calculated as well. A four-dimension set of data are collected for each of the mapped points in which the first three dimensions express the cartesian position of the selected point (x, y, z) while the fourth dimension specifies the value of the manipulability index m. For each feasible pose of the end-effector the related map is calculated and the one with higher values of manipulability is selected for further analysis. The last step named *"Optimal Cobot/Patient configuration"* focuses on the best manipulability map to identify the optimal placement of the selected trajectory. The data map is broken down into sub-zones that are wide enough to embody the trajectory bounds, derived by its length and space orientation. On each sub-zone, for a discrete number of points that relies on the trajectory the manipulability index is calculated and the minimum value m_{min} is assumed to weight the trajectory. For a given sub-zone, between all the available placements the one where the trajectories assume the greater m_{min} is chosen. The optimal trajectory within the Cobot workspace and for the selected end-effector pose is identified by the parameter m_{opt}.

2.2 Computer Aided Tools

The whole approach presented relies on the adoption of innovative digital tools and manufacturing technologies. The former are Computer Aided Platforms for the design of the collaborative assisted layout. 3DExpericence© by Dassault Systèmes is the integrated Computer Aided Design Platform suggested to implement the approach. It allows to create a digital twin of the layout by embodying human, Cobot and manufacturing constraints. Consequently, Cobotics is key technology since is at the base of collaborative action. Complementary to that, Additive Manufacturing enables the customization of assisted rehabilitation toward the patient's needs, e.g., by fabricating end-effectors that mimic everyday actions.

Specific to the aim of this work, the separated environment of Matlab within the Robotic Toolbox Plug-In has been exploited for the identification of optimal placement of the trajectory according to the manipulability index, as described in Section 2.1. Beyond the development of the functions to define Cobot direct/inverse kinematics from DH parameters and compute $m(\vartheta)$ on the workspace, it enables a graphical representation that helps the designer to identify the relative location between Cobot and the optimal placement of the trajectory. It exploits the URDF, Unified Robot Description Format, to build the 3D model of the Cobot and the auxiliary devices directly in Matlab. Following XML specification, the geometrical and dynamical characteristics of the Cobot joints and links as well as the visual and collision properties are modelled by importing tessellated neutral files of the bodies, e.g. the STL file format. Furthermore, it is also possible to recreate the whole layout of the station by importing the elements designed from the beforementioned 3DExperience platform. The final layout representation in Matlab allows to verify that the optimal placement of the trajectory is actually feasible with respect to patient comfort and that there aren't any obstacles for the patient in the layout.

3 METHOD VALIDATION

To prove the effectiveness of the proposed approach, the iterative procedure suggested in Sec. 2.1 has been assessed to weight two different placements of a selected trajectory related to a real rehabilitative exercise. The indexes related to the two different placements are compared to the values of joint torques from the real Cobot while performing the planned trajectory in the area suggested by the placement algorithm. The use case considered is the abduction movement for shoulder rehabilitation. The theoretical trajectory is approximated to a planar circular arc with the center in the shoulder and radius equal to the length of the arm, as depicted in the left part of Fig. 3. The Cobot selected to perform the exercise is the Panda Cobot by Franka Emika because the payload and the workspace dimensions are compatible to force exchange and trajectory encumbrance. The central and right areas of Fig. 3 provide the dimensions of the theoretical workspace of the Cobot. The URDF model of Panda Cobot has been imported into Matlab with the dynamic identification proposed by [9] and used to recreate the virtual layout in the Matlab environment, see Fig. 4a. Through the solver available in the Matlab Robotics Toolbox (Generalized Inverse Kinematics), the direct kinematic is completely defined and the inverse kinematic is performed.

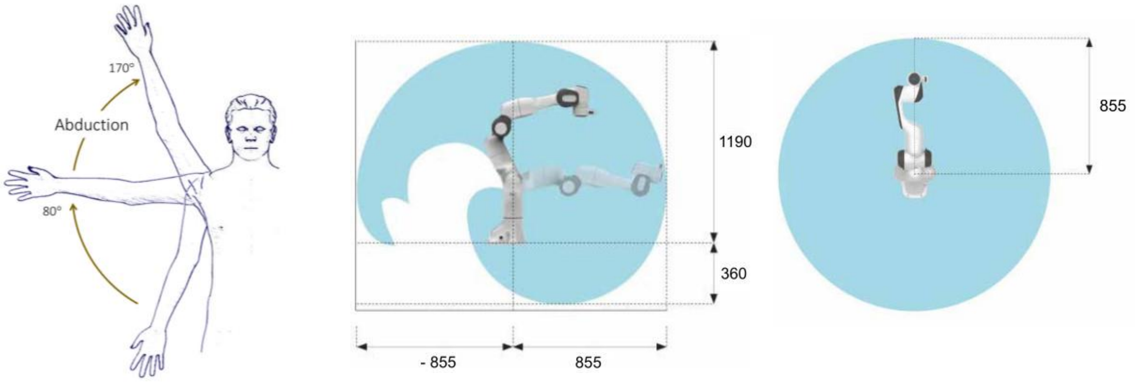


Figure 3: On the left, the selected rehabilitation exercise, abduction of the arm; on the right, workspace dimensions of Franka Emika Panda Cobot.

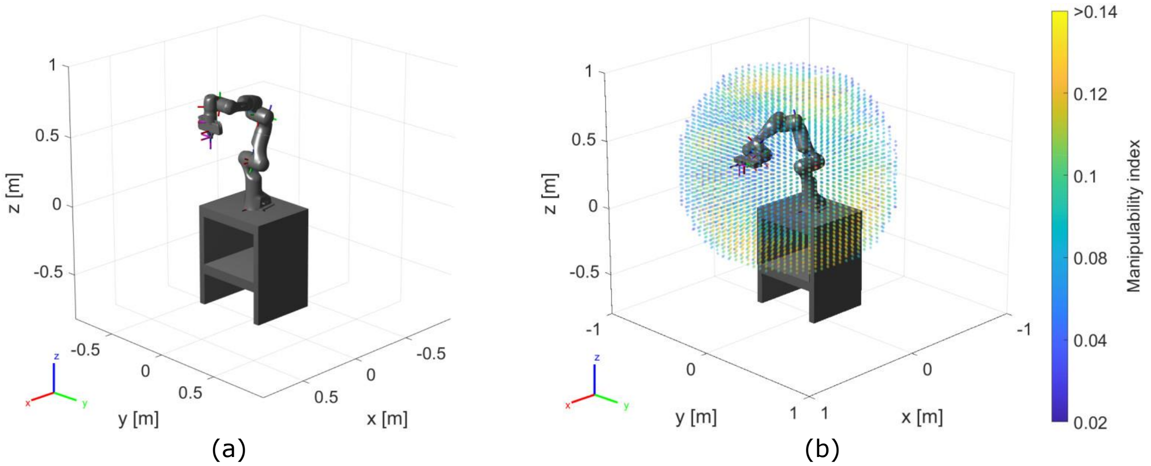


Figure 4: The virtual layout in the Matlab environment (a) and the manipulability map for the selected orientation of the end-effector, R_e^0.

Applying the equation 2.1, the workspace mapping has been recreated with a scale of colors to the values of m to have a 3D representation of the map for a fixed orientation of the end-effector. This procedure is performed for each feasible flange orientation to obtain the associated map. Figure 4b depicts the manipulability map related to the orientation $R_e^0 = (0\ \ 0\ \ 1,\ 0\ \ 1\ \ 0,\ -1\ \ 0\ \ 0)$, that has been selected for this use case.

This data map is broken down into sub-zones wide enough to encase the trajectory. Here, sub-zones are section planes since the trajectory lies on a planar surface. The range of section planes is further limited to those where the patient can perform the exercise outside encumbrances of the objects included in the collaborative layout, e.g. the bench where the Cobot is fixed (Fig. 5a). Comparing the value $m(\vartheta)$ assumed by the largest number of points, the section plane that may contain the trajectories with the highest manipulability is identified among others (Fig. 5b). A reference frame placed on the center of planar circular arc is used to place the trajectory with respect to base frame of the Cobot. Distances (x, y) and angle (β) are the three parameters used to set iterative calculation of m_{min} for each trajectory within the selected plane. Specifically, m_{min} is a local value related to a given location that represents the minimum value of the manipulability index between each point belonging to the selected trajectory. Conversely, m_{opt} is a global value that identifies the trajectory characterized by the highest m_{min}. Figure 5d returns the final position of the trajectory while Fig. 5e provides the final layout configuration for the selected exercise

3.1 Experimental Setup

To demonstrate that the placement of the chosen trajectory within the workspace of the Cobot is the optimal one as determined by the suggested approach, one further location of the trajectory in a different area is compared.

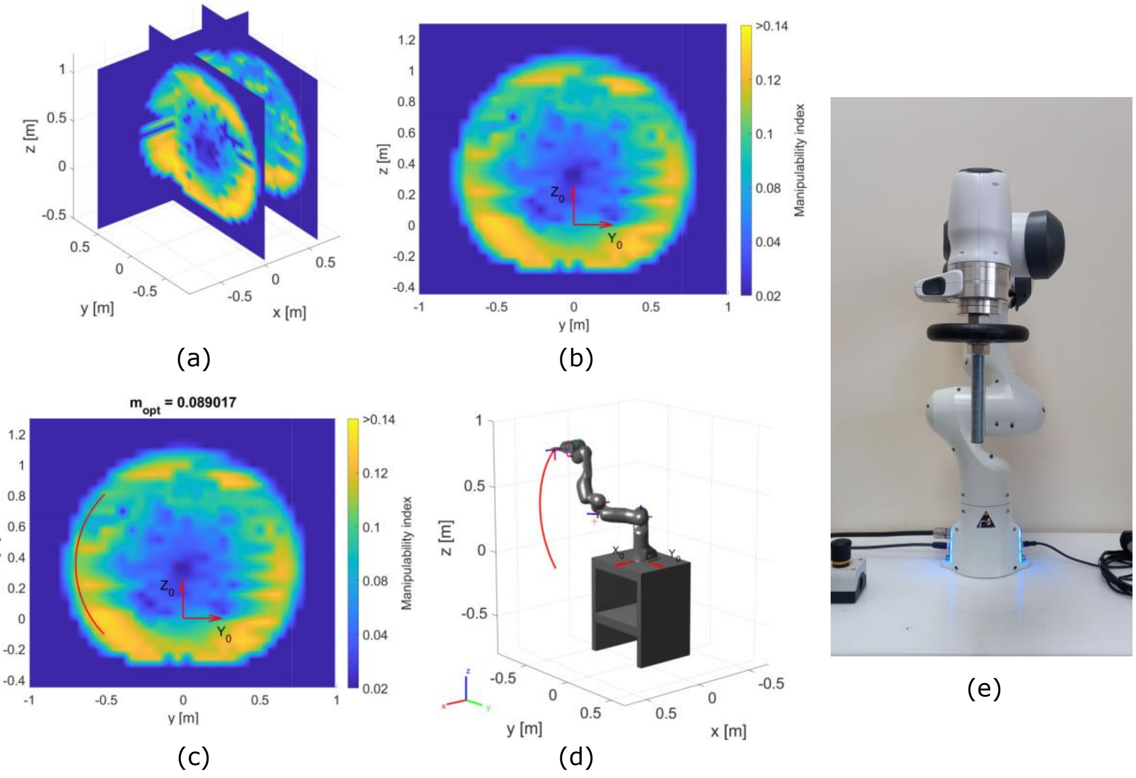


Figure 5: Slice planes of the manipulability data (a), selection of the best plane (b), the optimal position of the trajectory (c), the final layout (d), the experimental setup (e).

The same external forces are applied to evaluate the "effort" sustained by the Cobot in terms of torques at the joints. To perform the experimental tests the Panda robot of Franka Emika has been used. It is a collaborative robot with workspace dimensions shown in Fig. 3 and a payload of 3 kg. A demonstrative end effector with known weight and geometrical characteristics is designed and applied to the Cobot end flange, to allow the repeatability of the exercise (Fig. 5c). Moreover, the pose for the end-effector is selected to exert an external force whose direction remains constant along the z axis during the execution of the trajectory. To enable interaction with the patient, a dedicated controller that adopts a dynamic model that constrains the end-effector to move within a predefined path is developed. This dynamic model is based on an admittance model that receives the forces exerted by the patient on entry and returns the position of the terminal. Such position data is sent as input to the position control system with gravity compensation that generates the torque data. This data is then sent to the torque controller of the robot which implements the desired dynamics of the robot. The control architecture is detailed in a separate work by the same Authors [16]. To make the end-effector move forth and back along the trajectory, a sinusoidal forcing that keeps tangential to the constraint curve was applied in the dynamic model. The amplitude (1 N) and the frequency (0.3 rad/s) have been chosen in such a way that the speed along the trajectory is comparable to that of a patient who performs the rehabilitation exercise. The tests carried out on the exercise trajectory are two:

- the first considering the optimal positioning of the curve, obtained from the analysis of the workspace (Fig. 6a and Fig. 6b),
- the second by moving the trajectory to an area of the workspace with a low manipulability index to evaluate the behavior of the robot and, therefore, check the usefulness of the analysis method (Fig. 6c and Fig. 6d).

To properly evaluate the relation between the manipulability index and the position of the two trajectories, the external torques of the joints, τ_i , are considered to characterize and compare the two configurations of the Cobot, respectively named Low Manipulability Configuration, LM_{cfg} and High Manipulability configuration, HM_{cfg}.

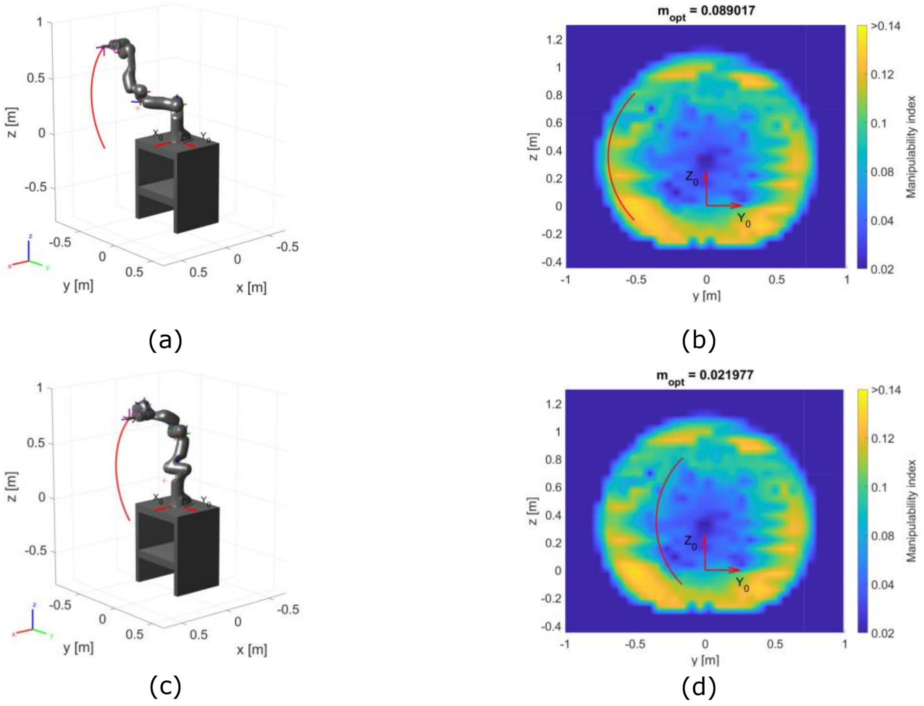


Figure 6: Trajectory placement with high (a, b) and low (c, d) manipulability index.

3.2 Results

The FCI (Franka Control Interface) [7] of the robot allows to directly read the torque signals thanks to the sensors that are installed in each joint. The values of τ_i for each Cobot joints, $i = \{1,2,3,4,5,6,7\}$ are reported in Fig. 7. The left column relates to LM_{cfg}, while the right column to HM_{cfg}. The torque trends for LM_{cfg} are very irregular with peaks that are higher than the HM_{cfg} case. From a practical point of view, where the torque signal begins to swing the manipulator begins to vibrate and becomes unstable.

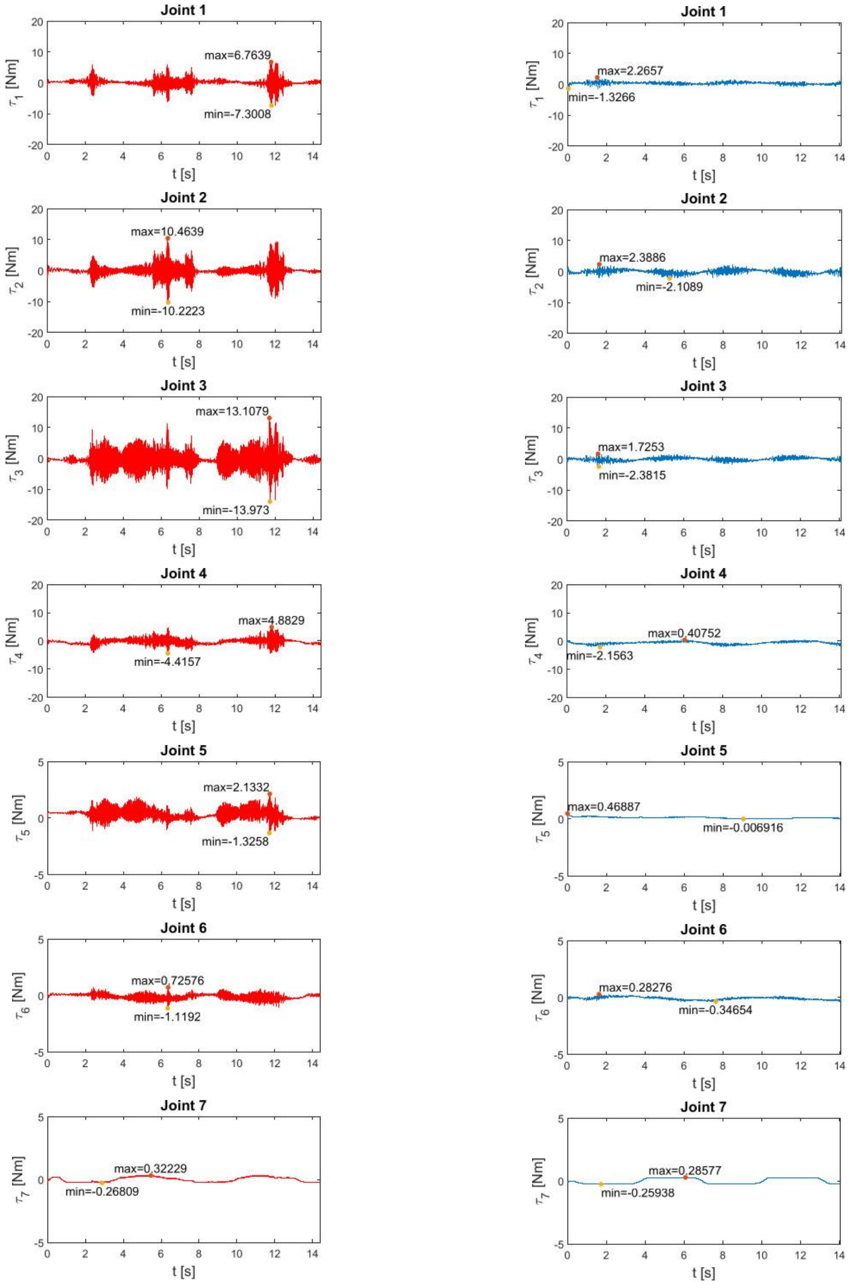
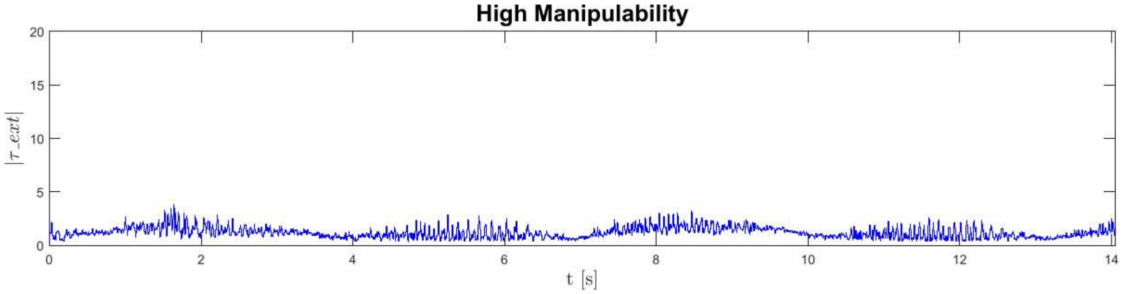
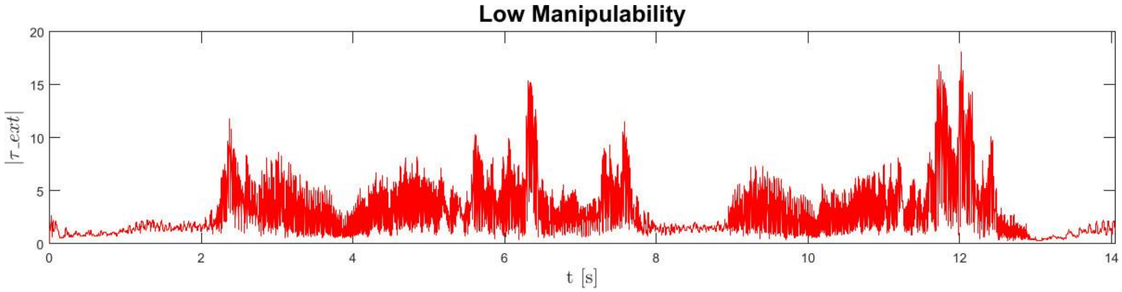


Figure 7: External torques trends at each joint: LM_{cfg} and HM_{cfg} respectively on the left and right column.

Furthermore, the comparison between the norm of the external torques returns a clear difference in the signal amplitude between the two trajectories. Figure 8 collects the plots for LM_{cfg} and HM_{cfg} on the top and bottom row, respectively. Consequently, it is possible to confirm that a higher manipulability index returns a stable behavior of the Cobot along the selected trajectory. In this way, the exercise can be carried out with better fluency and with a wider range of forces that the patient can apply at the end-effector.



(a)



(b)

Figure 8: Trends of the norm of the external torques on the Cobot joints.

4 CONCLUSIONS

The present work suggests a systematic approach to design effective Cobotic solutions to assist the rehabilitation of patients affected by limited mobility on upper limbs. To prove the feasibility of the development steps proposed, it is fundamental to evaluate the Cobot capabilities against the movement requested by the therapist and to be performed by the patient. The manipulability index is suggested here as the parameter that drives the evaluation of the characteristics of the selected Cobot with respect to the effort related to rehabilitating movement. Furthermore, this parameter can be also exploited to identify which are the workspace sub-zones where the Cobot expresses better performances for the selected exercise. Consequently, this work focus on the evaluation of the effective aid on the design of Cobot assisted rehabilitation solutions by adopting the proposed index. Among the steps of the systematic approach suggested, the phase named *"Workspace placement of motion trajectories"* is specifically addressed as well as the procedure suggested to identify the optimal placement by manipulability index. To demonstrate the effectiveness of the theoretical results, dedicated experiments are performed on a demonstrative Cobotic setup. The experimental data confirms that the index proposed provides a first suggestion about the right placement of the selected trajectory. Nevertheless, the selected trajectory was a simple curve which lied on a planar surface; furthermore, other parameters can be integrated to improve the design directions. Therefore, next developments will focus on investigating other parameters as well as extend the other phases of suggested approach, such as the control logic and the integration of design for additive manufacturing applied to end-effector customization.

5 ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Occupational Therapy expert for his valuable support to the development of the work. The work is supported partly by University of Modena and Reggio Emilia though the action FARD-2022.

Marco Caramaschi, https://orcid.org/0000-0003-0189-8804
Dario Onfiani, https://orcid.org/0000-0001-6734-1094
Fabio Pini, https://orcid.org/0000-0001-9263-426X
Luigi Biagiotti, https://orcid.org/0000-0002-2343-6929
Francesco Leali, https://orcid.org/0000-0001-6621-5379

REFERENCES

[1] Bertani, R.; Melegari, C.; De Cola, M. C.; Bramanti, A.; Bramanti, P.; Calabrò, R. S.: Effects of robot-assisted upper limb rehabilitation in stroke patients: a systematic review with meta-analysis. Neurological Sciences, 38(9), 1561–1569, 2017. https://doi.org/10.1007/s10072-017-2995-5

[2] Bertomeu-Motos, A.; Blanco, A.; Badesa, F. J.; Barios, J.A.; Zollo, L.; Garcia-Aracil, N.: Human arm joints reconstruction algorithm in rehabilitation therapies assisted by end-effector robotic devices. Journal of Neuroengineering and Rehabilitation, 15(1), 1–11, 2018. https://doi.org/10.1186/s12984-018-0348-0

[3] Chiriatti, G.; Bottiglione, A.; Palmieri, G.: Manipulability optimization of a rehabilitative collaborative robotic system. Machines, 10(6), 452, 2022. https://doi.org/10.3390/machines10060452

[4] Chiriatti, G.; Palmieri, G.; Claudio, P. M.: A framework for the study of human-robot collaboration in rehabilitation practices. In Zeghloul, S., Laribi, M., Sandoval Arevalo, J. (eds) Advances in Service and Industrial Robotics. RAAD 2020. Mechanisms and Machine Science, vol. 84, 190–198. Springer, Cham, 2020. https://doi.org/10.1007/978-3-030-48989-2_21

[5] Crea, S.; Cempini, M.; Moise, M.; Baldoni, A.; Trigili, E.; Marconi, D.; Cortese, M.; Giovacchini, F.; Posteraro, F.; Vitiello, N.: A novel shoulder-elbow exoskeleton with series elastic actuators. In 2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob), 1248–1253. IEEE, 2016. https://doi.org/10.1109/BIOROB.2016.7523802

[6] Fernandes, L.; Brito, T.; Piardi, L.; Lima, J.; Leitão, P.: A real framework to apply collaborative robots in upper limb rehabilitation. In 13th International Joint Conference on Biomedical Engineering Systems and Technologies, vol. 1, 176–183. Science and Technology Publications, 2020. https://doi.org/10.5220/0009004501760183

[7] Franka control interface. https://frankaemika.github.io/docs/index.html Accessed: 2022-10-26.

[8] Gassert, R.; Dietz, V.: Rehabilitation robots for the treatment of sensorimotor deficits: a neurophysiological perspective. Journal of NeuroEngineering and Rehabilitation, 15(1), 1–15, 2018. https://doi.org/10.1186/s12984-018-0383-x

[9] Gaz, C.; Cognetti, M.; Oliva, A.; Giordano, P. R.; De Luca, A.: Dynamic identification of the Franka Emika Panda robot with retrieval of feasible parameters using penalty-based optimization. IEEE Robotics and Automation Letters, 4(4), 4147–4154, 2019. https://doi.org/10.1109/lra.2019.2931248

[10] Krebs, H.; Volpe, B.: Rehabilitation robotics. Handbook of Clinical Neurology, 110, 283–294, 2013. https://doi.org/10.1016/B978-0-444-52901-5.00023-X

[11] Kyrkjebø, E.; Laastad, M. J.; Stavdahl, Ø.: Feasibility of the UR5 industrial robot for robotic rehabilitation of the upper limbs after stroke. In 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems, 1–6. IEEE, 2018. https://doi.org/10.1109/IROS.2018.8594413

[12] Loureiro, R.; Amirabdollahian, F.; Topping, M.; Driessen, B.; Harwin, W.: Upper limb robot mediated stroke therapy-GENTLE/s approach. Autonomous Robots, 15(1), 35–51, 2003. https://doi.org/10.1023/A:1024436732030

[13] Milot, M. H.; Spencer, S. J.; Chan, V.; Allington, J. P.; Klein, J.; Chou, C.; Bobrow, J. E.; Cramer, S. C.; Reinkensmeyer, D. J.: A crossover pilot study evaluating the functional outcomes of two different types of robotic movement training in chronic stroke survivors using the arm exoskeleton BONES. Journal of Neuroengineering and Rehabilitation, 10(1), 1–12, 2013. https://doi.org/10.1186/1743-0003-10-112

[14] Nef, T.; Guidali, M.; Riener, R.: ARMin III – arm therapy exoskeleton with an ergonomic shoulder actuation. Applied Bionics and Biomechanics, 6(2), 127–142, 2009. https://doi.org/10.1080/11762320902840179

[15] Nwosu, A. C.; Sturgeon, B.; McGlinchey, T.; Goodwin, C. D.; Behera, A.; Mason, S.; Stanley, S.; Payne, T. R.: Robotic technology for palliative and supportive care: Strengths, weaknesses, opportunities and threats. Palliative Medicine, 33(8), 1106–1113, 2019. https://doi.org/10.1177/0269216319857628

[16] Onfiani, D.; Caramaschi, M.; Biagiotti, L.; Pini, F.: Control of human-robot interaction for training during upper limb rehabilitation. "Submitted for publication"".

[17] Qian, Z.; Bi, Z.: Recent development of rehabilitation robots. Advances in Mechanical Engineering, 7(2), 563062, 2015. https://doi.org/10.1155/2014/563062

[18] Qingming, Q.; Yingnan, L.; Zhijie, H.; Jianghong, F.; Fei, Z.; Zewu, J.; Fengxian, G.; Jie, J.: The effect of applying robot-assisted task-oriented training using human-robot collaborative interaction force control technology on upper limb function in stroke patients: Preliminary findings. BioMed Research International, 2021(9916492), 8, 2021. https://doi.org/10.1155/2021/9916492

[19] Reddy, A. C.: Difference between Denavit-Hartenberg (D-H) classical and modified conventions for forward kinematics of robots with case study. In International Conference on Advanced Materials and manufacturing Technologies (AMMT), 267–286. JNTUH College of Engineering Hyderabad Chandigarh, India, 2014. http://dx.doi.org/10.13140/2.1.2012.9607

[20] ROBERT® - Life Science Robotics. https://www.lifescience-robotics.com/meet-robert/. Accessed: 2022-08-05.

[21] Siciliano, B.; Sciavicco, L.; Villani, L.; Oriolo, G.: Robotics: Modelling, Planning and Control. Springer London, 2009. https://doi.org/10.1007/978-1-84628-642-1

[22] Sugar, T. G.; He, J.; Koeneman, E. J.; Koeneman, J. B.; Herman, R.; Huang, H.; Schultz, R. S.; Herring, D.; Wanberg, J.; Balasubramanian, S.; Swenson, P.; Ward J. A.: Design and control of RUPERT: a device for robotic upper extremity repetitive therapy. IEEE transactions on neural systems and rehabilitation engineering, 15(3), 336–346, 2007. https://doi.org/10.1109/TNSRE.2007.903903

[23] Toth, A.; Nyitrai, D.; Jurak, M.; Merksz, I.; Fazekas, G.; Denes, Z.: Safe robot therapy: Adaptation and usability test of a three-position enabling device for use in robot mediated physical therapy of stroke. In 2009 IEEE International Conference on Rehabilitation Robotics, 940–945. IEEE, 2009. https://doi.org/10.1109/ICORR.2009.5209481

[24] Tucan, P.; Ulinici, I.; Pop, N.; Puskas, F.; Carbone, G.; Gherman, B.; Luchian, I.; Pisla, D.: Ankle rehabilitation of stroke survivors using Kuka LBR Iiwa. In Rauter, G., Cattin, P.C., Zam, A., Riener, R., Carbone, G., Pisla, D. (eds) New Trends in Medical and Service Robotics. MESROB 2020. Mechanisms and Machine Science, 29–36. Springer, Cham, 2021. https://doi.org/10.1007/978-3-030-58104-6_4

[25] Yoshikawa, T.: Manipulability of robotic mechanisms. The international journal of Robotics Research, 4(2), 3–9, 1985. [26] Zhang, L.; Guo, S.; Sun, Q.: Development and assist-as-needed control of an end-effector upper limb rehabilitation robot. Applied Sciences, 10(19), 6684, 2020. https://doi.org/10.1177/027836498500400201