# Cooperation or collaboration? On a human-inspired impedance strategy in a human-robot co-manipulation task

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# Cooperation or collaboration? On a human-inspired impedance strategy in a human-robot co-manipulation task

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*Abstract*— We investigate whether a robot should behave as a collaborator or as a cooperator of a human partner in a co-manipulation task. In a previous study, we addressed the same question for a human-human dyad and found that collaboration is preferable to make fewer errors at the expense of increased arm stiffness for the humans, who behave as if they were both leaders. In this study, the human is coupled with a Franka robot and they jointly engage in the same co-manipulation task in different conditions. In the cooperation conditions, the robot is either a leader or a follower, exhibiting fixed impedance strategies. In the collaborative conditions, the robot exhibits either reciprocal or mirrored adaptive impedance strategies that vary according to an EMG-based online estimation of the human arm stiffness. Our results show that, for the co-manipulation task, a robot collaborator seems more preferable than a robot cooperator, leader or follower, and that the reciprocal strategy for impedance seems to be the most indicated.

## I. INTRODUCTION

Robotics solutions have the potential to improve the working conditions of human operators in industry [1]. Thanks to improved sensing and control, robotic manipulators can physically interact with human operators, not only sharing the same workspace but also providing physical assistance to reduce the human physical workload [2]. However, it has been pointed out that the acceptance of collaborative manipulators may not be straightforward for human workers [3], [4]: in particular, it could be easier to interact with a robot that has a fixed role in the interaction, rather than with a robot with more complex behavior. This preference may not necessarily relate to better performance in task execution. This observation led to the current investigation of whether it is more convenient or efficient for a human to cooperate or collaborate with a robot to execute a co-manipulation task, and whether this behavior has any relation with the way two humans cooperate or collaborate to solve the same task.

We adopt the distinction between cooperation and collaboration as defined by Jarrassé et al. [5]. If before the co-manipulation, the agents have been assigned, or have agreed upon, different roles (asymmetric responsibilities) to execute the task, then the interaction is classified as a *cooperation*.

In contrast, during a *collaboration*, both agents form a "spontaneous" coalition to accomplish the task [6]: their "activity is synchronized and coordinated in order to build and maintain a shared conception of a problem" [7]. That is, in collaboration, the agents may deliberate and negotiate their roles in executing the task to accomplish the dyad's common goal. A typical example of cooperation happens when the agents have leader-follower roles. In co-manipulation, this is usually characterized by high stiffness profiles for the leader's arm endpoint, and low stiffness for the follower's [8]. It is frequent to find this configuration in rehabilitation robotics, for example, when robotic arms (leaders) guide the patients' arms (followers) along desired trajectories [9]. Between the two extreme roles and corresponding stiffness values, there is a continuous range of stiffness values that can be exploited to obtain more stiff or more compliant behaviors: for this reason, previous work investigated how to adapt the arm stiffness (and the corresponding impedance) in this range to implement adaptive compliant behaviors in robotic arms [10]. Other research on tele-impedance [11], shared control [12] and co-manipulation [13], [14] confirms that an adaptive stiffness behavior determines the performance of a human-robot collaboration.

In this paper, we focus on a human-robot co-manipulation task where an object has to be carefully extracted from a tube and inserted into another one, without making contacts. This task requires precision, and we expect the stiffness of each agent to be critical to reject disturbances that may lead to task failure. In this context, we ask the following questions: is it more efficient and task-performing for the dyad to cooperate or to collaborate? When collaborating, should the robot behave as a human collaborator? Among the possible collaboration strategies, should the robot imitate or reciprocate the human's stiffness behavior?

To answer these questions, we conducted a human-robot co-manipulation study in the same experimental setup/scenario of a prior analog study [15] where we investigated the performance and the arm stiffness of human-human dyads when they were cooperating and collaborating. Dyads were more accurate (i.e., fewer task errors) when there was no clear role allocation (i.e., when they were collaborating) at the expense of a higher effort. Indeed, during collaboration, both human partners had similarly high levels of arm muscle co-contraction, therefore, higher levels of arm stiffness, as if they were both leaders. This study showed that collaborating humans mirror their stiffness: could this be a legitimate collaborative strategy also for a robotic collaborator?

In the human-robot study, we investigated the performance

and arm stiffness of the human interacting with a robot (Franka) when the dyad is cooperating and collaborating, across four conditions. In cooperative conditions, the robot is either leader or follower, and vice-versa for the human. In the collaborative conditions, we implemented two possible collaborative impedance strategies: the first, inspired by the previous study, mirrors the human stiffness, while the second, inspired by [16], reciprocates the human stiffness.

Our human-robot study confirmed that in co-manipulation it is more convenient to collaborate because collaboration leads to fewer task errors. Both collaborative impedance strategies give similar results in terms of human effort (i.e., arm muscle co-contraction), however subjective evaluations indicate a clear preference of the human participants for the reciprocal impedance strategy.

In this paper, we briefly overview the first study and report on the methodology and results of the second study, discussing the implications of the results for future collaborative robotics technologies.

## II. RELATED WORK

Human-robot cooperation is often formalized by fixed roles determined by coordination between the agents. Typically, fixed roles such as leader and follower are determined by the endpoint impedance. The leader-follower role allocation approach in which the human is always the leader of the task is likely the most traditional coordination strategy in physical Human-Robot Interaction (pHRI) [17]. In this case, the robot may be controlled to guarantee only certain aspects of the task execution, such as rejecting disturbances, or sustaining forces and positions in different axes from the ones controlled by the human [18]. Ficuciello *et al.* [19] uses a more sophisticated strategy that explores the null-space of a redundant robot to decouple the apparent inertia at the robot end-effector, reportedly improving the intuitiveness of the task for the leader. Even though the leader-follower approach meets great success in some applications such as robotic surgery [20], [21], and telemanipulation, there are instances in which adaptive or continuous roles could be preferred [22]. Cherubini *et al.* [14] alternates the leader and follower roles of a robot in a pHRI application for industry according to visual and haptic cues by the human co-worker. Khoramshahi and Billard [23] propose a method to automatically detect when the human co-worker is physically trying to guide a robot that is executing an autonomous task. After the intent detection, the robot switches into a follower mode, and only goes back to leader mode when the human stops correcting the robot. Agravante *et al.* [24] interpolate between a humanoid robot's behavior from a total leader to a total follower (each behavior corresponds to a different walking pattern generator to the humanoid robot). During the leader behavior, the robot controller minimizes the errors for the desired trajectory (high-impedance), whereas for the follower behavior it minimizes the forces applied at the human operator (low-impedance).

Therefore, in the literature, it is often the case that either the roles are fixed (cooperation) or they are adapted according to a strategy (collaboration). However, to the best of our knowledge, little is known about the effect of the two approaches on the same joint task, to inform about the best strategy to adopt for humans. In this work, we compare both approaches in the same co-manipulation task, having in mind the outcome of a previous study that investigated human cooperative and collaborative behavior in the same task/scenario. Our rationale is that if collaboration is preferable for a joint task realized by a human dyad, there is a possibility that it would be preferable also for human-robot interaction in joint tasks. At the same time, we are aware that a robot cannot fully reproduce complex human behavior. We target the question of which impedance behavior the robot should exhibit to collaborate proficiently and whether this behavior should imitate the one of a human partner.

Transferable impedance from human signals to robot behavior is often referred to in the literature as *tele-impedance* [11]. Here, we use an index of co-contraction (Sec. IV-A.4) to estimate the modulation of human stiffness, and consequently, our tele-impedance profiles (Sec. IV-B). Peternel *et al.* [25] proposed a method for human-robot collaboration where the robot behavior is adapted online to the human motor fatigue. The same authors presented in [16] two control strategies (robot reciprocal and robot mirrored) based on the concept of tele-impedance. During Reciprocal tele-impedance the robot and the human operator execute two behaviors that are reciprocal in terms of phase of operation (e.g. sawing task). On the other side, during mirrored tele-impedance, both agents produce the same behavior in a certain phase of the task (e.g. valve turning). Their work led us to question whether this kind of adaptation could in any way be traced back to the collaboration observed during the human-human experiment.

## III. BACKGROUND: HUMAN-HUMAN DYAD EXPERIMENT

Previously [15], we proposed an experiment with a task executed by two physically interacting human partners, i.e. a human-human dyad (Fig. 1a). The participants executed the task under two main conditions: *Cooperative*: Agent 1 is assigned the leadership while Agent 2 is the follower and vice-versa; *Collaborative*: there is no pre-assigned leadership. During the task execution, we measured the participant's muscle activation, as well as their accuracy at executing the task for each trial. The human-human dyads made fewer errors without pre-assigned roles than when there was a leader. In addition, we observed that when there was no pre-assigned leader, the agents had a muscle co-contraction level as high as when they were leaders of the task. Since muscle co-contraction is associated with arm stiffness, we hypothesize here that robots similarly modulating their impedance could emulate the aforementioned human motor behavior.

## IV. METHODS

To investigate how human-human dyads' motor behavior transfers to human-robot dyads, we conducted an experiment in which human participants performed a co-manipulation
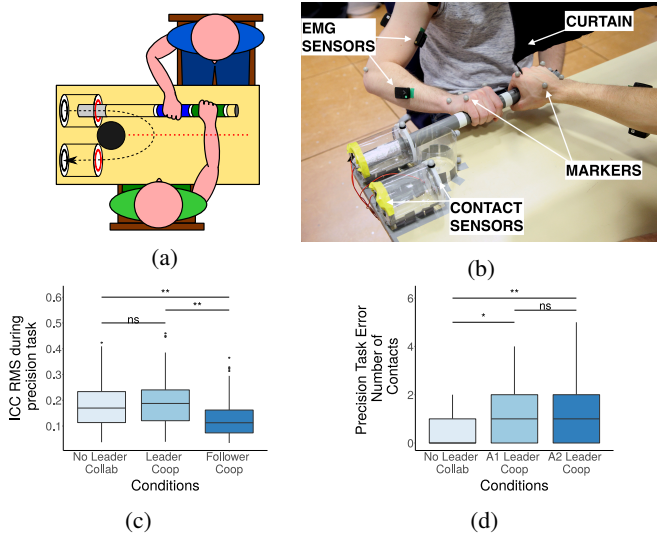
(a)

(b)

(c)

(d)

Fig. 1: Human-Human co-manipulation study [15]: (a) Top-down view of the experiment set-up. The black dashed line approximates the pipe trajectory. The red circles are contact sensors used to detect any contact between the pipe and the tubes' front walls. The red dashed line represents a curtain placed between both agents to prevent visual eye-to-eye communication. (b) Experimental set-up. (c) Root Mean Square value of the index of co-contraction (ICC) during the extraction and insertion phases, for each condition. (d) Number of contact between the pipe and the tubes' walls (errors), for each condition.

task with a robot under different conditions. Namely, four profiles were defined for the robot end-effector impedance, to implement *cooperation* and *collaboration* conditions. The experiment is detailed hereafter.
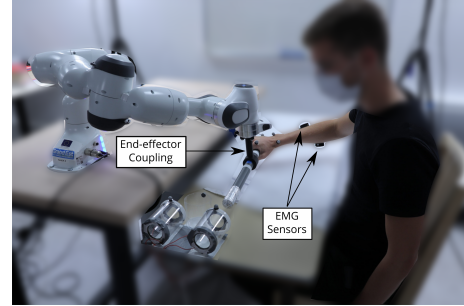
### A. Experimental set-up

*1) Task description:* The task consisted in co-manipulating an object ($0.2\,kg$ pipe of diameter $3\,cm$ and length $50\,cm$) with a collaborative robot, in order to bring it from a start to an end point (Fig. 2). The task was divided into 3 phases. In phase 1 the pipe is within a tube (tube 1, close to the robot) and is extracted from it while avoiding contact with its front wall (hole diameter: $4.5\,cm$). In phase 2, the pipe is moved in free space in a horizontal plane, from tube 1 to tube 2, around a cylindrical obstacle. In phase 3, the pipe is inserted in a second tube (tube 2, close to the human) while avoiding contact with its front wall. The return motion (from tube 2 to tube 1) was not part of the task. Performing the task once took between 15 and $25\,s$ on average, though there was no time instruction or limit. Participants were seated on a chair facing the robot and were instructed to avoid moving their backs during the task. They held the pipe with their right hand, on the designated handle, while the other handle was attached to the robot end-effector with a dedicated 3D-printed part.

*2) Participants:* Twelve healthy adults took part in the experiment (4 females and 8 males, aged 24–55). All par-
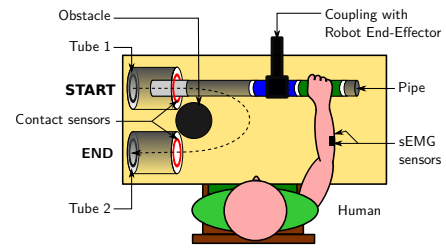


(a) Top-down view. The dashed line shows the pipe trajectory.



(b) A participant performing the task with the Franka Emika robot.

Fig. 2: Experimental set-up for the human-robot co-manipulation study.

ticipants performed the task with their right dominant hand. Participants were naive to the purpose of the study, and none reported any chronic motor disease or health condition that could influence the results. Participants signed an informed consent form before starting the experiment. The study was approved by INRIA's ethical committee COERLE and was conducted in accordance with the Declaration of Helsinki.

*3) Experimental design:* Each participant performed the task in 4 different conditions, corresponding to different impedance behaviors of the robot (detailed in section IV-B):

- *Condition 1 – Robot Follower and Human Leader (RF):* Participants are instructed to lead the movement, while the robot is compliant to the human movement;
- *Condition 2 – Robot Leader and Human Follower (RL):* The robot leads the movement, while participants are instructed to be compliant.
- *Condition 3 – Robot Collaborator with Reciprocal Stiffness (RR):* Participants are not given any fixed role and are instructed to simply collaborate with the robot, which modulates its end-effector stiffness inversely to the human end-point stiffness.
- *Condition 4 – Robot Collaborator with Mirrored Stiffness (RM):* Participants are not given any fixed role and are instructed to simply collaborate with the robot, which modulates its end-effector stiffness proportionally to the human end-point stiffness.

According to the definition by Jarrassé *et al.* [22], conditions 1 and 2 correspond to a *cooperation* situation where the role of each agent (leader/follower) is pre-assigned, whereas conditions 3 and 4 correspond to a *collaboration* situation where agents have symmetric responsibilities.

Each participant performed 15 trials for each condition in a

block manner, for a total of 60 trials. Participants were given a $30\,s$ break between each trial, and a $5\,min$ break between each condition. Condition 1 (*robot follower*) was always performed first, as it was used to estimate scaling parameters needed for the implementation of the robot control in the two *collaboration* conditions (see Section IV-B.2). The order of the 3 remaining conditions was randomized. Before starting the actual experiment, participants performed a few practice trials in *robot follower* condition to familiarize themselves with the task and the robot.

*4) Instrumentation and performance metrics:*

*a) Human end-point stiffness:* Participants were equipped with 2 Delsys Trigno wireless sEMG sensors on antagonist muscles of their right forearm (FCU: Flexor Carpi Ulnaris and ECU: Extensor Carpi Ulnaris) to record muscle activity. EMG signals were recorded at $2\,kHz$, and filtered on-line using a $100\,ms$ RMS window followed by a low-pass 3rd order Butterworth filter with a $10\,Hz$ cutoff frequency. The filtered signal $u^k$ (for muscle $k$) was then normalized by its maximum voluntary contraction value $u^k_{MVC}$ measured before starting the experiment. Finally, a co-contraction index $icc$ was computed based on the normalized EMG value of both muscles [26], [27], that served to estimate the human end-point stiffness:

$$icc(t) = min\left(\frac{u^{FCU}(t)}{u^{FCU}_{MVC}}, \frac{u^{ECU}(t)}{u^{ECU}_{MVC}}\right). \qquad (1)$$

*b) Pipe-tube contact:* The main objective of the task was to extract/insert the pipe from/into the tubes without touching their front walls. Those walls were therefore equipped with custom contact sensors to detect contacts with the pipe. The contacts were recorded at $1\,kHz$ using a Raspberry Pi. Due to the reaction time of the human, contacts that were separated by less than $0.5\,s$ were counted as a single contact.

*c) Task duration:* Even though there was no time objective or constraint in the experiment, the task duration (between the start and end points) was monitored to evaluate the efficiency of the interaction.

*d) Questionnaires:* At the end of each experimental condition, participants were asked to fill out a questionnaire including 2 questions: *Q1: From 1 to 10, how easy was it to do the task with the robot (1=not at all easy, 10=very easy)?, Q2: From 1 to 10, how much did the robot prevent you from doing the task the way you wanted (1=much prevented, 10=not prevented at all)?* At the end of the entire experiment, participants also reported orally their preferred condition.

### B. Robot control and collaborative impedance strategies

The experiment was performed with a Franka Emika robot. The robot was controlled with an end-effector Cartesian impedance scheme, that allowed to easily implement different compliance behaviors. Let us consider the robot equation of motion: $M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau - J^\top F_{ext}$ with $M \in \mathbb{R}^{n\times n}$ the inertia matrix, $C \in \mathbb{R}^{n\times n}$ the matrix of Coriolis and centrifugal effects, $g(q) \in \mathbb{R}^n$ the vector of gravity forces, $J \in \mathbb{R}^{6\times n}$ the end-effector Jacobian, $\tau \in \mathbb{R}^n$

the joint torque vector, and the interaction wrench at the end-effector is $F_{ext} \in \mathbb{R}^6$. Using feedback linearization, $\tau$ can be computed to achieve a desired mechanical impedance at the end-effector, such that:

$$F_{ext} = K(x_{ee} - x_d) + D(\dot{x}_{ee} - \dot{x}_d) \qquad (2)$$

where $K \in \mathbb{R}^{6\times 6}$ and $D \in \mathbb{R}^{6\times 6}$ are the desired stiffness and damping matrices in Cartesian space, and $x_{ee}$ and $x_d$ are respectively the actual and desired end-effector poses. The four different robot behaviors described in section IV-A.3 were implemented by changing the values and profiles of the $K$ and $D$ matrices, as explained hereafter. Only the translational stiffness and damping were modified across conditions, whereas the rotational part remained identical.

*1) Cooperation conditions:* The two cooperation conditions (RF: *robot follower*, RL: *robot leader*) were implemented using fixed values for $K$ and $D$ throughout the entire task execution. The diagonal coefficients of $K$ were set to a low (resp. high) value in the RF (resp. RL) condition, as listed in Tab. I (all 6 coefficients have the same value). The coefficients of $D$ were computed from $K$ and the Cartesian mass matrix using factorization design [16], [28].

*2) Collaboration conditions:* The two collaboration conditions (RR: *reciprocal stiffness*, RM: *mirrored stiffness*) were defined and implemented based on the work by Peternel *et al.* [16]. In both cases, the robot Cartesian stiffness is adjusted on-line throughout the task depending on the human co-contraction index $icc$ (Eq. 1). First, the human wrist stiffness trend $c_h(t)$ is estimated from the $icc$ using a sigmoid function

$$c_h(t) = b_1 \frac{1 - e^{-b_2 icc(t)}}{1 + e^{-b_2 icc(t)}} \in [0, 1] \qquad (3)$$

where $b_1, b_2 \in \mathbb{R}$ define the amplitude and shape of $c_h$, and are determined experimentally to reflect the actual operational range of the $icc$ of a participant during the task execution.

For the *reciprocal stiffness* behavior (RR), $K$ is:

$$K(t) = K_{cte} + S\Big((1 - c_h(t))(K_{max} - K_{min}) + K_{min}\Big) \qquad (4)$$

where $S$ is a selection matrix that defines the axes where the stiffness is modulated, $K_{min}$ and $K_{max}$ contain the maximum and minimum desired stiffness for those axes, and $K_{cte}$ contains a constant stiffness for the axes that are not modulated (the numerical values of these matrices' diagonal coefficients are summarized in Tab. I). In this experiment, the translational stiffness in the horizontal plane was modulated, while the vertical translational stiffness was constant. In this condition, the robot behaves as a leader if the human is compliant, whereas it effectively cedes the autonomy of the task to the human when the human co-contracts.

For the *mirrored stiffness* behavior (RM), $K$ is:

$$K(t) = K_{cte} + S\Big(c_h(t)(K_{max} - K_{min}) + K_{min}\Big) \qquad (5)$$

In this condition, the more the human co-contracts, the higher the robot stiffness is.

| Robot role | Stiffness Profile | $K_{\min}$ $(N.m^{-1})$ | $K_{\max}$ $(N.m^{-1})$ | Reference Trajectory |
|---|---|---|---|---|
| Follower | $\boldsymbol{K} = \boldsymbol{K}_{\min}$ | 100 | - | No |
| Leader | $\boldsymbol{K} = \boldsymbol{K}_{\max}$ | - | 1000 | Yes |
| Reciprocal | $\boldsymbol{K}(t) \propto (1-c_h)$ | 100 | 1000 | Yes |
| Mirrored | $\boldsymbol{K}(t) \propto c_h$ | 100 | 1000 | Yes |

TABLE I: Definition of the robot stiffness profile and reference trajectory for the four different conditions.

*3) Robot reference trajectory:* The robot reference trajectory $\boldsymbol{x_d}$ was predefined offline for the RL, RR and RM conditions. The desired end-effector orientation and vertical position remained fixed for the entire task, while the trajectory in the horizontal plane was defined from straight lines and a parabolic curve (Fig. 2a). In the RF condition, $\boldsymbol{x_d}$ was set equal to the robot Cartesian pose at the previous timestep, which, associated with low stiffness, made the robot very compliant. The duration of the reference trajectory was tuned experimentally and set to 25 seconds, which corresponded to a comfortable pace for users.

## C. Statistical analysis

The dependent measures that were analyzed are: the RMS value over a trial of the human co-contraction index, the number of contacts between the pipe and the tubes, the duration of the task, and the score of each item in the questionnaire. The co-contraction index, task duration and number of contacts were evaluated for every single trial. To get rid of any short-term learning effect that might happen in the early trials, we calculated linear regressions between the trial number and these dependent measures to identify when participants reached steady state performance. Regressions were calculated for each of the four conditions, iteratively for the last 15, 14, 13 trials, and so forth until the slopes were not significantly different from zero (i.e. the 95 % intervals did include zero). This occurred when the regression was computed over the last 13 trials (i.e. excluding the first 2 trials). Hence, the first 2 trials of each condition were excluded from the subsequent analyses. In addition, since only steady-state performance was considered, each metric was averaged over the last 13 trials to obtain one single data point for each participant and condition.

Co-contraction index and task duration data were checked for normality with a Shapiro-Wilk test and then analyzed with a one-way repeated-measures analysis of variance (ANOVA) with *condition* as a within-subject factor and *participant* as a random factor. Pairwise multiple comparison post-hoc tests with Bonferroni corrections were conducted when a significant effect of *condition* was detected by the ANOVA. Questionnaire scores and number of contacts were analyzed with non-parametric Friedman tests given the nature of the data. Post-hoc tests were conducted when a significant effect of *condition* was detected. A significance level of 5 % was adopted for all statistical tests. Analyses were performed with the R software.
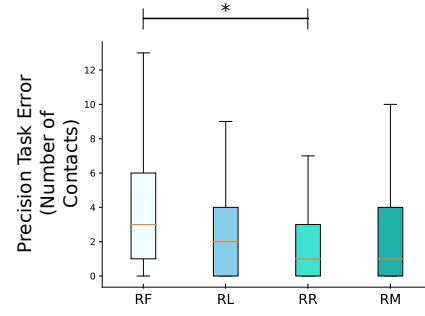
(a) Task errors (i.e., number of contacts).
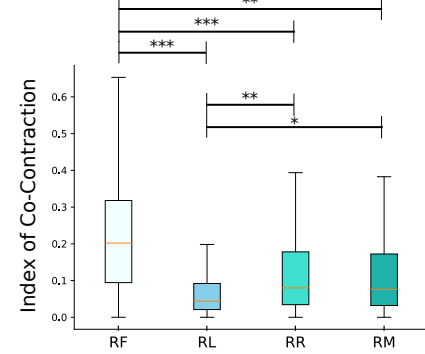
(b) ICC of the participants.
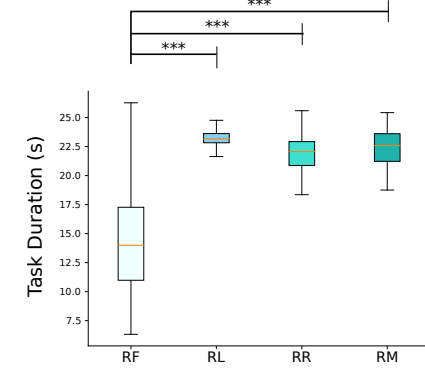
(c) Task duration.

Fig. 3: Performance metrics across the 4 conditions.

## V. RESULTS

### A. Pipe-tube contacts

Fig. 3a displays the distribution of the number of contacts between the pipe and the tubes for all 4 conditions. The Friedman test revealed a significant effect of the *condition* factor ($\chi^2(3) = 13.22$, $p = .004$). Post-hoc tests indicated a significant difference only between the RF and RR conditions ($p = .031$). The other comparisons did not reach significance, though it was close for RF and RL ($p = .066$) and RL and RM ($p = .059$). The number of contacts (errors) was the largest when the humans lead the task (RF condition) where they could not benefit from the robot position accuracy, and the smallest in the collaboration condition where the robot adopted a reciprocal behavior (RR condition).

## B. Human co-contraction index

Fig. 3b displays the distribution of the co-contraction index for all 4 conditions. The ANOVA revealed a significant effect of the *condition* factor ($F(3, 33) = 28.1$, $p < .001$) on the co-contraction index. Post-hoc test revealed a significant difference between RF and RL ($p < .001$), RF and RR ($p = .001$), RF and RM ($p = .003$), as well as between RL and RR ($p = .012$) and RL and RM ($p = .049$). Other comparisons did not reach significance level. Co-contraction was the largest when the human was leading the task (RF condition), and the smallest when the human was only following the robot (RL condition).

## C. Task duration

Fig. 3c displays the distribution of the task duration for all 4 conditions. The ANOVA revealed a significant effect of the *condition* factor ($F(1.5, 16.7) = 38.0$, $p < .001$) on the task duration. Post-hoc test revealed a significant difference between RF and the 3 other conditions ($p < .001$ for all comparisons). Other comparisons did not reach significance level. The task execution was the fastest when the human led the task (RF condition), where the timing was not constrained by the robot reference trajectory, and the slowest when the robot was the leader (RL condition).

## D. Questionnaire

Fig. 4 displays the distribution of the scores for the questionnaire. The Friedman tests revealed a significant effect of the *condition* factor for question Q1 (*How easy was it to do the task with the robot?*) ($\chi^2(3) = 15.3$, $p = .001$), but not for Q2 (*How much did the robot prevent you from doing the task the way you want?*) ($\chi^2(3) = 2.65$, $p = .44$). For Q1, post-hoc tests indicated a significant difference between RL and RF ($p = .009$) and RL and RM ($p = .005$), while the other comparisons did not reach significance. Participants felt the task was the easiest to perform when the robot lead the task (RL condition), followed by the robot reciprocal behavior (RR behavior). This result suggests that the reciprocal behavior RR was the preferred strategy among the 2 collaboration conditions (RR and RM). For Q2, trends in Fig. 4 suggest that participants had very diverse opinions on how the robot was hindering them in the 2 cooperation conditions (RF and RL), whereas the opinions were much more similar across participants in the 2 collaboration conditions (RR and RM).

## VI. DISCUSSION

In this paper, we focus on a human-robot co-manipulation task. In our previous work, we investigated the performance and the arm stiffness of human-human dyads when they were cooperating and collaborating [15]. We observed an improved performance using collaborative strategies over cooperative ones. In this context, we investigated if the same results are observable in the human-robot scenario.
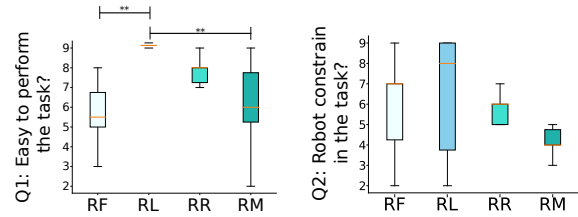


Fig. 4: Subjective evaluation: questionnaire results. Q1: 1=not at all easy, 10=very easy. Q2: 1=much prevented, 10=not prevented at all.

## A. Robot leader or Robot collaborator?

Fig. 3a reports on the task error, i.e. the number of pipe/tube contacts during the precision task. We expected the RL condition to be the most accurate in terms of task errors because the robot had a reference trajectory that could precisely accomplish the task. In this case, if the human complied with the robot's actions, without adding perturbations, then the risk of task errors would be close to zero. In the human-human experiment, the collaboration condition delivered less errors (Fig. 1d). Meanwhile, in the human-robot experiment, the two collaboration conditions result in errors comparable to the cooperation condition when the robot was the leader (RL), and fewer errors than when the robot was a follower (RF). Further, even though the distributions of RR and RM are not statistically different from the one of RL, the median of the task errors is lower in the collaboration conditions, similar to what was observed in the human-human experiment. Thus collaboration does not worsen the task performance. On the contrary, when collaborating with the robot, the human seems to benefit from its accuracy.

Fig. 3b reports on the distribution of ICC values. The highest ICC values occur when the human is the leader (RF), as expected, since it is the condition where the human makes the greatest efforts to execute the task. In addition, even if the robot is following the human in a very compliant mode, it is not entirely transparent; hence, some human effort is also needed to compensate for the lack of transparency of the robot. In the RL condition, the ICC is at its lowest: this result is coherent with the subjective feedback from the participants, who often reported that they "were just trying to relax and follow the robot" doing a minimal effort. This is also aligned with our observations in the human-human experiment. However, these low ICC levels and the subjective feedback point out a possible risk of "disengagement" from the task execution: if humans passively follow the robot across several repetitions of the task, they may risk progressively losing awareness of the task and their surroundings. Should something unexpected occur, the limited awareness decreases the chance of a prompt reaction, and at the same time the high robot stiffness of the RL condition strongly prevents the human to correct the robot or input changes in the task trajectory. The ICC values of the collaborative conditions (RR and RM) were in between RF and RL, having

the advantage of avoiding disengagement while requiring only a limited physical effort.

If we consider both the task precision and the effort, the most convenient conditions are RL and RM (no statistical difference in contact errors and weak difference in the ICC). This result is partly close to the one of the human-human experiment, where collaboration was more convenient than cooperation, at the expense of larger ICC values. However, the experimental context here is different: the human collaborators are not aware of the desired trajectory of their partner (which may vary across trials), nor do they know if it is efficient or accurate for completing the task. Conversely, in the human-robot experiment, the human participants are aware that the robot has a fixed reference trajectory that enables them to accomplish the task. In that sense, the comparison is not at equal terms, because the knowledge of the human is different in both cases. For a fair comparison, the robot should not have a reference trajectory and react to the intended human motion.[1]

We argue that giving some degree of autonomy to the human is overall positive. The human can still benefit from the robot's assistance, especially if the robot has a reference task trajectory. Furthermore, in the collaborative conditions, the robot compliance can leave the necessary degree of maneuver to the human to correct the task when needed, maintaining the task engagement, without degrading the task performance (no difference in the task errors). Additionally, the human could exploit the compliance to accelerate or decelerate the task at their convenience: indeed Fig. 3c shows a tendency to accelerate the task execution in the collaborative conditions. In fact, in the RF condition the task duration was shorter because the human could execute the task at their own pace (albeit probably "limited" by the robot). In our study, the robot reference trajectory and its duration were fixed: they were arbitrarily set to have a reasonable speed that would not challenge the participants. In future experiments, we will investigate whether conditions other than RF can enable a faster task execution and whether the cooperative or collaborative conditions enable the dyad to be faster without being detrimental to performance or effort.

### B. Preference for collaboration with reciprocal impedance strategy

Subjective evaluations suggest that it is easier to realize the task with a collaborating robot rather than with a cooperating robot. In Fig. 4, participants indicated that the task was easier to perform in the RR condition. To the question of whether the robot was interfering with executing the task in their way, participants had very variable opinions for cooperative conditions, whereas they judged that the hindrance was relatively acceptable for the collaborative conditions. This is an important element in favor of collaborative robot behaviors for industrial applications: if robots must be used by a diverse population of workers, it is possible to expect

a more consistent attitude towards collaborative rather than cooperative robots.

Interestingly, the majority of the participants reported preferring the reciprocal strategy, while the effort and errors do not show a significant difference from the mirror strategy. The preference for the reciprocal condition contrasts with our expectation from the human-human study, where we found that collaborators exhibit high arm co-contraction as if they are both trying to lead. In hindsight, humans might prefer to interact with a "docile" robot that complies with the human behavior, rather than competing with a robot that stiffens as the human does: lowering the stiffness when the human co-contracts may enforce the human feeling of being in control (empowerment), which has been frequently reported in the literature as one of the main drives for accepting and trusting a robot [3], [4], [30]. The reciprocal collaborative strategy has also the advantage of being more conservative concerning the passivity of the system, with notable safety implications [31].

In summary, for co-manipulation, a robot collaborator seems preferable to a robot cooperator (better than a robot leader, and definitely better than a robot follower), even if the way the human collaborates with the robot differs from when collaborating with another human. In addition, within the collaborative strategies, a reciprocal strategy for impedance seems the most indicated.

### C. Limits of the study

Our results suggest that in a human-robot co-manipulation task the robot should behave as a collaborator, adapting its impedance with a reciprocal stiffness law that relates to the human arm co-contraction. This control mode is efficient in terms of task accuracy and was also preferred by the participants.

However, our results should be considered carefully. First, the study was conducted with participants from the university environment, and while few participants were familiar with robots, the results cannot be generalized for a generic population, especially with industry workers that may have different attitudes when interacting with a robot [3]. Second, the co-manipulation task was very simple and the manipulated load was small and light. In this sense, we do not know if our results can be generalized to other co-manipulation tasks involving large and heavy loads, a situation that is often found in manufacturing where robots physically assist workers (e.g., manipulating car parts, such as wheels [32]). Third, the performance of each condition might change with more training and expertise with the robot and the task. We already accounted for the source of bias due to learning by not including the initial trials in our analysis (see Section IV-C). However, the RF condition was always executed as the first (for the reasons explained in Section IV-A.3) and this might partly explain the lower performance of this condition in terms of task errors. At the same time, the participants reported that it was not easy to do the task with the robot in this condition, and our intuition is that this is mostly because the robot was not entirely transparent. It is

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[1]This latter can be predicted from initial observations of the collaborative action, as we did in [29]. Studying the impact of this prediction in the collaborative strategies will be done in future studies.

possible that interactions over hundreds of trials may lead to lower ICC levels and fewer errors. Future studies should investigate whether there is a significant learning effect for longer interactions and whether this learning process is user-specific: this knowledge will be critical to recommend suitable training to workers that collaborate with robots on a particular workstation.

## VII. Conclusion

We investigate whether it is preferable and more performing for a robot to behave as a cooperator (leader or follower) or collaborator (variable impedance) during a co-manipulation task with a human. Our study shows that with a robot leader informed of the task trajectory the human makes less effort, but in terms of task accuracy and effort, a reciprocal collaborative strategy seems preferable for a human. Our results are relevant for the design of human-robot collaborative workstations. They also evoke new questions to further understand human behavior, precisely the human arm impedance, during joint work with humans and robots.

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