

High stiffness in teleoperated comanipulation: necessity or luxury ?

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Abstract—The present paper investigates if and in which conditions does the implementation of high stiffness controllers increase the performances of human dyads during comanipulative tasks in physical Human-Human Interaction (pHHI) settings. Two experiments are conducted which cover two fundamental aspects of pHHI: low-level interactions allowing interpersonal coordination, and high-level interactions allowing common decision-making and negotiation of strategies. The results of these experiments show that high stiffness is not necessary for good performances when the task only requires low-level interactions. On the contrary, when dealing with high-level interactions, higher stiffness increases task performance. The results presented highlight the importance of the quality of teleoperated control in setups used for the study of pHHI.

I. INTRODUCTION

In the future, robots should be able to interact smoothly with humans on a daily basis, and in a wide range of applications. This trend promises a pronounced development of human-robot interaction, and in particular of physical Human-Robot Interaction (pHRI), where human users are in direct physical contact with the machines.

The study of physical Human-Human Interaction (pHHI) has been proposed as a basis for the development of pHRI. The underlying idea is that to design better pHRI protocols, it is necessary to understand how humans interact when in direct contact. One of the main issues in the study of physical interaction between humans is the difficulty to extract reliable force information at the points of contact between humans.

One solution to this problem is to use an instrumented object as a point of indirect physical contact [?][?], in tasks where the goal is the comanipulation of said instrument. This method, which allows easier acquisition of force data, lacks some flexibility in its design. Moreover, it is interesting for some studies to be able to spatially separate the subjects, or to restrain their use of other sensory modalities.

For these reasons, the use of coupled haptic interfaces to recreate physical interaction has been steadily increasing in the literature. Teleoperation controllers can indirectly recreate the sense of physical contact, while keeping the interfaces (and thus the subjects) separated. The quality of the indirect contact recreated between the interfaces is commonly referred to as transparency. Perfect transparency is defined as a perfect transfer of impedance between the two interfaces, meaning that both forces and velocities are identical on each side.² Many criteria can be used to qualify the transparency of the interfaces. In the cases where the

interfaces are in continuous contact with an environment while a force is applied, which is the case in the study of pHHI, the most relevant criterion is the stiffness rendered by the controller [?]. Indeed, for fixed inertia and damping, higher transparency results in higher stiffness. The present work is thus focused on the stiffness aspect of teleoperation control.

In the literature, no clear consensus seems to exist on the best type of controller to use, and which stiffness should be rendered when studying pHHI. Melendez-Calderon et al. [?] used a rigid link to physically connect their interfaces, which guarantees an extremely high stiffness but limits the degree to which the subjects can be separated/decoupled. Ganesh et al. [?], and Che et al. [?] used interfaces linked with a position-position controller, simulating a link of adjustable rigidity between the two manipulated robots. Groten et al. [?][?], De Santis et al. [?] and Kucuyilmaz et al. [?] used admittance control to simulate a virtual object controlled by both subjects via spring-damper links between the positions of the interfaces and the virtual object. Among these studies, there is a great variability of the controller stiffness, but in most cases its maximal value is inferior to 300 N/m.

High values of stiffness are however essential to accurately render the full range of haptic information. For example, it is estimated that a minimal value of 10000 N/m is needed to create the feeling of a rigid contact [?]. There is however a technical cost to implement high stiffness in teleoperated haptic interfaces. Indeed, a controller able to recreate a highly rigid link between slave and master interfaces usually require high frequency real-time hardware, and precise force sensors. There is thus a conflict between the need for stiffness and the difficulties to implement it. Given this, one could ask the question : is high stiffness necessary to implement in teleoperation when studying pHHI ?

Some elements of answer exist in the literature : Christiansson et al. [?] showed that teleoperator stiffness has no influence on the ability for subjects to discriminate the size and stiffness of various environments. Another study by Aliaga et al. [?] showed that in real-life implementations, better transparency of the controller increases performances in telemanipulation. To our knowledge, no experimental study exists on the influence of quality of bilateral teleoperation control on the ability for human to perform efficiently as a dyad.

The present work is an effort to study the influence of teleoperator stiffness on performance in pHHI. Two funda-

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²A perfectly transparent interface is often compared to a stick of infinite stiffness and null mass.

mental aspects of pHHI are studied: low-level interactions allowing interpersonal coordination, and high-level interactions allowing common decision-making and negotiation of strategies.

Since the study is focused on the stiffness aspect of transparency, the setup used is designed to have extremely low apparent inertia and damping, in order to reduce their influence and accentuate the stiffness component of the controllers.

Section II presents the experimental setup, as well as the different controllers used for teleoperation. Section III will present the experimental protocol used in this study. Section IV details the results of the experiment and Section V discusses those results, and conclude the present paper.

II. MATERIAL AND METHODS

A. Control of teleoperated haptic interfaces

There are two main types of controllers used in the literature of PHHI study:

Admittance controllers take for input the forces applied to the end effector and output the displacement of the interface according the desired impedance of the robot. These controllers allow precise tuning of the characteristics wanted for the interface. However, to guarantee stability in impedance control, there is a limit on the mass/impedance ratio that can be rendered [?]. In the case of lightweight tasks, where the apparent mass of the haptic interface must be kept as low as possible, the range of possible stiffness rendered is generally limited. No admittance controller will thus be included in this study, although it would be interesting to evaluate them in the context of tasks involving larger forces.

Position-Position controllers (PP) are the most widespread controllers in the literature and also the simplest. In PP control, each interface is controlled with a Proportional-Derivative (PD) controller targeting the position of the other interface. The force command of each interface is therefore expressed as:

$$F_{\text{com},i} = K_P(x_{1-i} - x_i) + K_D(\dot{x}_{1-i} - \dot{x}_i) \quad (1)$$

with $i \in (0, 1)$ designing the interface number, $F_{\text{com},i}$ the force command for the interface i , x_i its position, and \dot{x}_i its velocity.

The result of this controller is a spring-damper-like link between the two interfaces, the characteristics of which can be controlled by tuning K_P (stiffness) and K_D (damping). The biggest advantage of the PP controller is its simplicity : its implementation only requires position sensors. However, like with admittance controllers, the maximal stiffness available with a PP controller is limited by the stability condition [?][?]. In order to reach higher stiffness with the same interfaces, the implementation of a better controller is needed.

In the field of teleoperation, multiple theoretical models have been proposed that can reach perfect transparency (and thus infinite stiffness), even when constrained by hardware limitations [?] [?].

Gain		Cm,0	Cm,1	C1	C2	C3	C4
Value	4C	$K_P + K_D s$	$K_P + K_D s$	Cm,0	1	1	Cm,1
	PP	$K_P + K_D s$	$K_P + K_D s$	Cm,0	0	0	Cm,1

TABLE I: Ideal gain values for 4C and PP controllers in symmetrical setups.

Historically, the first of these theoretically perfect controllers is the Four Channels Architecture (4C), proposed separately by Lawrence [?] and Yokohokohji [?]. It uses the same force command as the PP controller, in addition to the force applied on the other interface. In the case of a symmetrical setup with no time delay, the ideal force command sent to each interface is expressed as:

$$F_{\text{com},i} = F_{\text{ext},1-i} + K_P(x_{1-i} - x_i) + K_D(\dot{x}_{1-i} - \dot{x}_i) \quad (2)$$

with $i \in (0, 1)$ designing the interface number. $F_{\text{com},i}$ is the force command of the interface i , $F_{\text{ext},i}$ the force applied on interface i , x_i its position, and \dot{x}_i its velocity.

A schematic representation of the 4C architecture is presented in Figure 1. Gains C1 and C4 control the position communication channels between the interfaces. Gains C2 and C3 control the force communication channels. Gains Cm,i are the interfaces' controllers (in our setup, the two interfaces are identical physically and their controllers are the same). Zm,i are the interfaces' impedances and Zh,i are the users' hand impedances (variable). Usual values for gains are detailed in Table I. The 4C architecture also encompasses the PP controller when the force communication channels are set to zero.

Multiple improvements on the 4C model have been made in the field of teleoperation, mostly to improve the stability in presence of time delays or lack of sensing capabilities, but the basic 4C architecture is deemed sufficient for the scope of this study.

B. Material

The system used in the present experiments is composed of two one-degree-of-freedom haptic interfaces. The interfaces are identical and are represented in Figure 2.

The user places one finger on the end of the handle, and can perform leftward or rightward motions. The interfaces are actuated by a DC motor connected in direct drive to the handle in order to reduce backlash. Force feedback up to 20N can be produced at the end effector. The interfaces are equipped with force sensors in the handles (sensitivity of 0.05N), and position sensors (spatial resolution of 0.035mm at the end effector).

The controller of the handles and the data acquisition is implemented on a Real-Time operating system (Xenomai - 5 kHz actualization frequency), while the graphical interface runs on another computer. The communication between the two computers is realized by a direct Ethernet connection. The average time-delay in this connection is 0.02 ms and is considered negligible compared to both human response time and loop period.

During the task, users are given visual feedback about their interfaces positions on a screen (c.f. Figure 3). A green

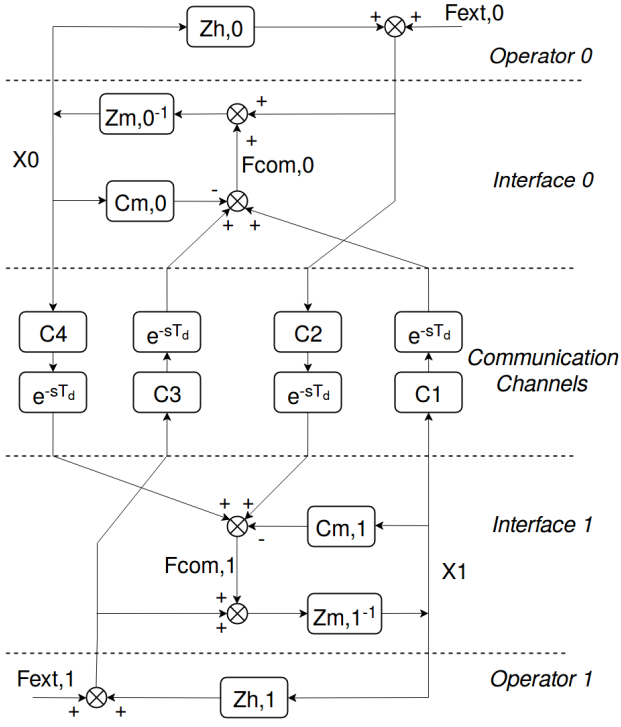


Fig. 1: The Four Channels (4C) architecture, a teleoperation controller allowing perfect transparency. Usual gain values for 4C and PP controllers are detailed in Table I.

dot is displayed with fixed vertical position, and horizontal position controlled on by interface's motions.

Additional information on the interfaces and setup can be found in [?]

C. Measures

This section presents the metrics used to assess the performances of the different controllers. Like most studies in the domain of pHHI, they will cover two important aspects of comanipulation: the performance during the task (linked to the precision of the tracking), and the energy expenditure for the users (linked to the forces applied to the interfaces).

The first metric is a measure of the performance attained by the participants during the task. Performance for a tracking task is linked to the precision during the trial. Mean Absolute Error (MAE) is used here over Root Mean Squared Error (RMSE) since there is no need to penalize great displacements more than small ones.

MAE is calculated as:

$$MAE = \frac{1}{N} \sum_{k=1}^N |X_{\text{cursor},k} - X_{\text{target},k}| \quad (3)$$

with N the number of data samples, $X_{\text{cursor},k}$ the position of the cursor at sample k , and $X_{\text{target},k}$ the position of the path at sample k .

The second metric is linked to the forces used by the subjects, and the corresponding energy expenditure. Different

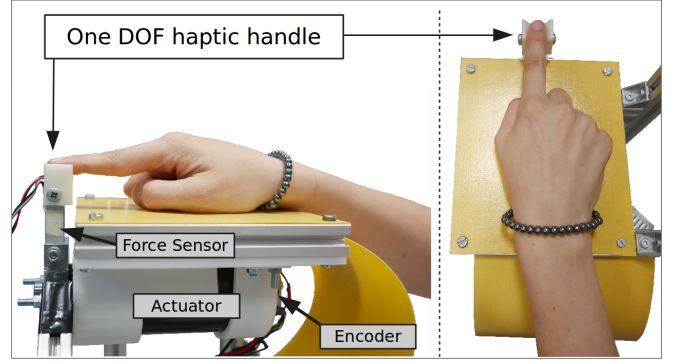


Fig. 2: Direct-drive haptic handle

parameters are used in the literature, each having advantages and drawbacks. The three main approaches are to consider either the forces in the system : external and interaction forces [?] [?] [?], forces applied to the interfaces [?] [?] or the energy/power flows in the system [?].

One of the experimental conditions used in the experiments artificially creates vibrations which add a lot of kinetic energy that would be calculated when using an energy or power metric for analysis. In order to fairly compare all conditions, a metric using the forces in the system is chosen. In the task presented here, the interface impedance is small compared to the user's arm impedance. Thus, the interaction forces make up most of the forces present in the system during the task. For this reason, the differences between interaction forces and total forces criteria is minimal in the present setup.

The chosen criterion will be referred as the Mean of Absolute applied Forces (MAF)

$$MAF = \frac{1}{N} \sum_{k=1}^N (|F_{0,k}| + |F_{1,k}|) \quad (4)$$

with $F_{i,k}$ the force applied on the interface i at sample k . The MAF criterion represents the amount of efforts expended by the users on the interfaces during manipulation; absolute values are taken to combine both interaction forces and forces used to displace the interface.

III. EXPERIMENTAL PROTOCOL

It has been proven that dyads outperform individuals in manipulation tasks where precision is required [?] [?] [?]. These results have been observed with different setups of varying stiffnesses: from the rigidity of a physical object [?] to a soft spring-like connection [?].

However, it is unknown which stiffness is the best to observe the benefits of dyadic interaction. The experiments presented in this section aim at finding if the quality of the teleoperator used in pHHI studies influences their results.

A. Experimental conditions

Multiple experimental conditions are tested, corresponding to controllers of different stiffnesses, and control conditions. The different controllers used are the following:

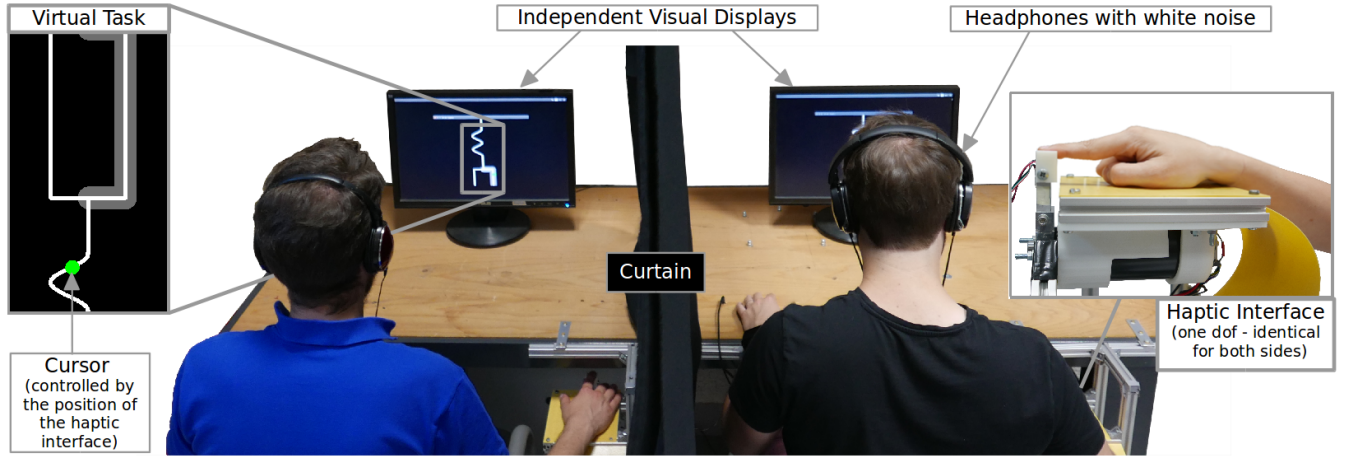


Fig. 3: Description of the experimental setup: The two participants use a one dof haptic interface to share the control over a virtual object. Visual feedback about the position of the object is given on their respective screen as a cursor.

- **No controller (ALONE)** No command is sent to the interfaces; only sensors are used. Each user has visual feedback on its own interface position.
- **Dyad with Visual Feedback only (DVF)** No force feedback in the interfaces. Visual feedback is common for both users and displays the median position of the two interfaces : $X_{\text{cursor}} = (X_1 + X_2)/2$
- **Position-Position with low stiffness (PPSOFT)** A PP teleoperation control is used. The stiffness of the link is 300 N/m, chosen as a minimal value allowing users to effectively sense the motions of the partner's interface at the scale of the task. Visual feedback is common for both subjects.
- **Position-Position with high stiffness (PPHARD)** PP teleoperation control, with a 3000 N/m stiffness, corresponding to a stiff spring. Visual feedback is common for both subjects.
- **Four Channel (4C)** A four channel teleoperation scheme with adaptive gain control is implemented. The stiffness of this controller changes according to the interaction force but is comprised between 10^4 and 10^5 N/m, actually simulating a rigid connection between the interfaces.
- **Noisy Four Channel (NOISY)** Same four channels architecture as the previous condition, with an artificial Gaussian sensing noise of 0.5mm standard deviation added to the position sensors. This noise produces perceptible vibrations in the handles but do not compromise stability nor stiffness performances.

B. Experimental tasks

The co-manipulative task that the subjects have to complete is a tracking task: a path (white line over black background) is scrolling down on their monitor, at a speed of 35mm/s. The subjects are asked to keep the position of the cursor controlled by their interfaces as close as possible to the scrolling path. In the dyadic conditions, to further incite each subject to cooperate, they are told that their goal is to

maximize the common performance of the dyad. Feedback about the performance is given by the color of the cursor, which changes based on the distance between the closest path and the cursor:

- Green if $|X_{\text{cursor}} - X_{\text{Path}}| < 5 \text{ mm}$
- Yellow if $5\text{mm} < |X_{\text{cursor}} - X_{\text{Path}}| < 15 \text{ mm}$
- Red if $|X_{\text{cursor}} - X_{\text{Path}}| > 15 \text{ mm}$

The path is composed of a procedurally generated succession of curves, and its structure depends on the task. Two tasks are performed by the participants, corresponding to two separate experiments. The first task is designed to evaluate low-level haptic interactions, and requires only precision in the tracking. The second one focuses on higher level interactions, imposing that the subjects share and negotiate a common plan when confronted with a choice [?].

In the pure tracking task (TRAJ), the path is composed of a continuous succession of curves and straight lines. Each subpart can be a straight line, sinusoidal curve, or a right angle, imposing a "jump". The total interface workspace used for the task is 40mm wide, centered around a vertical starting position.

In the high level task (CHOICE), the path alternate between two categories:

- 1) The "BODY" category is composed of sinusoidal paths of random direction but fixed duration.
- 2) The "DECISION" category: at fixed intervals, the path splits into a fork, imposing a clear choice to be made concerning the direction that the subjects need to follow (see Figure 3). Considering that the subjects can neither see nor hear each other, the only way they can come to an agreement about the direction to choose is to use either the visual feedback from the monitor, or the haptic feedback from the handles.

In the dyadic conditions, the presence of the choices forces the subjects to communicate in order to negotiate a common action plan concerning the direction to choose. This task was designed by Groten et al. in [?] and is described in more

	Cond.1	ALONE		DVF		4C		PPSOFT		PPHARD	
		p	d	p	d	p	d	p	d	p	d
TRAJ	DVF	1.0	-0.049	-	-	-	-	-	-	-	-
	4C	0.001	-0.123	0.499	-0.073	-	-	-	-	-	-
	PPSOFT	0.0	-0.13	0.298	-0.079	1.0	-0.007	-	-	-	-
	PPHARD	0.035	-0.092	1.0	-0.042	1.0	0.029	1.0	0.036	-	-
	NOISY	1.0	-0.001	1.0	0.049	0.006	0.122	0.003	0.128	0.146	0.091
CHOICE	DVF	0.0	0.648	-	-	-	-	-	-	-	-
	4C	0.0	0.277	0.0	-0.379	-	-	-	-	-	-
	PPSOFT	0.0	0.457	0.075	-0.179	0.017	0.192	-	-	-	-
	PPHARD	0.0	0.327	0.0	-0.334	1.0	0.048	0.189	-0.147	-	-
	NOISY	0.0	0.279	0.0	-0.381	1.0	-0.0	0.015	-0.193	1.0	-0.048

TABLE II: Bonferoni corrected p-values and Cohenn's d coefficients of pairwise comparisons of the MAE obtained for the different experimental conditions. Positive d-values indicates MAE is larger in condition 2 (left), negative d-values indicates MAE is larger in condition 1 (top).

	Cond.1	4C		PPSOFT		PPHARD	
		p	d	p	d	p	d
TRAJ	PPSOFT	0.0	-0.155	-	-	-	-
	PPHARD	0.337	-0.036	0.0	0.121	-	-
	NOISY	0.0	0.145	0.0	0.288	0.0	0.179
CHOICE	PPSOFT	1.0	-0.014	-	-	-	-
	PPHARD	1.0	0.043	1.0	0.054	-	-
	NOISY	0.0	0.17	0.0	0.179	0.004	0.124

TABLE III: Bonferoni corrected p-values and Cohenn's d coefficients of pairwise comparisons of the MAF obtained for the different experimental conditions. Positive d-values indicates MAF is larger in condition 2 (left), negative d-values indicates MAF is larger in condition 1 (top).

details in their article, this task was also used in [?].

At the beginning of each experiment, the subjects are explained the rationale of the setup and informed about all experimental conditions. They also run a training trial in order to familiarize with the setup. Afterwards, each dyad performs two blocks of 14 trials corresponding to the two experiments (TRAJ and CHOICE). The TRAJ experiment is always conducted first, followed by the CHOICE experiment. In each block, the participants perform the task twice for every experimental condition (ALONE, DVF, PPSOFT, PPHARD, 4C, NOISY) in randomized order. Trials last for 100 s in the TRAJ block and 110s in the CHOICE one. The subjects are not informed about which conditions they are testing before each trial.

The subjects are physically separated by a curtain to prevent any visual clue about the actions of their partners, and wear audio headphones playing white noise to prevent any auditory clue (see Figure 3).

The study involved 32 participants (18 males, 14 females) distributed in 16 dyads (5 Male-Male, 3 Female-Female, 8 Mixed). Participants' average age was 28.8 (± 8.7), 28 were right-handed and 4 were left-handed. None had previous knowledge of the experiment or experimental set-up.

IV. RESULTS

A. TRAJ experiment

1) *Method*: A single way ANOVA is performed on the data for both experimental blocks. Post-hoc pairwise t-

tests are then conducted for each experimental condition, and results are detailed in Table II and III for MAE and MAF respectively. MAF values for the ALONE and DVF conditions are omitted in Table III since no interaction force is taking place. Their values are kept in the figures for comparison : mean values are significantly lower compared to the teleoperated conditions because of the lightweight nature of the setup. Indeed, interaction force is the principal source of energy expenditure in the task performed. The p-values are given after Bonferonni correction for multiple comparisons. p-values inferior to 10^{-3} are given equal to 0. Cohenn's d coefficients for size effect are also precised. The sign of the d coefficients indicate which of the two compared groups has higher metric, and thus worse performance (cf legend in Table II and III). For the TRAJ experiment, the metrics are calculated over the whole trials.

2) *MAE*: A significant effect of the experimental condition on the MAE criterion is observed (ANOVA results : $F(6, 10764) = 205.46, p = 0, \omega^2 = 0.102$)

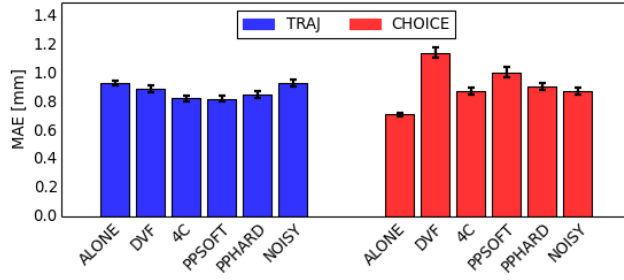
Post-hoc analysis shows that performances are the worst (i.e MAE was highest) respectively in the ALONE, NOISY and DVF conditions, without significant differences between them. Performances are the best for the teleoperated conditions (4C, PPSOFT and PPHARD), without significant differences between them. The average MAE values and standard errors can be seen on Figure 4a.

3) *MAF*: A significant effect of the experimental condition on the MAF criterion is observed (ANOVA results : $F(6, 10764) = 464.36, p = 0, \omega^2 = 0.205$)

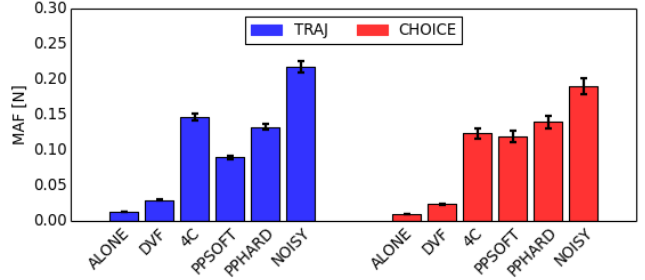
Post-hoc analysis shows that efforts are significantly higher (i.e MAF was higher) in the NOISY condition, and significantly lower in the PPSOFT condition. Performances for the 4C and PPHARD are in between these extremes, without significant differences between the two. The average MAF values and standard errors can be seen on Figure 4b.

B. CHOICE experiment

1) *Method*: The same method as in Part IV-A.1 is applied here. Pairwise t-test results are detailed in Table II and III for MAE and MAF respectively. The values of the metrics are calculated only in the DECISION parts for the



(a) MAE



(b) MAF

Fig. 4: Mean values and standard errors of the MAE and MAF criterion for the two experiments.

CHOICE trials. In the ALONE condition, the MAE values are calculated separately for each subjects.

2) *MAE*: A significant effect of the experimental condition on the MAE criterion is observed (ANOVA results : $F(6, 2274) = 168.06, p = 0, \omega^2 = 0.305$)

Post-hoc analysis shows that performances are significantly worse in the DVF condition, followed by the PPSOFT condition and significantly better in the ALONE condition. Performances for the 4C, PPHARD and NOISY conditions are in between these extremes, without significant differences between the three. The average MAE values and standard errors for the CHOICE experiment can be seen on Figure 4a.

3) *MAF*: A significant effect of the experimental condition on the MAF criterion is observed (ANOVA results : $F(6, 2274) = 150.93, p = 0, \omega^2 = 0.282$)

Post-hoc analysis shows that efforts are significantly higher in the NOISY condition. Efforts for other conditions (4C, PPSOFT and PPHARD) are lower and show no significant differences between them. The average MAF values and standard errors for the CHOICE experiment can be seen on Figure 4b.

V. DISCUSSION

A. TRAJ experiment

The first experiment consists on a pure tracking task, in which only precision and coordination is required. Different experimental conditions are tested in order to study the influence of haptic feedback and the stiffness of teleoperation controllers on the performance during the task.

The first important result of the TRAJ experiment is that the ALONE experimental condition leads to worse performances than the dyadic ones, which is a classical result in pHHI [?][?][?], although not observable in every scenario [?]. The advantages of the dyads compared to subjects alone are however only present in the presence of haptic feedback (DVF is not better than ALONE). This highlights the importance of haptic communication in the success of comanipulation [?][?].

Quite predictably, the presence of mechanical noise in the system degrades the performances of the dyads. However, this decrease in precision is limited and dyads in NOISY

conditions obtain performances similar to the ALONE condition, even if they use significantly more force to do so.

The most interesting result of the experiment is the fact that no significant difference in performance appears between the three teleoperation controllers. The dyads are able to outperform individuals with an equivalent margin as long as some (non noisy) haptic feedback is provided. This results seems to indicate that for comanipulative task requiring only precision (no high level decision making), the stiffness of the haptic feedback does not matter, but its quality does. The PPSOFT conditions led to lower average force applied to the interfaces compared to stiffer controllers, which may be preferable since it does not decrease the performances.

B. CHOICE experiment

The second experiment introduces a task requiring higher level decision making and interpersonal coordination, in the form of choices to make in the tracking task. The participants thus have to communicate their intention and negotiate a common action plan in order to succeed.

In this task, the performances are highest in the ALONE condition, since the subjects do not have to negotiate conflicting situations. Conversely, the performances are worst in the DVF condition, where the lack of haptic information decreases the negotiation possibilities. These results are in agreement with previous results from the literature [?][?].

Surprisingly, the presence of noise in the controller does not affect the performances of the dyads, as opposed to the first experiment. Which would mean that higher level coordination is less affected by perturbations than low-level coordination in precise tasks.

Contrary to the previous experiment, an effect of controller stiffness is observed: the PPSOFT condition leads to significantly lower performances than the 4C, PPHARD and even NOISY conditions. A high stiffness may thus be beneficial for comanipulative task where intention has to be communicated from one person to his/her partner.

No difference is observed in the average level of force applied by the participants in these conditions (the NOISY condition still leads to higher forces applied).

C. Conclusion

The results of the experiments suggest that the stiffness of the teleoperation controller does not influence performances

when the task only requires individual precision and low-level interaction. On the other hand, for tasks where some communication has to take place through the haptic channel, for example to negotiate a common action plan, a higher controller stiffness leads to better performances of the dyads. These findings highlight the importance of ensuring the quality of controllers in haptic interfaces, both for study of pHHI, and later for integration of pHRI protocols, especially for task requiring high-level interaction through touch.

The present study is limited to the framework of one degree of freedom lightweight tasks, and future work will include similar studies for tasks with higher impedance, and multiple degrees of freedom. Furthermore, a wider variety of tasks need to be studied to confirm the findings presented in this paper. Still, these experiments suggest that researchers should be careful to ensure proper quality of teleoperation when studying physical Human-Human Interaction.