Study of the Influence of a Force Bias on a Robotic Partner During Kinesthetic Communication

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Abstract: Numerous physical tasks necessitate collaboration among multiple individuals. While it's established that during comanipulation tasks, the exchange of forces between actors conveys information, the precise mechanisms of transmission and interpretation remain poorly known. Various studies have underscored that when a robot exhibits human-like motions, human understanding of its intentions is enhanced. Nevertheless, discernible disparities emerge when comparing Human-Human and Human-Robot interactions across diverse metrics. Among all the usable metrics, this paper focuses on the sense of control over the physical exchange and the average values of interaction forces. We demonstrate here that the addition of a subtle force bias on the robot motions results in a diminishing of the observed disparities on these metrics, making human interactions with this robotic partner more akin to those with other humans.

1 INTRODUCTION

Since the early concept of cobots (Peshkin et al., 2001), significant progress in control, conception, and safety has brought natural Human-Robot interaction closer to reality. Robotic devices have evolved from rigidly programmed entities to systems that can smoothly interact with their environment, and react to some amount of unknown parameters. Robots are now more often led to work alongside humans and to cooperate with them for numerous tasks in a wide range of applications, from industry to health care (De Santis et al., 2007) (Goodrich and Schultz, 2007). This cooperation often leads to interaction either via direct contact or via indirect contact through a jointly held object. Therefore, understanding the interaction's underlying processes is a crucial challenge, giving us new directions for improving robotic partners of all kinds.

The cooperation appears to be altered when cooperating with a robotic partner. (Obhi and Hall, 2011) has shown the difference in sense of agency when we believe it is a human partner. Then(Grynszpan et al., 2019) has shown that the sense of agency is hindered during kinesthetic cooperation. They have shown some discrepancy using three metrics related to efforts and the sense of agency. This prompts the question: What features in Human-Robot Interaction impede cooperation and alter the sense of agency? Analysis of the dataset from (Grynszpan et al., 2019) revealed that humans tend to maintain a constant light force, regardless of whether an action is executed or not. Furthermore, it was observed that individuals exert more force when engaging in kinesthetic communication exclusively (Mielke et al., 2017) (Parker and Croft, 2011). This leads to the question: Does force directly influence the perception of kinesthetic dyadic cooperation? Assessing this aspect involves implementing a robotic partner, named Virtual Partner (VP). Our study explore how humans perceive interactions with robots. Integrating force bias into robot models could offer means for them to enhance their communication capabilities.

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2 RELATED WORKS

Numerous studies showcase humans' capability to exchange information and intentions through force exchanges (Ganesh et al., 2014) (Candidi et al., 2015) (van der Wel R. P. R. D. et al., 2011) (Pezzulo et al., 2021). Nonetheless, the specific demands and content of the messages conveyed in such exchanges remain unclear. Two approaches have been employed to tackle this issue.

The first approach involves directly observing exchanges of forces and trajectories and developing tools for analyzing interactions. Within this approach, studies such as (Al-Saadi et al., 2021), (Madan et al., 2015), (Mielke et al., 2017), (Parker and Croft, 2011) and (Börner et al., 2023) present methods for decomposing interaction forces (e.g., distinguishing harmonious and conflicting interactions, identifying efforts contributing to joint action or not) or analyzing properties of motion during Human-Human interaction.

In the second approach, virtual partners are developed and features leading to similar interactions between Human-Human and Human-Robot pairs are observed. The study presented here falls within this category, alongside others such as (Takagi et al., 2017) and (Li et al., 2019). These studies demonstrate that during physical interaction between two humans, one participant incorporates the intentions of the other into their own command scheme. Their methodology entails creating models of virtual partners capable of adapting their behavior to that of their human counterparts. While these models exhibit the adaptive nature of humans in interaction, their limitations (Takagi et al., 2018) underscore the necessity for further advancements in this domain.

One apparent method for enhancing these models would involve considering the roles during interactions. Indeed, the dynamic exchange of roles and the specific roles each partner assumes significantly influence physical communication, as evidenced by (Jarrasse et al., 2013) (Mörtl et al., 2012) (Abbink et al., 2012) (Feth et al., 2011) (Reed and Peshkin, 2008). To the best of our knowledge, real-time determination of a person's role within an interaction is infeasible due to the multitude of potential roles and their subtle distinctions. Since this study does not focus on role identification, we have circumvented this issue by concentrating on brief and elementary interactions. In doing so, we assume: (1) the interaction begins with a brief negotiation phase followed by a relatively harmonious execution phase, (2) the roles of "Initiator" and "Follower" serve as adequate descriptors, and (3) each participant's role remains consistent throughout the physical exchange. Insights from a related study (Grynszpan et al., 2019) suggest that these assumptions generally hold true in most instances. Another supporting element for our hypotheses is the concept of "1st-Crossing," previously introduced in (Roche and Saint-Bauzel, 2021). The "1st-Crossing" descriptor predicts, with a 95% success rate, which actor will dictate the direction based on their initial voluntary movement in a dyadic physical exchange. This implies that the outcome of short interactions tends to be influenced by the first move. Building upon this premise, we have developed a Virtual Partner (VP) capable of assuming both roles, the algorithm of which is delineated in Section 3.

3 METHODS

3.1 Apparatus and Settings

Each participant controls a 1-dof (degree of freedom) haptic interface (Figure 1), called *1D-SEMAPHORO*. These interfaces, consisting of a platform and a paddle that moves from right to left on which are respectively placed the right hand and the tip of a finger, were designed and built in ISIR (Roche et al., 2018) and are published with a opensource license CC-BY-NC. The motor controllers and the sensors acquisition run at 2kHz.

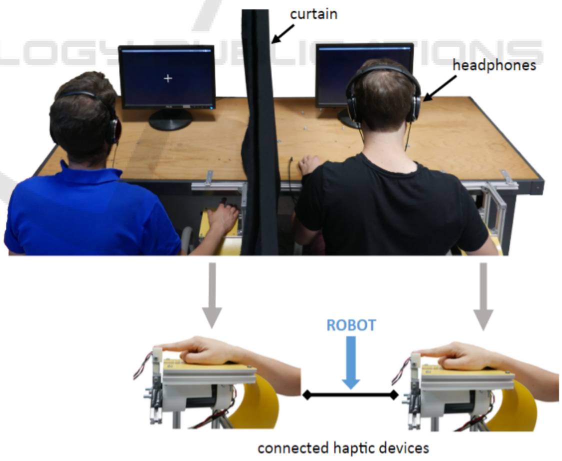

Figure 1: Image of the *1D-SEMAPHORO*.

The *1D-SEMAPHORO* comes with 3 different modes. When the 1st mode is selected, the paddles are free and receive no mechanical effort from the motors. There is no communication between users.
Selecting the second mode puts the haptic devices in bilateral teleoperation thanks to a 4-channel controller. The *1D-SEMAPHORO*'s mechanical structure makes it a good choice for a transparent and stable controller. When computing the command $F_{h,i}(t)$ for

the handle i, the operation can be summarize in (3.1).

$$F_{h,i}(t) = K * (X_i(t - Td) - \tilde{X}_i(t)) + \tilde{F}_i(t - Td)$$

Where Td represents the delay in the control loop (in our case, $Td = .5$ ms). X_i and $\tilde{X}_i$ are the states of both handles. The state is composed of the position and velocity. $\tilde{F}_i$ is the force measured by the sensor on the other handle i and K is a scheduled PD controller.

In the last mode, the haptic devices are both linked to two virtual partners (VP) (algorithm representation in Figure 5 (Roche and Saint-Bauzel, 2021)). At all times, the VP monitors the human partners' efforts. Depending on the amount of effort generated by the latter, the VP takes on the role of Leader or Follower. Then the VP chooses a position to reach, depending on its role and the targets on screen, and creates a minimum-jerk trajectory to it. A PD controller is then used to keep the VP on track with the reference trajectory.

3.2 Types of Partner

Based on these modes we defined several types of partner:

- *Alone*: Participants perform the task on their own, without any interaction between participants.
- *Human*: Participants physically communicate together using SEMAPHORO-1D in bilateral teleoperation.
- *Robot noFB* (no force bias): Each participant interacts with a VP (described part 3.1) without the added force bias.
- *Robot FB*: Each participant interacts with their own VP applying the additional force bias. The magnitude of this force bias is constantly $0.3N$ and its direction is randomly determined at the beginning of each trial. The magnitude of this force bias comes from previous data on 10 participants. It represents the average value of all the forces they generate when no specific action is performed.

3.3 Metrics

The sense of agency, which can be defined as one ability to feel in control of observable modifications in the environment through one's actions (Haggard et al., 2002) (Haggard, 2005), has been highlighted in humans during solo tasks or sequential group tasks. In our study, this concept is used to analyze the feeling of control during real-time collaboration tasks. This metric allows us to observe how interactions are perceived in relation to the behavior of the partner. It can be measured at two levels :

- the implicit (unconscious) level: The perception of the time interval between an action and its effect is used as a measure of Intentional Binding (IB). IB is an effect linked to the sense of agency, whereby an individual perceives her/his action and its effect as attracted towards one another (Haggard, 2005) (Capozzi et al., 2016) (see Figure 2).
- the explicit (conscious) level: measurement based on questionnaires where humans are asked to rate their feeling of control over the physical communication (Ivanova et al., 2020) (Obhi and Hall, 2011).

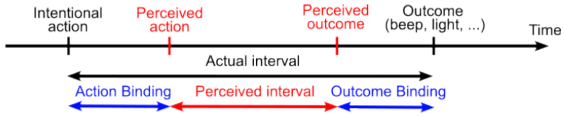

Figure 2: Representation of the Intentional Binding effect. The value of IB is the sum of Action and Outcome Bindings.

The feeling of control, represented by the study of agency, is refined by observing how it evolves in relation to each partner's role. We chose to use the contribution to the first motion of the dyad as the criterion to identify the role of each member (Initiator or Follower). To be more precise, the first member to generate an effort superior to a threshold becomes Initiator. If both members exceed this threshold, the one applying the greatest force is recorded as Initiator of the dyads' motion.

3.4 Experimental Design

3.4.1 Task and Stimulus

Throughout the experiment, participants must execute the same task with different partners. Regardless of the partner, they must move their paddles to the right or the left. When they reach an end position, they hear a beep and after a period of time, a second one. To implicitly measure their sense of agency, participants must quantify the time elapsed between the two sounds in milliseconds. The explicit measurement is done by asking them to rate their own level of involvement in the final group decision.

3.4.2 Procedures and Phases

The experimenter explains the context of the experiment and what kind of task they are asked to perform. Dyad members take the test in the same room, sitting side by side, and each has a computer screen and headphones. An opaque curtain separates them, preventing them from seeing each other.

During the training phase, participants have to focus on and develop their ability to estimate intervals

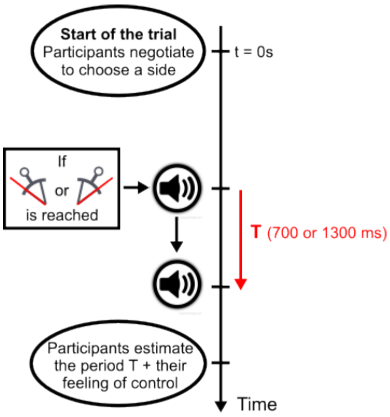

Figure 3: Representation of a trial during the evaluation phase. In the training, the period T of time is chosen randomly between 300 ms and 2000 ms.

of time that range from 300 to 2000 milliseconds. After an answer is given, they can see the correct value appearing beside it. This phase consists of 30 trials in *Alone* mode and 20 trials in *Human*. Training with *Alone* enables participants to improve their ability to estimate time intervals consistently while training with *Human* develops their ability to prioritize time estimation over the rest.

During the evaluation phase, they still have the same task but with three modifications. First, the interval duration is no longer picked at random (two possible intervals, 700ms and 1300ms). Second, Participants are linked to the 4 different partner types described previously (*Alone*, *Human*, *Robot FB* and *Robot noFB*). Third, the question about the explicit measure of the agency is included. To avoid asymmetries in haptic devices as much as possible and to collect enough data, they must follow a track with the four types of partners (the order is chosen randomly). Each partnership is passed twice (as illustrated in Figure 4) and participants swap seats halfway through.

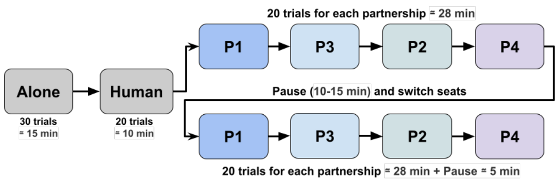

Figure 4: Representation of a passage. The order of the types of partners (P#) is chosen randomly for each dyad.

3.5 Participants

The participants were recruited through a process respecting the standard of experimental plans. Participants may be right or left-handed and must be free of any known visual or auditory deficits. To prevent possible effects on task performance, participants are paired in dyads consisting of people who have never worked together in a collaborative task. The minimum number of 40 participants has been established thanks to a G*Power 3 (Franz et al., 2007) analysis where the parameters are based on (Grynszpan et al., 2019) and are set to: $\alpha = 0.05$, Power ≥ 0.9 and an effect size $\simeq 0.5$.

44 participants were recruited during the campaign. Some technical problems with the 1D-SEMAPHORO resulted in data loss for 6 of them. Since the ability of the 38 participants to distinguish between short and long periods is essential for data processing, we monitor this throughout the experiment. Therefore, their given answers in **Alone** were sorted into two groups, depending on the correct time interval (700 ms or 1300 ms). If a t-test between the two populations of answers yields no significant difference in the means, the corresponding participant becomes an outlier and his/her data is excluded from the experiment campaign. By doing this, 3 participants were removed from the study, leaving a dataset of 35 participants.

3.6 Statistical Analysis

To summarize the statistical analysis carried out, we have 3 independent variables: *IV1:* the type of partner (4 conditions), *IV2:* the delay between the action and the sound (2 conditions) and *IV3:* the role of each participant during the interaction (2 conditions). The chosen dependent variables are: *DV1:* the absolute mean forces exchanged between partners, *DV2:* the implicit measure of the sense of agency and *DV3:* the explicit measure. It is expected that the association of these variables is relevant to analyzing the way physical cooperation is felt by humans when working with another human or with a robot.

On both implicit and explicit measures of the sense of agency, we conducted a 3-way repeated measures ANOVA to assess any effects. For the analysis of average interaction forces, as the Delay variable exerts no influence on the physical exchanges upstream, it was omitted as an independent variable, and a 2-way repeated measures ANOVA was conducted. Prior to analysis, normality and sphericity of the samples were assessed. Results indicated normal or near-normal distributions, as determined by Shapiro-Wilk tests. Mauchly's sphericity tests provided conclusive results for one variable and inconclusive results for others. When necessary, a Greenhouse-Geisser correction was applied to the ANOVA. In instances where significant effects were observed in our tests, pairwise comparisons were conducted using a Holm-Bonferroni correction.

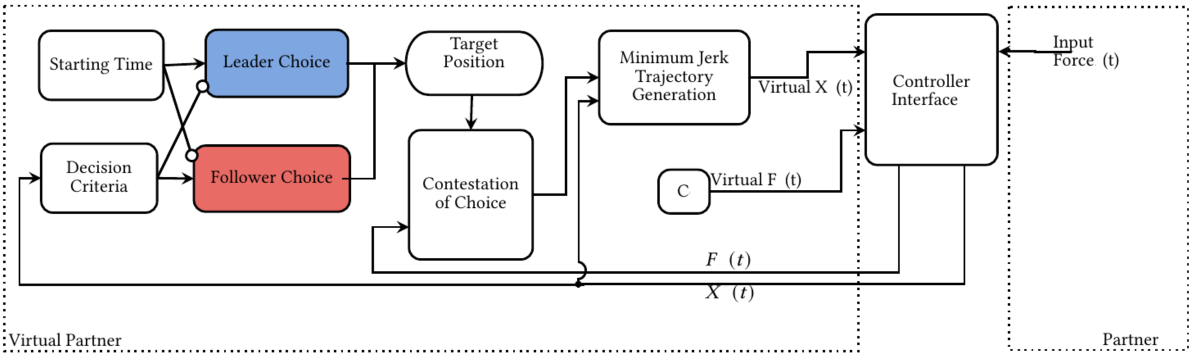

Figure 5: (Roche and Saint-Bauzel, 2021) Virtual Partner (VP) algorithm interacting with a Human partner. F(t), X(t), Virtual F(t), and Virtual X(t) are respectively the force and position of the human and the VP. The difference between *Robot noFB* and *Robot FB* lies in the value of Virtual F(t) ($C = 0N$ for *Robot noFB* and $C = \pm 0.3N$ for *Robot FB*.

4 RESULTS

4.1 Force Analysis

The analysis of the average exchange of effort focuses on physical cooperation to a strict definition. It presents several interesting results on the effects induced by the force bias and on human-robot cooperation. Figure 6 and the results of the statistical tests highlighted two major elements. Firstly, the results in *Robot FB* are slightly different from those of the other two groups and secondly, the average forces exchanged with the virtual partner are lower and more tightly concentrated on the mean than those between humans.

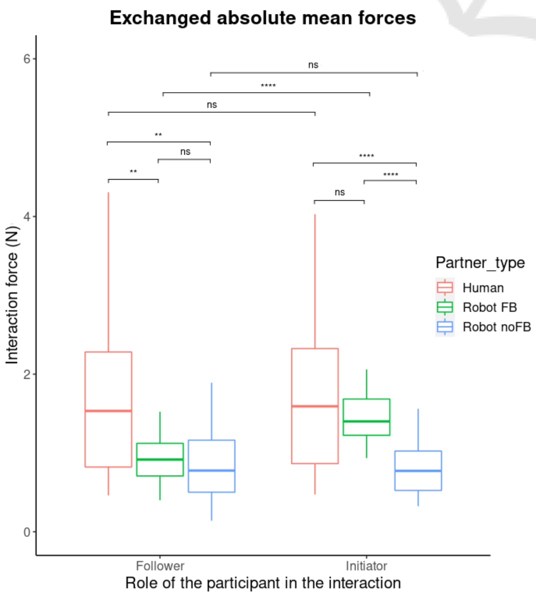

Figure 6: Boxplot showing the mean values of the absolute forces exchanged between partners.

Whereas *Human* and *Robot noFB* are invariant to the Role (respectively, t(1,34)=0.23, p=1.0 and t(1,34)=-0.69, p=1.0), *Robot FB* is not (t(1,34)=8.60, p<0.001). Moreover, while the mean exchange of effort of *Robot FB:Initiator* is close to that of *Human:Initiator* (t(1,34)=-2.27, p=0.18) and *Human:Follower* (t(1,34)=-2.16, p=0.19), the mean exchange of effort of *Robot FB:Follower* remains similar to that of *Robot FB:Initiator* (t(1,34)=-1.36, p=0.73) and *Robot noFB:Initiator* (t(1,34)=-0.33, p=1.0). The *Robot FB:Initiator* group demonstrates that the addition of a force bias significantly changed the nature of interactions beyond its own effect. Indeed, it is logical to observe an increase in interaction forces when a force bias is introduced. However, the force bias's magnitude is only $0.3N$, yet we observe a significant increase in average forces (t(1,34)=-10.18, p<0.001), around $0.7N$. This suggests that the light force bias has a direct effect on the overall interaction.

Although the incorporation of a force bias enhances interactions with the VP, its communicative capabilities remain constrained. The first constraint manifests in the significant variability of average effort within the *Robot FB* condition as a function of the Role, whereas outcomes in the *Human* condition indicate that Role should exert no discernible influence. Our observations during several passages revealed that participants tended to assume a dominant role in their interactions with the virtual partner, while their interactions with each other were more evenly distributed. This observation, in conjunction with our findings, suggests that our virtual partner elicits specific behavioral responses from participants: either the human participant assumes leadership, and the virtual partner resists or follows, or the virtual partner assumes leadership and the human adopts a passive-like demeanor, resulting in minimal resistance from him/her. The second limitation is evident in the disparity in variances between the *Human* condition and the other two groups. These two limitations underscore not a constraint of the force bias effect, but rather a limitation inherent in the virtual partner model employed. While our model accounts for the actions of the human partner in its decision-making process, its capacity to generate a range of efforts is overly restricted, necessitating modifications to the model.

4.2 Sense of Agency - Implicit Level

The ANOVA highlights the effect of the Delay on participants' time interval perceptions (F(1.34)=44,367, p<0.001). Indeed, neither the Role (F(1,34)=0.38, p=0.54) nor the type of partner (F(2,68)=0.98, p=0.38) had a significant effect. This result is quite surprising to us as it differs from that obtained in a previous experiment which was very similar (Grynszpan et al., 2019). In the latter, we observed a significant difference between the Human-Human group and the Human-Robot noFB group, which is no longer the case here with equivalent groups *Human* and *Robot noFB*. We believe that this difference is due to an overestimated effect size, resulting in a sample size too small to draw firm conclusions on this part of the results.

4.3 Sense of Agency - Explicit Level

The ANOVA on the feeling of control underlines the effect of the interaction between the Type of partner and the Role (F(1.69,57.53)=12.402, p<0.001).

Firstly, we observe that this feeling of control varies very little in the *Human* group in relation to the role assumed (t(2,69)=-1.72, p=0.63). A similar observation can be made for *Robot FB* (t(2,69)=0.78, p=1.0) but not for *Robot noFB*. The responses for *Robot noFB* showed a significant difference in the means with *Human* (t(2.69) = 3.67, p=0.005), and different variances depending on the role assumed by the participant. Moreover, the mean values for the *Human* and *Robot FB* groups are around 50%, while they are higher for *Robot noFB*. These initial observations highlight the effects of adding the light force bias, namely (1) reducing the standard deviation of responses, (2) making them independent of the role played, and (3) bringing the feeling of control with the VP closer to that with a human partner.

Refining the analysis according to each participant's role reveals slight differences in results. The *Table 1* shows similar trends for both roles, but with greater differentiation when the human initiates the group's first movement. Looking at our results, we believe that this difference is due to a large standard deviation in the *Robot noFB:Follower* group.

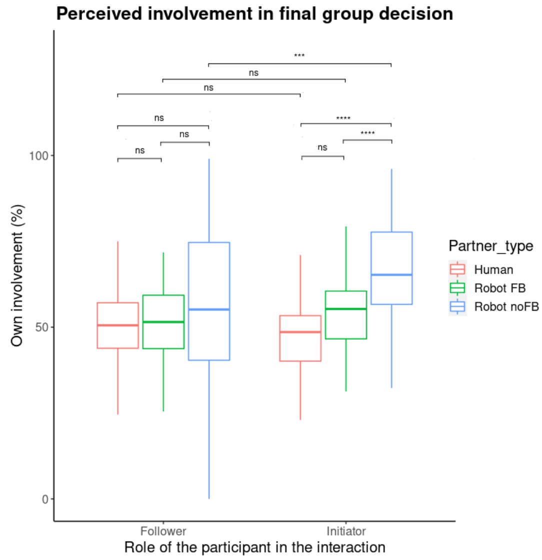

Figure 7: Boxplot showing the estimation of participants' level of involvement in group decisions.

Table 1: Main results of the posthoc test on participants' level of involvement in the group final decision.

Participant's role	Group 1	Group 2	t(2, 69)	Adj. p-value
Initiator	Human	Robot noFB	8.989	< 0.001
	Human	Robot FB	1.994	0.45
	Robot FB	Robot noFB	6.663	< 0.001
Follower	Human	Robot noFB	1.998	0.45
	Human	Robot FB	0.25	1
	Robot FB	Robot noFB	1.718	0.63

Our results show that the addition of a light force bias alone had a significant impact on the human partner's sense of agency. Indeed, the significant differences between the *Human* and *Robot noFB* groups were significantly reduced between the *Human* and *Robot FB* groups. Thus, constantly feeling a constant light force bias altered their perception of control.

5 DISCUSSION

The findings presented in this paper show that integrating a subtle constant force bias into physical interactions between humans and virtual partners slightly alters their exchanges, rendering them more akin to those observed in human-human interaction. Specifically, notable distinctions emerge when comparing virtual partners with and without this force bias across two dimensions: the explicit perception of agency and the magnitude of interaction forces. In both aspects, the virtual partner employing the force bias demonstrates outcomes more reminiscent of human interaction. These disparities underscore that the force bias not only influences the magnitude of forces exchanged between partners but also impacts the human's perceptual experience of interaction with their virtual counterpart.

Nevertheless, our observations underscore significant disparities between human-human and human-robot pairings, despite the presence of the force bias. Participants often exhibit dominance in interactions with the robot, albeit to a lesser extent when the force bias is active. Furthermore, instances where participants opt to follow the virtual partner are accompanied by a passive-like demeanor not typically observed in human-human interactions. Additionally, exchanges with virtual partners entail considerably smaller efforts compared to interactions between humans.

The effect of the force bias is highlighted through mean force exchanges and the explicit measurement of the sense of agency. However, no specific effect was observed at the level of implicit measurement. In a previous and similar work (Grynszpan et al., 2019), significant differences in implicit agency measurement were obtained between human-human and human-robot dyads. We believe two reasons explain this phenomenon. Firstly, the effect size of partner type on implicit measurement may have been overestimated, indicating a number of participants too small to draw any conclusion. Secondly, implicit agency measurement can be disrupted by the experimental framework. According to (Howard et al., 2016), this measurement requires a certain amount of cognitive resources, and when these resources are already engaged in another task, the measurement is disrupted and unreliable. Tasks capable of disrupting the measurement include memory exercises and light physical efforts (such as pulling on an elastic band). Our prior findings suggested that the efforts exchanged between the partners did not induce a substantial cognitive load capable of interfering with the implicit measurement of the sense of agency. However, our recent findings appear to support this assertion. This observation is also of interest as it underscores a potential angle of analysis of kinesthetic interaction that focuses on the cognitive load.

6 CONCLUSIONS

This study examines the impact of a consistent low-intensity force bias applied throughout dyadic kinesthetic cooperation. Findings indicate that the force bias fosters an interaction more akin to human-human engagement when the human initiates movement, generating forces comparable to those exerted by a human partner. These promising outcomes motivate further investigation into this force bias.

We propose that the physical connection between two humans mirrors a traditional communication channel, allowing a kinesthetic discourse between them. Building upon this premise, we intend to enhance the interaction capabilities of our Virtual Partner (VP) models by integrating elements of non-verbal communication from other languages. Through preliminary investigations into sign language, we have identified intriguing parallels between sign language and the kinesthetic communication channel. Certain components of sign language can be feasibly implemented in VP models by using a variable force bias. Subsequent works will delve into these modalities in greater depth and employ a methodology akin to the one utilized here to examine their impact on the physical interaction between humans and robots.

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