

Gesture coordination in collaborative tasks through augmented haptic feedthrough

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Abstract

This article explores the use of haptic feedback for interpersonal communication in Collaborative Virtual Environments. The investigated approach enables the improvement of communication and coordination during closely coupled collaboration presenting several communication constraints (e.g., large and complex environments, distant collaboration, etc.). After the presentation of involved communication mechanisms, we propose the investigation of a low level communication approach through a haptic feedthrough mechanism. This channel is used to communicate kinematic information about a partner's gestures during closely coupled collaboration. Several communication metaphors, with complementary behaviors, were investigated to improve the coordination between two partners during an assembly task. The results clearly show the role of the proposed strategies for the improvement of gesture coordination and highlight the correlation between applied force and the level of coordination.

Categories and Subject Descriptors (according to ACM CCS): H.5.3 [INFORMATION INTERFACES AND PRESENTATION]: Group and Organization Interfaces—Computer-supported cooperative work

1. Introduction

Nowadays, we can setup reliable Collaborative Virtual Environments (CVE) characterized by a stable and transparent haptic interaction between remote partners through manipulated objects [BHI93] [RI08]. However, with the deployment of CVE in new applications involving a close collaboration between distant experts or partners (collaborative design and assembly, military training, collaborative learning, remote surgical operations, etc.), new kind of problems and constraints arise, the most critical of which are probably the limits on communications between partners during collaborative tasks (e.g., manipulation of shared objects, reviewing, etc.). In fact, communication plays a strategic role during many exchanges between partners, for instance by supporting explicit and implicit direct exchanges between partners (e.g., oral dialog, gestural and emotional communication, etc.). At a higher level, it supports the awareness of the presence of others participants and the understanding of activities (Awareness) [CBY89]. All these exchanges enable the establishment and the maintenance of a shared background of understanding called common ground [Dix97]. Moreover,

they improve the coordination of gestures and actions of partners during closely coupled collaborations (e.g., manipulation of shared objects, overlapped tasks, etc.). Thus, the inhibition of some components of communication has a significant impact on the effectiveness of collaborative tasks and the relevance of the CVE.

This paper focuses on the improvement of action awareness between partners during closely coupled collaborations [Car03]. In fact, during collaborative tasks, people have to establish and maintain awareness of one another's intentions, actions and results during the manipulation of shared artefacts. Beyond existing communication and notification strategies in CVE (e.g., avatars, gesture guidance through virtual fixtures, static notification, etc.), we propose the exploration of new approaches for the augmentation of the natural exchange between partners through collaborative communication metaphors (see Figure 1). These metaphors will support some components of the activity awareness mechanism and extend a standard process with no accessible and abstract information to improve gesture coordination between partners. The proposed approach exploits the haptic

sensorial channel through the feedthrough communication channel [GLB05].

The paper is organized as follow. Section 2 presents a detailed review of the use of haptics in collaborative environments. Section 3 shows the limits of communication and awareness in CVE. Section 4 presents the proposed concept for the improvement of communication and awareness processes. Section 5 presents the experimental results and discusses the contribution of the proposed approaches.

2. State of the art

During human-human interaction, several levels of communication can take place according to the fulfilled task. These exchanges vary from high level communication, like written and spoken language, to the most elementary and implicit communication, like facial and gestural expressions. Although these several ways of communication are the subject of work in several fields of research, haptic communication hasn't received much attention. In fact, in usual tasks, the haptic channel conveys many social messages like hostility, level of intimacy, sexual exchanges or dependence [Col85]. Thereby, the haptic channel plays a strategic role in interpersonal communication.

Early work focused on the understanding of how two partners physically cooperate in common tasks like lifting and moving a bulky object, teaching manual skills, dancing, and handing off a baton or a drinking glass [PGG03]. Several studies were carried out to characterize the mechanisms of anticipation, coordination and reaction to each other's forces. In [SBFW03], Shergill et al. highlight the relationship between the perceived force and the level of communication amongst partners. They observe that when the transfer of forces is hindered, communication can be significantly diminished. Moreover, this work highlights the incidence of force escalation in collaborative work. In fact, when working cooperatively with a partner on the same task, each subject may want to contribute equally. However, self-generated forces are perceived as weaker than externally generated forces, which leads to an escalation in performance.

Reed et al. [Kyl07] carry out some work about the involved forces during collaboration. This work highlights the importance of the applied force in comparison with one user configuration and confirm the results of Shergill et al. [SBFW03]. Moreover, Reed et al. [Kyl07] identify two types of forces involved during collaboration. The first one is in opposition of partner's gesture (dyadic-contraction) and the second one is in cooperation. The dyadic-contraction has two roles. On the one hand, it allows the stabilization of the interaction during the collaboration, and on the other hand, it enables a communication between the two collaborators through a shared artefact (tools, objects, etc.). This research highlights the difficulty of understanding how the force and motion of two people combine during everyday collaborative tasks.

Thereafter, Glynn et al. [GFH01] carry out experiments to understand the type of information that can be communicated through haptic modality. These experiments show that the physical interaction between partners allows the communication of force and position simultaneously and without ambiguity, since the position information does not overlap the force information.

In [Gen05], Gentry et al. study how haptic interaction works between dancers. The physical connection in dancing is maintained through the follower's right hand holding onto the leader's left hand. This physical connection allows the leader to send messages to the follower allowing both partners to exchange energy. A good follower will keep her hand in the same position relative to her body, which enables the leader to communicate. Most of the communication is based on haptic cues even though the dancers can see each other, it thus allows an efficient coordination and fast synchronization of movements.

Basing on this observation, Sallnas et al. [SRGS00] and Basdogan et al. [BHSS00] demonstrate the role of kinesthetic feedback in the representation of a partner's movements for virtual assembly and manipulation tasks. Beyond the improvement of communication between partners, the haptic channel brings social presence into virtual and remote environments.

Several strategies for managing the simultaneous interaction of shared artefacts have been investigated. Early work concerns the design of airplane command. The proposed solution consists of averaging orders coming from the pilot and the copilot [SSWS87]. However, it gives mitigated results in terms of performance. Thereafter, several works proposed a direct coupling between collaborators through a rigid or flexible interconnection. Hannaford et al. [SH07] propose the exploitation of several connection schemes including virtual coupling mechanisms to ensure the connection between remote partners. The aim is to ensure position coherence between remote representations. However, we can consider these approaches as a mean for managing interaction between two partners with several levels of priority (symmetric or asymmetric priority).

Beyond the simultaneous interaction between partners, some work further explores methods for the simultaneous access to shared objects. These approaches define a priority strategy according to the role of each partner and the structure of collaboration. MacLean et al. [CMM08] propose a set of vibrotactile perceptions indicating to partners the several states of control (who control the object). These perceptions concern (1) request for control and loss of control, and (2) the gentle and urgent request for control. These perceptions concern both users with current floor control and users who have made requests. It consists of assembling elementary haptic icons.

3. Limits of communication and awareness in CVE

During synchronous collocated collaboration, several exchanges take place between partners. These intuitive exchanges can be conscious or unconscious and can be classified according to two main levels of communication [Gut99]:

Direct communication is the most common and natural way to communicate between participants. We can distinguish two levels: (1) explicit communication (e.g., oral and verbal communication, etc.) and (2) back-channel feedback communication (e.g., gesture, emotion, vocal activity, etc.).

Feedthrough It concerns implicit information delivered to several users reporting actions executed by one user. This communication occurs between participants through shared artefacts. In fact, each action or manipulation of artefacts implicitly informs the other partners about the evolution and modification of the environment. Thus, artefacts are not only a tool or a support; but also a mediator for communication. Feedthrough is essential to provide group awareness and to construct meaningful contexts for collaboration.

On the basis of these exchanges and communication mechanisms, the collaborative work involves an abstract and non-observable dimension: awareness. This process is the ability to be conscious of the presence of other participants and to understand their activities. With this consciousness, each participant can adjust and plan their behavior based on what they know of each other. The awareness process exploits standard communication mechanisms, through the several sensorial channels (visual, haptic, auditory), and has three main functions:

- The collective economy of movement and action through peripheral vision and understanding of the other participant's movement and gesture. This function is very useful for tasks that involve a close collaboration of partners.
- The need for non-intrusive communication through the understanding of the peripheral environment.
- The need to avoid collisions and conflicting actions in the shared space.

Beyond static information (e.g., social structure, partners' states, etc.), awareness concerns dynamic knowledge of colleagues' activities and actions. Carroll et al. [Car03] highlight two levels of dynamic components:

Activity Awareness refers to the knowledge that a person has about: creation or changes to shared plans, evaluations, or rationale; the assignment or modification of project roles; task dependencies based on roles, timing, resources, etc.; exception handling. It is an answer to questions like "How are things going?".

Action Awareness refers to the knowledge that a person has about: timing, type, or frequency of collaborators' interactions with a shared resource; location and focus of

collaborators' current activity. It is an answer to questions like "What is happening?".

If collaboration in the real environment exploits these mechanisms effectively, the use of CVE introduces some limitations on natural and intuitive communication process and inhibits some conscious and unconscious exchange mechanisms (gestural, emotional, etc.). We identify two main categories of constraints related to CVE and VR:

Distance to virtual environments this level of constraint concerns the distance between users and the virtual environment. In fact, natural interaction on real artefacts involves a geometrical superposition between gestural interaction and corresponding visual feedback. However, usual VR technologies create a distance between users (real end-effectors, haptic arm, hand, etc.) and manipulated artefacts (e.g., virtual end-effectors, virtual artefacts, etc.), which constrains and inhibits several inter-referential communication and awareness mechanisms (e.g., designation/indication of ROI, collaborative selection, etc.). In addition to this constraint, we can identify other VR limitations like time delays between actions and corresponding feedback (visual/audio/haptic updates) and the limits of rendering metaphors (efficiency of collision detection, limits and constraints of stereovision rendering).

Distance between partners natural close collaboration involves the simultaneous presence of several partners in the same physical environment, which enables the establishment of natural communication process. However, CVE can present real or virtual distance between partners. The real distance comes from the non-collocated collaboration that results when partners work in different physical environments. The virtual distance concerns collaborations occurring in large or complex virtual environments. In fact, applications like molecular manipulation or computational fluid dynamics involve complex environments with large dataflow to analyze and with multiple degrees of freedom (DoF) to manipulate. Thus, several potential collaborative tasks (deformation of molecules, assembly of molecules) can involve simultaneous manipulations of large artefacts (e.g., manipulation of large molecular structures, manipulation of two molecules, etc.); or requiring an important focus of users' resources on the current activity and action (perception of complex environment, control of several DoF, etc.) with less resources for communication with partners (direct communication, awareness).

Thus, these two levels of constraints have a direct impact not only on the implicit and explicit communication process (e.g., gestural communication, emotion on face, feedthrough communication, etc.) but also on the several levels of awareness (static and dynamic components). The consciousness of the presence of other partners and the understanding of their activities becomes a very difficult task. This has a direct consequence, on one hand, on the grounding and understanding

processes, and on other hand, on the coordination of actions and gestures during closely coupled collaboration. Thereby, the efficiency of collaborative work in CVE decreases significantly.

Beyond available tangible information in common real collaborative tasks, efficient collaboration in CVE requires an adapted communication framework suitable for fulfilling the task either by (1) filtering the existing communication, in order to improve the focus on individual tasks, or by 2) augmenting the existing communication framework with abstract or inaccessible information which are important for an efficient accomplishment of global collaborative tasks (e.g., coordination, etc.).

All these constraints coupled with the potential of virtual reality lead us to propose a new approach to improve collaboration and coordination between partners in CVE through adapted communication metaphors. Unlike virtual reality metaphors that concerns information about the environment and tasks' constraints (e.g., sensorial metaphors, virtual fixtures, etc.), the proposed concept provides an intuitive representation of information related to the partners' actions, activities and states.

4. Improvement of awareness and communication

Direct communication exploits natural languages (e.g., semantic, syntax, etc.) and conveys complex information with a high level of abstraction. The required perception, interpretation and motor reaction mechanisms are complex. Moreover, this communication level involves important cognitive efforts and important processing time delays [PGG03]. Furthermore, this level of communication is characterized by direct information transfer without a physical medium (shared artefact).

On the contrary, the feedthrough mechanism, beyond the stabilization of interaction between partners, supports mainly simple physical information with a low level of abstraction like directions, forces, positions, etc. The interpretation and reaction process for feedthrough events and information are the same as for standard haptic perception and interaction (with real or virtual environments) [CMM08] and thus inherits all of the psychophysical behaviors of the standard haptic channel (reactivity, local perception, temporal integration of information, etc.). Thus, in addition to standard perception, feedthrough enhances standard interaction with a new source of perception corresponding to a partner's actions and states.

4.1. Improvement of feedthrough

Even though feedthrough is an important channel for indirect communication, it only conveys, in the real environment, a limited class of elementary tangible information about a partners' activity (direction, position, velocity, applied force, etc.). Moreover, the natural and real mechanism

(in everyday tasks) of feedthrough rendering is not necessarily optimal. Thus, in the virtual environment, conventional rendering of feedthrough exchange can sometimes be incompatible with some constraints of the partner's gesture (direction, perturbation, etc.) or with some other perception of data in the virtual environment (superposition of several similar perceptions, etc.). The exploitation of feedthrough in virtual environments allows us to go beyond the constraints of the real environment: 1) limited communication and 2) incompatibility with other perception. In fact, beyond conventional and accessible information, it would be interesting to convey more information about the current actions and activities between partners. This information can be standard, abstract or not directly accessible (change of direction, delay between actions, distance, acceleration, etc.). Moreover, the sensorial rendering of this information can be adapted according to the several involved constraints (e.g., several perceptions, manipulation, etc.). Thereby the role of this additional information is to improve the interaction through an enhanced perception of the artefact's states.

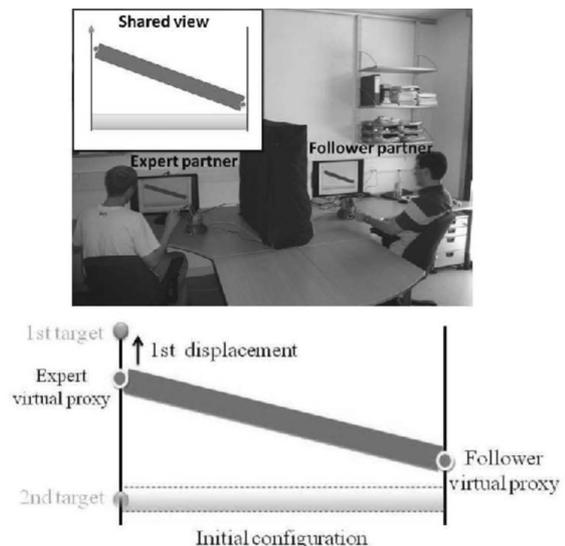


Figure 1: The investigated 1DoF assembly task: the expert participant is asked to reach a series of targets (high/low), and the follower participant follows the expert

We can summarize the objectives of the improvement of standard feedthrough in the following points:

- Augmentation of standard communication with new and additional information. This information can be standard, abstract or inaccessible data.
- Improvement of the rendering of existing and augmented information with efficient communication metaphors.

In this paper we propose the investigation of assembly tasks by focusing on gestures' coordination for 1DoF movement (Figure 1). In fact, before the generalization to the

3DoF environment, it's important to understand and improve basic coordination mechanisms pertaining to 1DoF activity.

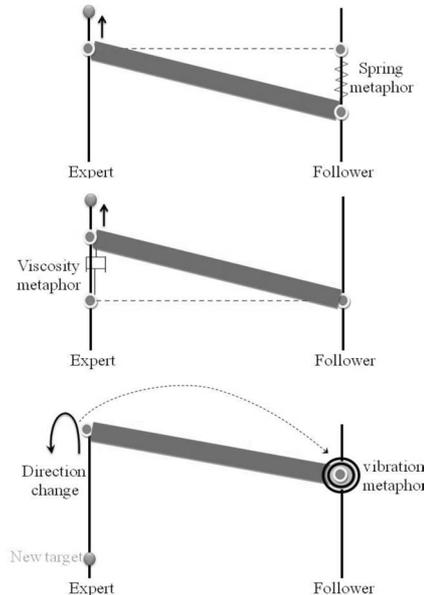


Figure 2: Proposed communication metaphors: (1) spring, (2) viscosity and (3) vibration

4.2. Augmented information

Since the focus of this work concerns the coordination between the partners' gestures, we consider in this study only the communication of some kinematic information, namely: position and velocity. Thus, gesture coordination consists of reducing the position and velocity differences between the two partners. We propose the following strategies:

Position Communication of the difference of positions between the assistant (follower) and the expert. When the distance between the two partners reaches a certain value, some qualitative information are sent to the follower (important difference, weak difference, etc.).

Velocity

- Communication of the difference of velocity between the two partners. When the velocity of the main expert exceeds that of the assistant, the expert is informed about a qualitative difference between the two velocities (relative velocity).
- Communication of the change of the movement's direction. When the expert changes the direction of movement, a quick signal informs the assistant (follower) about the switch of direction.

4.3. Communication metaphors

The augmentation of feedthrough with this new kinematic information must be enhanced by a suitable and an intu-

itive rendering. Different strategies presenting several levels of abstraction can be used for this rendering. MacLean et al. propose in [CMM08] the exploitation of a set of haptic icons to request and indicate to partners several states of control. This level of communication presents an important vocabulary and therefore can be used to render a lot of information. However, this level of communication requires an important learning step before an efficient understanding and use. This communication strategy requires also important cognitive processing that reduces the reactivity of users to some fast events or information presenting a high temporal dynamic (nanoworld force, important acceleration, etc.). Thus, this communication strategy is more adapted to render information presenting limited static states or information pre-setting a very low frequency bandwidth (standard dialogue, group states, etc.). For tasks requiring an important dynamic with fast gestures, greater reactivity is required. Therefore, it is necessary to exploit elementary and intuitive haptic representations. This haptic feedback should not require substantial cognitive processing and can use reflex mechanisms. We can summarize the requirements for haptic stimuli in the following points [EMC06]:

Differentiable All stimuli must be distinguishable from one to another when presented either alone or in any used combination.

Identifiable Once a meaning has been associated with stimulus, it must be easy to remember.

Learnable The associations between meanings and stimuli should be intuitive and easy to learn.

Reactivity stimuli must correspond to great reactivity and presents a low cognitive load for understanding.

Among the several haptic rendering approaches, perceptions based on elementary physical forces (friction, viscosity, etc.) are good candidates to address these constraints. In fact, human user are accustomed to interacting intuitively, and with a good reactivity, with environments presenting everyday physics forces. Moreover, the understanding of these perceptions requires only a short period of learning, mainly for the association between these physical representations and corresponding events and gestures (meaning) [AF07]. We develop in the following sections the proposed haptic rendering (Figure 2).

Communication of the difference of positions The most intuitive model to map the difference of positions onto force is a spring model. In fact, the rendered force through this model is directly proportional to the elongation of the spring (distance between the two ends).

Communication of the difference of velocity If the spring model expresses a direct relation between distance information (or position) and resulting force, the viscosity model produces a force proportional to the gesture velocity. The generated force is opposed to motion that tends to slow the movement. Thus, this model is more adapted to render a difference of velocity between the two part-

ners. Moreover, it plays the role of dynamic virtual fixtures, limiting the relative velocity.

Communication of the change of direction In a real environment, haptic warning is usually the result of a physical impact with the environment or with another partner. Beyond this representation, and for several technical constraints and ergonomic recommendations (interfaces portability, actuators technology, etc.), haptic warning is displayed, in the virtual environment (collision, forbidden regions, etc.), with success through vibrotactile signals.

5. Experiments and evaluation

We performed several experiments to evaluate the contribution and the complementarity between the different communication metaphors. Four experiments were carried out for a 1DoF collaborative manipulation:

- The first experiment (Exp. 1) corresponds to the native configuration without augmentation of feedthrough.
- The second experiment (Exp. 2) concerns the communication of the difference of positions through a spring metaphor. This information concerns the follower partner.
- The third experiment (Exp. 3) concerns the communication of the difference of velocity through a viscosity model (in addition to using spring metaphor). This information concerns the expert partner.
- The fourth experiment (Exp. 4) concerns the communication of the change of direction of the main expert. This information is communicated to the follower partner through a vibration metaphor (in addition to spring and viscosity metaphors). This information concerns the expert partner.

5.1. Hardware and software setup

The collaborative platform is based on a client-server architecture [Dix97]. The server node supports the main physical simulation and haptic calculation modules. The clients' nodes support the graphics and haptic rendering modules. The several nodes are connected through a local network without significant time delay (< 50 ms). The physical calculations are based on ODE (Open Dynamics Engine). This software is an open source high performance library for simulating 3D rigid body dynamics [HG03]. The haptic module generates the haptic communication metaphors on the basis of the 3D physics engine and the partners' kinematic information (positions, velocity, etc.). The clients' nodes display the 3D scene, on desktop screens (24 inch) with an OpenGL based graphic module, and render the calculated communication metaphors with Omni haptic arms (Sensable) through the OpenHaptics library.

5.2. Procedure

Virtual Collaborative Tasks The investigated assembly task includes two components (Figure 1): (1) a mobile component and (2) a fixed component.

The mobile component is modelled by a rigid link (line) between the two virtual proxies. This link supports the usual haptic interaction and the feedthrough between partners. The base (fixed component) is modelled by a static line on which the partners will set the mobile component. The task is carried out in a 2D space ($X - Y$) and the movement of the partners is constrained according the Y axis through a virtual fixture.

During 30s, the expert participant is asked to reach a series of 12 sequential targets aligned with the Y axis (Figure 1). The follower partner must follow and coordinate his movement with the expert (minimization of position and velocity differences). The follower participant uses the visual indicators (e.g., artefact tilt) and the feedthrough information (e.g., tension force).

Communication between Partners During the experiment, the two subjects were located in the same room but were unable to see each other. Only verbal communication was allowed between them (see Figure 1). The two partners did not meet, speak to or see each other prior to the experiment. Each subject had a personal haptic interface and an LCD monitor.

Measures We collected several measures including execution time, position difference (error in position) and the sum of applied force on master and slave arms. These measures concern the expert and the follower partners. In addition to these objective measures we asked the participants about their global appreciation for the several proposed communication metaphors.

Participants 14 participants (10 male, 4 female; age range from 20-45 with median 27) took part in this study; most were university graduate students in Computer Science. Each experimental configuration was executed in a block of 10 trials (two partners for each configuration).

5.3. Results and discussions

We ran an ANalysis Of VAriance (ANOVA) for the four configurations (native configuration and for the three communication metaphors) according to three factors: (1) position error, (2) applied force at the master arm (3) and applied force at the slave arm. The analysis revealed a significant effect of spring (Exp. 2 / $p = 0.011, p < 0.05$) and vibration (Exp. 4 / $p = 0.03, p < 0.05$) metaphors for the position error factor. There was no significant effect of the viscosity metaphor (Exp. 3) ($p > 0.05$) on the position error factor.

For the applied force factor, the ANOVA analysis reveals a significant effect of the viscosity metaphor (Exp. 3

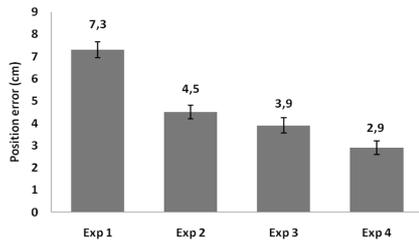


Figure 3: Mean position error between the master arm and the slave arm in the fourth experiments

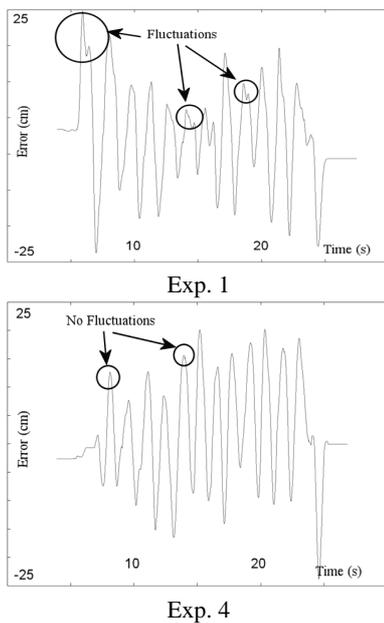


Figure 4: Position error between the master and slave arms in Exp. 1 and Exp. 4

$p = 0.017, p < 0.05$) on the applied force at the master arm and a significant effect of the spring metaphor (Exp. 2 / $p = 0.035, p < 0.05$) on the applied force at the slave arm. There was no significant effect of the other metaphors on the applied force at the master and slave arms ($p > 0.05$).

Figures 3, 5, and 6 summarize the results. Figure 3, shows a clear decrease of position errors between the two partners according to the several communication metaphors. We observe that the spring metaphor (Exp. 2) introduces a significant reduction in position error. In fact, the spring effect plays the role of a guidance tool which helps the follower partner to reach easily the "Y" configuration of the expert partner.

The viscosity metaphor (Exp. 3) introduces a less significant error reduction compared with Exp 2. This metaphor acts on the velocity factor by slowing the gesture of the ex-

pert partner which enables the follower partner to more easily follow the assembling movement.

Finally, the vibration metaphor acts mainly during the change of movement direction (expert partner). In fact, during this step, the dyadic-contraction decreases substantially which reduces the feedthrough between the partners and decreases the level of coordination. Moreover, we observe some gesture fluctuations during this step (Figure 4.Exp. 1). Thus, the vibration metaphor informs the follower partner about the event when the expert stops his movement. The spring metaphor acts in a second time as a reinforcement in order to improve the coordination between the partners. Figure 4.Exp. 4 shows the improvement of the follower reactivity and the level of coordination between the partners.

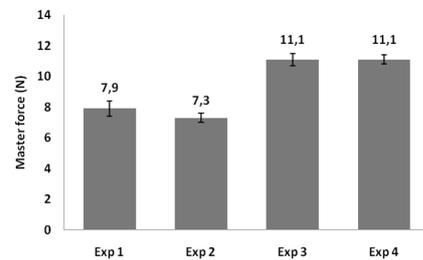


Figure 5: Mean applied force at the master arm in the fourth experiments

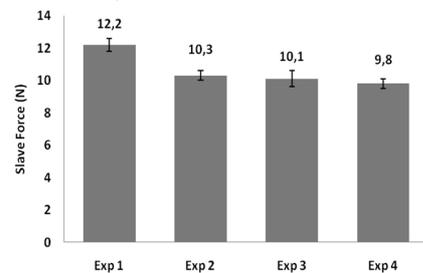


Figure 6: Mean applied force at the slave arm in the fourth experiments

Figure 5, and 6 show the evolution of the mean force applied at the master and slave arms according to the several communication metaphors. We observe that the spring metaphor greatly reduces the force applied at the slave arm and slightly less at the master arm. In fact, the improvement of the coordination between the two partners reduces the stabilization component of the dyadic-contraction. The viscosity metaphor greatly increases the force applied at the master arm. In fact, the viscosity force has an opposite direction to the master movement which slows the gesture and adds an additional component to the current applied force. Finally, the vibration metaphor has no significant impact on the force

applied on the slave and master arms. This metaphor has a tactile effect without a kinesthetic component.

On the basis of these results we can conclude that the proposed communication metaphors greatly improve coordination during closely coupled collaborations. The proposed approach enables a dynamic and continuous communication of several types of kinematic information. These metaphors act, on the one hand, on the coordination of position and velocity between partners, and on the other hand, on the applied force by the involved partners. Beyond the improvement of coordination, it is necessary to take into consideration the applied force factor. In fact, long collaborative tasks can be penalized by partner fatigue. For these configurations, we propose the exploitation of spring and vibration metaphors which slightly reduce the applied force.

6. Conclusion

This paper explores the communication channel of haptic modality through feedthrough mechanisms. Several communication metaphors highlight the potential of feedthrough to convey kinematic information about partner gestures. The spring metaphor acts on the coordination of partners' positions. The viscosity metaphor improves coordination of partners' velocity and finally the vibration metaphor plays an important role during the change of direction between the gestures of the two partners. Furthermore, the results highlight the impact of these communication metaphors on the applied force by the two partners. If the spring metaphor reduces the applied force at the slave arm, the viscosity metaphor substantially increases the involved force at the master arm. Thus according to the required level of coordination and the specifications of the collaborative tasks (accuracy, fatigue, tasks durations, etc.) it is necessary to integrate the most suitable combination of communication metaphors.

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