Human-human physical interaction in the joint control of an underactuated virtual object

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***Abstract*— Human-human physical interaction has proven to be advantageous especially in contexts with high coordination requirements. But under which conditions can haptic communication bring to performance benefits in a challenging cooperative environment? In this work we investigate which are the dynamics that intervene when two subjects are required to switch from a bimanual to a dyadic configuration in order to solve a complex reaching and stabilization task of a virtual tool in the presence of an unstable dynamics. Results show that dyadic cooperation can improve the performance respect to the individual condition, while minimizing the effort. However, in the joint task, when the stiffness of the system becomes harder to manipulate the feedback delays appear to be critical in determining the maximum achievable level of performance.**

I. Introduction

Physical interaction is essential for learning about the world and shaping our behavior. Very often our everyday life brings us to interact with others either constructively, as in dancing or handling bulky objects, or disruptively, as when fighting in a scuffle or in a 'tug of war' game. In the last decade there has been a growing interest in studying physical coupling between humans. In particular, it has been found that haptic interaction with a partner leads to a better performance than individuals in tasks like fast reaching movements [1], tracking a moving target [2], and actions relying on force control [3]. Interestingly, it seems that the presence of a human partner and specifically his/her reactions are essential ingredients for inducing performance benefits [1], [2]. This observation leads to the hypothesis that the haptic channel can enhance the sharing of intentions between the two partners at an implicit level. Indeed, it has been found that mutual haptic feedback can enhance the process of intention integration [4]. Moreover, physical interactions are consistently beneficial to the interacting individuals and enable them to improve their motor performance both during and after interactive practice [2]. This makes dyadic interaction extremely appealing from a motor learning perspective, since the use of paradigms that promote dyadic motor adaptation can be of great advantage during rehabilitation and training. However, it is not yet clear how dyadic physical interaction shapes motor adaptation to bring to an improvement of the overall performance. It has been shown that there is a general tendency towards a non-equal dominance distribution and that the interacting partners benefit from role distributions which can be associated with different energy flows [5]. A recent and very interesting experiment that compared bimanual versus dyadic coordination in a pole balancing task suggests that dyads amplify their forces to create a haptic information channel. Indeed, dyads could solve the balancing problem by producing much more overlapping forces than individuals performing the task bimanually, especially when coordination requirements are higher [6].

In this work we aim at investigating how skill transfer and adaptation occur when two subjects are required to switch from a bimanual to a dyadic configuration in order to solve a complex reaching and stabilization task of a virtual mass in the presence of an unstable dynamics. Several authors investigated skill transfer from a bimanual to single-limb configuration [7]–[9] and reported that bimanual training is beneficial to unimanual performance, even if the transfer is in general incomplete [10]. These studies support our hypothesis that subjects trained in a bimanual paradigm are able to transfer the skills acquired to the new cooperative environment. Previous studies generally used to rigidly couple the partner's limbs [5] or make the subject perform a single task together. Similarly to [2], in our design the compliance of the interconnection between the hand and a virtual object allows each subject to choose their own motion independently from the partner. However, in this case no direct link exists between the two cooperating subjects and they experience the interaction forces indirectly through the motion of the controlled object.

We believe this design to be very interesting for several reasons. Firstly, the presence of an anisotropic force field and saddle-like instability make the problem of timed coordination essential. Secondly, this task forces the subject to finely tune his motor output in response to force perturbations to contrast the instability. We have previously demonstrated that, despite the task being very challenging for a naïve user, it supports the learning of two specific different patterns of bimanual coordination that solve the balancing

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problem [11], [12]: a high stiffness feedforward strategy and a low stiffness positional feedback strategy. In this work, we analyze how these two patterns accommodate in the case of a dyadic configuration and test whether it allows for performance advantages compared to a bimanual scheme.

II. Methods

A. Experimental setup and Task description

Each of the two subjects (M, 29 y; F, 27 y) stood in front of a screen and grasped the handle of two identical planar robotic manipulanda [13] in a mirror configuration, as shown in Figure 1. The height of the robotic arm was adjusted to keep an angle of approximately 90° between the arm and the bent forearm while moving on the horizontal plane. The vision of the arm and screen of the other participant was obscured by a vertical panel that acted as a divisor, while each subject could see his own arm and received visual feedback of both. The task consisted of bringing a virtual mass (green circle, 1 cm diameter) into a target area of 2 cm of diameter (grey circle) and to subsequently maintain this condition for 4 s. For doing so, each subject had to control the motion of the mass by stretching a non-linear elastic linkage joining his hand with the mass itself. The device provided each subject with the haptic feedback of the applied elastic force. No direct haptic coupling existed between the two of them. Moreover the virtual mass was immersed in an unstable saddle-like force field that affected its dynamics, as described in the following subsection.

B. Force Field design

In order to provide the subject with novel dynamical conditions that make him/her naïve to the task, we designed a saddle-like virtual force field as in [12], centered in the origin of the workspace (x_0, y_0), with the unstable manifold aligned with the x-axis and the stable one aligned with the y-axis as follows (K_u = 592 N/m):

$$\vec{F}_u = \begin{bmatrix} +K_u & 0 \\ 0 & -K_u \end{bmatrix} \begin{bmatrix} x - x_0 \\ y - y_0 \end{bmatrix} \tag{1}$$

The subject had to indirectly control the position of a virtual mass immersed in the force field. For doing so he/she could modulate the force transmitted to the mass by means of two non-linear springs attached both to the hands and the mass. The generated elastic force is the sum of a linear and a quadratic elastic contribution as in the following equation:

$$\begin{cases} F_1 = K_s L_1 + 2\rho_s L_1^2 \\ F_2 = K_s L_2 + 2\rho_s L_2^2 \end{cases} \tag{2}$$

where L is the distance between the hand and the mass, K_s = 148 N/m and ρ_s = 1480 N/m^2 are the spring parameters. We called the hands-springs-mass system Virtual Underactuated Bimanual Tool (VUBT) and its dynamics can be described by (3):

$$M \frac{d^2\vec{p}}{dt^2} + B\frac{d\vec{p}}{dt} = \vec{F}_u(\vec{p}) + \vec{F}_1(\vec{p}, \vec{p}_1) + \vec{F}_2(\vec{p}, \vec{p}_2) \tag{3}$$

where M = 15 kg is the mass of the tool, $\vec{p}$ its position; $\vec{p}_1, \vec{p}_2$ are the hands position vectors; $\vec{F}_1, \vec{F}_2$ are the forces of the two springs; B = 132 Ns/m is the coefficient of the viscous component of the force field. Given the VUBT dynamics in (3), the equivalent stiffness of the tool can be computed from the total force acting on the virtual mass as in (4):

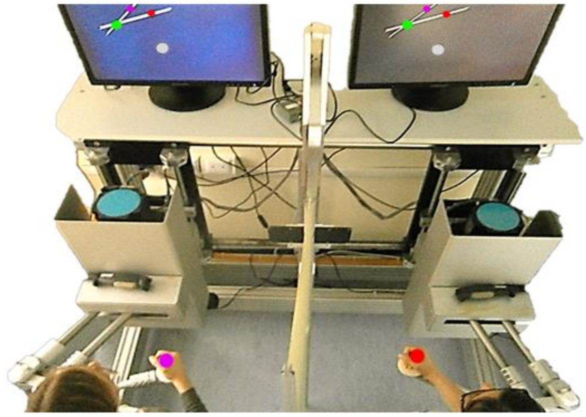

Figure 1. Experimental setup. The green circle (2 cm diameter) represents the virtual mass (1 cm diameter); the red circle and the purple circle represent respectively the position of the right and the left robots' end-effector connected to the virtual ball by the two elastic linkages colored in gray; the gray circle is the target area (2 cm diameter).

$$K_{VUBT} = \begin{bmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{bmatrix} = \frac{\partial \vec{F}}{\partial \vec{p}} \tag{4}$$

Saha et al. [12] demonstrated that, if the falling time constant of the mass dynamics is not too fast (about 0.3 s), users can deal with the instability of the task by applying two distinct strategies:

- **Stiffness Stabilization Strategy (SSS)**, in which the user exploits the elastic properties of the tool and increases the tool stiffness by stretching the springs apart horizontally. In this way, the equivalent stiffness of the tool is oriented along the instability and the user can make use of a direct implicit positional feedback from the muscles and the tool's elastic properties.
- **Positional Stabilization Strategy (PSS),** in which the subject controls the position of the mass by overlapping the two hands stretching the springs intermittently by the same amount through event-driven bursts. The stiffness of the tool has no preferred orientation and the positional feedback is explicit, thus delay-affected.

The two strategies also differ in terms of effort. The elastic properties of the linkages in conjunction with the force field characteristics make the SSS disadvantageous, since it involves the coactivation of agonist and antagonist muscles. The PSS allows for a halved effort level at the expenses of reactivity due to the smaller bandwidth.

C. Experimental Protocol

Following the results of [11], previously to the beginning of the present experiment two subjects (E1, E2) had been trained to become expert users of the bimanual tool in the two aforementioned strategies for 14 sessions on 7 days, 2 sessions per day. Consecutive sessions were no more than 2 days apart. The training paradigm consisted of reaching and stabilizing for 4 s the virtual mass inside 9 different circular target regions distributed in the origin of the workspace and on the periphery of a circle of 8 cm diameter around the center. In every session the subject had to perform 24 reach-and-stabilize actions (12 center-out movements and 12 return movements) in the presence of the non-linear perturbing dynamics, first by using the SSS and then by applying the PSS. Once the two subjects became proficient in performing the exercise, they performed a shorter training of 7 sessions as a dyad following the same protocol as for the individual training. Both subjects practiced using their right hand.

D. Outcome Measures

We quantified both the individual and dyadic performance before and after the training in terms of effort and stabilization proficiency. Therefore we computed the following indicators:

- **Effort index (*EI*) [N]:** it measures the average total force required for stabilizing the virtual mass (F_1+F_2).
- **Time to target (*TT*) [s]**: it corresponds to the time interval from the deactivation of the previous target to the last time the tool-tip enters the current target area before its successful stabilization.
- **Mean amplitude of the Velocity Peaks (*MVP*) [cm/s]**: it is computed during the 4 s stabilization phase as the mean amplitude of the peaks of the virtual mass velocity that exceed the 80% of the mean speed and are at least 200 ms apart.

In order to evaluate dominance mechanisms and the degree of cooperation, we evaluated two following indicators:

- **Mean Effort Difference [%]:** it is computed as the difference in the average mean force applied by the two subjects in a session normalized to the mean total effort. In the case of the subjects performing the task bimanually it is computed as the ratio $E[F_{RIGHT}-F_{LEFT}]/E[F_{RIGHT}+F_{LEFT}]$; in the case of the dyad as $E[F_{E2}-F_{E1}]/E[F_{E2}+F_{E1}]$.
- **Hand Synchronization index [s]:** it estimates the maximum average synchronization delay in the speed profiles of the two end-effectors. It is computed from the cross-correlation functions obtained sliding a window of 150 ms on the speed profiles in steps of 100 with 50 ms of overlap. The mean synchronization in a trial is computed as the average of the distance between the maximum of each cross-correlation function from the center of its window. Zero delay means perfect synchronization. Positive values identify a delay of the left hand profile with respect to the right one (or in the dyadic case E1 falls behind E2). To obtain the mean maximum delay in a session, we computed the standard deviation from the mean value in each trial and we averaged the values over the trials.

E. Statistical Analysis

To test if the training was beneficial to the dyad, we performed a repeated-measure analysis of variance ($\alpha = 0.05$) considering the target directions as fixed effect and sessions as a within factor. Whenever the sphericity condition, assessed through the Mauchley sphericity test, was not met, we used the adjusted p-value and F-value according to the Greenhouse-Geisser correction (p_{G-G}). We reported all the values in the Results section as the mean value and we used their standard deviation to measure the dispersion.

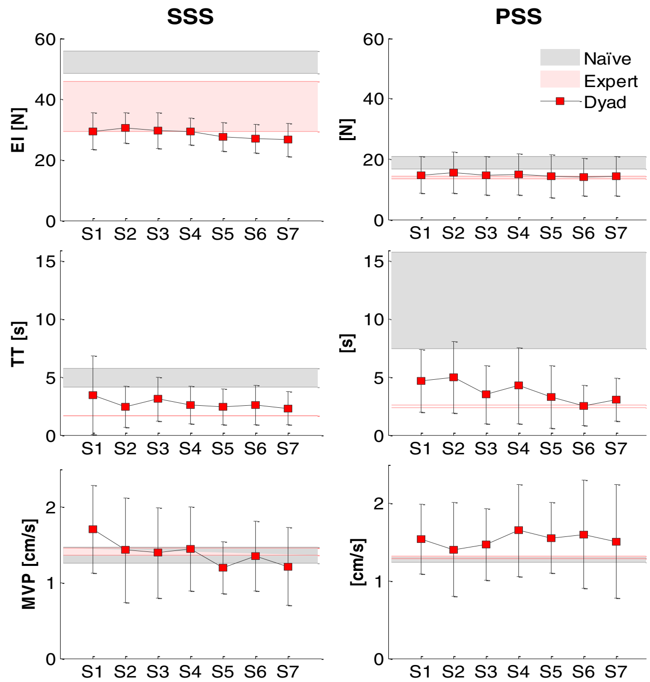

Figure 2. Mean dyad performance indicators along the 7 training sessions. Vertical bars represent the standard deviation; red squares are the mean values over the trials in every session. The dyad performance is compared against the mean performance of the same subjects in the naïve (grey area) and the expert (pink area) condition.

III. RESULTS

Figure 2 shows the performance of the dyad compared to the individual performance of the two subjects in the naïve (grey area) and in the expert condition (pink area). Let us consider the SSS condition first (left panels). At the beginning of the training the dyad generally performed much better than in the average naïve condition as for the *EI* (naïve: 52.15 N; dyad S1: 29.41±6.13 N) and *TT* (naïve: 4.96 s; dyad S1: 3.45±3.43 s), but was less accurate in stabilizing the virtual mass position inside the target area (naïve: 1.36 cm/s; dyad S1: 1.71±0.58 cm/s). The repeated measure analysis highlighted a significant reduction in the mean employed effort with practice (p_{G-G} = 0.033, $F(3.39, 50.93)$ = 3.00). Indeed, in the last session, the dyad outperformed the experts in terms of mean effort (expert: 37.55 N; dyad S7: 26.51±5.52 N), while being on average slower in reaching the target (expert: 1.67 N; dyad S7: 2.32±1.42 N). Moreover, the minimization of the effort did not penalize the dyad in the stabilization phase, since the mean MVP indicator was the lowest in the end of the training (expert: 1.41 cm/s; dyad S7: 1.21±0.51 cm/s).

As for the PSS, the indicators revealed an interesting behavior: the mean effort employed in the first session was already close to the expert level (naïve: 18.84 N; dyad S1: 14.77±6.18 N) and did not vary significantly as a consequence of the training (expert: 13.81 N; dyad S7: 14.37±6.50 N), while the reaching time markedly improved (p_{G-G} = 0.001, $F(3.10,46.45)$ = 6.09; naïve: 11.65 s; dyad S1 4.68±2.72 s; expert: 2.48 s; dyad S7: 3.05±1.87 s). On the contrary, the MVP values reported no variation (naïve: 1.27 cm/s; dyad S1 1.54±0.45 cm/s; expert: 1.30 cm/s; dyad S7: 1.50±0.73 cm/s), indicating a flaw in the stabilization phase that was not present in the bimanual condition, no matter the skill level. This result suggests that the dyad might not fulfill the coordination demands in the PSS condition. One possibility is that the level of synchronization was insufficient to damp the mass oscillations below a certain level. To examine this eventuality, we estimated the delay in the speed profiles of the two subjects when performing as a dyad compared to them bimanually controlling the tool as expert subjects.

TABLE I. MAXIMUM AVERAGE HAND SYNCRONIZATION DELAY

		Hand Synchronization index [s]	
		SSS	***PSS***
D	S1	[260.22; -3.26]	[205.27; -86.62]
	S7	[155.58; -31.52]	[231.48; -118.12]
E1	Naïve	[16.47; -74.94]	[57.89; -116.15]
	Expert	[26.18; -186.84]	[48.49; -106.35]
E2	Naïve	[52.83; -48.02]	[117.06; -102.28]
	expert	[104.74; -66.95]	[106.97; -114.66]

Table I summarizes the maximum estimated range of the Hand Synchronization index. Except for E1 in the SSS expert condition, the bimanual execution of the task entailed around 110 ms of synchronization delay that is inferior to the visuomotor delay (150-180 ms). In the case of the dyad, this value was almost doubled in the PSS condition, independently of practice, suggesting less ability in the compensation of the delayed sensory feedback [14].

Figure 3 shows the Mean Effort Difference computed both for the expert subjects and the dyad force profiles while applying the SSS and the PSS. In this latter condition the two experts had almost perfect force balance, being the difference very close to 0 (E1: -0.17 N; E2: 0.98 N). When acting in cooperation instead, E2 (rightward robot) was dominating: the effort for E2 was 11% bigger than for E1 (D S1: 2.36 N). However, the interactive practice was able to attenuate the mismatch by almost 70% (D S1: 0.81 N).

IV. Discussion

Our preliminary study highlighted a dyad advantage in the minimization of the effort required to carry out the task using both strategies. Results shown that the observed performance of the dyad is susceptible to adaptation, as long as that the instability arising from the environment and the interaction with the partner is predictable. Indeed, when the virtual tool became more compliant to force perturbations, stability was more difficult to achieve. We suggest that the lower effectiveness of the dyad in rejecting disturbances in the PSS condition compared to individuals bimanually performing the task can be imputed to a failure to compensate for the delayed sensory feedback. In fact, whenever stiffness control of the tool is allowed, the delayed

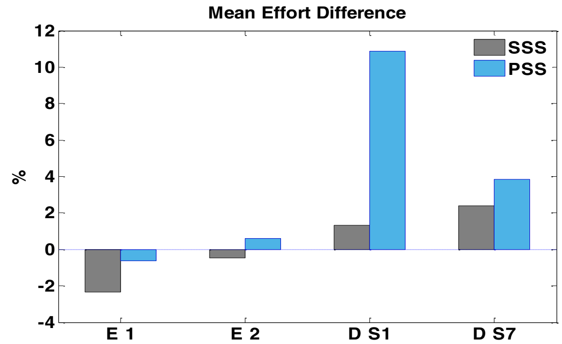

Figure 3. Mean Effort Difference computed for the two expert subjects when performing the task bimanually (E1, E2) and when interacting as a dyad in the first (D S1) and in the last (D S7) training session.

feedback became less critical and the dyad proved to be more effective in contrasting the local instability than the more proficient expert subject alone.

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