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Hi5: a versatile dual-wrist device to study human-human interaction and bimanual control

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Abstract— **Our goal is to investigate the mechanisms of human-human interaction in collaborative and competitive tasks. In this regard, previous groups have suggested simplified motor tasks involving dual robotic interfaces. However, these interfaces involved arm movements with a high degree of kinematic and muscle redundancy. This paper introduces a simple, yet versatile dual-wrist robotic interface, *Hi5*, that allows us to investigate the motor processes behind human-human and bimanual interaction control, and avoid confounds inherent of arm movements. This paper presents the design of *Hi5* and the implemented safety measures. Performance tests then demonstrate its capacity to yield high dynamics, and exhibit low values for inertia and friction. Preliminary experiments show how *Hi5* allows us to analyze the specific kinematic, torque and muscle activation patterns of each partner and disambiguate their roles in force and impedance control.**

I. INTRODUCTION

HUMANS are, by nature, social animals. Social interaction involves frequent or continuous exchange of haptic information and coordination between individuals in tasks such as in carrying heavy objects together or dancing. While language and gestural communication has been the subject of much research, very few works have investigated haptic communication. What are the mechanisms used by humans to control haptic interactive tasks? This question is critical to implement efficient haptic collaborative behavior on a robot agent or for physical neurorehabilitation [1].

Examining the mechanisms of human-human haptic interaction during real-world activities involves difficult challenges due to the complex control requiring coordination of the redundant muscle systems, multi-joint coupled nonlinear dynamics, etc. To avoid confounds, and focus on human-human interactive control, a few recent studies [2-5] have suggested simplified motor tasks involving dual robotic interfaces. For instance, Reed and Peshkin [2] designed a two-handled crank mechanism, which allowed them to study point-to-point movement in a simple yet controlled environment. Their interface was equipped with a central actuator, which enabled them to replace one partner by emulating a corresponding control strategy using a synthetic algorithm.

Using two linear actuators and individual displays placed in front of the partners enabled Feth et al. [5] to implement more complex protocols based on lateral arm movements. The authors studied how two subjects collaborate in tracking a laterally moving target, when the lateral movement was displayed horizontally and the time vertically. The computer-controlled connection between the partners was used to study the effect of time delay in the transmission. Similarly, Stefanov et al. [6] used the same system to investigate the different roles each partner take during a collaborative task.

We are particularly interested in understanding how the central nervous systems of the dyad deal with noise and instability [7]. Attenuation of such perturbations typically occurs from mechanical impedance due to muscle properties and reflexes [8]. While an individual controls the endpoint impedance through coordinated muscle activations [9], in an interaction task performed by two subjects it can be controlled using various strategies between the partners, including co-contraction by one partner, pulling or pushing together, etc.. Therefore, a dyad system has, in addition to the kinematic redundancy, a large muscle redundancy, both of which need to be examined.

A simple way to investigate the modulation of impedance is to study force and muscular activity using electromyography (EMG) [9]. Dual interfaces used in previous literature [2-5] use arm movements, on which EMG activity would be complicated to analyze systematically. This prompted us to develop *Hi5*, a dual-wrist robotic interface for the study of haptic interaction. To simplify study of muscle control and redundancy, we decided to focus on wrist flexion/extension movements. Our system allows implementation of computer-controlled dynamic conditions and record interaction forces and EMG signals of both partners in a reliable way during the course of collaborative tasks. This paper first presents the design and performances of *Hi5*, and then describes some experimental paradigms we have used to explore the study of interaction control in human-human collaborative tasks.

II. HI5 SYSTEM

The system consists of two wrist interfaces fixed to a table on which subject(s) place their arm, hold a handle and interact with wrist flexion/extension movements as illustrated in Fig. 1A. One of these interfaces (*green*) is equipped with a DC motor that allows the experimenter to

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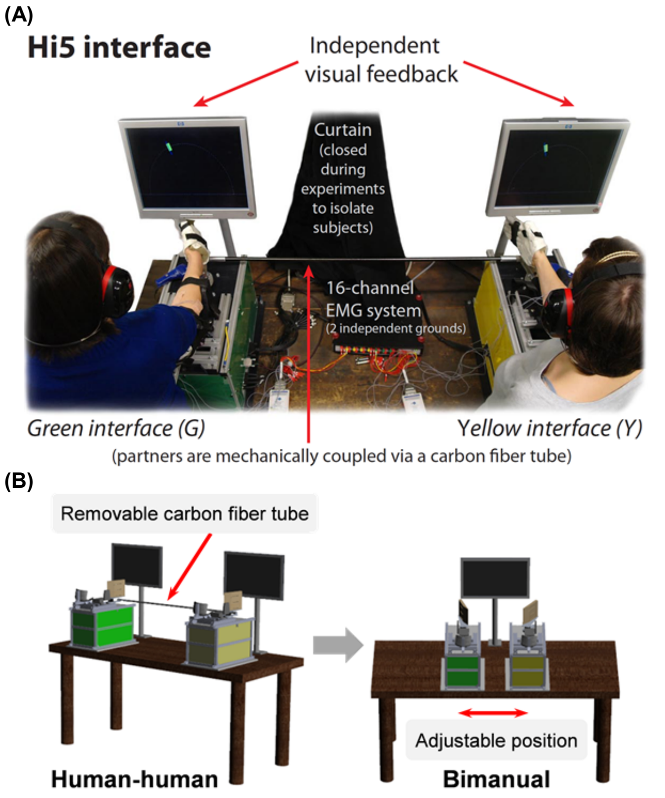

Fig. 1. Overview of *Hi5*. (A) The figure shows the partners of a dyad performing a collaborative tracking task by holding handles, mechanically coupled via a carbon fiber tube. Surface EMG, interaction torques and kinematic data is recorded from both participants. Subjects are separated by about one meter and by a curtain, and wear hearing protection to avoid non-haptic interactions. (B) Examples of setup configurations for the versatile Hi5 system: for human-human interaction experiments using a rigid mechanical coupler (right), or for bimanual experiments with independent control between devices (left).

program external torques to the wrist joint. The second interface (*yellow*) has no motor in the version presented in this paper but can be equipped with a similar actuator as the other interface, depending on the target experiment. Both interfaces are equipped with the same set of sensors for redundant safety and to allow control of both hands with a second actuator.

Two 22" monitors, one in front of each device, allow presentation of independent visual feedback to the subjects. Depending on the experimental requirements, the subjects can be provided with visual cues indicating their wrist position, the applied force, movement performance or muscle activity during the task. In a typical experimental setup, subjects stand on a height-adjustable platform and are asked to perform some simple tasks like moving their hand from a start to target position, or track a moving target, while the robot applies external torque or position perturbations. Hearing protections are worn by both participants, and a black curtain is used to separate them to minimize non-haptic interactions.

Both interfaces are fixed to a table allowing configurations for both human-human and bimanual experiments (Fig. 1B). The two interfaces are mechanically coupled with an interchangeable carbon fiber tube ($Ø_{ID}$ =12*mm*, $Ø_{OD}$ =14*mm*), so both hands experience the same external perturbations. For human-human interaction experiments the two interfaces are coupled by a 1*m* long tube allowing sufficient distance between the partners. For bimanual experiments a 35*cm* or 45*cm* tube can be used to accommodate the subject's anthropometry. In contrast to a computer-controlled connection, which might attenuate high frequencies and suffer delays, this direct and stiff mechanical coupling between the interfaces enables an optimal transmission of interaction forces between the partners. However, *Hi5* is designed such that an additional actuator can be added to the *yellow* device; the interconnecting carbon fiber tube is then removed and independent control is implemented on each device. This enables investigating how subject-specific dynamic conditions affect the collaborative behavior, e.g. when a partner suddenly receives higher perturbations, reaction to transmission delay in noisy environments, etc.

A. *Mechanical specifications*

An ideal device for motor learning/control experiments would be backdriveable, have low friction, low inertia, low backlash, and a high force bandwidth. To achieve backdriveability, the use of highly geared motors is to be avoided, and direct drive actuation was thus selected. Further, biomechanical factors were taken into account to determine the optimal actuator for our device. Delp et al. [10] reported that wrist flexors can provide torques ranging from 5.2 to 18.7 *Nm* (mean±std = 12.2±3.7*Nm*; 10 healthy males, aged 23-33*y*) while extensors from 3.4 to 9.4*Nm* (mean±std = 7.1±2.1*Nm*). Based on this, we considered that a wrist torque of 10*Nm* was sufficient for our purposes.

A DC motor (MSS8, Mavilor) capable of producing a peak torque of 15*Nm* (T_{max}) was chosen for our system. The motor is current-controlled using a DC brush motor amplifier (413C, Copley). Each interface is equipped with a 5000*cpr* differential encoder (RI 58-O, Hengstler). These two encoders enable the implementation of redundant safety measures, and are both used in the version with two actuators. A torque sensor (TRT-100, Transducer Technologies) with a measuring range of 100*in.lbs* (11.29*Nm*) is mounted between the rotating shaft and the handle on each device. We note that two sensors are necessary to record individual torques in the separated configuration as well as in the joined configuration, as for example both (-2*Nm*, 3*Nm*) and (-4*Nm*, 5*Nm*) yield 1*Nm* interaction torque.

To minimize the system's inertia, we first estimated that wrist flexion/extension range of motion can vary between 120° to 140°, then calculated the minimum distance needed between the wrist's center of rotation and the carbon fiber tube joint allowing this movement range. High-quality ABEC-5 ball bearings were selected to minimize friction and backlash in the system.

B. *Software architecture and control*

The system is controlled using Labview Real-time v10.0.

A dedicated computer (*target PC*) running on a Real-Time OS reads the sensor inputs, processes them, and sets the outputs (motor command to the servo amplifier, emergency latch) through a data acquisition card (DAQ-PCI-6221, National Instruments) under a 1*kHz* loop. Data can be saved at either 1*kHz* or at a selected lower frequency in the *target PC*. A graphical user interface on which the experimenter monitors the subjects' performance is implemented on a second computer (*host PC*) that runs on Windows 7. Data is sent from *target* to *host PC* at 66.6*Hz* via an Ethernet network. The *host PC* is equipped with a two dual-graphics cards (NVIDIA Quadro NVS 295) that allows independent control of four displays (two for the experimenter and one each for the two participants).

The system is implemented with predefined functions facilitating programming of customized experimental protocols. These functions include automatic normalization of EMG signals based on maximal voluntary contraction/torque; automatic torque sensor calibration; inertia compensation; predefined control modalities such as position, impedance, torque; friction compensation; and modifiable safety parameters.

C. Ergonomic aspects

Two main aspects are considered in the design of the handle: *i*) Its position can be adjusted in order to align both the wrist and the fingers are mechanism's center of rotation; *ii*) Ergonomic finger shape to minimize finger contractions when stiffening the wrist joint. The latter is important in order to minimize artifacts in the EMG recordings due to finger flexion. To achieve this, the handle shape constrains the subject's hand such that the slightly flexed and abducted (Fig. 2A); this position makes finger flexion difficult and therefore forces the subject to use mostly wrist flexors/extensors muscles.

Since joints are controlled by a redundant system of muscles, it is important to monitor muscles activation in order to obtain a complete picture of movement learning and control. Our setup is designed such that EMG recordings can be performed easily on Flexor/Extensor Carpi Radialis and Ulinaris (Fig. 2B). The muscle activity of the subjects is monitored using a medically certified non-invasive 16-channel sEMG (g.BSamp+g.LADYBird+g.GAMMABox, g.Tec,). As subjects interact with the device standing on a height-adjustable platform, the 16-channel sEMG system allows to the monitoring of EMG activity not only from muscles performing the task, but also from proximal muscles. This enables the monitoring of inadequate postures and identification of artifacts from the recorded EMG data.

D. Redundant safety

Several redundant safety systems are implemented at various levels. Each interface has adjustable mechanical constrains to prevent hyper flexion/extension of the wrist. Electro-mechanical switches attached to these constrains halt the current flow to the DC motor. Emergency switches are at reach to both the experimenter and the participants. Electronic circuits limit the maximum current supplied to the motor. Redundant sensors and a software program monitor system faults such as sudden torque changes and high control outputs. A watchdog circuit is implemented to immediately halt the system ("OFF state") when any safety issue is detected. This prevents sudden high supplies of energy to the motor, which could cause discomfort or pain to the wrist. To return the system to an "ON state", a reset button must be pressed. This button is accessible only to the experimenter.

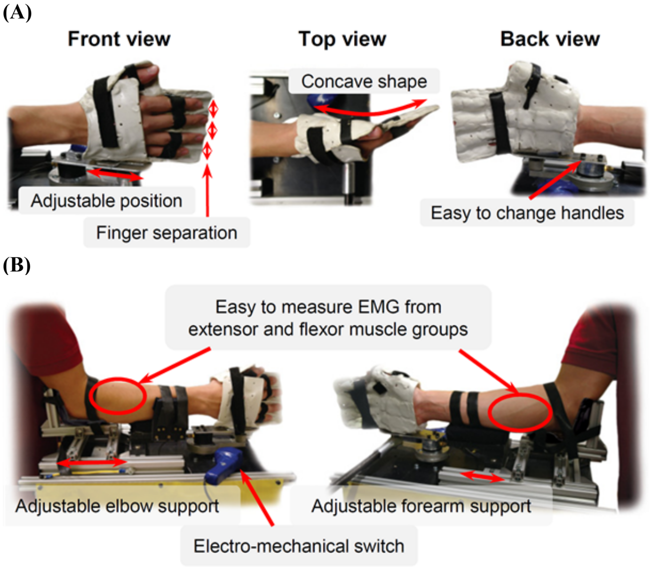

Fig. 2. (A) Handle characteristics: *i*) Adjustable position for wrist joint alignment, *ii*) finger separation and concave shape to minimize finger flexion when an increase in the wrist joint stiffness is required, *iii*) easy to remove and change handles, *iv*) low-weight material. (B) Separate adjustable supports for both elbow and forearm facilitate the measurement of clean EMG. This also enables user-specific adjustments that minimize incorrect postures that could potentially introduce artifacts in the EMG recordings.

The system has been approved for its use in motor learning/control experiments by the Ethics Committee at Imperial College of Science Technology and Medicine and has been assessed successfully by the Health and Safety Committee at the Department of Bioengineering of the same institution.

III. MEASUREMENTS

A. Real-time performance

One important requirement of a haptic device is a high-level of determinism, i.e. the timing of its control loop should be guaranteed to run stably at a desired frequency for long periods of time. A real-time system has to deal with the control algorithm and with tasks related to networking, data transferring, data logging, etc. Such tasks may halt the system and introduce jittering, thus decreasing its performance. To test the robustness of our real-time configuration, we executed a ten-minute test on which the real-time system had to execute high-demanding tasks (for both CPU processor and RAM memory). These tasks included changing variables, saving large amounts of data, change graphics on all monitors, etc. while controlling the position of the handles in closed loop given a user-defined function. The execution time within the control loop was monitored at every iteration. In 93% of the cases it was comprised between 0.99*ms* and 1.01*ms* (i.e. it had 1% error or less), and it was always between 0.95*ms* and 1.05*ms* (i.e. the maximal error was less than 5%).

B. *System parameters*

A real-time parameter identification was performed in order to estimate the values of inertia, viscous and Coulomb friction of the dual interface, in which the system was stimulated in open-loop with a randomized torque signal u [Nm] given by:

$$u(k) = A(k)Sin(2\pi f(k)t) \tag{1}$$

$$A(k) = \begin{cases} A(k-1) & t - t_o(\mathrm{k}-1) \le \dfrac{1}{f(k-1)} \\ \alpha_1 \in \mathbb{R} \mid 0 \le \alpha_1 \le 0.3 & else \end{cases} \tag{2}$$

$$f(k) = \begin{cases} f(k-1) & t - t_o(\mathrm{k}-1) \le \dfrac{1}{f(k-1)} \\ \alpha_2 \in \mathbb{R} \mid 1 \le \alpha_2 \le 10 & else \end{cases} \tag{3}$$

$$t_O(k) = \begin{cases} t_O(k-1) & t - t_o(\mathrm{k}-1) \le \dfrac{1}{f(k-1)} \\ t & else \end{cases} \tag{4}$$

where $\alpha_{1,2}$ are uniformly distributed pseudo-random numbers, t [s] represents the computer global time, and k the current iteration number.

The system can be modeled as a parallel mechanism as illustrated in Fig. 3 and the Lagrangian of the mechanism can be expressed as:

$$\begin{aligned} \mathcal{L} &= \frac{1}{2}J_A\dot{\theta}^2 + \frac{1}{2}J_P\dot{\theta}^2 + \frac{1}{2}m_T\dot{\vec{r}}^2 \\ &= \frac{1}{2}\dot{\theta}^2(J_A + J_P) + \frac{1}{2}m_T\left(\left(-L_H\cos(\theta)\dot{\theta}\right)^2 + \left(-L_H\sin(\theta)\dot{\theta}\right)^2\right) \\ &= \frac{1}{2}\dot{\theta}^2(J_A + J_P + m_T{L_H}^2) \end{aligned} \tag{5}$$

Therefore the dynamic equation can be then expressed as:

$$\begin{aligned} &\frac{d}{dt}\frac{\partial\mathcal{L}}{\partial\dot{\theta}} - \frac{\partial\mathcal{L}}{\partial\theta} = \tau_O \\ &(J_A + J_P + m_T{L_H}^2)\ddot{\theta} = J_{Tot}\ddot{\theta} = u - \tau_{\mathrm{F}} \end{aligned} \tag{6}$$

$$\tau_{\mathrm{F}} = \begin{cases} \beta_1\dot{\theta} + \beta_3\,sign(\dot{\theta}) & sign(\dot{\theta}) > 0 \\ \beta_2\dot{\theta} + \beta_4\,sign(\dot{\theta}) & sign(\dot{\theta}) < 0 \\ 0 & else \end{cases} \tag{7}$$

where τ_O [Nm] represents the torques with respect to the origin (*green* interface), u [Nm] the external torque produced by the DC motor, τ_{F} [Nm] the frictional torques, $\dot{\theta}\,[rad/s]$ and $\ddot{\theta}\,[rad/s^2]$ the angular velocity and acceleration of the handle, $\beta_{1,2}$ [Nms] the viscous friction coefficients, $\beta_{3,4}$ [Nm] the Coulomb friction coefficients, $J_{A,P}[kgm^2]$ the inertia of the rotating components, i.e. handle, torque sensor, motor armature, etc., of the *green* and *yellow* interfaces with respect to the wrist joint, L_H [m] the distance between the handle joint and the connection with the carbon fiber tube, m_T [kg] the mass of the carbon fiber tube, and $J_{Tot}[kgm^2]$ the total apparent inertia at the origin. The dynamic equation can be expressed in the following linear way:

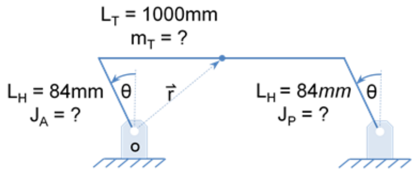

Fig. 3. Hi5 system modeled as a parallel mechanism. L_H and J_H denote the length and the inertia of the handle (H), while L_T and m_T denote the length and mass of the carbon fiber tube (T).

$$u = \psi(\dot{\theta},\ddot{\theta})^T\,p \tag{8}$$

$$\psi(\dot{\theta},\ddot{\theta})^T = \begin{pmatrix}\ddot{\theta} & \dot{\theta}F(\dot{\theta}) & \dot{\theta}F(-\dot{\theta}) & sign(\dot{\theta})F(\dot{\theta}) & sign(\dot{\theta})F(-\dot{\theta})\end{pmatrix} \tag{9}$$

$$F(\dot{\theta}) = \begin{cases} 1 & sign(\dot{\theta}) > 0 \\ 0 & else \end{cases} \tag{10}$$

$$p = \begin{pmatrix}J_{Tot} & \beta_1 & \beta_2 & \beta_3 & \beta_4\end{pmatrix}^T \tag{11}$$

The system was excited during three 30*s* periods and recursive least-squares estimation (RLS) was used to identify the parameters p. Convergence of the estimated parameters is shown in Fig. 4. The average value over the three sessions was taken as the final estimation: J_{Tot} = 0.00692 [$kg\ m$], β_1 = 0.0677 [$Nm\ s$], β_2 = 0.0512 [$Nm\ s$], β_3 = 0.0313 [Nm], β_4 = 0.0414 [Nm].

To validate the model, a computer simulation was run using the same torque values used for exciting the system. A comparison between the estimated and the pre-recorded values is shown in Fig. 5A. As it is an open loop simulation, it is expected that small inconsistences between the real

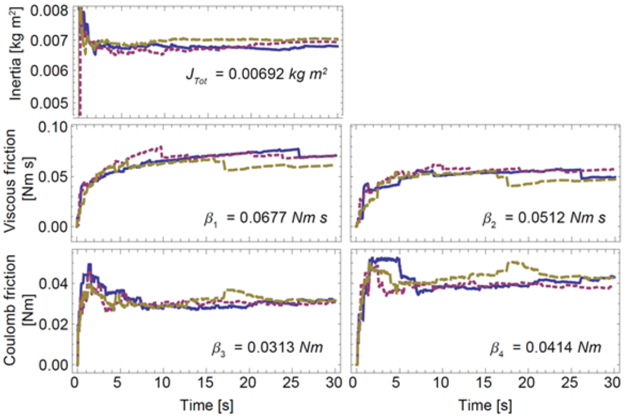

Fig. 4. Convergence of the estimated parameters over three different 30*s* excitation sessions. The average final value of the three sessions are indicated.

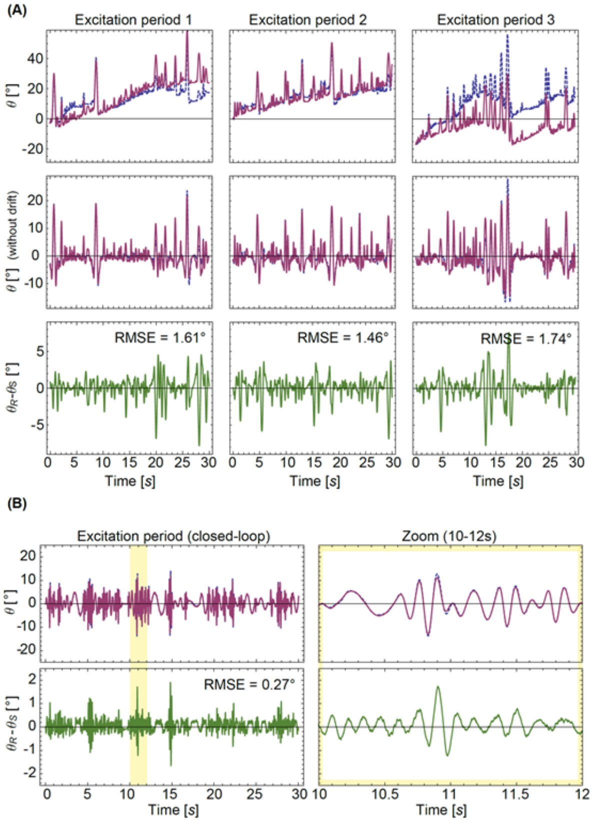

Fig. 5. Comparison of wrist angle comparison between modeled (solid-red) and real (dashed-blue) systems during (A) open-loop excitation trials and (B) closed-loop using a PD controller.

device and the model would drift the output of the simulation. Therefore, for a fairer comparison, we removed the drift of both estimated and real angular trajectories using an offline, zero-lag, 2nd order, high-pass Butterworth filter with 0.25*Hz* cut-off frequency. The largest root mean square error (RMSE) between the simulation and the real trajectories was 1.74°.

For further validation, a position proportional-derivative (PD) controller was implemented while a noisy, randomly generated reference trajectory was input into both the real device and the computer model. The model estimations for the angle were similar to the real ones (RMSE=0.29°). A comparison between the predicted and the real angular positions is shown in Fig. 5B.

C. *Torque bandwidth*

To obtain the torque bandwidth of the system, the handles were locked so that the torque sensor could only measure the torque produced by the motor. The system was excited for three 30*s* periods with randomly generated torque commands between [-3,3]*Nm* that were updated every 4*ms*. For every excitation period, a fourth order ARX model was estimated using RSL. The average estimated RMSE after the three trials was 0.023*Nm*. The model parameters were averaged and the resulting model was considered to be representative of the system. The torque bandwidth was estimated to be at 156.4*Hz* (gain=-3*db*), with a resonant peak at 103.8*Hz* (gain=7.6*db*).

IV. EXPERIMENTAL DATA

A series of human-human collaborative task with Hi5 were performed to explore the capabilities of this device for interaction studies. These experiments consisted of tracking a periodically moving target in cooperation, i.e. the 2 subjects were mechanically coupled and had to track the same target. Each subject was presented with the same visual feedback, which consisted of a moving target (represented by a solid polygon of 4° width) and their (common) wrist angular position (represented by a blue line). The target was programmed to move periodically at 0.2Hz on a [-20°, 20°] range using minimum jerk movement patterns. Subjects were instructed to track the target during intervals of varied time duration. During each interval, external 3Hz sinusoidal torque perturbations of different amplitudes were applied to the subjects' wrist joint by the robotic device.

These experiments have enabled us to identifying forms of specialization and strategies in cooperative scenarios [11]. For instance, we identified strategies on which an agent damps the movement by pure co-contraction or on which both agents simultaneously pull or push away or against each other, but both contributed with different levels of co-activation.

As an example, consider the evolution of interaction torques between partners in Fig. 6. In this figure, both dyads were able to keep a consistent tracking error regardless of the different levels of external torque perturbations. Dyads achieved this by adjusting their interaction torques as illustrated in the figure. Interestingly, while one dyad (Dyad 2) kept a consistent strategy throughout the whole experiment, Dyad 1 switched strategies during its course. The strategy adopted by Dyad 1 at the beginning was that participant guided the movement (*yellow*) while the other damped or resisted to it (*green*) to avoid overshooting. Data

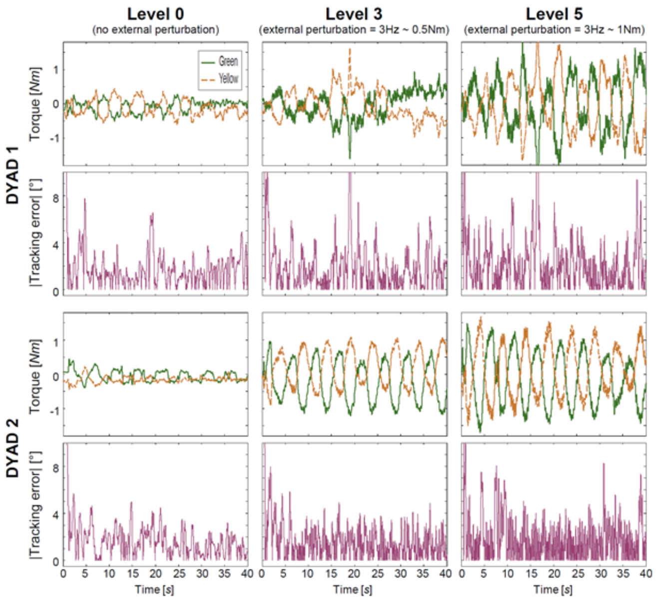

Fig. 6. Evolution of interaction torques and tracking errors in two dyads during a tracking task with different levels of external torque perturbations.

from the torque sensors suggested that not only did the *green* participant damped the movement by applying a torque against the movement, but also damped the torque perturbations by co-contracting (indicated by larger 3*Hz* oscillations in the torque sensor signal). Dyad 1 changed this strategy after approximately 15*s* of initiation of level 3, and then, after another 15s, subjects adopted a strategy on which both participants pull away from each other to counteract the external perturbations. Interestingly, their performance measured by the tracking error remained the same. At the beginning of level4, Dyad 1 started with this “pull apart” strategy but throughout the trial, subjects converged back to the first strategy they adopted; this strategy remained constant throughout the last trial (level 5).

Differently from previous studies on which only interaction forces were analyzed, our system allowed us to systematically analyze EMG activity from both participants, and thus, redundant strategies could be analyzed systematically, as we present in [11].

V. CONCLUSION

This paper presented *Hi5*, a novel, versatile dual wrist interface to investigate the control of human-human or bimanual interaction. While previous dual interfaces developed for this purpose have involved arm movements, we have targeted one DOF motion for each agent in order to simplify the study of the redundancy between dyads. In particular, with two agents, the control of mechanical impedance can occur from muscle co-activation in at least one of them, or when both simultaneously push or simultaneously pull [11]. Therefore, it is necessary to study a simple movement with well measurable and interpretable muscle activation. Wrist flexion/extension was selected as one DOF task that can be well modeled using a linear dynamic model [12], and with well measurable muscle activation [13].

Hi5 consists of two wrist interfaces, on which participants attach their hand(s) to ergonomic handles, and interact in wrist flexion/extension tasks. In the version tested in this paper, the two interfaces are mechanically coupled using a stiff, low-weight carbon fiber tube. This direct mechanical coupling between the two interfaces yields optimal power transmission between the two users, in contrast to a computer-controlled connection that may attenuate high frequencies and bring time delays. Yet, the same system can easily integrate a second actuator, offering the opportunity of subject-specific dynamic environments, e.g. to make a partner more noisy, and see how this would modify the coordination. In this regard, the interface can be quickly and easily reconfigured to investigate symmetric or asymmetric tasks on both human-human or bimanual interaction experiments. *Hi5* allows us to measure the kinematics, dynamics and muscular activity of the users. It has been implemented with redundant sensors and safety features, and has been approved by ethical and safety committees at Imperial for its use in human sensorimotor experiments. Performance tests demonstrated a high-level of determinism and minimum amount of jittering in the real-time system, low friction and inertia, and a high capability to render torques, as suggested by the estimated torque bandwidth. Dynamic identification provided a good dynamic model that can be used in further experiments.

Experiments were carried out with dyads that had to track a periodically moving target despite of a 3*Hz* sinusoidal torque perturbation. The redundant strategies taken by dyads in this kind of tasks would be difficult to identify by looking solely at the interaction forces as done in previous experiments [2, 6], but could be disambiguated easily with *Hi5*.

VI. ACKNOWLEDGEMENTS

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