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The impact of stiffness in bimanual versus dyadic interactions requiring force exchange

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***Abstract*—During daily activities, humans routinely manipulate objects bimanually or with the help of a partner. This work explored how bimanual and dyadic coordination modes are impacted by the object's stiffness, which conditions inter-limb haptic communication. For this, we recruited twenty healthy participants who performed a virtual task inspired by object handling, where we looked at the initiation of force exchange and its continued maintenance while tracking. Our findings suggest that while individuals and dyads displayed different motor behaviours, which may stem from the dyad's need to estimate their partner's actions, they exhibited similar tracking accuracy. For both coordination modes, increased stiffness resulted in better tracking accuracy and more correlated motions, but required a larger effort through increased average torque. These results suggest that stiffness may be a key consideration in applications such as rehabilitation, where bimanual or external physical assistance is often provided.**

***Index Terms*—Virtual object manipulation, object stiffness, bimanual control, human-human interaction**

I. INTRODUCTION

HUMANS routinely use their hands to manipulate objects with varying mechanical properties. Some tasks, such as holding a box, are carried out bimanually, while tasks like transporting a mattress or handling a large table require interaction with a partner. Given that bimanual and dyadic interactions may differently use the exchange of forces during such tasks, how does the stiffness of the shared object influence performance and the resulting motor behaviours?

Inter-hemispheric connection plays a critical role in integrating feedback from the hands during bimanual actions [1]. This may help coordination during object manipulation as it assists the prediction of the contralateral hand's actions (e.g. as observed during an unloading task [2], [3]). In contrast, in dyadic tasks the partner's actions need to be estimated using shared haptic information [4]. However, this does not necessarily lead to worse performance [5]. In fact, compared to solo performance, human-human interaction can result in better tracking accuracy [4], [6], [7]. Similarly, compared to bimanual interaction, dyads have achieved faster motions in both discrete [8] and cyclical [9] aiming tasks and displayed similar performance and adaptation rates during rhythmic tasks [10]. However, factors such as the amount of practice [11] or the partners' relative skill [12] can impact these results.

Besides potentially impacting performance, bimanual and dyadic interactions may lead to different motor behaviours. For example, dyads use higher forces than individuals in some tasks [5], [10]. Dyadic interactions have also led to asymmetric behaviours, with the partners adopting different roles (e.g., accelerating versus braking a shared object) [8]. Although some bimanual tasks have shown similar role assignment [13], functional specialization during bimanual actions has been mostly observed as a result of lateralization. Here, (in right-handers) a non-dominant hand's proprioceptive advantage [14] and a dominant hand's trajectory control advantage [15] can lead to the hands adopting complementary roles (i.e., stabilizing versus guiding) [16]. These roles can however be flexibly assigned [17] and change with task requirements [18], [19].

Object stiffness acts to filter haptic information, and has been observed to influence both performance and perception [20], [21]. In dyadic studies carried out by two mechanically connected partners, more rigid connections have been shown to yield better performance during both reaching [22] and tracking [4] tasks. However, while it is known that the presence of haptic feedback improves performance for bimanual tasks that require continuous force control (i.e. object holding and transport [23]), connection stiffness has not shown an impact on performance during bimanual tracking tasks [24].

It is unclear if the additional inter-hemispheric connection that exists during bimanual interaction enables an improved ability to compensate for reduced haptic feedback (i.e., lower connection stiffness), when compared to dyads, during tasks that require force exchange. We therefore studied the impact of coordination mode (bimanual or dyadic) and connection stiffness on user performance, motor behaviour and perception with a task inspired by object handling. We focused on two task phases: the initiation of force exchange and its continued maintenance while tracking. We hypothesised that lower object stiffness will degrade performance in both coordination modes due to its filtering of haptic information (*Hypothesis H1*). We further expected that the degraded feedback would have a larger impact on dyads as they lack inter-hemispheric communication (*Hypothesis H2*).

II. METHODS

Participants and experimental setup. The experiment was approved by the Imperial College Research Ethics Committee

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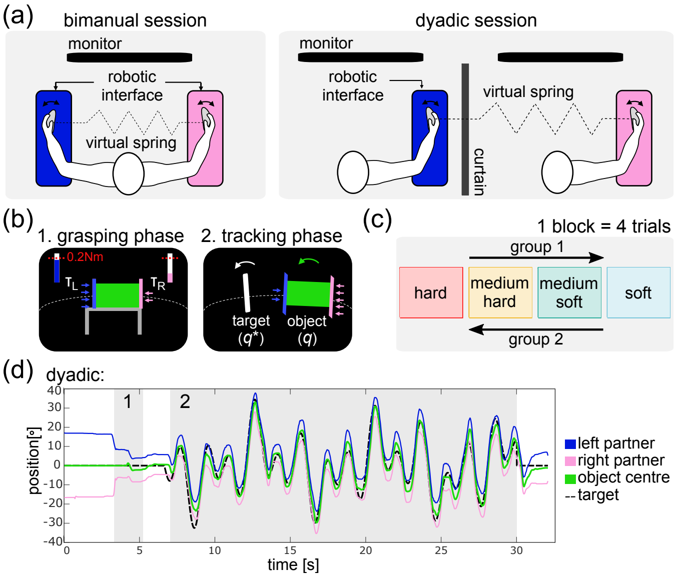

Fig. 1. Experiment description. (a) Participants sat in front of a monitor and controlled a cursor with wrist flexion/extension movements. They moved a virtual object using either their two hands (bimanual session) or with a partner (dyadic session). (b) Participants first moved their hands to grasp the virtual object with a minimum torque of 0.2 Nm (*grasping phase*). Then they tracked a target (while keeping their grasp) before releasing the object at the trial's end (*tracking phase*). See object's behaviour in[1]. (c) Each experiment block consisted of four trials each using one of the four stiffness levels. Group 1 reduced the stiffness with each block trial while Group 2 had the opposite order. (d) Trajectory example (hard object/dyadic mode), showing the position of the two partners and the object for the grasping (1) and tracking (2) phases.

(reference 15IC2470) and carried out by 20 healthy young adult participants (7 females; 17 right-handed based on [25]) with no known musculoskeletal or neurological injuries. All participants were naïve about the experimental conditions and gave their informed consent prior to starting the experiment. The experiment was conducted using the Hi5 dual robot (Fig. 1a, [26]), which is a one degree-of-freedom (DoF) interface (per wrist) that uses computed torque control to flex/extend each wrist. The interface was controlled at 1000Hz, while position and torque data was recorded at 100Hz.

Object handling task. Participants were asked to interact with a virtual object (either bimanually or as a part of a dyad, see Fig. 1a). This task considered 1 DoF object transport, requiring participants to grasp the object with a minimum torque to prevent slip and to move it horizontally to track a target. The object was represented by a rectangular box with dimensions 144 x 72 pixel^2 (Fig. 1b). Its position q was updated through the net torque $\tau = \tau_L + \tau_R$ resulting from each robotic handle, such that at time step k

$$q[k] = q[k-1] + \dot{q}[k-1]dt + \tau dt^2/2I,$$
$$\dot{q}[k] = (1-\mu)\dot{q}[k] + \tau dt/I.$$

with $I = 0.01\,\text{kg}{\cdot}\text{m}^2$ (object inertia), $\mu = 0.2\text{kg}{\cdot}\text{m}{\cdot}\text{s}{\cdot}\text{rad}^{-1}$ (horizontal viscous friction) and $dt = 0.001\,\text{s}$ (time step).

Participants received 1 DoF (horizontal) haptic feedback of the interaction between each wrist (with position ϕ_L, ϕ_R) and the object (with position θ_L,θ_R) through the torques: $\tau_L = -K\left[\phi_L - \max\{\phi_L,\theta_L\}\right]$ and $\tau_R = -K\left[\phi_R - \min\{\phi_R,\theta_R\}\right]$. At rest, $\theta_L = -9°$ and $\theta_R = 9°$ (i.e., they were 9° to the left and right of the object's centre), where the angle and the torque are positive in the counterclockwise direction. Additionally, visual feedback for the experiment was displayed on the monitor through the motion of the box-shaped object, as well as two vertical bar cursors, one for each wrist. Here, while the object's width always remained constant, its height h increased linearly with the applied torque such that

$$h = h_0 + h_0(\max\{\min\{\tau_L,\tau_R\},\tau_{min}\} - \tau_{min}),$$

with $\tau_{min} = 0.2Nm$ (minimum torque needed for grasping the object) and where the initial height h_0 was set to be half of the object's width. The object's color also varied with increasing applied torques, transitioning from green to red.[1]

At each trial's beginning, participants needed to move their hands towards the object and exert a τ_{min} torque to virtually grasp it (*grasping phase*, Fig.1b). This minimum torque had to be maintained throughout the entire trial, otherwise the object would start to slip down the monitor. If the grasp was not reestablished before the object slipped below the hand cursors, the trial was failed. Once grasped, participants were instructed to wait 2.5 s before *tracking* with the object's centre of mass (CoM) a pseudo-randomly moving target which was represented by a cursor with trajectory

$$\begin{aligned} q^*(t) = &-9.3\sin(0.38\,t) - 1.97\sin(0.88\,t) + 11.2\sin(1.16\,t)\\ &-12.74\sin(1.98\,t)\,,\quad 0 \le t \le 22.5s. \end{aligned}$$

The object had to be released at the end of the tracking.

Experimental protocol. The experiment was composed of two sessions, conducted either on the same day or in consecutive days, where the order was counterbalanced across participants. They did not receive any prior training. In the *bimanual session* the participant held the object with both of their hands, while in the *dyadic session* they held one side of the object while a partner held the other side (with both participants using their dominant hand). Each session contained 48 trials divided into twelve blocks of four trials each. Here, each of the four trials in a block was associated with a different level of object stiffness K between the hands (Fig. 1c): hard ($K = 0.18\,\text{Nm}/°$), medium-hard ($K = 0.05\,\text{Nm}/°$), medium-soft ($K = 0.025\,\text{Nm}/°$) and soft ($K = 0.015\,\text{Nm}/°$). These values were chosen based on previous work on the same setup that observed a clear perception of the interaction with values over $0.05\,\text{Nm}/°$ [27], with the exact final values determined through pilot testing.

Participants were randomly assigned to two groups to determine the object stiffness ordering. Participants in Group 1 experienced a hard (H), medium-hard (MH), medium-soft (MS) soft (S) order, while participants in Group 2 experienced the reverse order. At each session's end participants were asked to choose between stiffness conditions from the set {hardest, softest, no preference} in terms of both their preference and their difficulty. At the end of their second session they were similarly asked to choose between coordination modes from the set {bimanual, dyad, no preference} (see Fig. 3).

Data analysis. Data was processed in MATLAB and RStudio. Within each trial, the *grasping phase* (i.e., force exchange

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[1] A video of a participant performing the task and their associated feedback can be found at `https://youtu.be/XvPo7kITiRY`.

initiation) was defined from when participants first "touched" the object until 1s after exerting the minimum torque to grasp it. The *tracking phase* considered data from 0.5 s after the target started moving (to avoid including reaction time), keeping 22 s of tracking data (Fig. 1d). If participants managed to hold the object for all 22s, the trial was considered successful.

The number of successful individuals (or dyads) per trial and per condition (*success rate*) was computed to assess whether participants were able to carry out the task. We observed that 90% of participants were successful in the last 4 trial blocks (for all but the soft-dyadic condition, Fig. 2a). We therefore only used data corresponding to successful trials of these four blocks for the remaining analysis.

Three metrics were computed to explore participant performance. First, the *grasping* time, defined as the time taken from initial object contact to when the minimum torque was applied. Second, the *object deviation*, calculated as the object motion's standard deviation during grasping. Finally, the root mean square *tracking error* (RMSE) between the target q^* and the object's CoM.

Three metrics assessed the participant's motor behaviours: i) the *average torque* on the object, as $0.5(\tau_L + \tau_R)$; and the *Spearman correlation ii) between the hands' position (CHP) and iii) between the hands' torque profiles (CHT).*

The mean values across the last four trials per participant were calculated. Shapiro-Wilk tests showed that some groups were not normally distributed in all metrics except the RMSE. Therefore, the data was analyzed using repeated measures ANOVA for the RMSE and Aligned Rank Transformed ANOVA (ART ANOVA) for all other metrics. We explored the two factors' effects – object stiffness (with 4 levels) and coordination mode (with 2 levels) – and their interaction. Post-hoc analysis was conducted using paired t-tests for the RMSE and Wilcoxon paired tests for other metrics, where P-values were adjusted using the Holm-Bonferroni correction to control for type I error in multiple comparisons. The following comparisons were tested: (i) within-subject differences among consecutive stiffness levels for each coordination mode and (ii) within-subject differences across coordination modes for each stiffness level. Here, (i) was conducted when a stiffness main effect was found. Instead, when a interaction was found, we tested (i) and (ii) and only reported the interaction results, regardless of whether main effects were also observed.

Finally, each stiffness level's tracking accuracy and average torque along (all) trials was explored using linear mixed effects (LME) analysis via restricted maximum likelihood (REML). The coordination mode, trial number and their interaction were considered as fixed effects with the participant ID as a random intercept. The Satterthwaite approximation was used for the DoFs. Moreover, Spearman's correlation analysis was used to assess the relationship between the average torque and RMSE.

III. RESULTS

A. How is performance affected by the object stiffness and coordination mode?

1) Overall success: The evolution of the success rate showed a slower improvement in dyads where it took 7 to 9 trials (depending on the condition) for 90% of dyads to be successful (compared to 1 or 2 trials for individuals, Fig. 2a).

2) Grasping: A coordination mode and stiffness interaction was observed for the grasping time (F(3,57)=9.03, p<.001), where participants took more time to grasp softer objects. While individuals tended to be faster than dyads, this difference was only clear for the medium-soft object (Table I).

However, dyads deviated the object around the origin more than individuals, as indicated by a main effect of the coordination mode (F(1,19)=80.41, p<.001). The stiffness also had an impact (F(3,57)=12.57, p<.001), with less stiff objects resulting in larger deviations (MH vs MS: W=605, Z=-2.21, p=.027, MS vs S: W=579, Z=-1.98, p=.048).

3) Tracking: Objects with lower stiffness were perceived as more difficult to track with (Fig. 3b,c) and led to worse tracking performance, as confirmed by a main effect of the stiffness on the tracking error (F(3,57)=95.11, p<.001; H vs MH: t(39)=2.17, Z=-2.10, p=.036; MH vs MS: t(39)=7.83, Z=-5.92, p<.001, MS vs S: t(39)=11.60, Z=-7.44, p<.001). Here, the difference in performance between successive stiffness levels tended to decrease for stiffer objects (see tendencies in Fig. 2e).

Interestingly, neither a main effect of the coordination mode (F(1,19)=0.136, p=.716) nor an interaction (F(3,57)=0.262, p=.853) were observed. This suggests that, independent of the object's stiffness, and despite dyads requiring more time to adjust to the task requirements (as per Fig. 2a), participants transported the object equally well bimanually or as a part of a dyad (Fig. 2e). Both individuals and dyads tended to decrease their tracking error along trials, independently of the object stiffness (Fig. 2c), and they did so at a similar rate except for the MH object where a faster error reduction was observed for dyads (s=-0.06, t(384.82)=$-$1.99, p=.047). Despite similarly adjusting their tracking performance and achieving the same accuracy, participants perceived the bimanual mode to be easiest. However, they preferred the dyadic mode (Fig. 3a).

B. How does the motor behaviour change depending on the object stiffness and the coordination mode?

1) Grasping: Participants grasped stiffer objects with a higher average torque. This was confirmed by a stiffness main effect (F(3,57)=90.13, p<.001; H vs MH: W=57, Z=-4.74, p<.001; MH vs MS: W=23, Z=-5.24, p<.001, MS vs S: W=5, Z=-5.24, p<.001).

2) Tracking: An interaction was found for the object's average torque (F(3,57)=7.83, p<.001). As during grasping, both coordination modes put more torque on stiffer objects (Fig. 2f, Table I). Interestingly, despite individuals and dyads showing similar torques for each stiffness level, individuals decreased their torque along trials (except for the soft object), while dyads increased it (except for the hard object, Fig. 2d). These different trends were confirmed by an interaction between the slopes for all stiffness values via LME analysis (H: s=0.013, t(359.15)=2.96, p=.003; MH: s=-0.018, t(385.34)=5.19, p<.001; MS: s=0.013, t(369.04)=5.04, p<.001; S: s=0.005, t(312.40)=2.57, p=.010).

Higher average torques were associated with lower tracking error only when dyads tracked with soft (r_s=-0.67, p<.001)

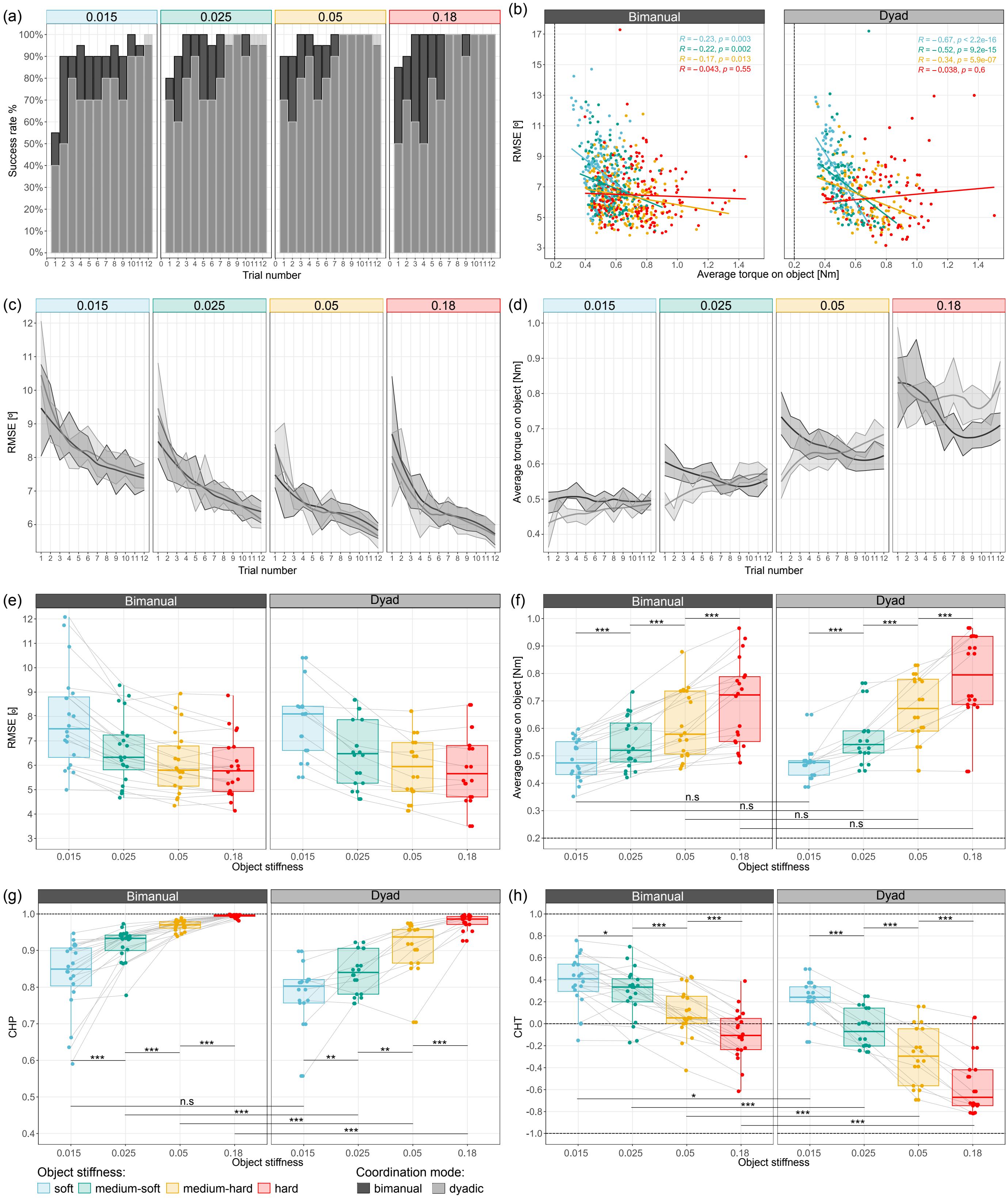

Fig. 2. Influence of object stiffness on bimanual and dyadic performance. (a) Percentage of participants that were successful (success rate) for each of the twelve trials performed at each stiffness level. Experimental results during the tracking phase for only successful trials showing: (b) the relationship between the average torque on the object and the tracking error including a dot per participant and trial, linear fits for each stiffness levels and the resulting Spearman correlation coefficients, (c-d) tendencies along trials for the tracking error and average torque on the object, respectively. Mean across the last four trials per participant and condition for the (e) tracking error, (f) average torque on the object, (g) correlation between the hands positions (CHP) and (h) correlation between the hands torque profiles (CHT). Note that for both coordination modes data points are displayed for every individual (n=20), with the individual or dyad trend across stiffness levels depicted by grey lines. In (e-h) significance in shown for all post-hoc comparisons only when an interaction was found: $n.s: p > .05$, $*: p < .05$, $**: p < .01$, $***: p < .001$.

TABLE I

Post-hoc comparisons for metrics where an interaction was found. (I) Within-subject differences among consecutive object stiffness levels for each coordination mode. (II) Within-subject differences across coordination modes for each stiffness level.

			Average Torque			**CHP**			**CHT**			**Grasping Time**		
			W	**Z**	**p**	**W**	**Z**	**p**	**W**	**Z**	**p**	**W**	**Z**	**p**
(I)	**Bim**	**H vs MH**	4	-3.87	<.001	0	-4.27	<.001	208	-4.02	<.001	185	-2.31	.021
		MH vs MS	1	-4.12	<.001	0	-4.27	<.001	197	-3.43	<.001	184	-2.31	.021
		MS vs S	3	-3.93	<.001	0	-4.27	<.001	172	-2.29	.022	210	4.27	<.001
	Dyad	**H vs MH**	3	-3.37	<.001	0	-3.55	<.001	210	-3.45	<.001	153	-1.08	.278
		MH vs MS	0	-3.41	<.001	15	-3.07	.002	210	-3.43	<.001	207	-3.21	.001
		MS vs S	0	-3.41	<.001	22	-2.87	.004	210	-3.45	<.001	126	-0.77	.444
(II)	**H**	**Bim vs Dyad**	51	-1.35	.176	206	-3.94	<.001	203	-3.62	<.001	59	-1.08	.278
	MH	**Bim vs Dyad**	61	-1.00	.315	210	-4.27	<.001	204	-3.67	<.001	44	-1.55	.119
	MS	**Bim vs Dyad**	86	-0.01	.996	206	-3.94	<.001	201	-3.51	<.001	18	-2.89	.004
	S	**Bim vs Dyad**	122	-0.01	.996	154	-1.81	.069	170	-2.29	.022	56	-1.08	.278

and medium-soft objects (r_s=-0.52, p<.001), where Spearman correlation analysis showed significant moderate-to-high correlation values (Fig. 2b). Instead, harder objects in the dyadic session and all objects during the bimanual session yielded non-significant and/or low correlation values.

Finally, an interaction between the coordination mode and object stiffness was observed for both the CHP (F(3,57)=8.37, p<.001) and the CHT (F(3,57)=13.29, p<.001) as per Figs. 2g,h. Both dyads and individuals showed greater CHP when transporting stiffer objects. However, except for the soft object, dyads showed lower CHP than individuals (Table I). There was a tendency for stiffer objects to lead to lower CHT, where the values for dyads were consistently lower (Table I). This suggests that despite achieving a similar performance, dyads and individuals displayed different coordination patterns.

IV. Discussion

We investigated how coordination mode and connection stiffness impact performance, motor behavior and perception in a task that required force exchange. For this purpose we used a task where participants needed to grasp and transport a virtual object. Objects with reduced stiffness were perceived as more difficult to control (Fig. 3b,c) and resulted in worse tracking performance (Fig. 2e). This was however coordination mode independent, where dyads required more trials to be successful (Fig. 2a), but showed similar tracking accuracy and improvement across trials to individuals (Fig. 2c). Some differences between coordination modes were however observed, where dyads deviated the object more during grasping, increased their average tracking torque across trials (Fig. 2d) and showed different hand coordination patterns (Fig. 2g,h).

Reduced object stiffness resulted in inferior task performance (H1): Consistent with the hypothesis and previous work in dyadic reaching [22] and tracking [4], our participants were less accurate when handling less stiff objects. This differs from findings in bimanual tracking, where the connection stiffness did not impact the tracking accuracy [24]. In contrast to that task, our study required continuous force exchange to maintain the grasp, such that the object stiffness may have had an impact on task execution even in a bimanual setting. It is therefore possible that the filtered haptic information from the softer objects made it harder to coordinate the hands, resulting in reduced performance. This is supported by the CHP results, which showed lower values for softer objects (Fig. 2g).

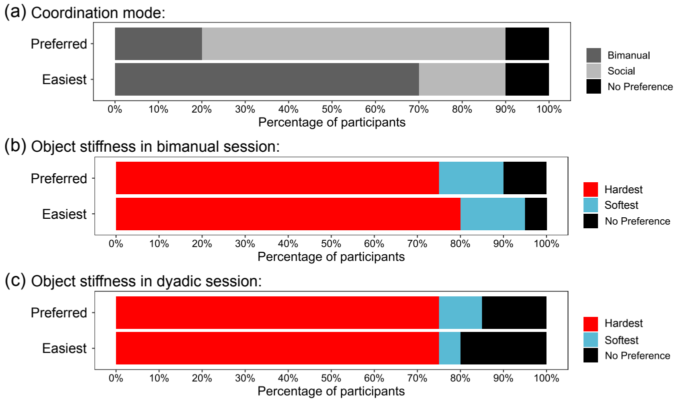

Fig. 3. Subjective assessment. (a) After the final session, participants chose their most preferred mode and the easiest to control from {bimanual, dyad, no preference}. At the end of the (b) bimanual and (c) dyadic sessions, participants chose their most preferred object and the easiest to control from {hardest, softest, no preference}.

The reduced stiffness also led to behavioural changes, for example participants decreased their torque on the object independently of the manipulation phase. The increased torque for stiffer objects could be unintentional, as (i) a biproduct of position noise or (ii) our study's lack of vertical tactile feedback, which has been shown to cause increased normal forces [28], [29]. However, (i) is unlikely since the median torque for the soft object (0.45 Nm, Fig. 2f) is considerably larger than the torque required to grasp the object (0.2 Nm), such that effect of noise is minor compared to the offset, and (ii) would explain a generally higher torque offset but not a modulation for different stiffness levels. Alternatively, the increased torque could reflect that participants were (mechanically) constrained to have a lower than desired safety margin for low stiffness. This does not seem the case for the bimanual data which exhibits a decreasing torque tendency (Fig. 2d). More likely, it may derive from the participants attempting to maximise their force feedback to account for the limited kinaesthetic feedback available in the stiffer objects [30].

The object stiffness resulted in similar performance but different motor behaviours in individuals and dyads (H2): In contrast to our hypothesis, dyads were as accurate as individuals when tracking with a soft object (Fig. 2e). However, the different CHP, CHT and grasping behaviours (i.e., during force exchange initiation) in dyads may be the result of reduced information transfer. This suggests that while the lack of inter-hemispheric exchange did not affect the ability to track with the object, it did have an impact on the participants' ability to coordinate their motions and to keep the object from dropping (Figs. 2a,g). It is possible that the motion of the object's CoM relied mostly on visual feedback, while the haptic feedback was used to control holding, such that once the force constraint was satisfied both individuals and dyads tracked similarly. Alternatively, the task may be too simple for performance differences between coordination modes to manifest. However, the bimanual mode was perceived as easier (Fig. 3a). Finally, dyads may have simply adopted different approaches with the available haptic information. Interestingly, these strategies did not rely on squeezing the object more (Fig. 2f), an approach observed in previous work [5], [10].

While dyads and individuals exhibited similar performance improvements and final average torques, they adjusted their torque differently (Fig. 2d). Here, as previously observed [31], individuals reduced their effort with learning. In contrast, dyads tended to increase their effort, which may suggest an attempt to have a larger safety margin as they were less sure about their partner's actions prediction. This strategy could be associated with the observed increase in dyad success across trials (Fig. 2a). It is possible that dyads could have ultimately improved their tracking by further increasing their torque for the softer objects. However, this is unlikely the case for the harder objects (see increasing tendency in by Fig. 2b).

Finally, the CHT of each coordination mode was differently affected by stiffness. In particular, the more negative values for dyads in the stiffer objects (Fig. 2h) may be an indication that they are reacting to and opposing each other's actions (where in the softer objects the filtered forces would make "reacting" more complicated). Instead, the neutral CHT and higher CHP found in bimanual interaction may be an indication of centralized control [1] dominating over the haptic transfer.

In conclusion, our findings suggest that bimanual and dyad coordination modes can lead to similar performance but different motor behaviours in a one DoF task requiring force exchange, where increasing connection stiffness led to better performance and more correlated motions at the cost of increased effort. However, our chosen task was a simplified version of object handling for which the impact of our visual feedback and model simplifications (e.g., one-dimensional motion and no feeling of friction in the vertical direction) would need further investigation. These findings can be of interest for applications such as rehabilitation, where guidance is often provided via a physical connection to a partner or the unimpaired hand.

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