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## ► To cite this version:

Jonathan Eden, Mahdi Khoramshahi, Yanpei Huang, Alexis Poignant, Etienne Burdet, et al.. Comparison of Solo and Collaborative Trimanual Operation of a Supernumerary Limb in Tasks With Varying Physical Coupling. IEEE Robotics and Automation Letters, 2025, 10 (2), pp.860-867. 10.1109/LRA.2024.3515734 . hal-04870384

**HAL Id: hal-04870384**

**<https://hal.science/hal-04870384v1>**

Submitted on 7 Jan 2025

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# Comparison of Solo and Collaborative Trimanual Operation of a Supernumerary Limb in Tasks With Varying Physical Coupling

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**Abstract**—Through the use of robotic supernumerary limbs, it has been proposed that a single user could perform tasks like surgery or industrial assembly that currently require a team. Although validation studies, often conducted in virtual reality, have demonstrated that individuals can learn to command supernumerary limbs, comparisons typically suggest that a team initially outperforms a supernumerary limb operating individual. In this study, we examined (i) the impact of using a commercially available physical robot setup instead of a virtual reality system and (ii) the effect of differences between limb couplings on user performance during a series of trimanual operations. Contrary to previous findings, our results indicate no clear difference in user performance when working as a trimanual user, in the pick and place of three objects, compared to when working as a team. Additionally, for this task we observe that while users prefer working with a partner when they control the majority of the limbs, we find no clear difference in their preference between solo trimanual operation and when they work with a partner and control the third limb. These findings indicate that factors typically not present in virtual reality such as visual occlusion and haptic feedback may be vital to consider for the effective operation of supernumerary limbs, and provide initial evidence to support the viability of supernumerary limbs for a range of physical tasks.

**Index Terms**—Supernumerary Limbs, Human-Robot Teaming, Human Performance Augmentation, Trimanual

## I. INTRODUCTION

VIA the use of *supernumerary limbs* (SLs) that grant additional effective *degrees of freedom* (DoFs), human users may be able to perform tasks that would otherwise not be possible with a single person. This promises possible efficiency improvements for a range of tasks including multi-hand teleoperated surgery [1], [2], overhead assembly [3] and the locomotion of heavy loads [4]. However, with these additional DoFs there also comes the need for additional computational resources for their control [5]. It is known that

humans only possess finite resources for sensorimotor control such that the integration of additional information can increase workload and reduce performance [6]–[8]. This may lead to a trade-off in the benefits of using SLs, where the capacity of human users to exploit additional DoFs as well as the main factors that influence their performance are not yet completely understood.

The current validation of the ability to use a supernumerary arm has mainly considered either application-specific studies that validate the user’s ability to perform that specific application on physical hardware [1], [9] or abstracted evaluations that are intended to be more generalisable to other tasks but are predominately conducted in virtual reality (VR) [10]–[13]. While both forms of validation indicate a capacity for users to control a third arm, it is unclear how well these results generalise to different tasks, and direct comparisons to the current alternatives to the use of a SL, such as working with a partner, are rare [11], [14].

To ensure the generalisation of SL evaluations to different application scenarios it is needed that the key features of different tasks are abstracted so that they can be tested. Here, building from bimanual motion taxonomies [15], [16], it has been proposed in [5] to classify trimanual tasks in terms of: i) whether or not the dynamics of the limbs can be influenced by the actions of another limb (*coupling*) [15]; and ii) whether or not the desired output behavior of each limb end-effector depends on the position of the other end-effectors (*dependence*) [17]. Using this classification (Fig. 1) trimanual application scenarios can be categorised into nine possible cases based on the (coupling, dependence) pair as well as representative applications for each case. Here, current evaluation have typically either considered independent SL motion [10], [12] or elements only along the main diagonal of the matrix [11], [14], where the (all uncoupled, three goals) case has been used to represent the absence of coupling and dependence and the (three coupled, one goal) case has been used to represent the presence of coupling and dependence.

For SLs to be adopted they should also enable users to complete a range of different tasks with a similar level of performance as through collaboration such that there is an overall improvement in the efficiency of task execution. However, the initial comparisons to working with a partner (primarily conducted in VR) have found that two humans were better at performing tasks than a single human operating trimanually regardless of the evaluated task [11]. It is

Manuscript received: July, 23, 2024; Revised October, 18, 2024; Accepted December, 2, 2024

This paper was recommended for publication by Editor Jee-Hwan Ryu upon evaluation of the Associate Editor and Reviewers’ comments. This work was supported by the European Commission grants H2020 NIMA (FETOPEN 899626) and ICT 871767 REHYB grant, and by a fellowship to MK from the Swiss National Science Foundation (Grant number 191698).

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Digital Object Identifier (DOI): see top of this page.

		Cognitive dependence		
		Three Goals	Two Goals	One Goal
Coupling	All Uncoupled	Multi-object pick and place	Tying shoelaces while holding an object	Triangulation
	Two Coupled	Soldering while getting the next part	Holding a box while opening a door	Camera endoscopy
	Three Coupled	Holding a board while fixing the ends	Drawing on a balanced table	Manipulating an elastic membrane

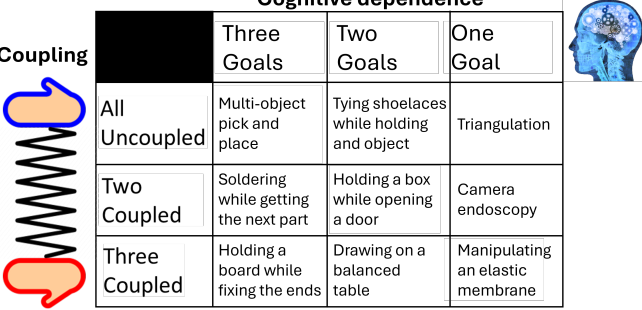


Fig. 1. Possible coordination types for trimanual operations between one SL and the two natural limbs with representative tasks for each combination. Rows denote the dependence of the end-effector task goals and columns denote whether there is coupling present in the limb dynamics.

however unclear if such findings were influenced by one (or a combination of): i) a comparative lack of experience with trimanual coordination compared to working with a partner, where motor skill learning can enable the learning of new motor skills [18] and the previous single-session studies may have provided insufficient time for learning; or ii) a lack of realism in the virtual reality platform. Here, it is noted that previous VR studies [10], [11], [14] have used cursor control instead of robot motion, leading to different dynamics and feedback when compared to a physical study [19], [20]. These differences may change perception and performance, where a cursor’s motion may be easier for a dyad to predict than a robot, and it has been shown that VR representations may elicit different behavior than real robots [21].

Recently, we have investigated the effect of training on trimanual coordination in VR. Here, the task consisted of (three coupled, single goal) manipulation of an elastic triangle, so that the interaction forces had to be controlled. Our results found that after 1-hour of trimanual training, solo participants performed at least as well as when working with a partner [14]. In this paper, we instead use the coupling-dependence classification first presented in [5] to systematically evaluate the effect of using a physical setup in place of a VR cursor on trimanual coordination for both (three coupled, single goal) and (all uncoupled, three goals) reaching. Moreover, we also investigate the effect of coupling strength on the resulting collaborative and trimanual task behavior. We hypothesised that, similar to previous VR studies, the participant would both perform better in the dyad and prefer it to the trimanual configuration (Hypothesis H1) and that the participants would prefer and do better with less coupling when operating as a dyad (Hypothesis H2).

## II. MATERIALS AND METHODS

### A. Participants and experimental setup

The experiment was approved by the Research Governance and Integrity Team at Imperial College London (Reference: 21IC6935). 24 participants (9 female, 15 male) without known motor impairment aged  $25.3 \pm 3.4$  years participated in the experiment and provided their written informed consent before starting. 18 of them were right-handed (with Edinburgh handedness inventory score  $> 60$  [22]), 3 were left-handed and

the remaining 3 were inconsistent handers favouring their right hand. Moreover, 21 participants were right-footed according to the ball-kick dominant leg test [23] and the 3 left-handers were also left-foot dominant. Each participant was partnered with another randomly chosen participant to form a dyad. The members of each dyad were consistent across all dyadic tasks within the experiment.

### B. Experimental Design

The experiment task, which was inspired by the tasks in [11] to aid in comparison with those results, was designed as a three-object pick-and-place activity (Fig. 2a) using a participant’s natural hands in conjunction with a foot-controlled robot arm. Here the arm while not worn by the user (to remove the confounding variable of the physical load) was mounted close to the operator and placed such that it extended from a location consistent with being an additional third arm on their left-hand side. The participants controlled both their own arms and the robot arm. They were asked to simultaneously grasp all three objects and move them from their initial position to a displayed final position (located directly in front of the initial position) with different mechanical couplings to i) modulate the effective number of control DoFs within the task and ii) generate realistic haptic feedback for the natural effectors. Although participants were instructed to “move the objects as fast as possible and accurately place them in the target region”, they were free to move them at different speeds.

The setup consisted of a Kinova<sup>®</sup> Gen3 robotic arm (with Robotiq gripper, Fig. 2a) mounted close to a table controlled by a custom-built 4-DoF passive foot interface [24], a motion capture system (Optitrack), and a set of instrumented (optical markers) objects to be picked and placed on the table. The controller, motion capture, and other software components ran on a standard computer (CPU Intel Core-i9 2.4 GHz, RAM 32 GB), where the robot was controlled at 100 Hz through the foot-interface. Here, the foot displacement was mapped to a velocity command and then sent to a task-space velocity controller that ensured safe operation of the robot arm [25], where Y-axis motion was controlled by tilting the foot interface and X/Z-axis motion was controlled by translating the foot interface in the corresponding direction.

Participants performed the experiment task in two different configurations (Fig. 2c). In the *trimanual configuration*, one operator was seated in front of the objects using their natural hands while also controlling the robot arm through the foot interface. In the *dyad configuration*, two operators were seated side-by-side, where the participant in front of the objects used their hands while the other participant used the foot interface to control the robot arm. Three types of coupling were used (Fig. 2b): *free* (no-coupling), *elastic* (elastic bands between objects), and *rigid* (metallic articulated rods that connected the objects through pivot joints). This means that the task possessed one condition in the (all uncoupled, three goals) case and two conditions in the (three coupled, one goal) case of Fig. 1, where the impact of different coupling types was considered.

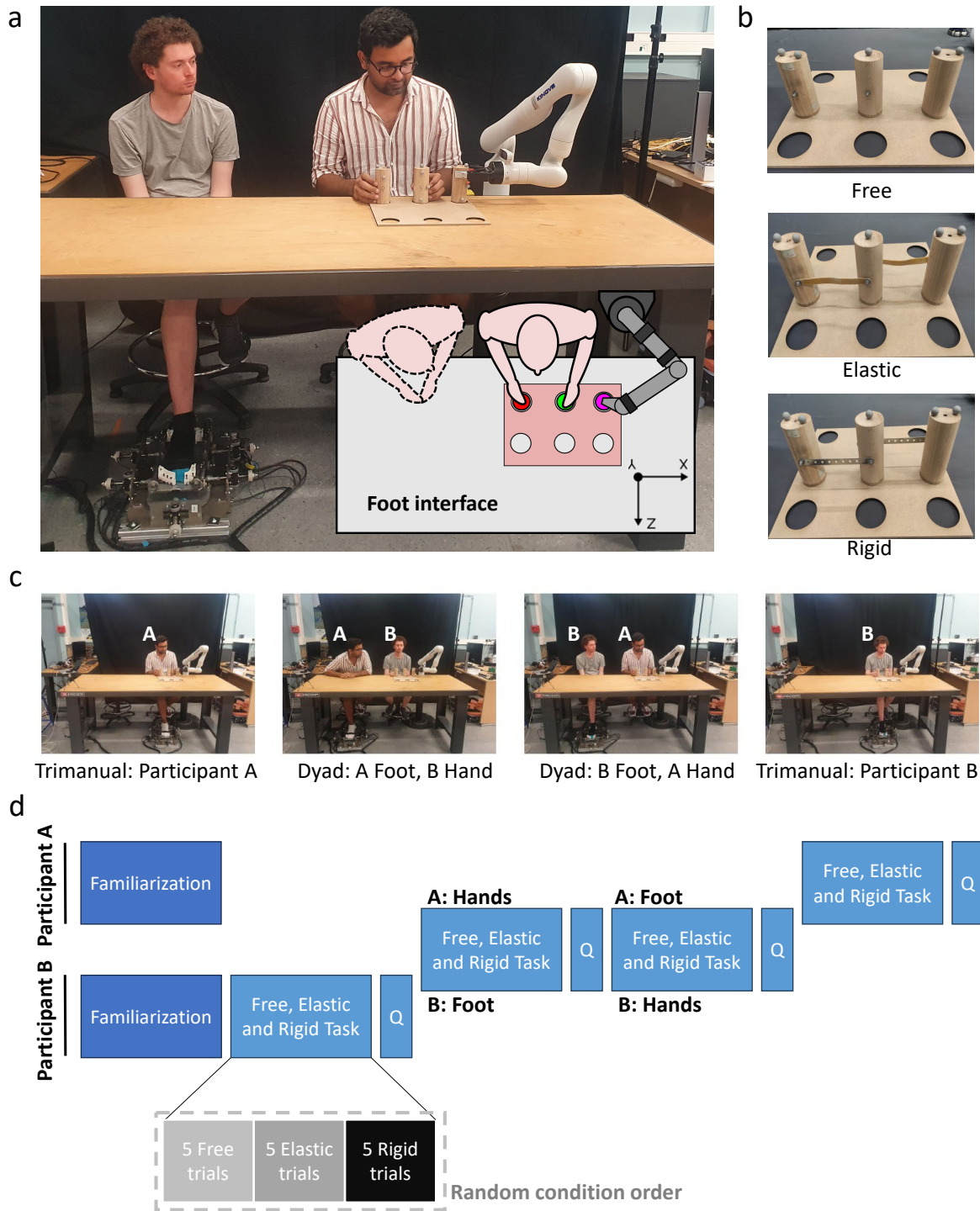


Fig. 2. Experiment setup and protocol. (a) Experimental setup of the pick-and-place task using the non-worn configuration of the Sorbonne SRL and a custom-built foot interface [24]. The experiment was conducted by a dyad using three different couplings (b) and two different configurations, each with two roles, resulting in four different test arrangements (c), with complete protocol shown in (d).

C. Protocol

Each dyad completed the experiment within a 90-minute session consisting of a *familiarization* phase for each member of the dyad followed by a *testing* phase carried out together. In the *familiarization* phase, a single participant used the foot interface to control the robotic arm for picking and placing an object over a five-minute duration. In the *testing* phase, participants performed the pick and placement with all three

objects, considering two factors: *coupling* and *configuration*.

Within a single dyad, each participant took each role {controlling the hands, controlling the foot} such that there were four tests for a single testing phase. The tests were organised in an A, AB, BA, and B arrangement (Fig. 2c, AB denoting that participant A used their natural limbs, while B controlled the robot and BA the converse), where each participant conducted the familiarisation before their first test

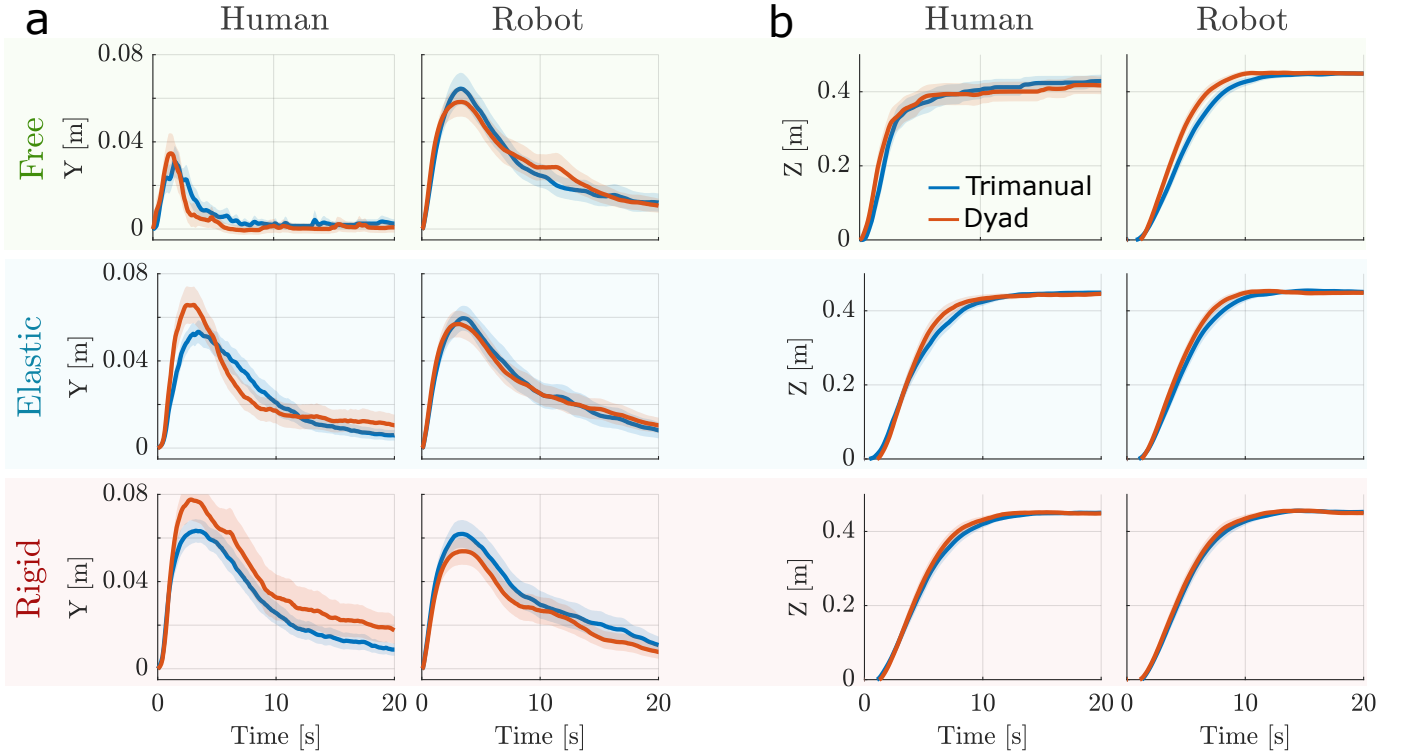


Fig. 3. Participant right-hand, and robot motion trajectories over the first 20 seconds. Y-axis motion (a) and Z-axis motion (b) are shown for all coupling types, where the mean participant behavior is shown with a solid line, and the variance is shown through transparent regions. Each row of subplots corresponds to the ‘Free’, ‘Elastic’, and ‘Rigid’ conditions, respectively. The first column of each subfigure corresponds to human motion while the second column illustrates the robot’s motion.

using the foot interface. The experimental protocol is detailed in Fig. 2d. Within each configuration’s test, the participants conducted the main task five times for each of the three coupling levels {free, elastic, rigid}. The ordering of the coupling levels was fully randomised between participants and configurations.

Three *questionnaires* were also provided to evaluate the *roles*, which consisted of the solo trimanual configuration and both dyad roles and coupling types: (i) The NASA Task Load Index (TLX) questionnaire [26] was evaluated three times (at the end of testing for each role). This consists of six questions associated with the perceived mental load including the aspects of mental, physical, temporal demands, performance, effort, and frustration; (ii) The participants’ ranking of the coupling type with respect to difficulty and their preference was asked three times (once for each role) at the conclusion of testing for a role; (iii) The ranking of the roles was asked once, for each coupling type, at the conclusion of the experiment.

#### D. Data analysis

Participant performance in the testing phase was evaluated through the time that it took to complete the reaching task (*completion time*), which corresponded to the time at which all limbs had finished reaching. To support this measure and to understand how the different limbs behaved, the percentage of completion of each of the limbs was also computed throughout the trials. Here, we compared the percentage of completion for each limb in the Z-axis at 4 s (*completion rate*) to one another, where this particular time and axis was chosen as it represented

the time and dimensions within trials for which the variance in the trajectories was maximum. Moreover, we computed the right-hand and robot hand maximum speed, which was defined as the mean of the top 95% of measured speed to ensure robustness against noise.

The perceived workload, for each configuration, was evaluated as a single raw NASA-TLX [26] metric, which uses the average of the six NASA-TLX subscores. The perceived preference/difficulty was directly evaluated as a ranking with respect to role {dyad configuration controlling the foot, dyad configuration controlling the hands, trimanual configuration} and coupling type {free, elastic, and rigid}.

Shapiro-Wilk tests were conducted to examine the distribution of the data. While the raw NASA TLX workload was found to be normally distributed, all other metrics were non-normally distributed. Therefore the workload was evaluated using a one-factor repeated measure ANOVA (rmANOVA), while the completion time and rate measures were evaluated using a two-factor Aligned Rank Transform ANOVA (ART ANOVA), to account for their non-parametric nature, and the ranking information was evaluated using Friedman tests. Post-hoc analysis made use of t-tests and Wilcoxon tests as appropriate. When ART ANOVA was used, the mean  $\pm$  standard error contrasts were also reported to provide additional insight into the differences between conditions.

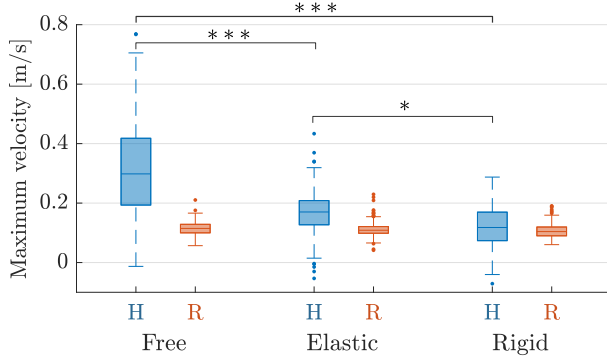


Fig. 4. The maximum velocity for (H) the participant's right hand and (R) robot in each condition. The individual variations (in each configuration) have been removed by replacing the participants' means with the overall mean.

### III. RESULTS

#### A. Intra-trial behavior

Fig. 3 depicts the  $Y$  and  $Z$  axis intra-trial behavior of the robot and participant's right hand for each coupling and configuration. Qualitative inspection of the plots suggests that the dyad and trimanual configurations typically resulted in similar trajectories (for each coupling type), where, the dyads indicate a trend of larger inter-participant variance in the trajectory profiles. The different coupling types also appear to have resulted in different right-hand speed behaviour (coupling type main effect:  $F(2, 46) = 72.312$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.759$ ), without changes in the robot speed (coupling type main effect:  $F(2, 46) = 2.528$ ,  $p = 0.091$ ,  $\eta_p^2 = 0.099$ ), where the natural hand trajectories appear fastest when there was no coupling to the robot (Fig. 4, Table I).

This suggests that the robot did not appear able to produce motion at the speed that the natural arms operate at, which may have both slowed the arms and led to compensatory behaviors during the interaction. The overall performance and motion characteristics across participants are further evaluated in the subsequent section.

#### B. Performance and motion characteristics

The completion time (Fig. 5) was affected by the coupling type ( $F(2, 46) = 14.290$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.383$ ) but there was no clear effect for either the configuration ( $F(1, 23) = 0.254$ ,  $p = 0.619$ ,  $\eta_p^2 = 0.011$ ) or the interaction between the coupling type and configuration ( $F(2, 46) = 0.800$ ,  $p = 0.455$ ,  $\eta_p^2 = 0.034$ ). Here, the free coupling type was observed to result in a  $1.49 \pm 0.62$  s faster task completion than the elastic coupling type and a  $2.88 \pm 0.62$  s faster task completion than the rigid coupling. The Elastic coupling type was also found to be  $1.40 \pm 0.62$  s faster than the rigid coupling (see Table I).

Different to these results, the completion rate for the robot hand (Fig. 6a) was not clearly affected by the configuration ( $F(1, 23) = 1.522$ ,  $p = 0.230$ ,  $\eta_p^2 = 0.062$ ), coupling type ( $F(2, 46) = 1.380$ ,  $p = 0.262$ ,  $\eta_p^2 = 0.057$ ) or the interaction between the coupling type and the configuration ( $F(2, 46) = 0.837$ ,  $p = 0.439$ ,  $\eta_p^2 = 0.035$ ).

Interestingly and similarly to the completion time results, the human right-hand completion rate (Fig. 6b) was found to

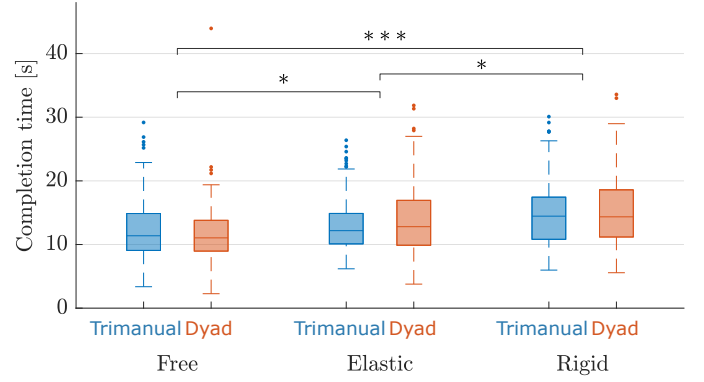


Fig. 5. Completion time in seconds across coupling types {free, elastic, rigid} and different configurations {trimanual, dyad}. While the coupling type had a clear effect on completion time, no clear difference was detected between the trimanual and dyad configurations.

be affected only by the coupling type ( $F(2, 46) = 44.323$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.658$ ). No clear effect was found for configuration ( $F(1, 23) = 0.232$ ,  $p = 0.635$ ,  $\eta_p^2 = 0.010$ ) nor interaction effect ( $F(2, 46) = 0.010$ ,  $p = 0.990$ ,  $\eta_p^2 < 0.001$ ). Here, regardless of the configuration, the free condition led to  $28.2 \pm 4.31\%$  better completion rate compared to elastic and  $38.4 \pm 4.31\%$  compared to rigid. Elastic conditions resulted in  $10.1 \pm 4.31\%$  better completion rate compared to rigid.

These results show that while the coupling type had some effect on the overall performance, there was little evidence of a difference in performance between the trimanual and dyad configurations.

#### C. Questionnaire Results

The workload perception (Fig. 7a) changed between participant roles (One-way rmANOVA:  $F(1.54, 35.48) = 67.52$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.746$ ). Controlling the natural limbs on their own was perceived to have less workload than both trimanual coordination and controlling only the foot, while trimanual coordination was perceived to have less workload than foot control. The difficulty ranked by role showed similar trends (Fig. 7b Table II). Here, for all couplings, the ranking was impacted by the configuration (all Friedman tests  $p < 0.0001$ , Kendall's  $W = 0.475$ ,  $0.482$  and  $0.465$  for free, elastic and rigid couplings, respectively). The hands-only control was for all coupling types and ranked as less difficult than both trimanual and foot-only control. While, the foot and trimanual configurations were only found to be clearly different with rigid coupling, where the trimanual configuration was ranked less difficult.

Only the elastic coupling was found to have an impact on the perception ranked by role (Fig. 7d,  $\chi^2(2) = 6.08$ ,  $p = 0.0477$ ,  $W = 0.127$ ). While post-hoc analysis did not reveal a clear preference for any condition, the trend (for all couplings) suggested that the trimanual configuration was most preferred. These results suggest that for this pick and place task trimanual control was perceived as equal or less difficult to work as an assistant and that if anything it is more preferred.

The coupling type was found to have an impact on the ranking of difficulty (Fig. 7c) for each role (all  $p < 0.001$ ,

TABLE I  
POST-HOC COMPARISONS FOR PERFORMANCE AND MOTION CHARACTERISTIC METRICS WHERE AN EFFECT WAS FOUND. THE TABLE SHOWS COMPARISONS OF COUPLING TYPES FOR A FIXED CONFIGURATION.

	Free vs Elastic			Free vs Rigid			Elastic vs Rigid		
	Cohen's d	t(46)	p	Cohen's d	t(46)	p	Cohen's d	t(46)	p
Natural hand maximum speed	1.113	7.708	<.0001	1.490	10.324	<.0001	0.378	2.616	.012
Completion time	-0.345	-2.391	.042	-0.670	-4.640	.0001	-0.325	-2.250	.042
Human right-hand completion rate	0.945	6.550	<.0001	1.285	8.904	<.0001	0.340	2.235	.023

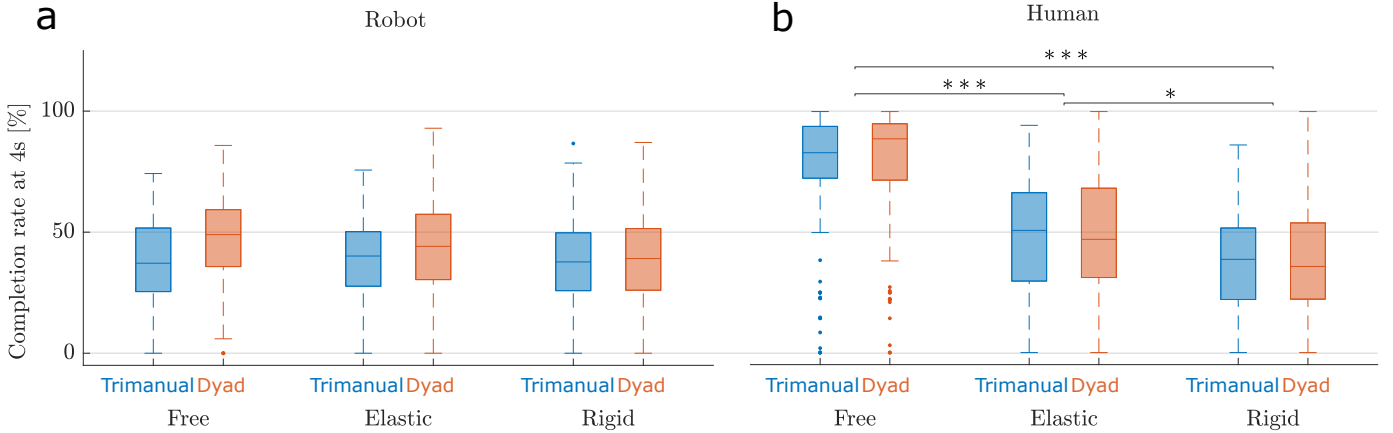


Fig. 6. The completion rate after 4 seconds. (a): robot movement. While no interaction effect was detected, there was a trend in the mean difference. In free condition, dyad leads to  $8.63 \pm 4.87\%$  faster completion rate ( $p = 0.082$ ), in Elastic condition  $4.61 \pm 4.87\%$  ( $p = 0.349$ ), and in Rigid condition,  $1.47 \pm 4.87\%$  ( $p = 0.763$ ). (b): human right-hand was affected by coupling type. In these boxplots, the individual variations are removed by replacing the subjects' means with the overall mean. These results show that natural hand movement is affected only by the coupling type.

Kendall's  $W = 0.298$ ,  $0.676$  and  $0.627$  for trimanual, dyad-hands and dyad-foot configurations, respectively). Here, the difficulty was perceived to increase with the coupling strength where the rigid was more difficult than both the elastic and the elastic was more than the free. While the perception ranking (Fig. 7e) showed the inverse trend, there was only a clear effect for the trimanual configuration ( $\chi^2(2) = 10.99$ ,  $p = 0.004$ ,  $W = 0.229$ ) for which the free coupling was ranked higher than the elastic.

#### IV. DISCUSSION

Our results indicate that while the pick and place task performance was affected by the coupling type, it was not clearly affected by the configuration. Here, the coupling type findings, including that the dyad performs best in the free condition, are consistent with Hypothesis H2. In contrast, the configuration-related findings are contrary to Hypothesis H1 and previous observations in similar tasks from studies conducted in virtual reality [11], [14], where dyad performance has consistently outperformed trimanual operation, across all tested tasks, over the initial session of evaluation, and where dyadic operation (in both roles) has been preferred. This suggests that in addition to the positive effect that learning can have on trimanual performance [14], that some of the factors of the physical interaction that are different from virtual reality may cause differences in the dyad and/or trimanual performance/perception such that previous VR results may not be reflective of the comparison between physical trimanual operations and its current alternatives. However, this study only considers a subset of all tasks, such that further investigation is

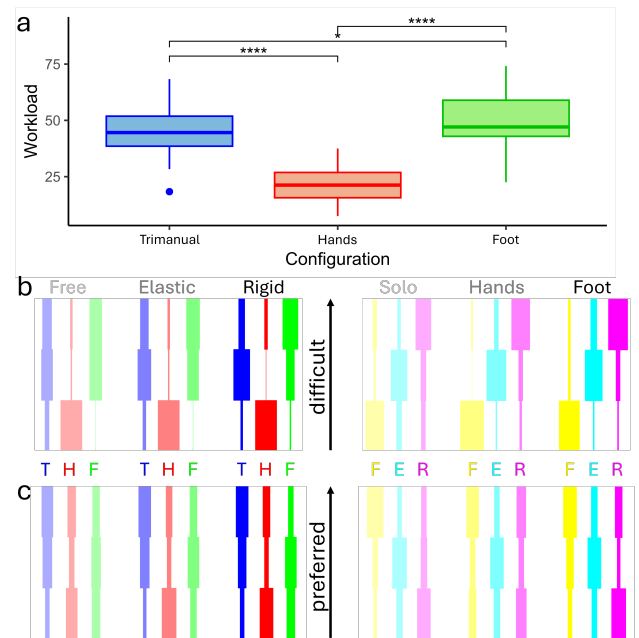


Fig. 7. Questionnaire results. (a) Workload evaluated through NASA-TLX for each of the trimanual, dyad (hands), and dyad (foot) roles. How operators ranked the (b) "difficulty" and (c) "preference" of the different roles (left) and coupling types (right). Note that (b) and (c) depict discrete violin plots in which the bar width represents the percentage of participants for a given response. Different colours represent different possible roles {(T)rimanual, dyad controlling the (H)ands, dyad controlling the (F)oot} and coupling types {(F)ree, (E)lastic, (R)igid}.

needed to see if this result is task type or difficulty specific, or if instead, it holds for all other tasks that have been previously

TABLE II

POST-HOC COMPARISONS FOR QUESTIONNAIRE METRICS WHERE AN INTERACTION WAS FOUND. THE TOP HALF SHOWS THE COMPARISON OF ROLES FOR A FIXED COUPLING TYPE, WHILE THE BOTTOM HALF SHOWS THE COMPARISON OF COUPLING TYPES FOR A FIXED ROLE. UNCLEAR EFFECTS ARE SHOWN IN RED.

		Trimanual vs Hands			Trimanual vs Foot			Hands vs Foot		
		Cohen's d	t(23)	p	Cohen's d	t(23)	p	Cohen's d	t(23)	p
<b>Workload</b>		1.64	8.01	<.0001	-0.547	-2.68	.013	-1.96	-9.61	<.0001
		Trimanual vs Hands			Trimanual vs Foot			Hands vs Foot		
		r	W	p	r	W	p	r	W	p
<b>Difficulty</b>	<b>Free</b>	0.623	233.5	.006	<b>0.275</b>	<b>108</b>	<b>.183</b>	0.818	14	.0002
	<b>Elastic</b>	0.624	253.5	.005	<b>0.333</b>	<b>100</b>	<b>.106</b>	0.819	11	.0002
	<b>Rigid</b>	0.610	250.5	.006	0.417	87.5	.043	0.756	25.5	.0007
<b>Preference</b>	<b>Elastic</b>	<b>0.471</b>	<b>211</b>	<b>.069</b>	<b>0.273</b>	<b>193.5</b>	<b>.372</b>	<b>0.254</b>	<b>108</b>	<b>.372</b>
		Free vs Elastic			Free vs Rigid			Elastic vs Rigid		
		r	W	p	r	W	p	r	W	p
<b>Difficulty</b>	<b>Trimanual</b>	0.421	68	.044	0.576	225.5	.017	0.492	210	.033
	<b>Hands</b>	0.860	10	<.0001	0.835	262	.0001	0.553	216	.007
	<b>Foot</b>	0.788	21.5	.0003	0.858	269	<.0001	0.543	198	.01
<b>Preference</b>	<b>Trimanual</b>	0.497	230	.040	0.521	58.5	.040	<b>0.194</b>	<b>98.5</b>	<b>.348</b>

evaluated.

The observed difference to previous VR-based findings could be caused by a number of factors including i) the more realistic haptic feedback resulting from the physical coupling of objects; ii) the physical setup introducing previously unconsidered factors such as occlusion; and iii) the robot's motion is constrained by safety factors that were not present in virtual tasks. For factor (i), it is worth noting there was no clear difference in the completion time between configurations for any coupling type. Given that this includes the free condition, that did not have haptic feedback, it suggests that our differing findings are likely not caused by the added haptic feedback.

With regards to factor (iii) we note that our setup used a robot whose motion was atypical to ideal trimanual behavior (due to its safety constraints) given that its coupling led to noticeably slower natural limb motion. Furthermore, our foot interface did not provide force feedback that was consistent with the feedback produced by the different coupling types. These limitations were consistent for both configurations, such that they likely were not the main cause of our atypical finding that task performance was not affected by the configuration. However, SLs ideally provide an effective additional and equally capable limb, where the atypical limb motion is likely harder for participants to predict given their lack of exposure to it. Since the dyad configuration, unlike the trimanual configuration, requires the participant to control with their natural limbs to predict the behavior of the participant controlling the robot, it is possible that this configuration is more affected by the atypical robot motion. Further investigation should be conducted with more dynamic robotic limbs and alternative interfaces to confirm the effect of this factor.

Considering factor (ii), our setup differs from previous experiments [11], [14] in that participants within the dyad were not given equivalent visualizations. This meant that the participant operating the robot could have issues with depth perception, and occlusion coming from their partner's arm. This was not the case in the trimanual configuration, such that these aspects are likely causes of the differences in previous findings. Participants anecdotally reported these challenges, which may explain the increased cognitive load when controlling the robot with a partner, as compared to operating it alone

(Fig. 7a) and a trend toward preferring trimanual operation (Fig. 7d). The increased cognitive load could also have led to a decline in dyad task performance, potentially offsetting the benefits of dyadic interaction observed in previous studies.

Given the large possible effect of the visual feedback, it is possible that our findings may not generalise to other visualisations. Here, our visualisation was chosen to be reflective of real-world scenarios (such as robotic surgery) for which the 'assistant' is often at the side (or in a different room) of the main surgeon. While other visualisations may enable clearer depth perception, the presence of occlusion will likely always be present in physical systems.

The results of this study extend previous results by showing that physical trimanual performance can be as good as working with a dyad in trimanual pick and place tasks. This suggests that trimanual operation with a SL can satisfy the basic requirements of augmentation adoption on real-world inspired tasks. Further investigations could be conducted to determine if these results hold across tasks with varying difficulty, (coupling, dependency) pairs and improved robot behavior as well as if the integration of greater robot autonomy can result in greater performance than is currently observed when working with a dyad.

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