2025 IEEE World Haptics Conference (WHC)
Suwon Convention Center, Suwon, Korea
July 8 ~ 11, 2025

Symmetric Movement Leads to Asymmetric Grip Forces in a Bimanual Peg-in-Hole Task

Niklas Heimburger
TUM School of Medicine and Health
Technical University of Munich
Munich, Germany
niklas.heimburger@tum.de

Clara Günter
TUM School of Medicine and Health, MIRMI
Technical University of Munich
Munich, Germany
clara.guenter@tum.de

Raz Leib
TUM School of Medicine and Health
Technical University Munich
Munich, Germany
raz.leib@tum.de

David W. Franklin
TUM School of Medicine and Health, MIRMI, MDSI
Technical University of Munich
Munich, Germany
david.franklin@tum.de

***Abstract*—Mechanically uncoupled bimanual tasks, where each hand manipulates an object independently, present unique challenges compared to unimanual tasks. When the two objects must be controlled such that they precisely interact, both hands must account for the combined motor noise and variability when coordinating their movements. Here, we investigated the motion, variability, and grip forces immediately prior to insertion of both hands during a simulated bimanual peg-in-hole task, where participants completed the task in both possible hand configurations for the peg and hole. By using three different peg diameters, we introduce a range of difficulty levels to the task. Participants moved both hands symmetrically in the task due to experimental constraints of the motion, with increased duration and corrective movements as the task difficulty increased. However, we found that grip force before insertion was consistently elevated in the left hand compared to the right hand. This asymmetry is evident despite similar forces acting on each object within the simulated environment, resulting in comparable forces acting on the two hands. Overall, we found a strong asymmetry in grip force before insertion, independent of the manipulated object and symmetry of the movements.**

***Index Terms*—object manipulation, bimanual manipulation, grip force.**

I. Introduction

Humans routinely use both hands to manipulate tools or interact with objects, such as putting a cap on a pen. While we are generally able to efficiently and precisely generate motor commands, all stages of sensorimotor control are affected by different types and levels of noise, which produces motion variability [1], [2] and require compensation to perform the tasks accurately [3], [4]. As the precision requirements of a task increase, there are increased submovements and larger corrective responses [5].

This work was supported by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - project numbers 521011355 and 467042759 and the Lighthouse Initiative Geriatronics by StMWi Bayern (Project X, grant no. 5140951) and the TUM Integrative Research Fund, provided by the seed funding initiative of the Munich Institute of Robotics and Machine Intelligence (MIRMI).

For example, when placing the cap on the back of a pen, which is usually cylindrical with only a slight size discrepancy to the cap, the accuracy demand is high. The tip of the pen is generally conical, reducing the accuracy demand to start the insertion. This means that in this general task, different accuracy demands may be present depending on the situation.

When performing a mechanically uncoupled bimanual task, that is, manipulating different tools, which are not physically linked, with each hand, this variability affects both arms. Consequently, if the two hands or tools need to be carefully aligned to perform a task, this effect of noise is combined, as each effector also needs to adjust to noise within the other effector. However, as motor noise is signal-dependent [2], leading to speed-accuracy tradeoffs [6], choosing to only move one of the two effectors will increase the overall noise within that limb. For example, while putting a pen into its cap, we can either put the cap on the pen, insert the pen into the cap, or move both hands simultaneously to solve the task; but each of these choices produces different patterns of variability that need to be controlled.

In addition to the strategy we may use during bimanual tasks, there are differences in how each hand is controlled [7]. It has been suggested that the dominant arm can better predict and compensate for the limb dynamics, whereas the non-dominant arm may rely more on impedance control [7], [8]. Thus, we can find higher curvature and variability in the motion of the non-dominant limb, while the final endpoint variability may be smaller due to the higher limb impedance. This raises important questions about how we might perform these uncoupled bimanual tasks with the two limbs, and whether limb dominance or object type might affect the manner in which we control the task.

Moreover, when manipulating tools, we need to apply adequate grip force to ensure a stable grasp, preventing slippage. Grip force consists of two components, a baseline amplitude and a predictive modulation according to predicted environmental forces [9]. The baseline amplitude reflects

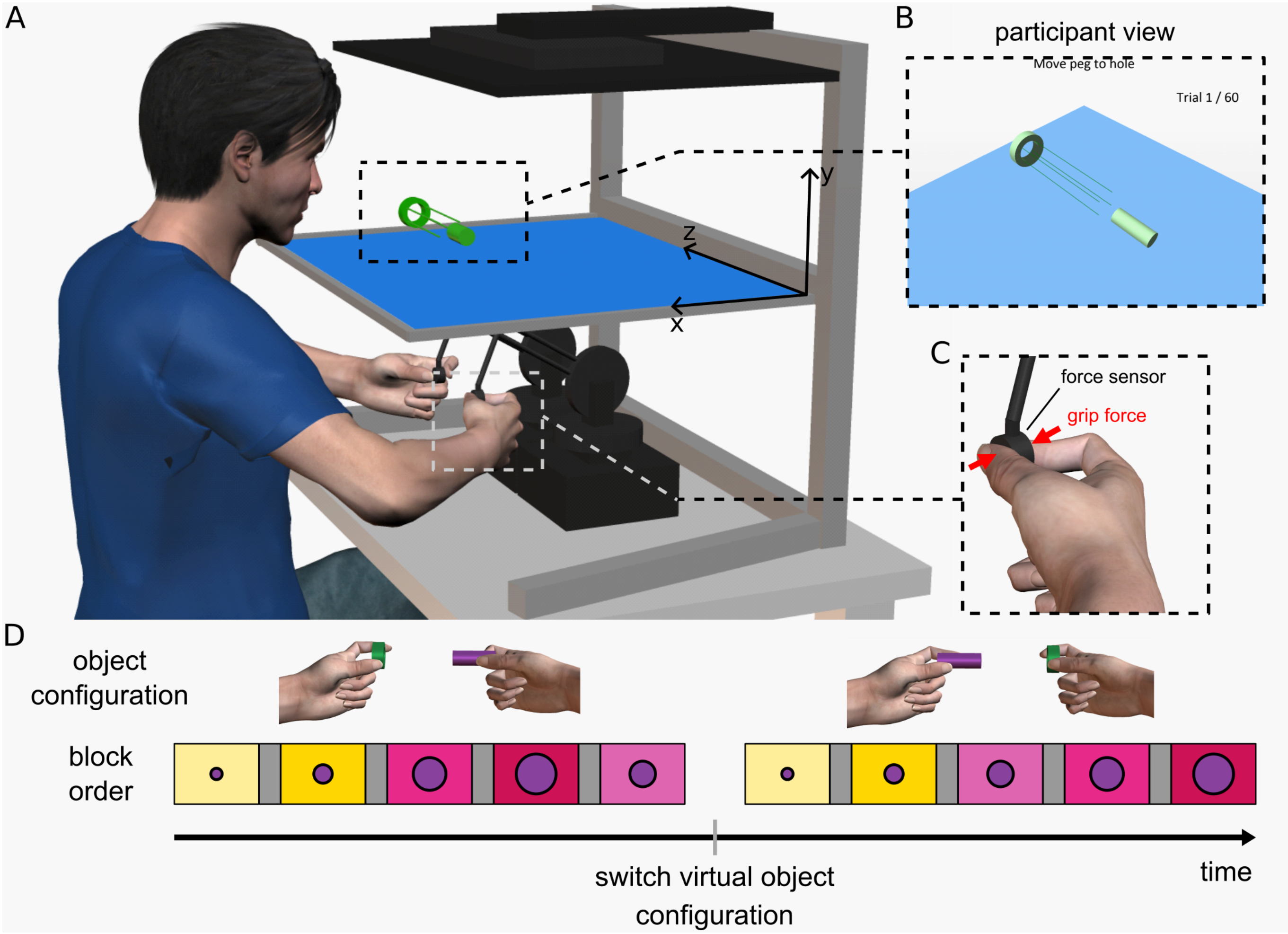

Fig. 1. Experimental Setup. A) The participant sat in front of the virtual reality setup while observing a mirror that had the reflection of a monitor located above. The participant held two force sensors. Each force sensor was attached to a haptic robot. B) The virtual environment as shown on screen to participants. Participants were asked to insert a peg, controlled by one hand, into a hole, controlled by the second hand. Guiding lines that were attached to the ring assisted participants in aligning the peg to the hole center. C) Magnified view of the participant's hand holding the force sensor between the index finger and thumb. The force sensors were used to capture the perpendicular grip force (red arrows) applied by each of the participant's hands. D) An example experimental protocol. Familiarization included one block of 60 trials with a very low accuracy demand (light yellow) and one block with slightly increased difficulty (yellow) before they experienced each of three experimental conditions that differ in task difficulty (marked using different red levels). The inset circles indicate the peg diameter. The order of configurations (indicated with the peg and hole pictograph) and the three highest difficulties (2, 3 and 4 cm diameters) were randomized across participants.

uncertainty about the environment, that is, it increases with increasing variability [10]. For example, as a task becomes more unpredictable or unstable, the grip force increases [11]. Additionally, applied grip force levels may indicate increased arm stiffness [12], a known strategy for decreasing movement variability [4], [13]–[15]. Therefore, if the non-dominant limb relies on impedance control, we might expect higher grip forces and lower motor variability [12], while the predominant movement and corrective actions may occur predominantly with the dominant limb. However, such effects may depend on the performed task. In the peg-in-hole task, for example, the peg may always be controlled in a specific manner to insert into the hole, rather than the controlling an object depending on whether the dominant or non-dominant hand is holding it. Understanding how two limbs are controlled and adjusted to perform complex object manipulations is critical for improving robotic surgery, telemanipulation and the appropriate design of prosthetic hands.

Here, we investigate how accuracy demands change the hand kinematics and grip force levels in a simulated mechanically uncoupled bimanual precision task (peg-in-hole), and whether the laterality of the peg or hole object affects these results.

II. Methods

A. Participants

Eleven right-handed (mean handedness score: 95, assessed using the Edinburgh Handedness Inventory [16]) participants (four male, seven female, aged 25±5 years) took part in the experiment. Before the experiment, participants were introduced to and familiarized with the haptic devices and provided written informed consent. All participants were healthy and naïve to the purpose of the study. The ethics committee at the Medical Department of TUM approved the research (763/20 S-KH).

B. Experimental Setup

Participants sat in front of a screen-mirror setup, which occluded their view of their hands (Fig. 1A). With each hand, they grasped one of two ATI Nano25-E transducers attached to a haptic robot interface (Phantom Premium HF 1.5; 3D SYSTEMS) using their index finger and thumb (Fig. 1C). The friction of the force sensors was standardized by applying P800 sandpaper to the grasp surfaces. Both hands were held in a mirrored configuration, with the index fingers pointing towards each other and the rest of the hand closed. The task was to insert a virtual cylindrical peg held with one hand into a hole (ring-like object) held by the other hand. The objects were visible on the screen, and the alignment between the peg and ring was indicated by four red guiding lines, which turned green when the objects were correctly aligned (Fig. 1B). As soon as the peg was inserted into the ring (in the z-axis), its movement in the xy-direction (object alignment plane) was fixed by a force channel (k=1000 N/m). The experiment was conducted in a virtual environment using CHAI3d [17] to render visual representations.

C. Virtual Model

By moving both hands, participants generated forces on the two objects. Each object was modeled as a point mass of 0.1 kg. The center of the object was linked to the respective robot with a spring-damper system (k_c=100 N/m, d_c=3 Ns/m). Consequently, the forces acting on the object in the environment were defined as:

$$F_{obj} = (x_h - x_{obj}) \cdot k_c + (\dot{x}_h - \dot{x}_{obj}) \cdot d_c \quad (1)$$

where x and $\dot{x}$ are the position and the velocity vectors in 3d, subscript obj refers to the object and subscript h to the hand (left/right). The forces exerted by the robot on the hands were defined as:

$$F_h = -F_{obj} \quad (2)$$

D. Experimental Paradigm

Each trial started with the robots moving each hand into one of three randomized pairs of starting positions. The positions were chosen so that the starting distance between the hands was the same in all trials, but different movement directions were necessary to reach object alignment. Participants were provided with an auditory cue to start each trial. After each trial, separate velocity feedback was given for each hand based on the peak velocity of the movement with a target of 25±10 cm/s. Participants were free to move their hands sequentially or simultaneously, with no requirements of the specific distance each hand moved. The experiment started with a familiarization phase consisting of two blocks with peg diameters of 0.2 cm and 1cm, respectively. The familiarization phase was followed by an experimental phase consisting of three blocks with different difficulties (peg diameters: easy - 2 cm, medium - 3 cm, hard - 4 cm). For all blocks, the inner diameter of the ring was fixed at 5 cm. The order of difficulties in the experimental blocks was pseudorandomized across participants. This procedure was performed twice in opposing object configurations with either the right or left hand holding the peg (order randomized across participants). An example of the block order is shown in Fig. 1. If the trial duration exceeded 10 seconds or the faces of the objects collided, the trial failed and was repeated.

E. Data Analysis

We performed data analysis in Python (version 3.12.7) and statistical tests in JASP (version 0.19.3) [18]. Grip forces were sampled at 500 Hz and filtered with a 20 Hz lowpass filter (zero-phase 6th order Butterworth). Kinematic and dynamic data produced by both hands were recorded at 1000 Hz and down-sampled to 500 Hz. Across the experiments we examined six different performance measures:

Completion Time: the duration from trial start to end.

Smoothness: the spectral arc length (sparc), calculated from the speed profiles of each object's movement; where lower values represent lower smoothness [19].

Corrective distance: the remaining distance after subtracting the euclidean distance between the start and end points from the total distance travelled in the xy-plane.

Force channel variance: the variance of forces applied by the force channels after the peg entered the ring.

Mean environmental force: the mean force applied by the system in the last 0.5 cm before insertion.

Mean grip force: the mean grip force computed as the normal force vector towards the grasp surface, recorded by the force transducers in the last 0.5 cm before insertion. We excluded three participants from the grip force analysis due to hardware issues that led to a loss of force sensor data.

F. Statistical analysis

To test the effect of the hands, configuration, and task difficulty on each of the performance measurements, we used independent three-way repeated-measures ANOVA with "hand" (2 levels; left and right), "object" (2 levels; left-peg, right-hole and left-hole, right-peg), and "difficulty" (3 levels; easy, medium, and hard) as independent factors. The statistical models included all possible interactions between independent factors. In the case of non-sphericity, we corrected the ANOVA using the Greenhouse-Geisser correction. We used Bonferroni correction for Post hoc multiple comparisons for statistically significant interactions. Statistical significance was determined at the 0.05 threshold in all tests.

III. Results

Participants bimanually performed a virtual peg-in-hole task in two different hand configurations. We analyzed the performance measures with respect to factors of difficulty (easy/medium/hard), hand (left/right), and object (peg/ring).

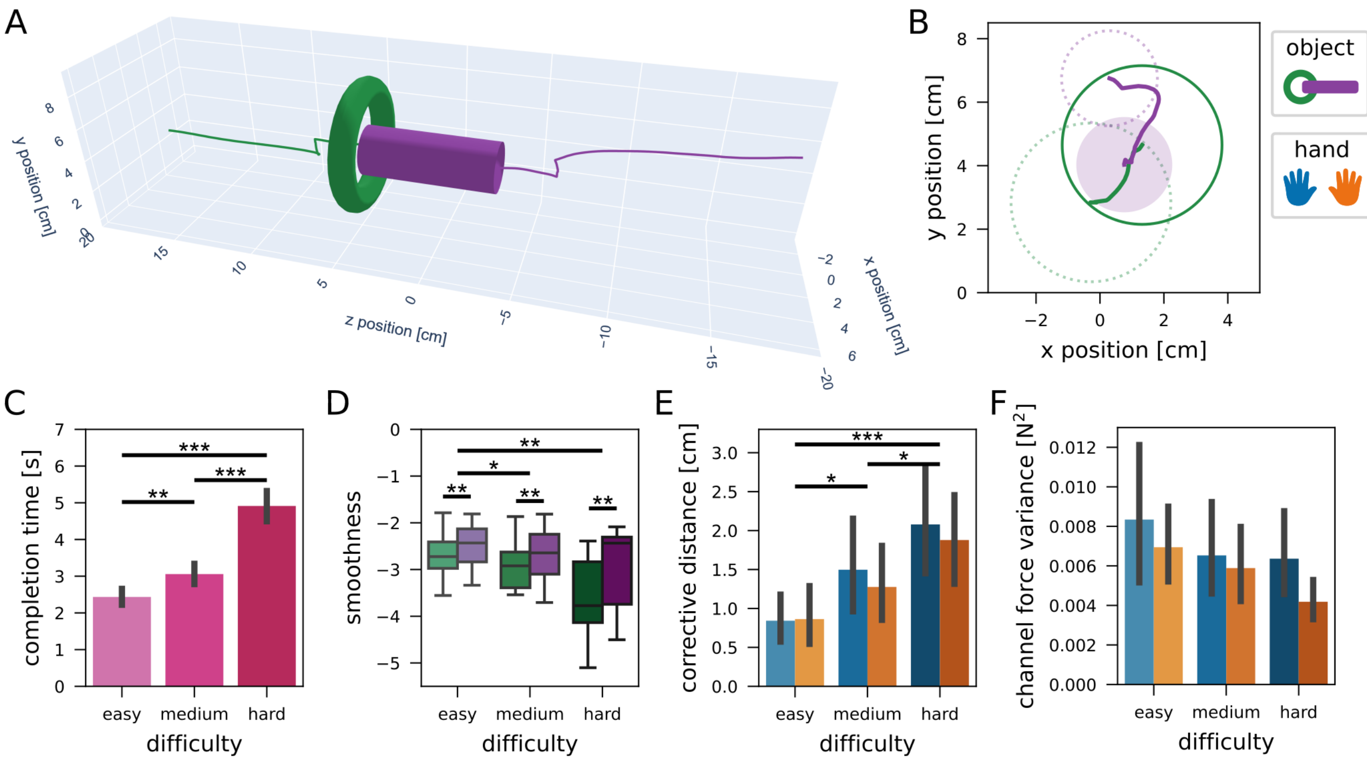

Fig. 2. Task difficulty affects performance measures. A) An example trial showing the whole 3D trajectory of the peg (purple) and ring (green). B) The xy-components of the same trajectories with marked start (dotted circles) and end locations of the objects C) Analysis of trial completion time between difficulties and configurations. D) Smoothness, measured as spectral arc length, differs between the held object within and between difficulty levels. Boxes indicate the quartiles. E) Corrective movement distance in the xy-plane after removing the distance between the start and end position from the overall distance (blue: left hand; orange: right hand). F) Channel force variance for the independent force channels applied to each hand after starting the insertion. (C,E,F) Black vertical lines indicate the 95% confidence intervals. Statistically significant differences following post-hoc tests are indicated by *.

Each trial required the participants to move the peg and ring towards one another and control the xy-position such that the peg entered the hole (Fig. 2A). Looking at the xy-plane (Fig. 2B), we can see that there is both a required motion component to align the peg and hole, and corrective movements that occur as the participants attempt to align and adjust to motions of the other limb. As expected, with increased peg-size (difficulty), the task completion time (Fig. 2C) significantly increased ($F_{1.966,17.697} = 67.533, p < 0.001$) but remained at similar levels in the two different hand configurations ($F_{1,9} = 3.893 \times 10^{-5}, p = 0.995$).

The difference in the control between the two hands was examined using movement smoothness (Fig. 2D). Movement smoothness helps quantify the continuity of the participant's movement, where for a straight-reaching movement, values around -1.6 are to be expected [19], and lower values signify less smoothness. Movement smoothness decreased with increasing difficulty for both hands ($F_{1.267,12.236} = 12.596, p = 0.003$). Additionally, smoothness was reduced in the hand holding the ring compared to the hand holding the peg ($F_{1,9} = 10.982, p = 0.008$) but was unaffected by the hand. The summary of the results from repeated measures ANOVAs conducted on the dependent variables is shown in Table. I.

As the required motion in the xy-plane increased with difficulty (due to the increased peg size), we subtracted this value from the total xy-path to obtain the corrective distance. The corrective distance (Fig. 2E) moved to adjust the alignment between the objects increased significantly with difficulty from easy to hard ($F_{1.681,15.130} = 20.981, p < 0.001$). This can be seen as a result of needing to find a more precise alignment point (1 cm in hard difficulty) and may be accentuated by the challenges posed by the visual environment. We did not observe a statistically significant effect of the hand on this metric (Tab. I).

Once the peg entered the hole, independent force channels fixed both hands in xy-direction, allowing us to measure the force variability in each hand separately (Fig. 2F). There were no observed significant differences in force variability for any of the analyzed factors (difficulty, hand, or object) (Tab. I).

While the environmental forces were generally low throughout the movements of both hands, the grip force was higher in the left hand than the right hand (Fig. 3A,B). To compare this difference across conditions, we quantified these forces in the last 0.5 cm prior to insertion.

We examined the grip force levels before insertion over trials to show the adaptation of each hand separately (Fig. 3C). Grip force before insertion decreased over the course of the first 10 trials in the left hand, while no adaptation in the right

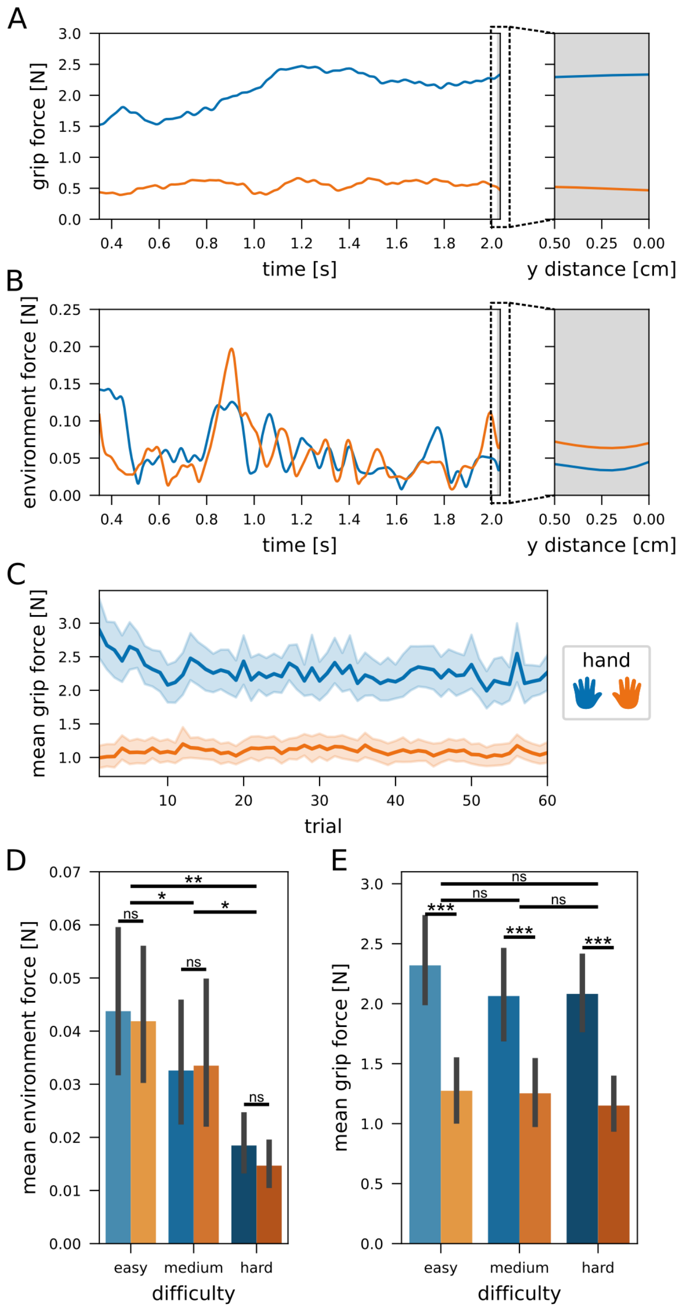

Fig. 3. Grip forces before insertion increased in left (blue) compared to right (orange) hand. A) Grip force in a representative example trial. The grey shaded area indicates the window over which the mean environmental force and the mean grip force were calculated. The right side shows a magnified view of the last 0.5 cm before insertion. B) Environmental force produced by the robots in a representative example trial. The grey shaded area indicates the window over which the mean environmental force and the mean grip force were calculated. The right side shows a magnified view of the last 0.5 cm before insertion. C) Mean grip force across participants in the last 0.5 cm before insertion over the course of the experiment. Shaded areas indicate the 95% confidence intervals.. D) Mean environmental force produced by the system in the last 0.5 cm before inserting the peg into the ring. Black lines indicate the 95% confidence intervals. Significant differences from post-hoc comparisons are indicated with *. E) Mean grip force in the last 0.5 cm before insertion.

hand was present.

In agreement with the corrective distance and completion time analysis, we also found that the mean environmental force between the point in which the objects were 0.5 cm apart from each other and the point of insertion (Fig. 3D) showed a significant decrease with increasing difficulty for both hands ($F_{1.248,14.113} = 14.113, p = 0.002$)(Tab. I). Since the environmental force mainly represents the hands' speed, this decrease in force values suggests that increasing the difficulty of the task made participants move slower and avoid big changes to the state of the system around the insertion point. Contrary to the dependency of the environmental forces on task difficulty, we found that the applied mean grip forces before insertion did not modulate according to task difficulty or the peg and hole configuration. Instead, the grip force before insertion tended to have a similar value for each hand across all difficulties, where the grip force before insertion applied by the left hand was elevated compared with the grip force before insertion applied by the right hand ($F_{1,6} = 43.980, p < 0.001$) (Fig. 3A,E). The lack of grip force modulation and the elevated grip forces in the left hand were evident across the entire movement before insertion and not just when the two objects were close to each other (Fig. 3A), suggesting the dissociation between the grip force before insertion from the movement control of the hands during the task.

IV. Discussion

We investigated the effect of hand configuration on kinematics and grip forces in a simulated bimanual peg-in-hole task. Using a mechanically uncoupled bimanual movement, where both hands could independently manipulate two objects, we observed consistent changes in different measures due to difficulty. Specifically, we found increases in completion time and corrective distance and decreases in smoothness and environmental force as the difficulty increased. However, changes in grip force before insertion were unaffected by the task difficulty or specific object held, but were instead based on the hand laterality.

Speed-accuracy tradeoff is a well-known feature in human motor control (e.g., [6]). In our task, the completion time increased with task difficulty (see Fig. 2C), that is, an increased accuracy demand. This increased completion time and the reduction in smoothness with difficulty suggests that the simulated peg-in-hole task on robotic devices captures the main characteristics of a bimanual precision task.

While we did not find significant differences in movement smoothness between the hands, the decrease of smoothness with increasing difficulty aligns with the additional adjustments performed by participants in the xy-plane. Part of the decreased smoothness with increasing difficulty might be related to the increased movement time, which has been reported to affect the smoothness measure [19]. This does, however, not apply to the effect of the object since both hands moved for the same time within each trial. The effects of the held object on the movement smoothness imply a role for the object. Participants performed smoother movements

TABLE I

RESULTS OF SEPARATE REPEATED MEASURES ANOVAS FOR THE EVALUATED VARIABLES WITH THE FACTORS DIFFICULTY, HAND, AND OBJECT.

Dependent Variable	corrective distance			force channel variance			smoothness		
Factor/Interaction	df	F	p	df	F	p	df	F	p
difficulty	**1.681**	**20.981**	**<0.001**	1.221	3.059	0.103	**1.267**	**12.596**	**0.003**
hand	1.000	0.143	0.714	1.000	4.621	0.060	1.000	1.436	0.261
object	1.000	1.154	0.311	1.000	1.061	0.330	**1.000**	**10.982**	**0.009**
Dependent Variable	environment force			mean grip force					
Factor/Interaction	df	F	p	df	F	p			
difficulty	**1.248**	**14.113**	**0.002**	1.517	2.498	0.143			
hand	1.000	0.333	0.578	**1.000**	**43.980**	**<0.001**			
object	1.000	0.005	0.943	1.000	2.225	0.186			

Note. Significant results are printed in bold text. While not shown here, all other interactions between the main factors were statistically insignificant for all performance measurments.
Note. Where applicable, statistics were corrected using Greenhouse-Geisser correction.

with the hand holding the peg regardless of which hand was holding it, which indicates that inserting the peg into the hole is performed more smoothly than putting the ring onto the peg. Since movement smoothness can also be used to indicate the level of control [19], these results suggest that participants were able to perform similarly with their dominant and non-dominant hands.

Theories of motor laterality [7], [8] might suggest that the left hand would use higher impedance control, causing a reduction in motor variability in that hand. However, we found no significant differences between the hands and difficulties, suggesting there was no decrease in motor noise in the left hand regardless of the increased mean grip force before insertion shown in Fig. 3E. With sufficient task experience and sensory information, it has been shown that the right hand shows decreased position error and variability compared to the left hand [20], which is consistent with the trends we observed. This may have occurred as all participants were right-handed, perhaps indicating increased motor noise in the non-dominant arm. In contrast, the right hand might be expected to be adjusted and controlled to perform the task, which is also not what we found in our experiment.

Grip force is usually scaled in relation to the applied load to prevent the held object from slipping [21], [22]. This means that an increase in load force should result in a proportional increase in grip force. Contrary to this assumption, a clear elevation of mean grip force before insertion is present in the left hand without a clear increase in environmental force. While we observed some reduction of the grip force before insertion in the left hand throughout the experiment, this did not continue until equal grip forces were reached in both hands (see Fig. 3C). Previously, grip force has been shown to represent a desire for increasing precision [23], however, we found no statistically significant difference in grip force before insertion based on difficulty. Grip force has also been shown to increase with increasing arm stiffness [12], suggesting a possible increase in stiffness in the left arm. The available data does not allow for a clear conclusion on this since we did not measure endpoint stiffness, and it is unclear how well the grip force to stiffness relationship translates to bimanual precision tasks using a pincer grip. This theory would, however, align with other studies suggesting a preference for the left arm to utilize impedance control [24]. However, if increased grip force reflected an increase in limb stiffness, we would expect a reduction in noise in the left hand [13], [25], [26], which was not found. Finally, previous work demonstrated that in bimanual object manipulation, grip force scaling may depend on hand position within a configuration rather than hand dominance [27]. While our current results seem to contradict those findings, this difference could be caused by a multitude of factors. For example, the imposed velocity requirements in the current task may have affected grip force scaling. Further, the scaling could be affected by manipulating one object per hand versus one object with both hands (mechanically coupled vs. mechanically uncoupled task). The investigation of such factors will be the subject of future work.

While we let participants decide on a movement strategy, the symmetry of arm movement might have been influenced by the task constraints since participants were incentivized to reach a certain peak speed with both hands. This might have encouraged participants to try to move the two hands symmetrically, which may not have occurred under more unconstrained or natural movements of the two limbs. For example, theories about limb laterality might propose that the left hand would be more likely to be stationary and stabilized through impedance control while the right hand performs the majority of the movement to bring the two objects together. Further studies are required to determine whether such constraints have driven the variability and grip force changes or whether these consistently occur in these bimanual peg-in-hole tasks.

V. CONCLUSION

One clear finding in our bimanual task was the increased mean grip force before insertion in the left hand, regardless of whether the hand controlled the peg or ring. The extent to which the grip force in the left hand exceeds that of the right suggests that this was a major control strategy of the participants. However, whether this grip force asymmetry indicates lateral differences in variability, impedance control, sensing or general control strategies is unclear. Regardless of this interpretation, the large increase in left hand grip force, independent of the controlled object, has potential implications for prosthetics, telerobotics and robotic surgery.

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