Exploration of Geometry and Forces Occurring within Human-to-Robot Handovers

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***Abstract*— This work presents an exploratory user study of human-to-robot handovers. In particular, it examines how changes in a robot behaviour influence human participation and the overall interaction. With a 2x2x2 experimental design, we vary three basic factors and observe both the interaction position and forces. We find the robot's initial pose can inform the giver about the upcoming handover geometry and impact fluency and efficiency. Also we find variations in grasp method and retraction speed induce significantly different interaction forces. This effect may occur by changing the giver's perception of object safety and hence their release timing. Alternatively, it may stem from unnatural or mismatched robot movements. We determine that making the robot predictable is important: we observe a learning effect with forces declining over repeated trials. Simultaneously, the participants' self-reported discomfort with the robot decreases and perception of emotional warmth increases. Thus, we posit users are learning to predict the robot, becoming more familiar with its behaviours, and perhaps becoming more trusting of the robot's ability to safely receive the object. We find these results exciting as we believe a robot can become a trusted partner in collaborative tasks.**

I. INTRODUCTION

A robot's ability to effectively give or receive an object, to or from a human partner, is an essential skill for physically interactive and collaborative operations. If robots are to work with people, they have to perform such handover interactions consistent with and respecting accepted human behaviours.

In this paper, we examine human-to-robot handovers; that is handovers where a human giver passes an object to a robot receiver, as illustrated in Fig. 1. As much of the existing literature focuses on the reverse robot-to-human interaction, we aim to attain a basic understanding of robots in the receiver role and how varying some basic elements of their behaviours may influence a human giver's own behaviours.

To achieve this goal, we conducted a user study examining both the physical execution as well as the participants social perception of the handover. Analysis and discussion of the social aspects of this work are reported separately in [1]. Here we focus on how human givers present the object to the robot (geometry) and what forces they imparted on the object (dynamics). The study varied the starting pose of the robot, potentially changing the negotiation of geometry. It altered how carefully or quickly contact was made during the grasp of the object, possibly affecting the givers perception of the robot and the interaction. Lastly, it modified how quickly the object was taken, exploring the givers release process. Through this study, we also aim to determine if users adapt to repeated interactions with the robot, i.e., to observe learning effects. Through observations of changes in the human givers behaviour, we hope to begin characterizing the design space for human-to-robot handovers and to be able to inform how subtle alterations of the robot may affect human users.

This work was supported by Disney Research and the University of British Columbia Institute for Computing, Information and Cognitive Systems.

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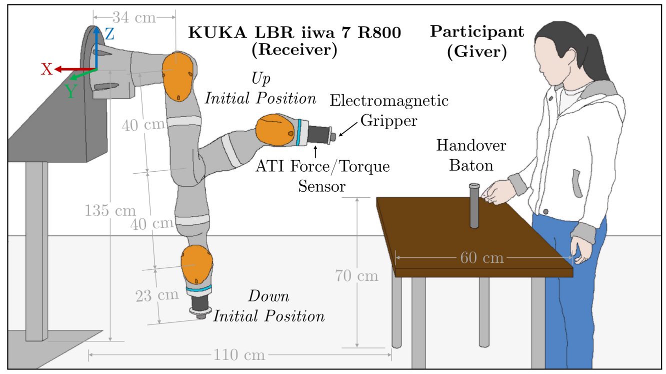

Fig. 1. Experimental setup for handover experiment. Diagram shows both the *up* and *down* initial arm positions tested as conditions in the experiment.

II. BACKGROUND

Prior work studying handovers has mainly been focused on human-to-human and robot-to-human handovers. Among these studies, there seems to be no consensus on what factors are most important in determining how handovers are carried out. Even seemingly inconspicuous factors can play an important part in coordinating and directing handovers [2]–[8]. Here, we consider prior work studying the kinematic and dynamic interactions within human-human and human-robot handovers.

A. Kinematics

There have been numerous studies trying to better understand the kinematics involved in human-to-human handovers, e.g., [2], [7], [9]–[12]. Several studies have looked at where handovers occur in the spatial domain [2], [7], and the joint/limb kinematics of both the giver and receiver during handover [11], [13], [14]. Kajikawa et al. and Koay et al. have both investigated motion planning of robots conducting handovers in close proximity to human counterparts, identifying typical kinematic characteristics in human-human handovers and developing appropriate handover trajectories based on such findings [11], [15]. Kajikawa et al. have determined that handovers between humans share several common kinematic characteristics, e.g., rapid increase in the givers arm velocity at the start of the handover, [11].

Other researchers have investigated robot handover trajectory and pose, reporting guidelines for how a robot arm should be positioned for robot-to-human handover and how that position should be achieved. For example, Agah and Tanie presented a handover motion controller that was able to compensate for unexpected movements of a human to achieve a safe interaction between human and robot [16]. Koay et al. identified human preferences for coordinated arm-base movement in the handover approach, observing that the majority of people preferred robots to approach a handover interaction from the front [15]. Pandey et al. and Mainprice et al. investigated the selection and recognition of handover locations based on the amount of human motion required to complete the handover [3], [17]. As a result of this work, Mainprice et al. designed an approach planner that considers both the mobility of the human receiver and robot giver in a cluttered environment. In a related stream of work, Sisbot and Alami used kinematic features, along with preferences and gaze of the human receiver, to help a robot giver plan trajectories to navigate to a handover location safely and in a socially comfortable manner [14]. In examining human-to-robot handovers, Edsinger and Kemp demonstrated study that humans inexperienced with robots were able to hand over and receive objects from a robot without explicit instructions [18]. They also found that humans tended to control object position and orientation to match the configuration of the robots hand in order to make the robots task of grasping the object simpler. Within the robot-to-human handover context, most of these studies have focused on having human behaviours and preferences dictate robot actions. Conversely, our investigation of human-to-robot handover interactions aims to determine how human behaviours may be affected by varying robot kinodynamic actions.

B. Dynamics

Another stream of work has examined how grip and load forces play an important part in givers and receivers negotiating handovers [8], [19]. In studies of grip forces during human-human object handovers, Mason and Mackenzie studied force profiles during transport and transfer of the object, finding that both giver and receiver use somatosensory feedforward control to synchronize transfer rate during handover [10]. Grip and load forces have also been shown by Chan et al. and Kim and Inooka to play a significant role in the coordination of handovers. Chan et al. showed that both the giver and receiver utilize similar strategies for controlling grip forces on the transferred object in response to changes in load forces. Through analysis of force loading on the transferred object, they found that the giver is primarily responsible for ensuring object safety in the handover and the receiver is responsible for maintaining the efficiency/timing of the handover [8].

In this work, we seek to determine how load forces in human-to-robot handovers compare to those previously observed between humans. We posit that such a comparison may lead to insights into how the efficacy of robot behaviours during the handover interaction might be improved.

III. EXPERIMENTAL DESIGN

In our studies, a human participant initiated a handover by holding out the baton towards the robot, similar to previous human-to-human studies [20]. The robot receiver then reacted, moving to and then grasping the baton before retracting. We varied three basic factors to explore the interaction: starting position of the robot arm, grasp type, and retraction speed.

We selected these factors to examine the user perception of the robot's attributes and to explore the geometry of and forces imparted during the handover interaction. In particular, variation of initial arm position could help determine how people approach and direct handover gestures to a disembodied robot arm and how these gestures compare to human receivers studied in prior work [20]. Modification of grasp type and retraction speed may help to illuminate the force interaction between the giver and receiver and to establish what dynamic negotiations occur during human-to-robot handovers.

A. Initial Robot Pose (Down or Up)

For this factor, we chose between two starting positions of the robot arm prior to handover: *up* and *down*. Both of these initial positions are shown in Fig. 1. We hypothesize that the initial robot position may affect the giver's perception and behaviour as they present the baton. For example, the *up* position could convey the robot is awaiting the handover object, whereas the *down* position might suggest that the robot has yet to recognize the giver's intent. In addition, different initial spacing and orientation of the robot end effector may affect where the handover takes place and how the object is oriented.

B. Grasp Type (Quick or Mating)

Gripper design and grasping is still an active area of research, attempting to match the speed, smoothness, dexterity, and conformity of a human grasp. Current state-of-the-art methods either carefully plan feasible grasps and execute them slowly, or apply brute force to 'robotically' grasp without the delicacy of human touch. We use a simple electro-magnetic coplanar interface that can emulate both extremes, denoted as *quick* and *mating* grasps in Fig. 2. In the *quick* grasp, the robot energizes the electromagnet when it comes to within 1 cm of the baton. The result is a quick, overpowering grasp that will pull in the baton and exhibit snapping forces. In the *mating* grasp, the robot proceeds into direct contact. Using 6-axis force/torque sensing, it applies small adjustments to reach flush contact before activating the magnet. The resultant forces are smooth though the process is slower and necessarily presses slightly against the giver. We believe this factor may affect the perception of efficiency and object safety during handover, as well as change the interaction force levels.

C. Retraction Speed (Slow or Fast)

We chose between two retraction speeds following the grasp to emulate a gentle tug or a firm yank. The *slow* and *fast* conditions command 10 cm/s and 20 cm/s, respectively, and may also affect the force levels between the giver and receiver.

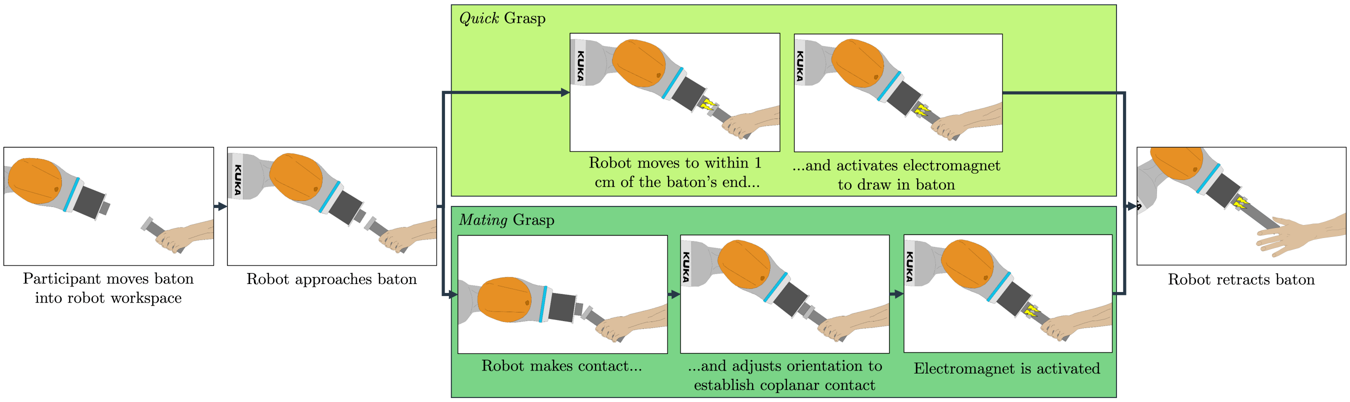

Fig. 2. Flowchart of *quick* (top row) and *mating* grasp types. The *quick* grasp pulls in the baton magnetically while the *mating* grasp establishes coplanar contact, gently pressing against the baton before activating the magnet.

IV. EXPERIMENT SETUP

A. System

This work used a KUKA LBR iiwa 7 R800 robot (KUKA, Augsburg, Germany), with an external ATI Mini45 force/torque sensor (ATI Industrial Automation, Apex, North Carolina, USA). The robot was mounted 135 cm above ground level, as shown in Fig. 1. It was fitted with a simple electromagnetic gripper that, when activated, securely held a baton via a coplanar interface.

A set of 12 OptiTrack Flex 13 motion capture cameras (NaturalPoint, Corvallis, Oregon, USA) were used to uniquely track the baton, participant's dominant hand, and end effector. The Flex 13 cameras have a frame rate of 120 frames per second with an average latency of 8.33 ms (as reported by OptiTrack's Motive software). Position and orientation tracking data of each object is transmitted via UDP to a second computer controlling the robot's behaviour.

As mentioned in Section III, participants initiated the handover by holding the baton out toward the robot, similar to how handovers have been initiated in previous studies [20]. When the baton was within the robot's reachable workspace, it proceeded to move to grasp the object from its initial position using either the *quick* or *mating* grasp method. Retraction moved 10 cm back along the baton's axis before returning the arm to the *down* position (see Fig. 1). If the giver refused to release the baton, overcoming the electromagnetic force, the robot immediately returned to and regrasped the baton.

B. Participants

This study was reviewed and approved by the Disney Research Institutional Review Board. Recruitment was performed within Walt Disney Imagineering Advanced Development and Disney Research. Twenty-two participants (11 females, 11 males), aged 22-52 years [*M*=30.32, *SD*=8.12] were recruited in total. All participants provided their informed consent prior to the experiment; they were notified that their participation was voluntary, and they were allowed to withdraw from the experiment at any time. Additionally, we obtained permission from all participants to record both video and motion capture data from the experiment. No reward was given for participation in this study.

C. Participant Task

Each participant wore a glove on their dominant hand; the glove was tracked by the motion capture system via a rigid arrangement of retroreflective markers attached to the back of the glove. To avoid any accidental collisions with the robot, participants stood behind a table for the duration of the experiment, as shown in Fig. 1. Only their hand entered the robot's reachable workspace. For each trial, participants picked up the baton from the table and initiated a handover to the robot after hearing the experimenter say 'go'.

We used a 2x2x2 experiment design to test the three factors, resulting in eight conditions. The conditions were counterbalanced between participants using a Latin square design to prevent carry-over effects. Three trials were performed per condition, accumulating to 24 trials per participant. Following each set of three handover trials for a condition, participants completed a Robotic Social Attributes Scale (RoSAS) inventory, as developed by Carpinella et al. [21], to subjectively rate the discomfort, warmth and competence of the robotic handovers they just performed. Each experiment session lasted approximately 30 minutes.

V. GEOMETRY

We recorded the position and orientation of the baton as held by the participants to initiate handover. Fig. 3 shows a scatterplot of positions with X measuring the distance to the robot, Y the lateral offset, and Z the height above ground (not plotted). Fig. 4 shows the orientation composed of elevation as the pitch angle of the baton relative to horizontal and azimuth as the lateral yaw angle. Rotation along the baton axis was not considered due to symmetry. As the factors of grasp type and retraction speed are non-causal of how participants initially pose the baton (e.g., these factors chronologically occur after the participants' initiation of the handover and should not affect how the baton is initially positioned and oriented by participants), we have only analyzed this data with respect to the *up* versus *down* initial robot poses.

Only the elevation angle was found to have a significantly differing mean. Participants pointed the baton more horizontally when the robot started in the *up* pose. The *up* pose also

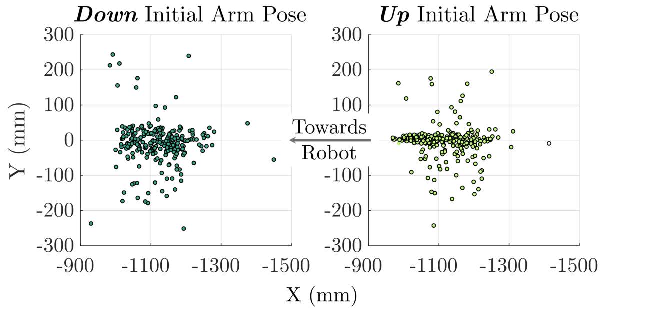

Fig. 3. Scatterplots of initial object positions (from the overhead perspective) for both the *down* (left) and *up* initial arm pose conditions.

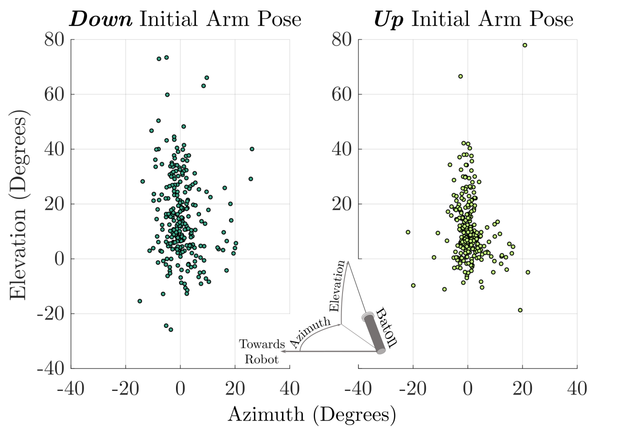

Fig. 4. Scatterplots of initial object azimuth and elevation angles for both the *down* (left) and *up* (right) initial arm pose conditions.

led to less variance in both the lateral position and azimuth angle.

A. Results

Paired samples t-tests showed no significant differences in means under *down* versus *up* conditions for all position axes and azimuth angle. Only the mean elevation differed for *down* [M=14.840°, SD=10.889°] and *up* [M=10.664°, SD=8.209°] arm pose conditions [t(21)=3.470, p=.002, d=0.433].

An equivalence test (TOST procedure) was conducted for each position axis using a ±25 mm margin of equivalence. This margin was based on statistical results obtained by Basili et al. in [7] examining the handover object to giver distance for 26 giver/receiver dyads [M=646.68 mm, SD=87.3 mm]. The sample size of 22 was calculated to be sufficient (with a two-sided 90% CI and 80% power) to establish equivalence, even with a 10% participant loss. Results yielded statistical equivalence between the *up* and *down* groups for all axes at $p < 0.05$.

F-tests for comparing variances was performed for each position and angle. The variance in the Y position was significantly different [F(21,21)=2.149, p=.043], with the variance for the *up* condition being smaller than for the *down* condition. Similarly, the variance in azimuth angles differed [F(21,21)=2.207, p=.04] between *down* [M=0.661°, SD=3.621°] and *up* [M=0.934°, SD=2.437°] conditions, again with the *up* condition leading to a smaller variance. Differences in variance for X and Z positions and elevation angles were not significant.

B. Discussion

1) Comparison to Human-Human Handovers: Relative to human-to-human handovers, in particular as studied by Basili et al. [7], we find participants in our study held the baton approximately 27 cm lower. To explain this discrepancy, we note our robot apparatus is approximately 150 cm tall, as seen in Fig. 1. Meanwhile the average human receiver height appears to be 180 cm in [7], presenting a roughly 30 cm difference. This apparent correlation suggests that givers may be influenced by the proportions of the receiver and place the object conveniently for the receiver. If true, this would imply robots should try to receive handovers at a height proportional to their stature.

Direct comparisons of lateral and distal positioning within the horizontal plane is challenged by differences in experimental procedure. For example, we placed a table between giver and robot receiver and allowed right- as well as left-handed handovers. Nevertheless, we note that regardless of receiver, the handovers occur roughly halfway and centered between giver and receiver.

2) Effect of Initial Robot Pose on Geometry: Our study shows that the initial robot pose significantly affects a giver's placement and orientation of an object for handover. When the robot starts in the *up* pose, thus closer to the giver and eventual handover location, the giver more tightly places and orients the object in the horizontal plane. They also lower the elevation angle, being more aligned with, though still significantly greater than the robot's end-effector angle of 5.94°[t(21)=2.698, p=0.014, d=0.575]. It appears that givers generally attempt to place and orient the object complimentary to the end-effector, at least as much as is comfortable.

This observation agrees with arguments made by Cakmak et al. maintaining that the spatial configuration may be an important tool for improving handover interaction fluency and legibility through implicit, non-verbal communication [5]. We suggest the robot's *up* pose implicitly communicates to users, better informing them where and in what orientation the robot can reach for the object.

Such communication is particularly important in human-to-robot interactions. Where human givers likely have lots of experience handing objects to human receivers, they may have limited a-priori understanding of robot handovers. Especially in the *down* pose, the amorphous shape of the KUKA LBR iiwa provides few cues and givers may remain uncertain how to present the object. Possibly poor placements could then require longer robot trajectories or awkward grasp angles, limiting fluency and efficiency of the interaction. Thus, we hypothesize that the robot's *up* pose, illustrating the preferred handover angles and location, increases handover fluency and efficiency.

VI. DYNAMICS

We were able to capture the interaction forces using the force/torque sensor attached to the robot's end-effector. For

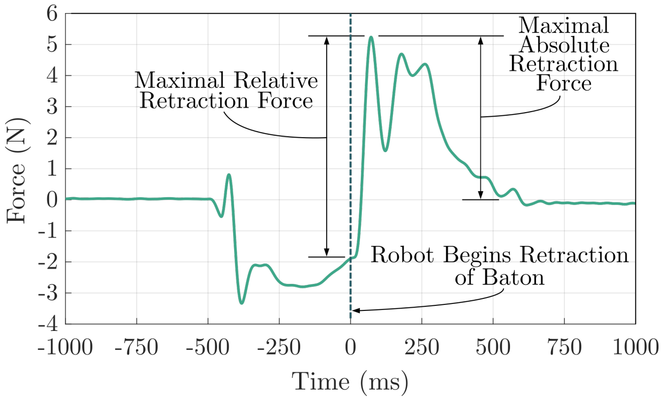

Fig. 5. Sample end effector axial force vs. time plot for a participant depicting features used in the analysis.

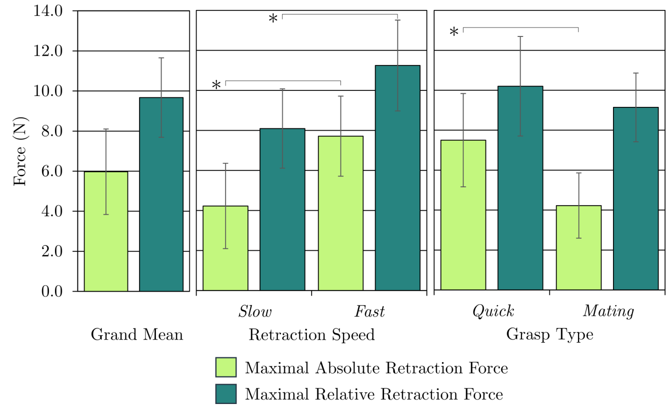

Fig. 6. Maximum absolute and relative retraction forces as experienced by the giver. Asterisks represent significant comparisons at the $p < 0.05$ level and error bars represent 95% CIs.

the purposes of this study, however, only the forces applied axially with respect to the end-effector were analyzed. Inertial and gravitational components were subtracted from the data using the observed kinematics to calculate the isolated interaction forces experienced by the human giver. Additionally, data was filtered using a fourth-order low-pass Butterworth filter with a 14 Hz cutoff, similar to [8].

In our analysis, we consider the maximum retraction/pull force applied by the robot to the giver. It has been postulated that this absolute level communicates that the receiver is in full control of the object and triggers the giver's release. We also consider the maximal change in retraction force, relative to the force immediately before retraction. Relative changes may provide additional information and triggers to the giver. These metrics are illustrated in Fig. 5. Pulling forces applied to the end effector are denoted as positive, whereas pushing forces are negative.

A. Results

The mean maximal absolute and relative retraction forces are depicted in Fig. 6. In particular, the overall mean maximal absolute retraction force was 5.48 N [*SD*=7.11 N] or 223% [SD=290%] of the baton's 250 g weight. A three-way repeated measures MANOVA was conducted to test the effect of the manipulated variables (initial arm configuration, speed of retraction, and grasp type) on the mean maximal absolute and relative retraction forces. Effect sizes in terms of partial eta squared ($\eta^2_{partial}$) are reported [1]. Results showed significant main effects of grasp type [F(1,21)=9.765, p=.005, $\eta^2_{partial}$ =.317] and retraction speed [F(1,21)=10.322, p=.004, $\eta^2_{partial}$ =.330] on mean maximal absolute retraction forces. For the relative retraction forces, a significant main effect was only observed for retraction speed [F(1,21)=10.888, p=.003, $\eta^2_{partial}$ =.341]. No other main or interaction effects were found to be significant.

B. Discussion

1) Comparison to Human-Human Handovers: Chan et al. report that human givers tend to delay the release of an object even after the receiver is fully supporting the object's weight [8]. They measured a maximum excess receiver load and hence a positive maximum retraction force of 2.36% [*SD*=4.16%] of their baton's 483-678 g weight. With the receivers pulling more than the object's weight, they hypothesized this may be a precautionary behaviour on the part of the giver to ensure safe object transfer.

For a robotic receiver, we see a nearly 100-fold increase in this metric. Following the above hypothesis that a giver only releases the object when they believe safety is guaranteed, this could imply participants were not as confident or trusting in our robot receiver. Such a lack of confidence would be consistent with inexperience in human-to-robot handovers. But this argument would necessitate that the interaction forces are only created by voluntary giver actions.

An alternative explanation would come from involuntary forces. If the robotic retraction follows a different timing, motion profile, speed, or even impedance than a human retraction, the interaction forces might also differ without any voluntary consideration. For example, the retraction forces could be generated before the receiver has a chance to react. As such, this could suggest an efficient human-to-robot handover will require subtle retraction movements.

2) Effect of Grasp Type: The grasp type had a significant effect on the maximal absolute retraction force, with *mating* grasps resulting in approximate half the force of *quick* grasps. Following the above logic, this could signify that participants felt more trusting of the *mating* grasp and thus released the object at a lower absolute force threshold.

However, recall that during the *mating* grasp, the robot initially applies a pushing force in an attempt to obtain flush contact. Meanwhile in the *quick* grasp, the magnet is already pulling the object. Indeed, the maximal relative retraction force does not show a difference between the two conditions. This could suggest that givers are relatively indifferent to the grasping type and trigger their release on a relative force change. And as before, any involuntary reaction forces may compound the observations.

3) Effect of Retraction Speed: The *slow* and *fast* retraction speeds may shed the most light on the issues of involuntary force buildup. Both the maximal absolute and relative re-

[1]As a rule of thumb, Cohen indicates that partial eta square values of .0099, .0588, and .1379 may serve as benchmarks for small, medium, and large effect sizes [22].

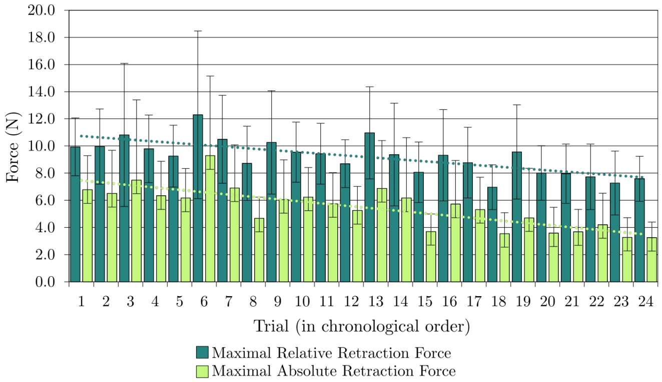

Fig. 7. Maximal forces during handover as experienced or applied by the giver over trials ordered chronologically. Lines of best fit for each are shown. Error bars represent 95% CIs.

traction forces were significantly affected by the retraction speed condition. In particular, twice the retraction speed resulted in nearly twice the retraction force. Also several participants noted that in the *fast* condition, they felt the robot yanking the baton out of their hand. Indeed, participants subjectively rated a fast retraction or a mating grasp as more discomforting than a quick grasp with slow retraction [1].

The differences in force profiles may have less to do with voluntary force thresholds and more with human reaction time, which is on the order of 150 ms for haptic stimuli. In the *slow* condition, the maximal retraction force occurs 147 ms [*SD*=50 ms] after the start of the retraction. In the *fast* condition, the timing is much shorter. A *fast* retraction thus exceeds the giver's grip forces before they can react. To avoid any sensation of yanking and generally to allow the giver to voluntarily control forces, releasing the object as appropriate, the robot receiver will need to carefully modulate and limit retraction speeds. At least until the robot can determine that the object has been released.

Finally we note that the apparent correlation between forces and retraction speeds suggests that the givers are presenting repeatable impedances during handover. Such findings could also help guide robot behaviours in handover to a human.

VII. LEARNING

Although the presentation order of conditions was counterbalanced across participants, we suspected each participant's perception changed over the course of their repeated handover interactions with the robot. To examine this effect, participants' trials are shown in chronological order in Fig. 7.

A. Results

Trend analysis was conducted for each factor with appropriate corrections for non-spherical data. Results showed significant negative linear trends for maximal absolute [$F(1,21)=11.924$, $p=.002$, $\eta^2_{partial}=.362$] and relative [$F(1,21)=7.607$, $p=.012$, $\eta^2_{partial}=.266$] retraction force. Higher order trends were non-significant for all measures.

B. Discussion

The observation of negative linear trends in both force measures over repeated interaction with the robot is notable as it indicates that participants are adapting their force behaviour to the robot. If we consider voluntary behaviour, the givers may be building up trust in the robot to safety receive the object and releasing sooner. If we consider involuntary forces, givers may be learning to predict the robot's behaviours and moving or relaxing predictively without necessarily releasing sooner. Indeed these two aspects may be fundamentally linked in the human givers, as the ability to predict would seem to go hand in hand with any willingness to trust.

Further evidence of learning can be derived from participant's subjective ratings of the robot during the experiment through the Robot Social Attributes Scale (RoSAS) inventory: ratings of the robot's warmth linearly increased over repeated interactions, while discomfort simultaneously decreased [1]. This suggests that the more people interact with the robot, the more they develop positive attitudes towards the robot. Both warmth and discomfort are known factors in the determination of trustworthiness of both humans and robots [23], [24]. Thus, when considering both sets of trends together - decreasing force and increasing positive social perception of the robot - there appears to be strong evidence that forces imparted on the object by the giver are related to how willing they are to trust the robot with the safety of the object. Although, again, it is unclear whether lower forces cause higher ratings of warmth and decreased discomfort (or vice versa), or whether both are effects of another factor at play, e.g. of familiarity or predictability of the robot.

VIII. CONCLUSIONS

Beyond providing a demonstration of a simple human-to-robot handover, the user study was able to elicit some basic lessons on appropriate behaviour. First we found that the robot's initial pose affects the handover geometry. As a result, we posit that a pose can communicate appropriate location and orientations for the handover, information that may not be obvious to an inexperienced giver. As such, the initial pose influences interaction fluency. We also found evidence that givers may cue off the robot's height, as they would off a human receiver's height.

The examination of interaction forces suggests that givers release the object when they detect an appropriately large change in retraction force. That is, an increase in the force by which the robot is pulling would indicate it is securely holding the object and trigger the release. We still believe this level depends on the giver's general trust in the robot's ability to grasp the object; however, we do not have a direct measure of this trust and hence, cannot establish direct correspondence at this time.

Results also show a main effect of retraction speed which caused significantly larger interaction forces for faster retraction speeds. Our findings suggest that a fast retraction preempts the giver's ability to react to the withdrawal. The robot simply overcomes the grip forces and yanks the object away. Thus, to provide a refined handover experience, human reaction time must be considered and retractions must be modulated carefully.

Compared with human-to-human handovers, the interaction forces were generally significantly higher. We might attribute this difference to the inexperience of participants in handing over to the robot; participants may seek a larger force to confirm that the robot has securely received the object. Symmetrically we might suggest that the robot is not acting exactly like a human receiver and hence presenting unexpected or unpredicted movements. Over time and repeated interactions, however, this effect and the force levels linearly decrease. Separate social perception evaluations (using the RoSAS) mirror this trend with a significant linear increase in warmth and linear decrease in discomfort. Together this may indicate givers are learning to predict the robot and developing trust in the robot to complete the handover successfully.

These findings show that slight changes to robot behaviours may significantly alter interaction dynamics of the negotiation that occurs during handovers: we have found significant differences to the way users kinodynamically participated as givers during the handover through varying three robot attributes. The results of this work more generally suggests that an exploration of the design space for human-to-robot handovers may assist in achieving more fluent and legible, though not necessarily human-like, handovers. Such improvements in handovers (and ostensibly other human-robot interactions) may be measurable through examination of interaction geometries and forces, as demonstrated here.

The results of this study have generated more avenues of future work to be explored. Specifically, we wish to continue addressing how repeated handovers with the robot affect force levels and, more broadly, trust in the robot with respect to the objects safety. Also, what factors can be changed or improved regarding the robots behaviour that allow users to trust the robot more quickly. To this end, in addition to tuning robotic behaviours, we may also consider providing inexperienced users with additional feedback information to improve legibility of robot behaviours during handover and other interaction contexts - e.g., audio or haptic feedback through wearable devices. Such human-centered approaches may speed up training of users and be removed once the user is acquainted with the task. Additionally, we wish to further explore how robot height and appearance as well as contact impedance and movement fluidity impact the interaction.

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