The Role of Closed-Loop Hand Control in Handshaking Interactions

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***Abstract*—In this paper we investigate the role of haptic feedback in human-robot handshaking by comparing different force controllers. The basic hypothesis is that in human handshaking force control there is a balance between an intrinsic (open-loop) and extrinsic (closed-loop) contribution. We use an underactuated anthropomorphic robotic hand, the Pisa/IIT hand, instrumented with a set of pressure sensors estimating the grip force applied by humans. In a first set of experiments we ask subjects to mimic a given force profile applied by the robot hand, to understand how human perceive and are able to reproduce a handshaking force. Using the obtained results, we implement three different handshaking controllers in which we varied the intrinsic and extrinsic contributions and in a second set of experiments we ask participants to evaluate them in a user study. We show that a sensorimotor delay mimicking the reaction time of the Central Nervous System (CNS) is beneficial for making interactions more human-like. Moreover, we demonstrate that humans exploit closed-loop control for handshaking. By varying the controller we show that we can change the perceived handshake quality, and also influence personality traits attributed to the robot.**

***Index Terms*—Physical Human-Robot Interaction; Natural Machine Motion; Modeling, Control, and Learning for Soft Robots**

I. Introduction

THE handshake is an important social interaction, common as a greeting in many parts of the world and in both business and social contexts [1]. Handshakes contribute to first impressions of a person; a drab handshake can have a negative impact on the perception of a person's character. However, there is little work in the literature studying human-human handshaking, and as such it is not yet possible to describe what constitutes a 'good' or a 'bad' handshake, or even describe a human-human handshake, in a quantitative manner.

In robotics, there are many examples of handshakes used as iconic example interactions for different robotic systems and anthropomorphic hands, often involving a photo opportunity. However, to date there has been relatively little work studying the handshaking interaction itself. The handshake is also interesting in a Human-Robot Interaction (HRI) context [2]. In typical HRI tasks, leader and follower roles are clearly defined: master action and intention is measured and elaborated to generate reference inputs for the slave controller. In a handshake, this identification of roles is not evident a priori, it is an inherently bidirectional action in which both sides actively contribute to the task by applying an active and a reactive action at the same time.

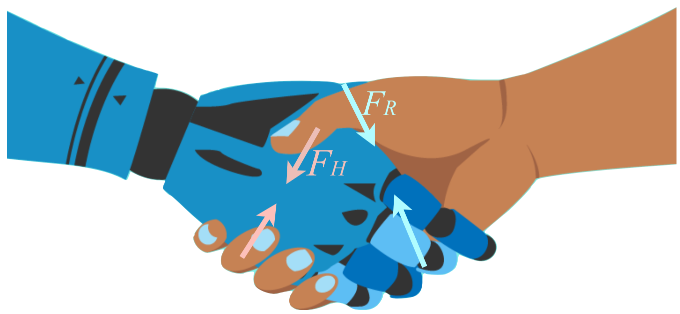

Fig. 1. Human-robot handshaking. While handshaking, human applies on the robot palm a force F_H that is measured by a set of pressure sensors, while robot applies a force F_R to human palm. In this paper we analyze some possible controllers relating F_H and F_R.

For the case of a human-robot handshake (Fig. 1), the robot will receive a force from the human which we will denote F_H, and also exert a force F_R on the human. The relationship between F_H and F_R would appear to form a central element in determining the quality of a handshake. In this work, we are examining this relationship more closely by implementing and comparing different possible controllers relating F_H and F_R on a robot hand.

The central question which we seek to answer is the role of feedback in handshaking behavior. We compare open-loop and closed-loop handshake controllers, in order to determine the importance of haptic feedback and closed-loop control in handshaking. We use a soft underactuated anthropomorphic robot hand, the Pisa/IIT SoftHand, instrumented with pressure sensors in order to measure the grasping force exerted onto it, and we estimate the grasping force exerted by the robot from its pose. We then implement three controllers combining open-loop and closed-loop to varying degrees. For closed-loop controllers, we show that participants perceive interactions as more human-like if a sensorimotor delay is added to the system. We objectively demonstrate that humans exhibit closed-loop handshaking control. In a user study, we evaluate the subjective perceived qualities of the different controllers

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and show that the choice of controller can influence the quality of the handshake as well as perceived personality traits of the robot.

II. Related Work

The area of HRI has received much attention, for example with regards to safety [3, 4] and looking at cooperative manipulation tasks [5] or handovers [6]. In this work, we focus on handshaking interactions, which have received limited study to date.

A. Understanding human handshakes

One of the key elements in realizing a human-robot handshake is the measure of the interaction force, in particular, the force that the human applies on the robot palm, indicated with F_H in Fig. 1. Contact forces in human interactions have been measured using sensorized gloves, both for object grasping [7] and for handshaking interactions [8, 9]. In [10] the authors study human–human handshaking interactions and measure contact forces along with IMU hand motion data. In [11] contact area and contact pressure are measured in human-human and human-robot handshaking tests, comparing the results obtained with two underactuated soft hands. The handshake grasp would appear to match well to the first postural synergy of the human hand, which the Pisa/IIT SoftHand has been designed to follow in an underactuated manner [12].

Furthermore, handshaking is a complex task from the cognitive point of view and poses interesting questions from the neuroscientific point of view. For instance, Vanello et al. [13] investigate the neural correlates of human–human and human–robot handshake using functional Magnetic Resonance Imaging.

B. Robots for hand interactions

There has been much work in the development of anthropomorphic robot hands, such as the Gifu hand [14], the DLR Hand 2 [15] or the Shadow Dexterous Hand (Shadow Robot Company). While human-robot handshakes may often be performed with various anthropomorphic hands, to showcase them, there has been limited work where handshaking was explicitly studied.

There are some examples of setups for tele-handshaking in the literature [16]. Pedemonte et al. [17] present the design and realization of a haptic interface performing a robotic handshake, the device is aimed at developing a communication system that allows two people to shake hands while being in different locations. Their system for human–robot handshaking interactions, includes a robot arm controller, a custom hand and a hand controller. The design of the system is informed by human performance, and the complete system is evaluated in a user study. In follow-up work [16], the same authors consider the communication system composed of two interfaces and propose a control algorithm that allows bilateral interaction between the two users. Another device for the realization of realistic human-robot handshake is presented in [18], in particular a standard model of the human-palm compliance is developed, based on human hand anatomy and an empirical study.

The goal of these systems is to appear as a transparent haptic link between the two participants, so that the dynamics of their interaction is similar to in a direct physical handshake. This is different to our goal, which is to realize a robotic autonomous setup able to emulate the human dynamics in handshaking tests. Tsalamlal et al. [19] study human-robot handshaking, investigating the effect on perceived affective properties as the arm stiffness, grasping force and robot facial expressions are changed. Also, Ammi et al. [20] study the emotional expressiveness of robots combining visual and haptic interaction (realized through human-robot handshake), and verified that in the identification of some emotional cues, namely dominance and degree of control of a situation, haptic interaction is more accurate.

Not concerning handshaking, but still mimicking human hand interactions with a robotic system, Fitter and Kuchenbecker [21] study hand interactions in hand clapping games between humans and robots.

C. Human consensus dynamics

There are many examples in robotics of modelling human motion as dynamical systems, frequently with the goal of then reproducing similar behavior with a robot.

Humans have been shown to exhibit synchronization, without a clear leader or follower, in joint action tasks [22].

Wang et al. [23] propose a haptic virtual reality system which allows human to make physical handshakes with a virtual partner. Two approaches are proposed: in the first one robot controller employs an embedded curve and disregards human interaction, in the second one an interactive control is implemented; they verified that the second one is perceived more human-like. Karniel et al. [24] propose a Turing-like handshake test to compare a human-human handshake, realized through a haptic interface, with different virtual handshake models. Both [23] and [24] focus on arm trajectory and disregard handshake force.

D. Human grip strength control

For grasping and manipulation tasks, there are a substantial number of studies looking at how the grip force is modulated [25, 26, 27], these works show that cutaneous feedback is used to avoid slip. This principle has also been applied to robotic grasping: Ajoudani et al. [28] propose a system for modulating the grasp strength in a reflexive manner to avoid object slippage. This is different to a handshaking interaction, and it is therefore not clear to what extent these dynamics will also be applicable for a handshake.

III. Experimental Setup

In the experiments presented in this paper, we need to control the force the robot squeezes the human with, F_R, and must be able to measure the force the human squeezes the robot with, F_H, as shown in Fig. 1.

We use a Pisa/IIT SoftHand for our experiments [12], an anthropomorphic robotic hand based on soft-robotics technology, exploiting the principles of synergies in an underactuated design that is safe for physical human-robot interaction, and adaptable to grasp different objects without any change in the control action.

The Pisa/IIT SoftHand is underactuated, and has a single actuated degree of freedom q corresponding to the reference position of the hand. More specifically, in this paper we indicate with q the main variable that we use to control the hand. It is a variable that ranges from 0 (hand fully opened) to 19000 (hand fully closed). The hand is underactuated and compliant, so, when it touches an object or a surface, it adapts to their shapes, and its consequent configuration q_a differs from the reference one, q. We define q_0 as the position where the hand is making contact with an object, but applying zero force. Once the hand reaches $q_a = q_0$, if the object can be modelled as a rigid body, the actual hand configuration cannot change. If the object is deformable, increasing the reference position results in a relationship between the difference $q - q_0$ and the force that the hand is applying to the object, F_R, i.e.

$$F_R = \begin{cases} f_R(q - q_0) & q - q_0 \geq 0 \\ 0 & q - q_0 < 0 \end{cases} \tag{1}$$

where f_R is a function mapping the difference $q - q_0$ to the force F_R, that depends on robot hand and object stiffness. The procedure that we implemented to identify f_R function from experimental data and the obtained results will be described in Sec. IV-A.

The specific value of q_0 is dependent on the object that is being grasped. This can be obtained in a manual calibration experiment, but we have also implemented an automated calibration procedure. In the automated procedure, which can be seen in the supporting video, the robot hand closes slowly while the current is monitored. When the robot hand makes contact with the human palm, a steep increase in the current relative to the free-closing value is seen. This rise is detected, and the hand position is used to estimate q_0.

To evaluate the interaction with the human and measure F_H, we attach 3 Force-Sensitive Resistors (FSRs) to the robot hand palm (Fig. 2 a)). The FSR sensors have a low profile, so they can be attached to the hand without requiring design changes. We use the histogram from [11] as a guide for where to place the sensors, we indicate with $F_{fsr,i}$, with $i = 1 \cdots 3$, the measure of the generic sensor. Sensors $1 - 3$ in Fig. 2 a), are used as triggers to identify the contact with the human hand, and 1 and 2 are used for estimating F_R as they were found to be robust towards small variations in the grasp.

Although we do not sensorize the entire contact area, we can assume that for similar grips we can estimate F_H from the sum of the FSR measurements. To identify the relation between F_H and FSR measurements, we attach the FSR sensors indicated with 1 and 2 to a sensorized palm, as shown in Fig. 2 b). The sensorized palm is a simple 3D-printed object whose shape and dimensions similar to a human hand palm, composed of two shells connected by a load cell [11]. Six calibration experiments were performed, with three different subjects. In

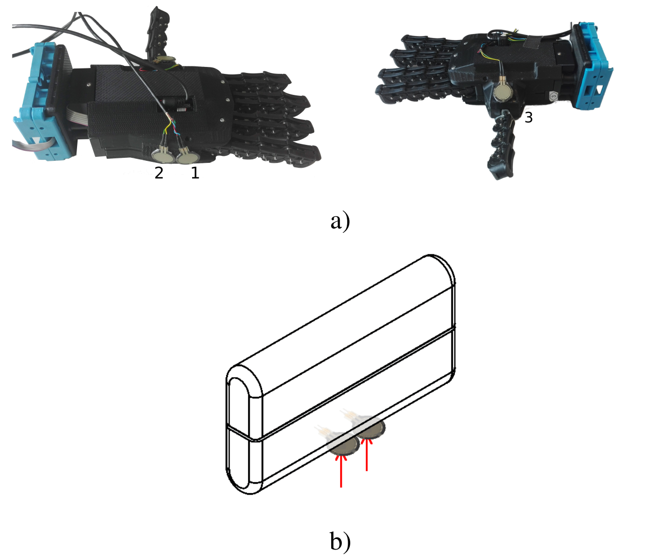

Fig. 2. Experimental setup. a) The Pisa/IIT SoftHand used in this paper, with 2 FSR sensors attached to the side of the palm to measure the force which the human applies to the robot (F_H). b) A sketch of the setup for FSR calibration, in which sensors are connected to a palm sensorized with a load cell.

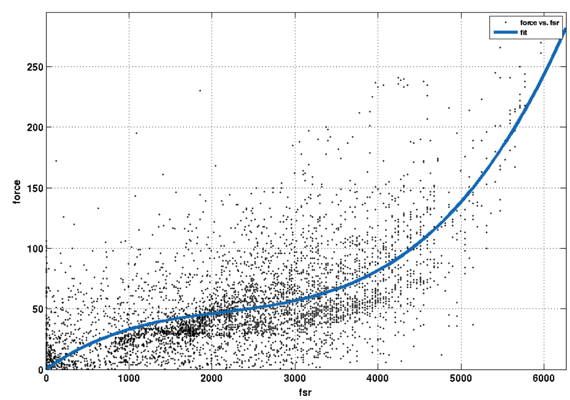

Fig. 3. Plot of F_{fsr} against F_H (measured with load cell), along with best-fit cubic polynomial.

each test, the subject was asked to repeatedly grasp and release the sensorized palm, and FSRs and load cell values were recorded. We then fitted a cubic polynomial to the data, as shown in Fig. 3. This allows us to estimate F_H. Although there is some error in the fit, we observed that for a given handshake grasp between a participant and the robot the estimate of F_H is monotonic and with relatively low variation—the main source of variation is variations in the human grasp configuration.

IV. Open-Loop Human Handshaking Dynamics

We now wish to understand the force dynamics of a human-human handshake. In a handshake between participants A and B, participant A squeezes participant B with a force F_{AB} and is squeezed by participant B with a force F_{BA}.

Before contact is made in the handshake, $F_{AB} = F_{BA} = 0$ and other sensory modalities such as vision are relied on.

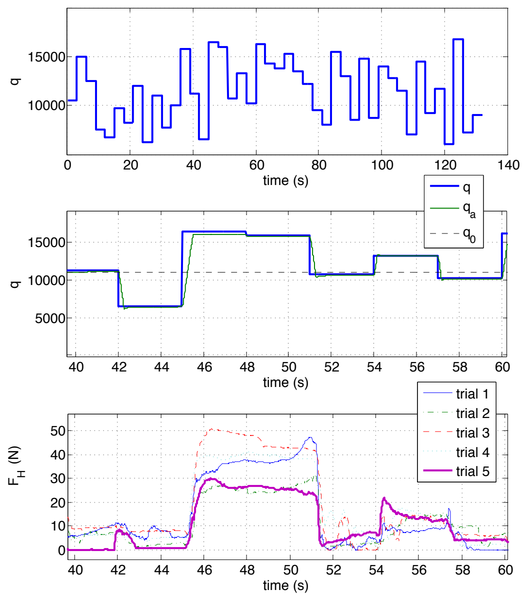

Fig. 4. Open loop test. Top: reference q profile applied in all the tests. Middle: q, q_a, q_0 profiles in a part of the experiment. Bottom: estimated F_H values for 5 different trials of the same subject, in the same experiment part.

During this phase, we can assume that each participant also identifies a nominal handshake strength to apply based on intrinsic factors such as prior expectation (F_{int}).

Once contact has been made, the haptic modality becomes dominating (as visual cues of grasping force are minimal). In the handshaking phase, each person squeezes with a force and receives a force. Once cutaneous sensory feedback is available, i.e. after the reaction time of the CNS, we hypothesize that the human can be modelled as a dynamical system, and that the interaction becomes closed-loop, so that for participant A the relationship can be expressed as

$$F_{AB} = f(F_{BA}) \tag{2}$$

To investigate this relationship, we performed an open-loop experiment where the robot followed a random fixed trajectory. We asked 8 participants to mimic the grasping force of the robot, as it moved through a random sequence of closures between 6000 and 17000, with each position maintained for 3 s. The sequence can be seen in Fig. 4 (top). Each participant repeated the experiment 5 times. Fig. 4 (middle) and Fig. 4 (bottom) show a zoomed-in view of the robot motion (middle) and the resulting F_H for one subject and for the 5 trials, as measured by the FSR sensors and calibrated as described in Sec. III.

By analyzing the experiments, we noticed a delay in the response of 0.2-0.4 s, in almost all the subjects and in most of force variations. This agrees well with the human response time to tactile stimuli [29]. In the following phase, we observe that the human is able to follow robot force variation as quickly as the variation is applied by the robot. After the transient phase, while the robot is applying a constant force, subjects show different behaviors: for example, in some cases we have a force overshoot and a following slower adaptation, and in other cases a steady state case is reached after some oscillation. The experiments showed that subjects are sensitive to force variations; a force adaptation is observed almost each time robot hand changes F_R value. The variation is realized with similar reaction time and force rates, however, the reached steady state levels exhibit high variability.

The force control employed by a human subject, even when they are asked to mimic a given profile, can be hardly represented as a SISO model as hypothesized in eq. (2), even if we could identify some analogies in the transient dynamics, the reached equilibrium force contains terms that could not be modelled in a simple way, such as memory effects, effects of time, and random variation.

A. Estimating F_R

As well as having an estimate of F_H, we also require an estimate of the force applied by the robot, F_R. It is very difficult to identify a tactile sensor configuration which would estimate F_R in a robust way, while not impairing the motion of the hand. Instead, as we are considering handshake grasps with relatively little variation in hand configuration, we assume that we can estimate F_R from the hand configuration, q, and the point of initial contact, q_0.

For this assumption to hold, the setup for the calibration experiment should be as similar as possible to a real handshaking grasp. For this reason, it is not desirable to use the sensorized palm described earlier.

Instead, we used the data from the open-loop experiment (Fig. 4) as a calibration source. In the experiment, we asked participants to match the force of the robot, so if we remove the transients and average across all participants we would expect a quasi-static interaction such that $F_H \approx F_R$. Although variability is observed in the data, we would expect the mean response to be robust to noise given a sufficient number of trials.

For each participant we measured the first contact position here noted as $q_{0,j}$ with $j = 1 \cdots 8$. Assuming $F_R \approx F_H$, we then look for a function

$$q = f(F_H) \tag{3}$$

In order to obtain a single equation to express the relation in (2), $q_{0,j}$ was used, for which an unique expression can be identified for $q_a \geq q_{0,j}$. It is worth to notice that eq. (3) can be generally expressed for $q \geq q_{0,j}$. In order to find this relation, in each experiment we consider $F_{H,j}$ values only for $q \geq q_{0,j}$; where $F_{H,j}$ is the force applied from the j-th participant to the robot hand during the experiment. In this phase we want to define an average behavior for the force exchanged during a human-robot handshake. More formally: in the average model we assume that the force F_H is hand size independent and is expressed as:

$$F_H = \frac{1}{8}\sum_{j=1}^{8} F_{H,j} \tag{4}$$

Using the Matlab Curve Fitting toolbox, we fitted a cubic polynomial to the experimental data and obtained a relationship between q and F_H and therefore approximating q and F_R:

$$q = 0.02 \cdot F_R^3 - 2.86F_R^2 + 157.2F_R \tag{5}$$

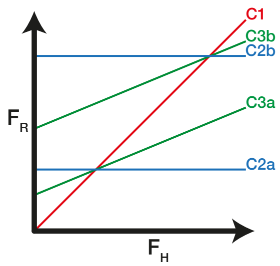

Fig. 5. F_R as a function of F_H in the proposed controllers. C1: robot follower, $F_R = F_H$. C2: robot open loop, F_R and F_H are independent; two levels of force are implemented: C2a (lower) and C2b (higher). C3: combined controller F_R is dependent both on F_H (as in C1) and on the robot's intrinsically preferred force (as in C2). C3a has a lower intrinsically preferred force, and C3b has a higher value.

The whole calibration procedure can be therefore summarized in two parts: we first use the sensorized palm to express F_H as a function of the FSR measurements, and we then use the results from the open-loop experiment to estimate a relationship between F_R and q.

V. Controllers for Robot Handshaking

We now wish to develop a set of possible controllers for robot handshaking, exhibiting different possible behaviors. Our goal is to develop a controller for robot handshaking which improves the handshake quality. It is reasonable to assume that a robot controller which closely mimics the control rules followed by humans in a handshake will result in an improved interaction quality.

Considering the haptic interaction part of the handshake, we propose 3 robot handshake controllers, as described below and illustrated in Fig. 5. We also refer to the accompanying video, where we showcase the behavior of the different controllers.

We note that the robot hand imposes an upper bound on F_R, measured to be 50 N. Controller forces are therefore saturated to this level.

1) Robot follower (C1): A simple controller, and one which has been implemented in the literature [17] is to have the robot follow the human and trying to match F_R to F_H. This is shown in red in Fig. 5. While this would be expected to produce a reasonable force profile over time, it is likely that one would perceive the robot as following and responding to the human motion. We would expect this to lead to the controller being perceived as less human-like.

2) Robot open loop (C2): An alternative simple controller is that the robot is open-loop in the handshaking phase i.e. it sets F_R to some value F_{int} which is independent of F_H. Thus, the robot behavior is governed by intrinsic factors rather than by extrinsic factors. We consider two versions of this, one with a lower force $F_{int} = 17.4$ N (C2a) and one with a higher force $F_{int} = 34.2$ N (C2b). This is shown in Fig. 5 in blue.

As the controller is not following the human it is more likely to impose dominance and cause the human to be the follower. Furthermore, we would expect the stronger controller (C2b) to be perceived as more dominant than the weaker one (C2a).

3) Combined controller (C3): It seems reasonable to hypothesize that the human controller for handshaking force combines both intrinsic and extrinsic information. To implement this, we combine controllers 1 and 2 to get

$$F_R = \frac{1}{2}(F_{int} + F_H)$$

We sketch this controller in green in Fig. 5. Again, we consider a lower (C3a) and higher (C3b) value of F_0.

We would expect this controller to be perceived as more responsive than C2. If it is the case that humans do combine intrinsic and extrinsic factors, this controller should be perceived as more human-like. Similarly to C2, we would expect the stronger controller (C3b) to be perceived as more dominant than the weaker one (C3a).

A. Handshake termination

In a human-human handshake, the termination must be initiated by one participant who reduces the grasping force to zero. For a synchronous termination, the other participant must detect this and also release their grasp. Thus, one participant acts as the leader and the other as the follower.

For a robotic handshaking controller, this means that in order to mimic human behavior the robot should terminate the handshake if it detects that F_H drops below a threshold. Also, the robot should initiate the termination e.g. if the duration exceeds some time limit.

In order to reduce variability in our experiments, we here only consider the case of the human leading the termination, and the robot following. If required, it would be straightforward to implement a time limit on the handshake after which the robot should initiate the termination. As a guideline, Wang [30] report a mean handshake duration of 1.0 s, and a maximum duration of 1.8 s. We note that this could contribute to the robot being perceived as a follower, rather than a leader.

B. Controller delay

It is known that for tactile stimuli, humans have a reaction time around of 250 ms [29]. For human closed-loop hand control, this delay would be expected to be present. When designing a robot controller mimicking the human response, it is therefore reasonable to consider the inclusion of a sensorimotor delay in the controller.

To determine whether such a delay would indeed be beneficial, and if so how large it should be, we implemented a version of Controller 1 (robot follower) where a variable delay could be applied to the sensory signal from the robot tactile sensors. The delay was controlled by a slider in a GUI, with a range from 0 to 300 ms.

We then carried out a study where we asked 5 participants to shake hands with the robot hand, and to adjust the delay time to the value which they felt provided the most human-like handshake response. Participants were free to control the delay time as they wished, and perform as many handshakes as they saw fit, until they found a suitable value.

We found that participants on average preferred a delay time of 120 ms (standard deviation 90 ms). This shows that

Fig. 6. Experimental setup for user study, with the robot hand attached to a fixed mount.

the inclusion of a sensory delay, or reaction time, is indeed beneficial for mimicking human closed-loop actions. The fact that the preferred delay time is somewhat smaller than the human response time could be explained by the additional response time introduced by the robot hand.

For the remainder of this work, we therefore implement a sensory delay of 120 ms for all the controllers. Note that the delay is applied to the extrinsic sensory signals (equivalent of mechanoreceptors), but not to the intrinsic hand dynamics.

VI. System Evaluation

The implemented handshaking controllers have been evaluated in a user study, where participants were asked to perform handshakes with the different controllers and rate each one of them individually on a set of Likert-scale questions.

The five controllers being tested were introduced in the previous section and depicted in Fig. 5. All controllers were implemented using the sensorimotor delay of 120 ms as described above.

A. Experimental procedure

The robot hand was attached to a rigid mount, as depicted in Fig. 6. For a more realistic test scenario, we did not impair the vision or hearing of the participants.

15 participants (12 male) were recruited for the study. They received cinema vouchers in return for their participation. The study was approved by the Disney Research IRB. Participants were briefed about the study, and asked to sign a written consent form.

For each participant, we first identified q_0. This was done manually, to ensure minimal variation.

Participants were then presented with a randomized sequence of the 5 handshaking controllers. Each controller appeared 3 times in the sequence, for a total of 15 trials. For each trial, we asked participants to perform a set of handshakes (not a prescribed number) with the robot hand and then answer 5 questions as listed in Tab. I. Responses were made on a 7-point Likert scale. The first 3 questions relate to the handshake quality and human likeness, and the last 2 questions relate to perceived personality traits of the robot.

B. Results

1) Handshake statistics: Across all handshakes, we can compute some statistics. In total, participants performed 1812 handshakes (on average 8 per trial), with a mean duration of 2.2 s and with a mean value of F_H of 24.8 N. This is

TABLE I
Likert-scale questions.

	Question	**Scale (1 to 7)**
Q1	Please rate the quality of the handshake	*very poor* to *very good*
Q2	Please rate the human-likeness of the handshake	*very robot-like* to *very human-like*
Q3	Please rate the responsiveness of the robot	*not responsive at all* to *very responsive*
Q4	Who was the leader of the handshaking interaction	*I was the leader* to *the robot was the leader*
Q5	How would you judge the personality of the robot	*shy, hesitant, introvert* to *confident, secure, extrovert*

longer than would be expected for a human-human handshake, suggesting that participants might be spending longer time in order to better understand robot behavior.

2) Do humans follow the robot in C2: For the open-loop controllers (C2a and C2b), F_R is independent of F_H. To determine if the human followed the robot in this controller, we computed the mean value of F_H across all participants for the two conditions C2a and C2b. A t-test showed a significant difference between F_H in C2a ($M = 19$, $SD = 10.4$) and C2b ($M = 27.4$, $SD = 19.9$) with $p = 0.0138$. This shows that humans do indeed incorporate closed-loop control for handshaking, and follow the behavior of the robot.

3) How are different controllers rated: To analyze the responses from the user study, we first computed for each participant their mean responses for each controller. For each question, we then performed pairwise t-tests with Bonferroni correction between all pairs of controllers. The results are summarized in Fig. 7.

For Q1 (handshake quality) we found a significant difference between controllers C2a ($M = 3.98$, $SD = 1.27$) and C3a ($M = 5.11$, $SD = 1.09$) with $p = 0.0012$. It can thus be seen that there is a perceived improvement in handshake quality between the weaker force open-loop controller and the weaker combined controller.

For Q2 (human likeness) we also found a significant difference between controllers C2a ($M = 3.62$, $SD = 1.39$) and C3a ($M = 4.93$, $SD = 1.27$) with $p = 0.0045$. The same trend as for Q1 is thus seen, with the weaker combined controller being perceived as more human-like than the weaker open-loop controller. In general, from Fig. 7, it appears that there is correlation between Q1 and Q2, as would be expected.

For Q3 (responsiveness) we found significant differences between C2a ($M = 3.36$, $SD = 1.54$) and C3a ($M = 5.18$, $SD = 1.32$) with $p = 0.0022$, and between C2a and C3b ($M = 4.76$, $SD = 1.55$) with $p = 0.0370$. The perceived responsiveness of the combined controller, both with stronger and weaker force, is therefore significantly greater than that of the weak open-loop controller. It can be seen that the two open-loop controllers are rated as less responsive than the 3 closed-loop controllers, as would be expected, however for the remaining pairs this difference is not statistically significant.

For Q4 (leader/follower) we did not find any significant effects. In general, responses are towards the lower end of the scale meaning that participants felt that they were the leader in

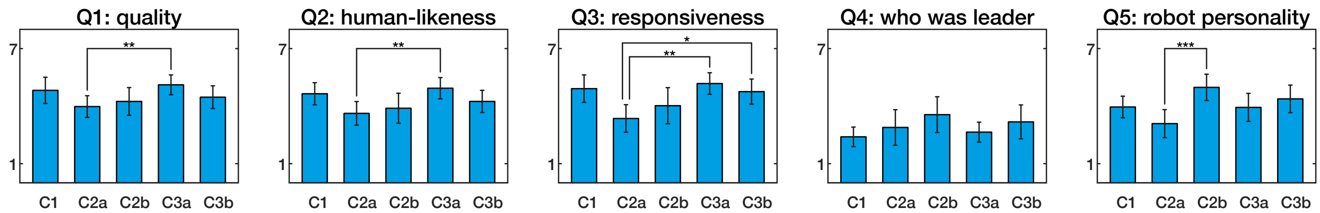

Fig. 7. Bar charts showing results from user study. Error bars show 95 % confidence intervals. Significant differences between controllers have been indicated with $*$ for $p < 0.05$, $**$ for $p < 0.01$ and $***$ for $p < 0.001$.

the handshake. We note that although there was no significant difference in leader/follower for C2a and C2b, there was still a significant difference in F_H between the two conditions meaning that humans did indeed follow the robot.

For Q5 (robot personality), we found a significant difference between C2a ($M = 3.09$, $SD = 1.58$) and C2b ($M = 4.98$, $SD = 1.67$), with $p = 0.00049$. For the two open-loop controllers, increasing the handshaking force therefore has the effect of making the robot be perceived as more *confident, secure and extrovert* while decreasing the force causes it to be perceived as more *shy, hesitant and introvert*. To a lesser extent, the same effect can be observed in C3, but in this case it is not significant.

VII. Discussion

We have shown that humans do employ closed-loop force control for handshaking, demonstrated with the significant difference in F_H for the open-loop robot controllers with high and low force. It is interesting to note that participants in general still reported that they were the leader of the interaction, even when the robot did not follow them. This is likely due to the human still being in charge of the initiation and termination of the handshake.

It can be seen that some error is introduced into our system both through the estimation of F_H and F_R. For soft and underactuated robot hands, grasping force estimation is in general a difficult problem, and there is no readily-available tactile solution for instrumenting a robot hand for grasping force estimation. Force estimation from the motor current, as we do here, inherently suffers from errors due to cable friction and natural variability in the grasp.

Despite this significant simplification, and the limitations of our hardware, we have shown that by changing the closed-loop hand controller we are able to change perceived qualities of the handshake. It would be expected that if other aspects of the handshake, such as arm dynamics, could also be modulated, then an even stronger response should be elicited.

The results show some directions and preliminary answers on how robot personality is perceived by humans in handshaking, for example, with C2b or C3b controllers robot shows a more evident character, while with C1 or C3a it is perceived as more comprehensive. However, human perception of robot personality deserves a more in-depth human-centered analysis, that will be the focus of future works.

Mimicking the delay imposed by the human sensorimotor system we were able to improve the perceived quality of the handshake. It is reasonable to assume that this type of delayed response could improve the perceived quality of other closed-loop physical human-robot interactions such as collaborative manipulation tasks. The preferred sensorimotor response time was found to be 120 ms, while the human tactile reaction time is around 250 ms. We can attribute the shorter preferred delay time of the robot to the additional response time added by the robot hand. It is also plausible that humans incorporate feed-forward elements to the hand control, predicting what the handshaking partner will do, in order to create a shorter apparent reaction time.

In this work, we used the preferred response time for the main user study. However, it would be interesting to further investigate how the addition of a sensorimotor delay in a robotic system influences the perceived qualities, both for handshaking interactions and also more generally for other collaborative tasks.

The robot hand used in this work is anthropomorphic and bears close resemblance to a human hand. It would be interesting to explore handshaking with simplified robot hands bearing less resemblance to human hands, to see if a similar response could be elicited. Looking further ahead, recent work has demonstrated brain-to-brain and muscle-to-muscle interfaces for closed-loop human-human interactions [31]. A better understanding of human handshaking could pave the way for more realistic handshake-like interactions through such interfaces.

The focus of this work has been on hand control for handshaking interactions, however it is clear that there could be many other factors of robot hand design that will also influence the perceived qualities, such as hand size, palm compliance, and also hand appearance. Nevertheless, we would expect our findings regarding the hand control to generalize to different robot hands.

VIII. Conclusion

We have objectively shown that humans perform closed-loop hand control during handshaking, with an increase in F_R causing an increase in F_H. With regards to the subjective perceived handshake qualities, our results also suggest that closed-loop controllers are preferred. Although we do not have sufficient evidence to conclusively select one of the closed-loop controllers, our results suggest that a combination of intrinsic and extrinsic control would be preferable.

Moreover, we found that the addition of a sensorimotor delay to the closed-loop robotic system was preferred by participants for creating a more human-like interaction, analogous to the sensorimotor delay exhibited by humans due to the reaction time of the CNS.

The use of an existing anthropomorphic hand, with minimal adaptation, means that our controllers could readily be implemented on robots with anthropomorphic and underactuated hands. For a deeper understanding of the closed-loop interaction dynamics, a specialized non-anthropomorphic test setup could have produced results with less variability.

We expect that our findings would be relevant for other closed-loop haptic interactions such as shared manipulation tasks and human-robot hugging.

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