# Effects of Force Feedback and Arm Compliance on Teleoperation for a Hygiene Task

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**Abstract.** Teleoperated assistive robots with compliant arms may be well-suited to tasks that require contact with people and operation within human environments. However, little is known about the effects of force feedback and compliance on task performance. In this paper, we present a pilot study that we conducted to investigate the effects of force feedback and arm compliance on the performance of a simulated hygiene task. In this study, each subject (n=12) teleoperated a compliant arm to clean dry-erase marks off on a mannequin with or without force feedback, and with lower or higher stiffness settings for the robot's arm. Under all four conditions, subjects successfully removed the dry-erase marks, but trials performed with stiffer settings were completed significantly faster. The presence of force feedback significantly reduced the mean contact force, although the trials took significantly longer.

**Key words:** force feedback, compliant arm, teleoperation, assistive robots

## 1 Introduction

Safety is an important design consideration for human-centered robotics [17]. Many industrial robot arms utilize high stiffness and high speed actuation to increase precision and efficiency. While appropriate for controlled settings, these design choices can exacerbate the consequences of unintended collisions with people and the environment [3]. Many researchers have proposed the use of compliant arms to increase the safety of robots operating within human environments [8, 10, 11]. In addition, arm compliance has the potential to improve task performance [5].

For teleoperated robots, haptic feedback can enable operators to perform manipulation tasks using less force [2, 6]. It can also reduce task error [2], increase safety [15], and enable the operator to perform new tasks [13].

Given their individual benefits, combining haptic feedback and arm compliance would seem to be a promising combination for teleoperated assistive robots. However, little is known about the effects of force feedback and compliance on task performance. Haptic feedback has primarily been studied with stiff arms, such as surgical robots like the da Vinci System (Intuitive Surgical Inc.) [2,6], or with arms that have only a little compliance, such as link flexion in surgical robots [12]. While

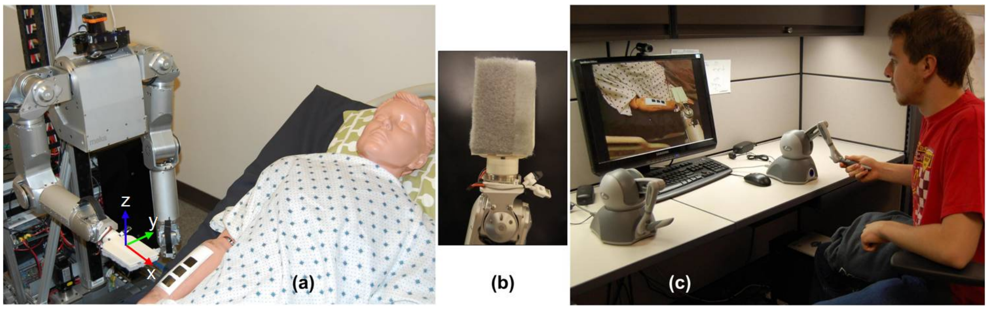

**Fig. 1.** The teleoperation system used during the experiment: (a) the compliant assistive robot Cody annotated with the end effector's coordinate system; (b) the customized end-effector used in this study; and (c) the master console with a PHANToM Omni and video.

a variety of compliant robots have been teleoperated, such as the Stanford/Willow Garage PR1 [16], and some have provided haptic feedback to the operator, such as DLR's Justin [7], formal user studies to assess the effects of haptic feedback and compliance on task performance do not appear to have been conducted.

We expect that haptic teleoperation of compliant arms would be especially important for assistive robots that are designed to help older adults and persons with disabilities perform activities of daily living (ADL). Research has shown that brushing teeth, shaving, cleaning and washing are high priority hygiene tasks for people with disabilities [4, 9]. Since this type of assistive task involves the robot operating near or in contact with a person, haptic feedback and arm compliance could be especially advantageous. As such, we chose to perform our study with respect to the task of cleaning a person's body. Although researchers have previously developed robots that assist with tooth brushing [4] and face washing [14], there has been relatively little work on robots that clean a person's body or provide other forms of hygiene assistance.

In this paper, we describe a teleoperated assistive robot that uses compliant arms and provides force feedback to the operator. We also present one of the first user studies to look at how force feedback and arm stiffness influence task performance when teleoperating a very low stiffness arm. Finally, we present evidence that teleoperated assistive robots could be used to clean a person's body for hygiene.

## 2 Teleoperation System

The teleoperation system consists of a master console and a slave robot. The slave robot is Cody (Fig. 1a), a statically stable mobile manipulator assembled at the Healthcare Robotics Laboratory (HRL). It consists of two MEKA A1 arms (MEKA Robotics), an omni-directional mobile base (Segway RMP 50 Omni), and a 1-DoF linear actuator (Festo DGE-SP-KF) that can raise and lower the torso. The arms are 7-DoF anthropomorphic arms that use series elastic actuators (SEAs) in all

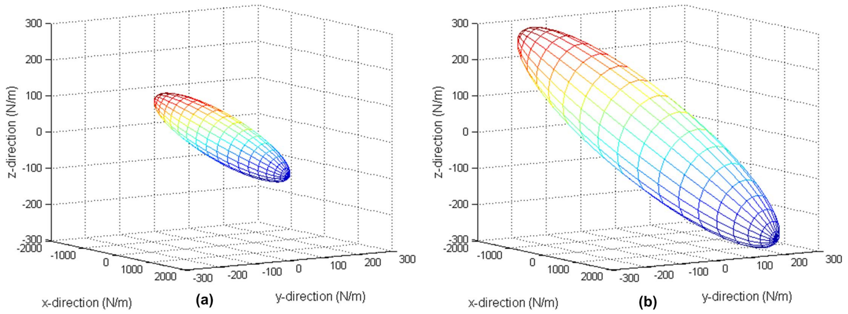

**Fig. 2.** Calculated stiffness ellipsoids based on manufacturer-provided specifications for (a) the more compliant setting and (b) the stiffer setting of the arm in its initial configuration (shown in Fig. 1(a)).

joints. The wrist is equipped with a 6-axis force/torque sensor (ATI Mini40). In addition, we mounted a video camera (Logitech Pro 9000) above the torso to provide video feedback. Two computers running Ubuntu GNU/Linux control the robot. The control software, operating at 100 Hz, was written in Python using various open source packages, including the Kinematics and Dynamics Library (KDL, The Orocos Project) and the Robot Operating System (ROS, Willow Garage). We also designed and attached a flat, 3D-printed, spatula-like end effector (7.8 cm x 12.5 cm, Fig. 1b) to resemble an extended human hand. We attached white board eraser felt to the bottom of this end effector.

The master console (Fig. 1c) consists of two PCs and a pair of PHANToM Omni (Sensable Technology) haptic interfaces that provide force feedback in position only. Information between the master and the slave is transmitted over the network using ROS at 50 Hz to: (1) transfer the position and the joint angle information from the Omni to Cody; and (2) return the force/torque sensor data on Cody's wrist to the Omni. The Omni controller operates at 1 kHz and provides force feedback to emulate the force measured by the robot's force/torque sensor with a gain of two. For example, a force magnitude of 1N from the robot's wrist-mounted sensor will result in 2N of feedback to the operator. We implemented a first-order hold approximation on the measured force values to improve stability in the feedback loop. This resulted in smoother motion of the arm. The master console uses Skype to display video (640x480 pixels) at 30 fps on average, but occasionally drops frames.

We scaled and mapped the position of the Omni's wrist to a cuboid workspace that corresponds to the workspace of Cody's 7-DoF arm. We use the KDL to determine the configuration for Cody's shoulder and elbow joints so that the position of Cody's wrist matches the scaled position of the Omni's wrist. The system controls the orientation of Cody's end effector to match the global orientation of the Omni's stylus.

Our code controls Cody's arm using equilibrium point control for all arm motions except two joints in the wrist [5]. For these joints (pitch and yaw) Cody uses

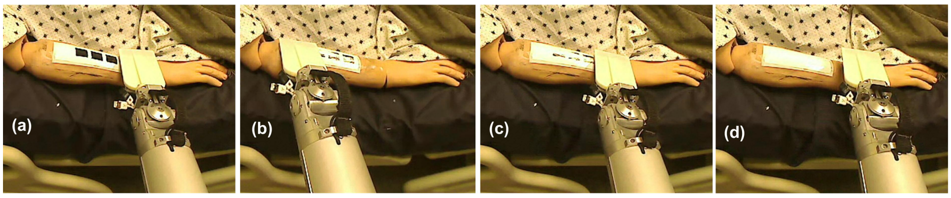

**Fig. 3.** Images of the robot during the dry-erase cleaning task: (a) the initial position of the arm; (b) swiping to the left; (c) swiping to the right; and (d) task completion.

position control, which relates the motor output to joint encoder values and ignores torque estimates from the deflection of the SEA springs.

We used manufacturer-provided stiffness values for the joints of the robot with a kinematic model to compute the expected stiffness matrix of the end effector. In Fig. 2, we show a visualization of the the stiffness ellipse for each of the two stiffness settings used in our study [1]. These ellipses correspond with the arm configuration and coordinate system shown in Fig. 1(a).

We also empirically measured the compliance in the upward direction (z direction, see Fig. 1(a)) at the end effector. Since the orientation of the surface to be cleaned in our experiments was approximately normal to gravity, we expected the end effector to be mostly displaced in this direction when making contact with the mannequin during cleaning.

We measured the approximate force per unit displacement for the two stiffness settings of the arm using a spring scale and a tape measure. Our results show that the stiffer arm (M=61.7 N/m; SD=0.781 N/m) was only 1.45 times greater than the compliant arm (M=42.5 N/m; SD=0.660 N/m), which differs from our model-based estimate.

## 3 Methods

For this study, we designed an experiment to investigate the effects of force feedback and arm stiffness on a dry-erase cleaning task. The protocol was approved by the Georgia Institute of Technology Institutional Review Board.

Each subject used his/her right hand to clean off three squares on a dry-erase sheet colored by a black dry-erase marker. We attached the dry-erase sheet to the top of the right forearm of a medical mannequin that was lying down. The sheet's flexible surface conformed to the shape of the mannequin's arm. The mannequin was lying down on a hospital bed in a separate room to simulate a hospital or home-care environment and we secured its arm to its body to prevent large displacement during the experiment. A total of 12 subjects (age range 21-32 years), which consisted of male (n=11) volunteers and female (n=1) volunteers participated in the study.

We gave subjects 5 minutes to familiarize themselves with the dry-erase cleaning task and the teleoperation system. During the experiment, we allowed subjects to use any technique they wished to perform the task. Fig. 3 shows images from a typical example of the dry-erase cleaning task.

The dry-erase cleaning task consists of four consecutive blocks of trials with the independent variables of force feedback and arm compliance. In each block, a subject performed one trial of the cleaning task on three approximately 1” x 1” squares on the dry-erase sheet. In Block FC, we tested the subject using the compliant arm with force feedback. In Block FS, we tested the subject using the stiffer arm setting with force feedback. In Block NC, we tested the subject using the compliant arm without force feedback. In Block NS, we tested the subject using the stiffer arm settings without force feedback.

Before each trial, we informed the subjects whether they would receive feedback or not, but we did not inform them about the compliance setting. In order to reduce the impact of learning, we counterbalanced the trial order across the four blocks, with each subject receiving a unique presentation order using three partial Latin squares.

We stationed the robot at the same location near the hospital bed throughout the experiment. We initialized the robot to the standby mode, in which the forearm was positioned parallel to the bed with the elbow bent at 90 degrees. Before each trial began, we cleaned the dry-erase sheet before drawing new squares with a black dry-erase marker using a square stencil. We used a tripod-mounted camera to take an image of the forearm with the dry-erase sheet before the trial began (Fig. 6a), and we imaged the same area again after the trial was completed (Fig. 6b). In addition, we recorded the force/torque sensing data at the robot’s wrist and the time to complete the task.

### 3.1 Data Analysis

For this study, contact force, task completion time, and the uncleaned marker area from the dry-erase cleaning test were the dependent variables. Since we were interested in the contact forces, we estimated when the end effector was in contact with the mannequin’s arm. First, we recorded the magnitude of the total force vector measured by the wrist-mounted force/torque sensor while the end effector was not in contact with anything. We then defined a threshold (0.5N) based on this data that was equal to the mean of these recorded force magnitudes plus one standard deviation. For the rest of our analysis, we assumed that the end effector was in contact with the arm whenever the measured force magnitude was above this threshold, and was not in contact with the arm when the measured force magnitude was below or equal to this threshold.

We defined the time to complete a task as the time between when the magnitude of the measured force first exceeded this threshold, and when it last transitioned from above this threshold to below this threshold. For each task, we calculated the mean contact force by averaging the above-threshold force magnitudes during the task.

We used an image taken before and an image taken after the task to quantify success at performing the cleaning task. Using standard machine vision techniques, we converted these two color images to binary images for which the white pixels represent dry-erase marks on the arm, and the black pixels represent the absence of dry-erase marks (see Fig. 6 (c) and (d)). Ideally, the image taken after the trial would have no white pixels, indicating perfect cleaning. We defined the marks-left

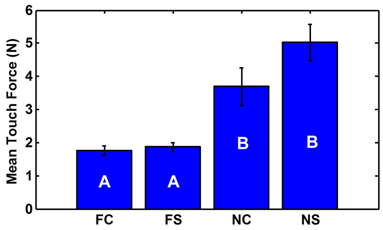

**Fig. 4.** The mean contact forces for each block: FC block uses the compliant arm with force feedback; FS block uses the stiffer arm with force feedback; NC block uses the compliant arm without feedback; and NS block uses the stiffer arm without feedback. Error bars show standard error of the mean. Bars with the same letter were not significantly different, while A and B were (p<0.01).

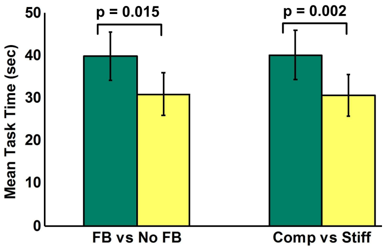

**Fig. 5.** Histogram of the mean completion time: all trials with force feedback (FB) versus without force feedback (No FB); all trials using the compliant setting (Comp) versus trials using the stiffer setting (Stiff). Error bars show standard error of the mean.

ratio as the number of white pixels in the second image divided by the number of white pixels in the first image. Hence, perfect performance would result in a marks-left ratio of zero, while not cleaning anything would result in a marks-left ratio of one.

## 4 Results

We used within-subject, two-way analysis of variance (ANOVA) and Tukey's Post-Hoc test to analyze the mean contact forces, time for task completion, and the marks-left ratio. We consider a p-value less than 0.05 to be statistically significant.

Fig. 4 shows the overall mean contact force of all four blocks. The results indicate that the addition of force feedback reduced the mean contact force by a factor of 2 or more. ANOVA showed that there were interaction effects [F(1,11) = 8.89, p = 0.01] between the independent variables on the dependent variable of force, and therefore we used Tukey's test to analyze the difference between blocks. The overall mean contact force during Block FS (stiffer arm setting with force feedback) was significantly less than during Block NS (stiffer arm setting without force feedback) ($p < 0.01$, Tukey's tests), while the overall mean force for Block FC (compliant arm with feedback) was also significantly less than for Block NC (compliant arm without feedback)($p < 0.01$, Tukey's tests). However, we did not find a significant difference between the overall mean force during Block FC and the overall mean force during Block FS ($p = 0.99$, Tukey's tests). The overall mean of the contact force during Block NC was less than during Block NS, but we did not find it to be a statistically significant difference ($p = 0.10$, Tukey's tests).

ANOVA of completion time showed no interaction effects. Subjects used significantly more time (Fig. 5) when using the more compliant arm [F(1,11) = 17.03, $p << 0.01$]. Subjects also used significantly more time when force feedback was present [F(1,11) = 8.30, $p = 0.01$].

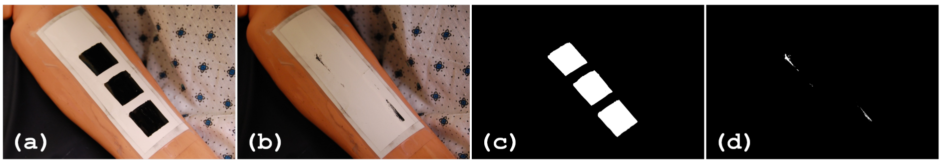

**Fig. 6.** (a) pre-trial image and (b) post-trial image of the dry-erase sheet on the mannequin's arm; binary image of (c) pre-trial image and (d) post-trial image where white pixels mean dry-erase marks remaining and black pixels mean no dry-erase marks.

The marks-left ratios of all trials in all four blocks were much less than 0.01. So in every single trial, the subject successfully removed over 99% of the dry-erase marks. ANOVA and Tukey's tests showed no interaction effects for this dependent variable, and we did not find a significant difference between blocks ($p >> 0.05$).

## 5 Discussion and Conclusion

For this pilot study, we developed a system to investigate the effects of force feedback and arm compliance on task performance with a teleoperated low stiffness arms. When no force feedback was present, subjects used significantly higher force to accomplish the task. This result is comparable to results obtained for teleoperation of stiff arms with force feedback [2, 6]. This suggests that a teleoperator may use unnecessary force when performing hygiene cleaning tasks without force feedback, and that force feedback might reduce negative effects due to hyperforce, such as bruising and discomfort. Further study will be required to understand the implications of contact force in this task. For example, applying too little force may cause undesirable tickling sensations, while excessive force may cause discomfort or injury. We did not find a significant difference between the mean contact force associated with the two compliance settings. This may be due to the two stiffness settings being too similar and a lack of data, due to our small number of subjects. A follow-up study with larger differences between the stiffness settings would be beneficial. A study involving stiffnesses comparable to stiff robot arms, such as the PUMA arm or the da Vinci System, would be especially interesting. It would also be worthwhile to consider providing additional haptic feedback from the robot's compliant joints, since important contact might occur anywhere along the arm.

Our time analysis showed that the task with force feedback required significantly more time to complete. One possible explanation is that subjects became more careful about the applied force when receiving feedback. For example, they may have reduced their speed to better control the forces. Another possibility is that reduced contact forces resulted in the removal of less dry-erase marking per stroke, and, hence, more strokes. Time analysis also showed that the task with a stiffer arm setting was completed significantly faster, which may be due to similar reasons. All subjects were novices to the task, so further research into the impact of long-term use and expertise could be worthwhile.

We designed our simulated task in order to objectively quantify performance of the task, and avoid complexities such as water, which could damage Cody. Future work with more subjects cleaning real people over larger surface areas of skin would be worthwhile. Moreover, it would be worthwhile to perform a study to better understand interactions between the person being cleaned, the robot, and the robot's operator.

We believe this paper presents one of the first studies to characterize the effects of force feedback and compliance on task performance when using a teleoperated compliant arm. We expect for these factors to become increasingly important as more robots enter human environments and provide assistance.

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