Whole-arm Tactile Sensing for Beneficial and Acceptable Contact During Robotic Assistance

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Abstract— **Many assistive tasks involve manipulation near the care-receiver's body, including self-care tasks such as dressing, feeding, and personal hygiene. A robot can provide assistance with these tasks by moving its end effector to poses near the care-receiver's body. However, perceiving and maneuvering around the care-receiver's body can be challenging due to a variety of issues, including convoluted geometry, compliant materials, body motion, hidden surfaces, and the object upon which the body is resting (e.g., a wheelchair or bed). Using geometric simulations, we first show that an assistive robot can achieve a much larger percentage of end-effector poses near the care-receiver's body if its arm is allowed to make contact. Second, we present a novel system with a custom controller and whole-arm tactile sensor array that enables a Willow Garage PR2 to regulate contact forces across its entire arm while moving its end effector to a commanded pose. We then describe tests with two people with motor impairments, one of whom used the system to grasp and pull a blanket over himself and to grab a cloth and wipe his face, all while in bed at his home. Finally, we describe a study with eight able-bodied users in which they used the system to place objects near their bodies. On average, users perceived the system to be safe and comfortable, even though substantial contact occurred between the robot's arm and the user's body.**

I. Introduction

Many assistive tasks for which robotic help would be desirable require that the robot manipulate near the care receiver's body. Approaches to robotic manipulation typically attempt to avoid contact between the robot's arm and the world, but the care-receiver's body and the objects upon which the body is resting can make this difficult. The surfaces with which contact would be disallowed have complex, variable, and dynamic geometry that can be challenging for robots to perceive with line-of-sight sensors. Within this paper, we propose that allowing unexpected, but regulated, contact between an assistive robot's arm and the care-receiver's body can both improve the robot's performance and be acceptable to care receivers.

In support of this proposition, we first show that in simulation, allowing contact between a robot's arm and a model of a person sitting in a wheelchair greatly increases the percentage of feasible end-effector poses near the person when compared with the poses feasible with state-of-the-art geometric planners that disallow contact. We then present a robotic system we have developed that uses a novel controller and whole-arm tactile sensing to achieve user-specified end-effector poses while keeping contact forces low. Next, we describe trials we conducted in which two people who have

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Fig. 1: *Henry Evans, a person with quadriplegia, pulls a blanket over himself while in bed at home using our robotic system with whole-arm tactile sensing. As shown, the robot's forearm made contact with his body and the bed.*

motor impairments interacted with our robotic system. Both users perceived it to be safe and comfortable. One of the users, who was familiar with the interface and the robot, also used the system to grasp and pull a blanket over himself and to grab a cloth and wipe his face, all while in bed at his home (see Fig. 1). Finally, in order to investigate the acceptability of contact between a robot's arm and the user's body, we conducted a study in which eight able-bodied users used the system to place objects near their bodies. We found that the users, on average, perceived the system to be safe and comfortable, in spite of substantial contact between the robot's arm and their bodies.

A. Related Work

Assistive robots for motor-impaired users have been tested for functional tasks in both home and office settings [1], [2]. For example, research on the Desktop Vocational Assistant Robot (DeVAR) [3] identified many challenges that remain relevant today. DeVAR also included force sensing at the wrist, allowing the robot to stop upon sensing "an obstruction greater than about 2kg (5lb)." With many of these systems, the intersection of the robot arm's workspace and the person's body was kept small for safety, which limits the tasks that are feasible for an assistive robot.

Tactile and joint-torque sensing for human-robot interaction have typically been developed to reduce the consequences of collisions, provide a user interface modality, or regulate applied forces during a constrained task (for examples: [4]–[7]), rather than improve maneuverability around the human body during unrestricted tasks.

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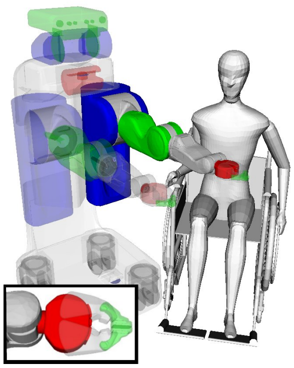

Fig. 2: *The configuration of the PR2 and care-receiver models used to evaluate the feasibility of end-effector poses. (Links used to evaluate pose feasibility are opaque)*

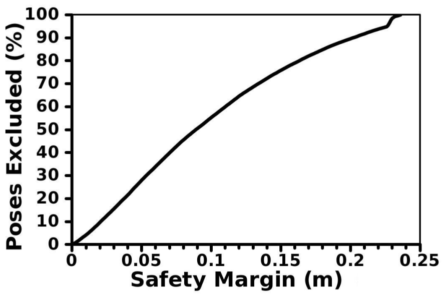

Fig. 3: *Percentage of feasible end-effector poses that become infeasible with a safety margin. This only considers poses near the care-receiver model.*

II. Allowing Contact Results in More Feasible End-Effector Poses Near the Care Receiver

For many tasks, a robot can provide assistance by moving its end effector to poses near the care-receiver's body. For example, helping with feeding often involves bringing food to the care-receiver's mouth and helping with dressing often involves manipulation of cloth near the care-receiver's body.

In robotics, the dominant strategy for achieving an end-effector pose is currently to plan a collision free trajectory for the manipulator using geometric models of the robot and the environment. However, due to the complex geometry of the human body and its surroundings, this strategy is problematic. First, the geometry can be difficult to infer or directly perceive via non-contact sensors due to real-world challenges including hidden surfaces, cloth, sensor noise, body motion, and variations in an individual's body geometry due to load-dependent deformations and other factors.

Second, in practice, even when geometric surfaces can be directly perceived or reliably inferred, a geometric planner needs to find a trajectory for the manipulator that maintains a minimum distance (i.e. safety margin) between the manipulator and the surface models in order to account for estimation errors, actuation errors, and changes in the scene [8]–[10]. In this section, we demonstrate that this requirement makes a large percentage of end-effector poses infeasible that would be feasible if contact between the robot's arm and the world were allowed.

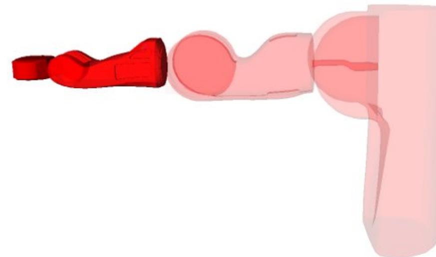

Fig. 4: *Arm links shaded according to the frequency with which they first make contact with the care-receiver model as the safety margin increases.*

Link	**% configurations**
Shoulder Pan Link	4.95%
Shoulder Lift Link (inside clevis of Pan Link)	0%
Upper Arm Link	7.07%
Elbow Flex Link	0.73%
Forearm Link	35.74%
Wrist Flex Link	5.19%
Gripper Palm Link	46.32%

TABLE I: **Frequency of links first violating safety margin.**

A. Method

To quantify the loss of feasible end-effector poses as the safety margin increases, we used a sample-based approach similar to the approach of Zacharias et al. [11]. Using OpenRAVE [12], we examined the feasible end-effector poses of the left arm of a PR2 robot around a model of a person seated in a wheelchair, as seen in Figure 2. We refer to the model of a person seated in a wheelchair as the care-receiver model and treat contact with any part of the model, body or wheelchair, in the same way. We downloaded this model from Trimble's 3D Warehouse [13], where it was documented as being created according to ANSI standard A117.1.

A common approach to mobile manipulation is to keep the mobile manipulator's base in a fixed position while moving its arm. For our analysis, we kept the position and orientation of the PR2's mobile base fixed relative to the care-receiver model. We also fixed the height of the spine of the PR2. This left 7 degrees of freedom (DoF) in the PR2's arm that could be used to achieve an end-effector pose.

We selected the pose of the PR2's mobile base and spine to have a large overlap between the workspace of the PR2's arm, which we visualized, and the model of the care-receiver's body. The configuration we selected also closely matched the configuration we have used in our previous research in which a real PR2 shaved the face of a person seated in a manual wheelchair [14]. In practice, we have found that this configuration enables the PR2 to reach a large portion of the care-receiver's face without contact between the robot's arm and the care-receiver's body or wheelchair. Notably, the difficulty we have encountered with this task has been an important motivation for the current paper.

Given this configuration of the PR2 and care-receiver models, we sampled from the space of goal poses for the PR2's fingertips near the care-receiver model. Specifically,

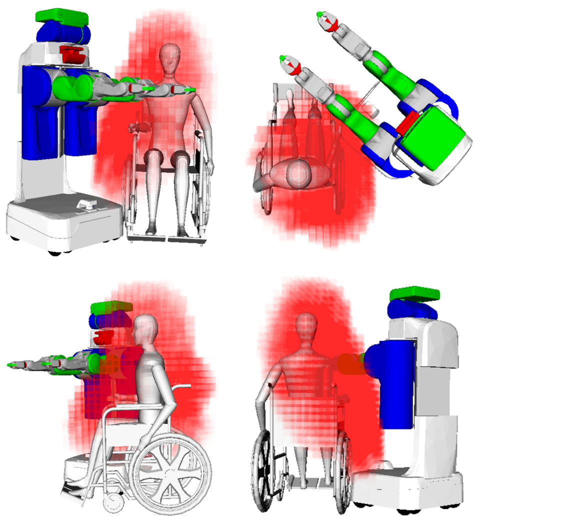

Fig. 5: *Poses made infeasible by a 4 cm safety margin, shaded by the number of orientations made infeasible at each point. Even poses far from the care-receiver model become infeasible due to contact with the robot's arm.*

Algorithm 1 Limiting Configurations for Reachable Poses

```
for all reachable_poses do
    pose.configs ← ALL_IK_SOLUTIONS(pose)
    for all pose.configs do
        SET_ARM_JOINTS(config)
        config.min_dist ← Inf
        for all arm_links do
            dist ← GET_DIST(link, user_model)
            if dist < config.min_dist then
                config.min_dist ← dist
                config.min_link ← link
    best_config ← ARGMAX(configs.min_dist)
    pose.limiting_dist ← best_config.min_dist
    pose.limiting_link ← best_config.min_link
```

we used OpenRAVE and the methods of [15] to uniformly sample 72 fingertip orientations for each fingertip position on a $5cm \times 5cm \times 5cm$ 3D grid around the care-receiver model. We then removed goal poses that were greater than or equal to 25cm away from the care-receiver model. Next, we used OpenRAVE's IKFast inverse kinematics solver to approximate the subset of these goal poses for which a contact free configuration of the arm exists. Note that we did not check if a collision-free trajectory existed to reach each pose. This process resulted in a total of 663,408 end-effector poses that would be feasible with no safety margin, which corresponds with allowing contact without interpenetration (i.e. nonnegative distance between the surfaces of the manipulator and the care-receiver models). In practice, this is a conservative estimate of the poses feasible with contact, since even light contact with compliant objects, such as clothing and the body, would result in deformation, corresponding with interpenetration of our rigid care-receiver model.

For each of these end-effector poses, we identified the link of the PR2's arm model that was closest to the care-receiver model. Specifically, we searched over the feasible arm configurations that could achieve an end-effector pose to find the configuration with the largest minimum distance to the care-receiver model (see Algorithm 1). For this configuration, we found the link with the minimum distance to the care-receiver model and the corresponding distance, which is the maximum safety margin for which the end-effector pose would be feasible. This computation excluded the fingers of the gripper (see. Fig. 2), since it is not uncommon to enable parts of a gripper to violate the safety margin during a task.

B. Results

Figure 3 shows the percentage of poses that become infeasible as the safety margin increases. Notably, 50% of the poses around the model of the care receiver become infeasible with an 11.8 cm (4.65 in) safety margin. Table I and Figure 4 show the links of the manipulator shaded according to the frequency with which each link is responsible for first making a pose infeasible as the safety margin increases. The general trend shows that contact with the distal links tends to make end-effector poses infeasible. As the safety margin increases, approximately 36% of the end-effector poses would be made infeasible due to contact with the PR2's forearm, while about 7% would be made infeasible due to contact with its upper arm.

Our results also show that a small increase in the safety margin makes end-effector poses that are far from the care-receiver model infeasible. Figure 5 shows the positions of poses that are no longer feasible with a 4 cm safety margin, which is comparable to safety margins used in practice. For example, 4 cm is smaller than the default used by the *pr2_arm_navigation* ROS package (5 cm), and slightly larger than 2σ where σ has been reported as the standard deviation of the sensor noise from a Microsoft Kinect, a common source of geometric information used by planners [16].

III. An Assistive Robot with Whole-arm Tactile Sensing and Contact-Regulating Control

For this work, we used a Willow Garage PR2 mobile manipulator with a custom-built fabric-based tactile sensing "skin" covering most of the left arm and gripper. The arm controller we developed uses this sensor to regulate contact forces while attempting to move the end effector to goal poses specified by the user. We also set the PR2's torque-controlled joints to have low stiffness.

A. Fabric-based tactile sensing skin

We first presented our fabric-based tactile sensor and a wrist cover for a Meka robot in [17], which details advantages of this sensor over other available tactile sensors, such as relatively low cost, large area, stretchability, and mechanical durability. Here, we present a new version of the tactile sensor covering an entire PR2 arm, which we have released as open hardware [18]. This sensor consists of 35 fabric tactile elements (taxels): 10 on the gripper, 22 on the forearm, and 3 on the upper arm. In addition, there are 6 taxels, front and sides of each finger, from the PPS finger-tip sensors on the PR2 gripper. This gives a total of 41 taxels on the robot's left arm. To support the larger number of

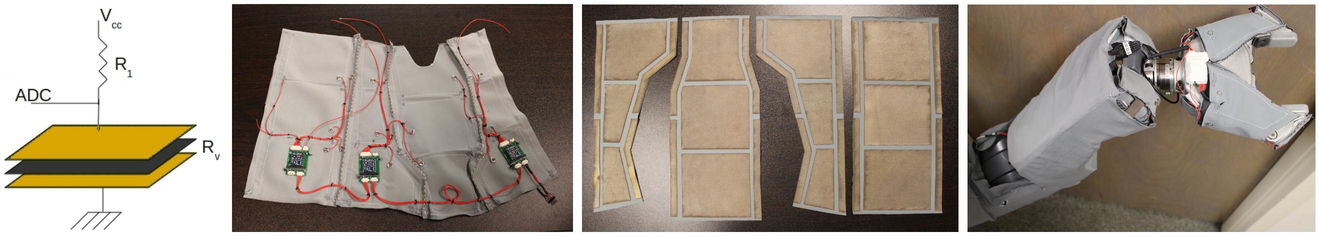

Fig. 6: *The fabric-based tactile sensor for the PR2 arm. From left to right: circuit diagram, wiring, taxel layout of forearm, and sensor on PR2.*

taxels and reduce wiring complexity, we use separate chips to perform analog-to-digital conversion of the taxel signals (see Fig. 6). Notably, the output of each taxel is a non-trivial function of both the applied force and the contact area, which neither allows for direct interpretation as newtons of total force nor pascals of pressure. This makes it difficult to quantitatively examine true contact force using this sensor. Nonetheless, in [17] we demonstrated that using the raw sensor measurements with our controller effectively reduces contact forces. In practice, we have found that by having the controller keep the raw sensor values low, the qualitative impression of the resulting contact is that the contact is light and comfortable.

B. Contact-regulating Controller

The controller we used is based on the model predictive controller (MPC) we presented in [19]. At each time step, the controller generates a quasi-static model of the robot's arm with linear torsional springs at the joints and a linear spring contact model at each taxel at which contact has been detected. The controller then solves a quadratic program based on this model that primarily minimizes the quadratic error between the predicted end-effector pose and the goal end-effector pose, subject to constraints on the predicted contact forces. The original version of this controller keeps contact forces low while successfully reaching goal positions in high clutter [19]. For this paper, we extend our original controller to control both the end-effector position and orientation, rather than just its position. We also present our first results that involve teleoperation of a robot with our controller and contact between the robot and a person's body.

We added orientation control by using the following new term to assign a cost that increases as the difference between the predicted end-effector pose and a waypoint end-effector pose increases. In contrast to [19], the term, $\mathbf{E}$, depends on both a desired change in position $\Delta\mathbf{x}_{desired}$ and orientation $\Delta\boldsymbol{\epsilon}_{desired}$.

$$\mathbf{E} = \begin{bmatrix} \Delta\mathbf{x}_{desired} \\ \Delta\boldsymbol{\epsilon}_{desired} \end{bmatrix} - \begin{bmatrix} \mathbf{J}_P \\ \frac{1}{2}(\eta\mathbf{I}_3 - skew(\boldsymbol{\epsilon}))\mathbf{J}_O \end{bmatrix} \Delta\mathbf{q} \quad (1)$$

where $\Delta\mathbf{q}$ is the predicted change in the robot's joint angles, $\boldsymbol{\epsilon}$ and η are components of a quaternion that defines the current end-effector orientation ($\mathbf{Q} = \{ \begin{smallmatrix} \boldsymbol{\epsilon} \\ \eta \end{smallmatrix} \}$), $\mathbf{I}_3$ is a 3x3 identity matrix, and $\mathbf{J}_P$ is the first three rows and $\mathbf{J}_O$ is the last three rows of the current geometric Jacobian [20]. We compute the desired change in orientation, $\Delta\boldsymbol{\epsilon}_{desired}$, at each time step using spherical linear interpolation ("slerp") between the current end-effector orientation and the waypoint orientation [21].

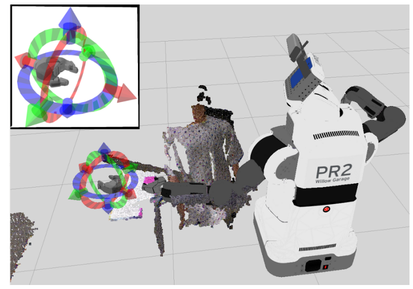

Fig. 7: *The interface used to control the robot's arm, with a close-up of the controls for commanding the gripper (inset).*

C. User Interface

To control the system, the user provides a goal pose for the robot's left end effector using an interface based on Interactive Markers for ROS RViz [22]. The 3D interface shows a rendering of the robot, a colored point cloud from a Kinect sensor on the robot, and a virtual gripper with a set of interactive controls (see Fig. 7). The controls consist of three rings and pairs of arrows aligned with the virtual gripper, which allow the user to translate and rotate it to specify a goal pose. Right-clicking the virtual gripper's controls presents options to set it as the goal pose, set it as the goal position only (original version of the controller), open the gripper, close the gripper, and recalibrate the tactile sensor to interpret the current readings as having a value of zero. When the user sets a new goal pose for the end effector, the MPC controller (Sec. III-B) attempts to reach the pose while maintaining low tactile sensor readings. When the gripper is gripping an object, the system ignores some of the tactile sensing elements. We have released this interface and the controller as open-source code [23].

IV. Two Motor-Impaired Users Test the System

We have performed tests of our robotic system with two motor-impaired users with intact sensation across their bodies. The first user, Henry Evans, has severe quadriplegia due to a brainstem stroke. He is able to control a mouse cursor via a head tracker and click a mouse button by moving his finger. We have worked with Henry as part of the Robots for Humanity project since January 2011 [14].

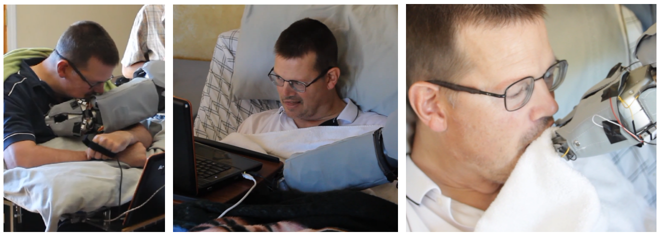

Fig. 8: *Left: Henry Evans becomes comfortable with the arm while in his wheelchair. Middle: While in bed, he grabs a cloth under his overbed table. Right: He then wipes his face with the cloth.*

Henry first used an earlier version of this robotic system on June 26 and 27, 2012 [24]. This version used a very similar whole-arm tactile sensing array with fewer taxels (14) on the forearm and an earlier version of the controller code and interface. On the first day he used it from his wheelchair and on the second day he used it from his wheelchair and from his bed. While in bed, Henry successfully performed tasks spontaneously, including grabbing a cloth and wiping his mouth with it, and grasping a blanket and pulling it up over himself (see Figs. 1 and 8). This was significant in that it was the first time he had manipulated around his body using the PR2 from bed, which is one of the potential advantages of an assistive mobile manipulator. More generally, our prior attempts to have Henry perform comparable freeform, near–body tasks using other methods, including geometric planning, were unsuccessful, primarily due to a combination of safety concerns and lack of reachability. In fact, in our first Robots for Humanity workshop in March 2011, Henry specifically requested to be able to pull up a blanket while he was in bed due to getting cold.

Since Henry lost the ability to speak as a result of his stroke, we asked him to provide typed feedback regarding the various technologies he used during the workshop, which included our robotic system. During the tests, Henry provided the following comments about the system: "It is very compliant," "I like it," "I think its a good safety feature because it hardly presses against me even when I tell it to," and "It really feels safe to be close to the robot." A week after the tests, Henry provided the following comments via email: "Overall awesome," "Feels VERY safe," "Faster than motion planning," "It just wriggles around obstacles," and "DEFINITELY keep developing this !"

In January 2013, a second motor-impaired user, with amyotrophic lateral sclerosis (ALS), recruited via the Emory ALS Center, worked with the current system. He had minimal motor function in his dominant (right) arm and hand, and so used a mouse with his non-dominant hand to control the robot to attempt an object placement task with the robot reaching across his chest (as in Sec. V). He did not successfully perform the object placement task, apparently due to difficulties using the 3D interface. While attempting to perform the task, the robot did make contact with his body. In addition, he spent time interacting with the robot without restrictions. When asked to describe the force of contact with the robot as "very strong," "very weak," or "in between," he stated that it was "very weak." When asked for any additional comments on his experience with the robot, he stated that he "felt very comfortable with robot, never concerned about safety at all with [the] robot touching [him]." In addition, on the questionnaire detailed in Sec. V, he reported "strongly agreeing" with all of the statements, which also indicates that he perceived the system as safe and comfortable.

V. A Study with Able-Bodied Users to Evaluate the Acceptability of Contact

Even if a robot could perfectly regulate contact forces while moving against a person's body, people might be unwilling to have the robot make contact with them [25], which could result in disuse of an otherwise effective assistive technology. In our first tests of our robotic system with Henry Evans, he expressed that he felt safe and comfortable when in contact with the robot. In order to investigate if other people would find contact with our robotic system acceptable, we conducted a study with eight able-bodied participants that involved substantial contact between the robot's arm and the participant's body.

How people respond to being touched by a robot depends on the context of the interaction [25]. We designed our experiment to emulate characteristics of our robotic system being used as an assistive device. We introduced participants to the robotics system, provided training and time to practice with the robot, gave them control of the robot, and had them perform a manipulation task that involved contact between the robot's arm and their bodies.

A. Experiment

We performed the experiment with IRB approval, and all participants gave their informed consent. For safety, the robot moved slowly and the tactile-sensing skin and controller were always active. The person conducting the experiment was also prepared to press a button that would stop the robot in the event of a problem. In addition, the experimenter encouraged the participant to say "stop" if he wanted the robot to stop for any reason.

The experimenter first instructed the participant in using the interface described in Section III-C. He then asked the participant to complete two practice tasks that required placing a bottle at two locations in front of the robot, while the participant was seated away from the robot. If the participant successfully placed both bottles, then he moved on to the next part of the experiment in which he was given up to 10 minutes to interact with the robot both physically and through the interface.

1) Experimental Task: The experimenter then seated the participant next to the robot, and placed a box wrapped in white paper on the participant's right side. This box had two goal locations on it (*near* and *away*) marked by pink regions (see Fig. 9). The participant used a mouse on a whiteboard sitting on his lap to operate the user interface, which was running on a laptop in front of him. The experimenter asked the participant to sit upright and move the chair forward until his body was aligned with a reference location on the

Fig. 9: *Image sequence from a trial in the* near *condition.* Contact with the robot indicated in red. *Far left: The robot in the starting position, the* near *goal* (**N**)*, and* away *goal,* (**A**).

#	**Likert Items**
1	The force of the contact made by the robot was appropriate for the task being performed.
2	I felt safe with the robot in close proximity to me.
3	I felt safe with the robot making contact with me.
4	I was comfortable with the robot making contact with me.
5	I was comfortable with the robot in close proximity to me.

TABLE II: Likert Items.

white box. This resulted in the participants' profiles being in similar locations relative to the robot and goal positions.

The experimenter then asked the participant to place the bottle onto one of the two goal locations, starting from a consistent initial configuration of the robot's arm with the bottle in its gripper. The experimenter asked each participant to perform the task twice, once for each goal location, with the order counterbalanced across participants.

For this paper, we consider the participant to have successfully performed the task if he released the bottle and it made contact with the goal. This is a weak sense of success, since the bottle may have tipped over or even fallen off the white box after being released. For this experiment, our primary goal was to investigate participants' perceptions of contact with the robotic system rather than their skill in using the system. Notably, we selected the *near* goal so that the robot's arm would make contact with the user's body, specifically bending around the user's chest to reach the goal.

2) Measures: We recorded video of each participant from two cameras with different perspectives in order to facilitate annotation of contact between the robot's arm and the person's body. In addition, the experimenter made note of contact and the time taken to complete the tasks. After each trial, the experimenter asked the participant to describe the contact, if any, made by the robot with the participant's body. The participant then completed a questionnaire with five Likert items, asking him to indicate his level of agreement with the statements in Table II on a 1-5 scale, with 1:'Strongly Disagree,' 3:'Neither Agree nor Disagree,' and 5:'Strongly Agree.' The questionnaire also asked the participant to explain his responses in writing. At the end of the experiment, the experimenter asked the participant for additional comments. During the experiment, we also recorded the tactile sensor signals, the commands given to the robot via the user interface, and the robot's joint angles.

Our main hypotheses follow:

1) *Hypothesis 1:* Placing the bottle at the *away* goal will result in contact during fewer trials than the *near* goal, and contact will be less extensive, as defined by a smaller integral over all tactile sensor signals.
2) *Hypothesis 2:* Participants will be more comfortable when performing the *away* task, as indicated by a greater tendency toward agreement with Likert items 4 and 5, $\alpha = 0.05$ according to a Wilcoxon signed-rank test [26].
3) *Hypothesis 3:* Participants will find contact acceptable under both conditions, as defined by positive responses to Likert items 1-3, $\alpha = 0.05$ according to a 1-sample Wilcoxon signed-rank test against an H_0 of 3: 'Neither Agree nor Disagree.'

B. Results

We recruited 10 able-bodied male participants who were told that the study would "involve physical contact with a robot." While this did not emphasize or detail the extent of contact, it may have resulted in participants who were more accepting of contact with a robot. We only recruited male participants due to the locations at which we expected contact to occur, which is a limitation of our study. Two participants withdrew citing time constraints after spending approximately 45 minutes at the training task, but not succeeding. Since they did not proceed to the main part of the experiment, we did not collect, nor do we report, any data from them.

The eight participants self-reported an average age of 26.1 years old (SD 8.6), at least two years of post-secondary education, and the following ethnicities: White (4), Asian (2), Hispanic (1), and African American (1). None indicated previous experience with robots. Four of the participants had experience using SolidWorks, a 3D visualization environment similar to the interface used in the study. The remaining four reported having no experience with any similar 3D visualization software, though some mentioned video-gaming experience.

During training, these participants required less than 15

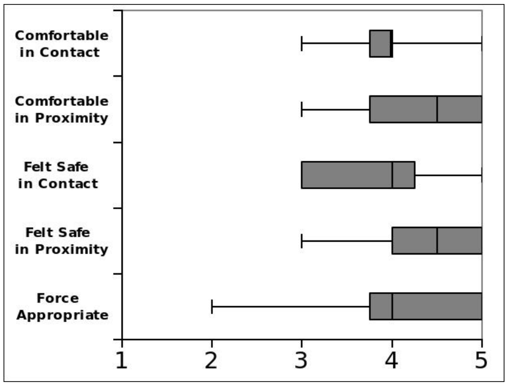

Fig. 10: *Responses to Likert items after the* away *condition. Boxes denote median and quartiles, whiskers denote range. 1:'Strongly Disagree' 2:'Disagree' 3:'Neither Agree nor Disagree' 4:'Agree' 5:'Strongly Agree'*

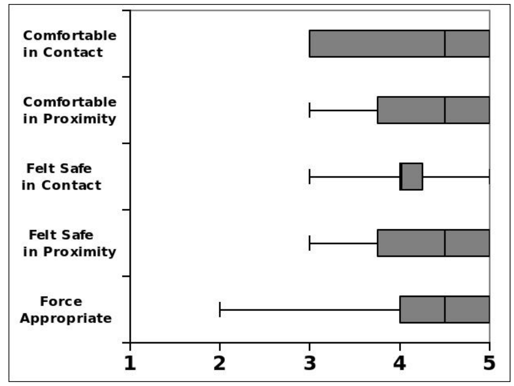

Fig. 11: *Responses to Likert items after the* near *condition. See Fig. 10 for details.*

minutes to complete the training tasks, and used a mean of 7.38 minutes (SD 3.13, min 2.5, max 10.0) in the free interaction time, during which five of eight participants made physical contact with the robot, including touching the tactile sensors.

In the tasks, all participants were successful for both tasks. The mean completion times were 3.53 minutes (SD 1.90) and 7.87 minutes (SD 5.88) for the *away* and *near* goals, respectively. Participants used a mean of 9.1 commands (SD 6.5, min 5, max 24) for the *away* goal, and 20.4 commands (SD 13.8, min 6, max 42) for the *near* goal.

1) Hypothesis 1: We expected some participants to perform the *away* goal task without making contact with their bodies, since we designed the task to be achievable without contact. However, the robot's arm made contact with each participant's body in each of the two tests. In support of Hypothesis 1, the contact typically appeared to be more extensive for the *near* goal. Also, integrating the output of the tactile sensors and summing over all taxels resulted in a mean of 190.65 (SD 137.31) and 521.99 (SD 378.88) for the *away* and *near* trials, respectively, which is a significant difference (p=0.0164) by a repeated-measures, 1-tailed t-test.

2) Hypothesis 2: Figures 10 and 11 show responses to the Likert items. The responses do not support Hypothesis 2, showing no significant difference in comfort between the two goal locations. For Likert item #4, "I was comfortable with the robot making contact with me": $p>0.5$, N=6, T^{+}=7. For item #5, "I was comfortable with the robot in close proximity to me": $p>0.5$, N=2, T^{+}=1.5.

3) Hypothesis 3: In support of Hypothesis 3, the responses were significantly positive (greater than 'Neither Agree nor Disagree') for Likert items 1-3. For Likert item #1, "the force of contact was appropriate": $p<0.0195$, N=8, T^{+}=33.5. For item #2, "I felt safe in proximity to the robot": p=0.0156, N=6, T^{+}=21. For item #3, "I felt safe in contact with the robot": p=0.0078, N=7, T^{+}=28.

C. Open-Ended Responses

1) Positive Responses: Multiple participants provided positive comments on the robotic system. One participant indicated that the robot "wasn't very forceful at all" and "agreed" that he felt safe in contact with the robot despite his belief that "if a sensor failed, [the arm] could probably knock [him] over." Other participants provided positive comments including that the robot had a "soft touch," "the tactile sensor works well," the "force was not strong, and it backed off quickly upon contact," and that "the force of contact was the same or more gentle than a human performing the same task."

One participant experienced significant contact between the robot's arm and his chest, arm, head, and face during both trials due to misunderstanding the interface, even though he had been successful with the training tasks. This participant, however, reported that the contact felt "soft" and "not threatening at all" and either "agreed" or "strongly agreed" with all positive statements on safety and comfort with the robot, both for contact and proximity. He did select 'Neither Agree nor Disagree' regarding the forces of contact being appropriate for the task, and commented that the contact, particularly on his face, was "kind of obnoxious." Errors, whether due to autonomous control or the user, are another important consideration for an assistive robot that manipulates near a person's body. The trials with this participant provide evidence that our robotic system can reduce the consequences of user error, which may have the benefit of making the user more willing to explore new ways of using the robot.

2) Negative Responses: We summed each participants' responses to the Likert items for each of the two conditions (*near* and *away*). The two lowest sums occurred in the *near* condition. In both cases the participants "agreed" that the force was appropriate, and "neither agreed nor disagreed" regarding comfort in contact or proximity and safety in proximity. One "neither agreed nor disagreed" regarding safety in contact, and provided no comments. The other "agreed" to feeling safe in contact, and stated that "[he] did not want the robot to contact [him], but [he] felt relatively safe. Its proximity felt more distracting than unsafe," that he "would prefer it did not [contact him]," and that "[he] felt a little nervous."

Only two responses to the Likert items were below a value of three ("neither agree nor disagree"). Two different participants "disagreed" with the statement that the "force of contact was appropriate for the task," one in the *near* condition and one in the *away* condition. In the *near* condition, the participant stated that "the force on [his] arm during the first few movements was more than from the [*away*] task. It was not uncomfortable, but more force than expected." He "agreed" to feeling safe in contact, and "strongly agreed" to the remaining three Likert items. In the *away* condition, the other participant only stated that "the force was high," and "neither agreed nor disagreed" with feeling safe in contact with the robot. Despite this, he "agreed" to feeling comfortable in contact, stating that "the robot didn't seem like it could hurt [him]."

VI. Conclusions

In general, people who have used our robotic system have been accepting of contact between their bodies and the robot's arm. For example, in our experiment with able-bodied participants, the participants did not avoid contact when performing the *away* goal task and, on average, were comfortable with even the extensive contact in the *near* goal task. Our results also show that when operating an assistive robot with whole-arm tactile sensing and contact-regulating control, a user can be accepting of contact with the robot's arm after only a short time with the robot. In conjunction with our simulation results that show the costs of forgoing contact and the successful use of our robotic system by Henry Evans, we have provided evidence that contact between the arms of assistive robots and care receivers' bodies can be both beneficial and acceptable. While much research remains to be done, including making the system easier to use, working with female participants, working with more motor-impaired participants, investigating longer periods of use, and looking at more tasks, our results begin to pave the way for a new paradigm in assistive robotics. The arms of able-bodied people frequently make extensive contact with their bodies without being noticed. Care-receivers allow frequent and extensive contact from the arms of human caregivers in the performance of assistive tasks. In the future, assistive robot arms may be able to attain a similar status to the arms of human caregivers, if not the care-receiver's own arms, and thereby provide more effective assistance.

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References

[1] W. Seamone and G. Schmeisser, "Early clinical evaluation of a robot arm/worktable system for spinal-cord-injured persons," *J Rehabil Res Dev*, vol. 22, no. 1, pp. 38–57, Jan. 1985.

[2] M. Busnel, R. Cammoun, F. Coulon-Lauture, J.-M. Dtrich, G. Le Claire, and B. Lesigne, "The robotized workstation "MASTER" for users with tetraplegia: Description and evaluation," *J Rehabil Res Dev*, vol. 36, no. 3, Jul. 1999.

[3] H. Van der Loos, "Lessons learned in the application of robotics technology to the field of rehabilitation," Fact Sheet, 1995.

[4] T. Sugaiwa, H. Iwata, and S. Sugano, "Shock absorbing skin design for human-symbiotic robot at the worst case collision," in *Humanoid Robots, 2008.*, Dec. 2008, pp. 481 –486.

[5] A. D. Luca, A. Albu-Schaffer, S. Haddadin, and G. Hirzinger, "Collision detection and safe reaction with the DLR-III Lightweight Manipulator arm," in *Intelligent Robots and Systems, 2006 IEEE/RSJ International Conference on*, Oct. 2006, pp. 1623 –1630.

[6] S. Haddadin, A. Albu-Schäffer, M. Frommberger, J. Rossmann, and G. Hirzinger, "The "DLR crash report": towards a standard crash-testing protocol for robot safety – Part I: Results," in *IEEE international conference on Robotics and Automation*, 2009, pp. 2663–2670.

[7] T. Mukai, S. Hirano, H. Nakashima, Y. Kato, Y. Sakaida, S. Guo, and S. Hosoe, "Development of a nursing-care assistant robot riba that can lift a human in its arms," in *Intelligent Robots and Systems (IROS), 2010 International Conference on*, Oct. 2010, pp. 5996 –6001.

[8] H. Choset, K. M. Lynch, S. Hutchinson, G. A. Kantor, W. Burgard, L. E. Kavraki, and S. Thrun, *Principles of Robot Motion: Theory, Algorithms, and Implementations*. MIT Press, May 2005.

[9] D. Hsu, R. Kindel, J.-C. Latombe, and S. Rock, "Randomized kinodynamic motion planning with moving obstacles," *The International Journal of Robotics Research*, vol. 21, no. 3, pp. 233–255, 2002.

[10] T. Fraichard and H. Asama, "Inevitable collision states. a step towards safer robots?" in *Intelligent Robots and Systems, 2003. (IROS 2003). Proceedings. 2003 IEEE/RSJ International Conference on*, vol. 1, oct. 2003, pp. 388 – 393 vol.1.

[11] F. Zacharias, C. Borst, and G. Hirzinger, "Capturing robot workspace structure: representing robot capabilities," in *Intelligent Robots and Systems. International Conference on*. IEEE, 2007, pp. 3229–3236.

[12] R. Diankov, "Automated construction of robotic manipulation programs," Ph.D. dissertation, Carnegie Mellon University, Robotics Institute, August 2010.

[13] P. Moyer, "Ada figure 4b, ansi305.5," Google SketchUp, Jun. 2008.

[14] T. L. Chen, M. Ciocarlie, S. Cousins, P. Grice, K. Hawkins, K. Hsiao, C. C. Kemp, C.-H. King, D. A. Lazewatsky, A. Leeper, H. Nguyen, A. Paepcke, C. Pantofaru, W. D. Smart, and L. Takayama, "Robots for humanity: Using assistive robotics to empower people with disabilities," *IEEE Robotics & Automation Magazine*, Mar. 2013.

[15] A. Yershova, S. Jain, S. M. Lavalle, and J. C. Mitchell, "Generating uniform incremental grids on so(3) using the hopf fibration," *Int. J. Rob. Res.*, vol. 29, no. 7, pp. 801–812, Jun. 2010.

[16] K. Khoshelham, "Accuracy analysis of kinect depth data," in *ISPRS workshop laser scanning*, vol. 38, 2011, p. 1.

[17] T. Bhattacharjee, A. Jain, S. Vaish, M. D. Killpack, and C. C. Kemp, "Tactile sensing over articulated joints with stretchable sensors," in *IEEE World Haptics Conference*, Apr. 2013.

[18] A. Jain, S. Vaish, and C. C. Kemp, *Low-Cost Fabric Tactile Sensing Skin*, Healthcare Robotics Lab, Georiga Tech, Mar. 2013. [Online]. Available: http://www.hsi.gatech.edu/hrl/project_fabric_tactile_sensor.shtml

[19] A. Jain, M. Killpack, A. Edsinger, and C. Kemp, "Reaching in clutter with whole-arm tactile sensing," *International Journal of Robotics Research*, vol. 32, no. 4, pp. 458–482, Apr. 2013.

[20] B. Siciliano, L. Sciavicco, L. Villani, and G. Oriolo, *Robotics: modelling, planning and control*. Springer, 2011.

[21] K. Shoemake, "Animating rotation with quaternion curves," *ACM SIGGRAPH computer graphics*, vol. 19, no. 3, pp. 245–254, 1985.

[22] A. Leeper, K. Hsiao, M. Ciocarlie, L. Takayama, and D. Gossow, "Strategies for human-in-the-loop robotic grasping," in *Proceedings of the seventh annual ACM/IEEE international conference on Human-Robot Interaction (HRI'12)*, 2012, pp. 1–8.

[23] J. Hawke and P. M. Grice, *Haptic Controller*, Healthcare Robotics Lab, Georiga Tech, Mar. 2013. [Online]. Available: http://hsi.gatech.edu/hrl-wiki/index.php/Haptic_controller

[24] A. Jain, "Mobile manipulation in unstructured environments with haptic sensing and compliant joints," Ph.D. dissertation, Georgia Institute of Technology, Aug. 2012.

[25] T. Chen, C.-H. King, A. Thomaz, and C. Kemp, "Touched by a robot: An investigation of subjective responses to robot-initiated touch," in *Human-Robot Interaction (HRI), 2011 6th ACM/IEEE International Conference on*, Mar. 2011, pp. 457 –464.

[26] S. Seigel and N. J. Castellan, Jr., *Nonparametric Statistics for the Behavioral Sciences*, 2nd ed. McGraw-Hill, Inc., 1988.