Lead Me by the Hand: Evaluation of a Direct Physical Interface for Nursing Assistant Robots

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***Abstract*—When a user is in close proximity to a robot, physical contact becomes a potentially valuable channel for communication. People often use direct physical contact to guide a person to a desired location (e.g., leading a child by the hand) or to adjust a person's posture for a task (e.g., a dance instructor working with a dancer). Within this paper, we present an implementation and evaluation of a direct physical interface for a human-scale anthropomorphic robot. We define a direct physical interface (DPI) to be an interface that enables a user to influence a robot's behavior by making contact with its body. Human-human interaction inspired our interface design, which enables a user to lead our robot by the hand and position its arms. We evaluated this interface in the context of assisting nurses with patient lifting, which we expect to be a high-impact application area. Our evaluation consisted of a controlled laboratory experiment with 18 nurses from the Atlanta area of Georgia, USA. We found that our DPI significantly outperformed a comparable wireless gamepad interface in both objective and subjective measures, including number of collisions, time to complete the tasks, workload (Raw Task Load Index), and overall preference. In contrast, we found no significant difference between the two interfaces with respect to the users' perceptions of personal safety.**

***Index Terms*—healthcare robotics; assistive robotics; direct physical interface; nursing; user study.**

I. Introduction

Increasingly, robots are operating in human environments alongside people. This presents new opportunities for humans to make contact with a robot's body in order to change the robot's behavior.

People often use physical contact to guide one another. For example, caregivers will often lead a child or elderly person by the hand. Similarly, people often use physical contact to change one another's motion or posture. For example, coaches in sports, physical therapists, and choreographers all use physical contact to help people achieve desirable motions and postures. These examples indicate that even highly-experienced adults benefit from haptic communication.

Within this paper, we present an implementation and evaluation of a direct physical interface inspired by these forms of human-human interaction. We define a direct physical interface (DPI) to be an interface that enables a user to influence a robot's behavior by making contact with its body. The user directs our anthropomorphic, omni-directional robot by moving the robot's highly-compliant arms and applying forces to the robot's hands. This enables the user to lead the robot by the hand, move the robot's torso up and down, and move the robot sideways.

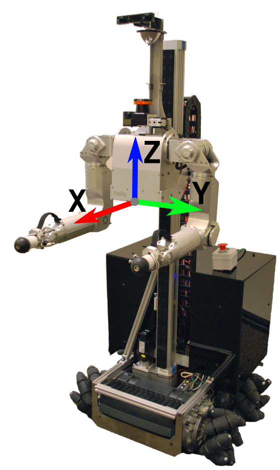


Fig. 1. **Mobile manipulator robot used in this study**. Coordinate frame of robot is shown at the center of the robot's torso.

A. A Healthcare Scenario

Although direct physical interaction can plausibly be beneficial in a wide variety of HRI scenarios, we believe that evaluating interfaces in the context of a specific application domain offers substantial benefits. As shown by numerous researchers, including [23], [7], [11], grounding the evaluation in a real-world application provides the opportunity to work with naive users from the expected user population, and helps to contextualize the results in terms of their significance for real-world operation.

For this study, we have designed the testing scenarios to be representative of situations relevant to a robot that assists nurses. Specifically, we have evaluated the interface in the context of leading the robot through a cluttered environment and positioning its arms in preparation for lifting a patient. We believe that this is a plausible, high-impact, near-term application for this form of interface.

B. Opportunities for Robotic Nursing Assistants

There is well-documented shortage of nurses and direct-care workers in the U.S. and around the world, which is expected to become more problematic as the elderly population grows and prepares for retirement [24], [16]. In a study of the effects of high patient-to-nurse ratio, Aiken et al. showed that each additional patient per nurse was associated with a 7% increase in patient mortality and a 23% increase in nurse burnout [2]. Consequently, studies have suggested that lowering the patient-to-nurse ratio would result in less missed patient care [16], [27].

Nurses frequently experience work-related back injury [22], [41] due to the physical demands of manually handling patients. These injuries force nurses to take time off work, further compounding the nursing shortage and increasing hospital cost. Technology has the potential to both reduce this source of injury and make nurses more efficient. For example, the Barton Patient Transfer System and the sling-suspension lift system, were both shown to place less stress on a nurse's lower back when moving patients than traditional manual techniques and were more desirable to use [40]. One caveat to using a mechanical lift system is that while a patient is in the lift, there is risk that a nurse may begin to perform another task and leave the patient unattended and prone to injury or death [9].

We believe that robots have the potential to deliver superior assistance with patient lifting and transfer. Robots such as RI-MAN, RIBA, and Melkong are already being developed to assist with patient lifting [37], [1], [20]. However, a critical unaddressed issue for the success of these robots will be moving to a patient's room, entering a patient's room, and positioning the arms in preparation to lift a patient. We have designed our test scenarios to simulate the challenges inherent in these critical tasks.

C. Options for Achieving the Tasks

In the long run, robots may be sufficiently perceptive, agile, and intelligent to autonomously perform these tasks. However, healthcare facilities in general, and hospitals in particular, present daunting challenges for autonomous operation. Within these highly-cluttered environments, errors can have deadly consequences. For example, the potential for a robot to damage an intravenous line due to a failure of perception, dexterity, or lack of contextual understanding could be a high risk when moving to the bedside of a patient. Moreover, even if human-scale, nursing assistant robots are able to operate autonomously, we expect that direct physical contact will still be an important form of interaction. For example, a nurse may wish to grab hold of a robot in order to override its autonomous control, help it avoid an error, or efficiently repurpose it.

In the nearer term, we expect that interfaces which encourage close human supervision will be important. Several feasible interface methods exist for guiding robots and could potentially be used in nursing-related tasks. For instance, people following [15], [30], teleoperation [35], [14], and spoken commands [38], [12] all have merit. We expect DPIs to add value and be complementary to these and other interfaces.

D. Direct Physical Interaction

We expect that DPIs will be especially valuable as intuitive, effective, and safe interfaces that can work in isolation or in conjunction with other interfaces. There has been extensive research into physical human-robot interaction. For example, cobots have guided human movement through virtual fixtures [13], and researchers have developed dancing robots that respond to physical interaction with a human dance partner [43]. Among other tasks, DPIs have been implemented for rehabilitation robots [29], for object transfer [10], to direct robot's attention during learning [6], to demonstrate tasks [5], and to distinguish interaction styles [39].

There are previous examples of DPIs for human-scale mobile manipulators. In public demonstrations, presenters have led and positioned Willow Garage's/Stanford's PR1 [3] and DLR's Justin [33] by making contact with their torque-controlled arms. And most recently, in parallel with our research, RIKEN has released a video and press release that shows its nursing-care assistant robot RIBA being controlled via touch sensors on the robot's upper arm [1]. The demonstration shows RIBA moving to the side of a bed, picking up a person seated on the bed, and placing the person in a chair, all while the user makes contact with the robot. This demonstration lends additional credibility to our approach.

Although similar robotic systems have been implemented and demonstrated, we believe our work represents the first formal user study of this type of interface for user-guided navigation and arm positioning with a human-scale mobile manipulator.

II. Implementation

In our study, we asked participants to control a robot to complete a set of four tasks using two different interfaces: a gamepad interface and a DPI. In this section, we will describe the robot used for this study and the implementation details for both of the interfaces.

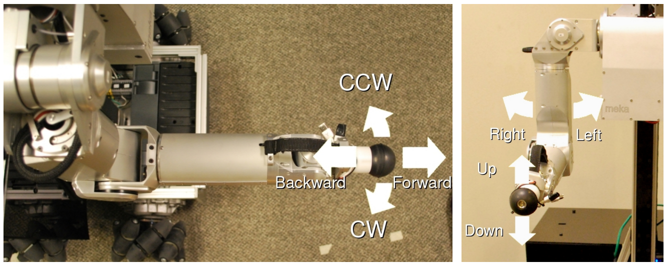
A. System description

The robot is a statically stable mobile manipulator. The components of the robot are: arms from MEKA Robotics (MEKA A1), a Segway omni-directional base (RMP 50 Omni), and a 1 degree-of-freedom (DoF) Festo linear actuator. The arms consist of two 7-DoF anthropomorphic arms with series elastic actuators (SEAs) and the robot's wrists are equipped with 6-axis force/torque sensors (ATI Mini40). The robot uses two computers running Ubuntu Linux and we wrote the interface software in Python.

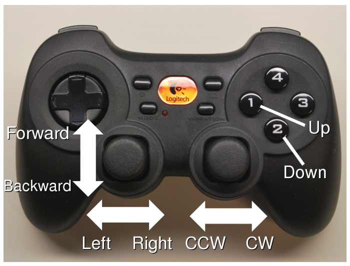
B. Gamepad Interface

The gamepad interface consists of a Logitech Cordless RumblePad 2 game controller (see Figure 2(b)). The gamepad is used by gripping the two handles in both hands and using the thumbs to control the analog sticks and buttons.

As illustrated in Figure 2(b), when the user tilts the left analog stick forward or backward the robot moves forward or backward. The velocity of the robot is proportional to



(a)



(b)

Fig. 2. **Interface usage.** (a) The direct physical interface. (b) The gamepad interface.

the degree to which the stick is tilted. The forward/backward velocities are capped at a maximum of 0.35 m/s. When the user tilts the same stick to the left or right, the robot moves to the left or right. The left/right velocities are capped at a maximum of 0.15 m/s. When the user tilts the right analog stick to the left or right, the robot rotates counter-clockwise or clockwise. The angular velocity of the robot is also proportional to the degree to which the stick is tilted and is capped at a maximum of 0.185 rad/s. To move the robot up or down along the linear actuator, the user must press the button that says ”1” or ”2”. All motions can be performed simultaneously.

C. Direct Physical Interface (DPI)

The DPI makes use of the Meka arms and the force/torque sensors at the wrists (Figure 2(a)). For both interfaces, the robot's arms maintain a single posture, which we refer to as the *home position*. The forearms are situated so that they are parallel to the ground and the elbows are bent at 90 degrees as shown in Figure 1. Each of the torque-controlled arm joints acts like a damped spring with a low, constant stiffness. When the user applies force to the end effector, the arm moves in a very compliant, spring-like manner. In contrast, the two wrist joints that hold the wrist parallel to the forearm are position controlled with relatively high stiffness, and, consequently, do not bend significantly.

As illustrated in Figure 2(a), when the user grabs either of the end effectors (the black rubber balls) and moves it, the robot responds. Pulling forward or pushing backward makes the robot move forward or backward. Moving the end effector to the left or right causes the robot to rotate, while moving it up or down, causes the robot's torso to move up or down. The user can also grab the robot's arm and abduct or adduct it at the shoulder, which causes the robot to move sideways.

We now describe the control in more detail. All of the following spatial quantities are defined with respect to the robot's coordinate frame shown in Figure 1. When the user interacts with either of the arms, the forces and displacements are used to calculate the following four velocities for the robot:

$$
\begin{aligned}
x_{vel} &= \text{the robot's forward/backward velocity}\\
y_{vel} &= \text{the robot's left/right velocity}\\
a_{vel} &= \text{the robot's angular (CW/CCW) velocity}\\
z_{vel} &= \text{the robot's up/down velocity along the linear actuator}
\end{aligned}
$$

These velocity values are computed for each arm, then the maximum value for each velocity is used to command the robot.

The user input consists of the forces applied in the x-direction at the robot's wrist (f_x in Newtons), position changes of the end effector (Δx, Δy, and Δz in meters) with respect to the end effector's home position (x_{home}, y_{home}, and z_{home} in meters), and the angular displacement of the shoulder joint from its home position ($\Delta\theta$ in radians). In order to map these quantities to velocities, we use the following scaling factors:

$$
\begin{array}{llll}
x_{vel}^{max} & = 0.35m/s & f_x^{max,human} & = 15N\\
y_{vel}^{max} & = 0.15m/s & \theta^{max,human} & = 0.26rad\\
a_{vel}^{max} & = 0.185rad/s & \phi^{max,human} & = 0.62rad\\
z_{vel}^{down} & = 1cm/s & z_{vel}^{up} & = 3.6cm/s\\
x_{home} & = 0.4m & &
\end{array}
$$

$$
x_{scale} = \frac{x_{vel}^{max}}{f_x^{max,human}} \quad y_{scale} = \frac{y_{vel}^{max}}{\theta^{max,human}} \quad a_{scale} = \frac{a_{vel}^{max}}{\phi^{max,human}}
$$

These scaling factors linearly map the range of expected human input values to bounded robot velocities. The robot's maximum velocities for the DPI are identical to its maximum velocities with the gamepad interface. We calculate the four velocities for the right arm using the following equations:

$$\phi = atan2(\Delta y, x_{home} + \Delta x) \tag{1}$$

$$x_{vel} = sgn(f_x)min(x_{scale}|f_x|, x_{vel}^{max}) \tag{2}$$

$$y_{vel} = sgn(\Delta\theta)min(y_{scale}|\Delta\theta|, y_{vel}^{max}) \tag{3}$$

$$a_{vel} = sgn(\phi)min(a_{scale}|\phi|, a_{vel}^{max}) \tag{4}$$

$$z_{vel} = \begin{cases} z_{vel}^{down} & \Delta z < -5cm \\ z_{vel}^{up} & \Delta z > 10cm \\ 0 & else \end{cases} \tag{5}$$

Additionally, we do not allow the robot's base to move if the magnitude of the user's input force in the x-y plane is below a threshold. This reduces the chance of the robot moving when no user is in contact with the controls, and serves as a form of dead-man's control. We also average the control signals from the user in order to reduce noise and smooth velocity transitions, which reduces the potential for undesired oscillations.

D. Similarity of the interfaces

We chose to use a gamepad controller as a basis for comparison with the DPI since it is a widely-used form of tele-operative mobile robot control [21], [31], [26]. It is important to note that we have attempted to make the gamepad interface and DPI comparable. Both interfaces control the same degrees of freedom, use proportional control, and have the same maximum speeds. Furthermore, we believe the gamepad interface is represented fairly in this study. It closely matches the interface for popular first-person shooter games such as Halo [32] (see Figure 2(b)). Moreover, members of the Healthcare Robotics Lab have used the the gamepad interface extensively and reported satisfaction with it. We started developing it prior to any plans for a study, and developed it from January to August 2009. We developed the DPI over a slightly shorter period of time from March to August 2009.

E. Safety

Several factors contribute to the safety of the interfaces. The use of robot arms with low mechanical impedance reduces the risk of injury due to contact with the arms. When navigating with the DPI, the majority of contact is with the robot's end effector, which enables the user to keep some distance from the robot's upper body and base. Likewise, the wireless gamepad allows users to be far from the robot. Both the DPI and gamepad interface have forms of dead-man's control, which reduces the chances of the robot moving if the user ceases to make contact with the end effectors or analog sticks, respectively. For all of the trials in our experiments, a researcher held an emergency stop button that would be pushed at the first sign of risk to the user. The button was not pushed at any time during the experiments.

III. METHODOLOGY

In this section we describe the experimental methods we used to test the performance of the two interfaces. Our methodology was influenced by several published mobile robot controller evaluations [36], [25], [14] as well as HRI studies in other areas of research [34], [17].

A. Participants

We recruited 18 nurses from the Atlanta area of Georgia, USA, specifically from: Wesley Woods Geriatric Hospital, the Shepherd Center, Children's Healthcare of Atlanta Pediatric Hospital, Dekalb Medical Center, and Emory Healthcare. We left recruitment open to those with nursing certification including: registered nurses, licensed nurse practitioners, nurse assistants, and nurse technical assistants. We shall refer to this population as "nurses" for the remainder of the paper. To recruit the participants, we emailed a flyer to contacts at these healthcare centers and scheduled appointments with nurses who responded by phone and email. See Table II for the demographic information about the nurses who participated in the study.

B. Task description

We asked the subjects to complete four tasks that simulate scenarios they might encounter when moving a robot in a nursing environment. We referred to the DPI as the "touching interface" to make the name easier for the participants to understand.

1) Navigation task, Forward and Backward: The navigation task simulated the scenario where a nurse wishes to move a robot through a hospital hallway while taking care to avoid hitting obstacles such as other people or equipment. Figure 3(a) shows the experimental setup for this scenario where the four white boxes placed in the center of the room were meant to mimic such obstacles and a dotted path marked with tape on the floor mimicked the path a nurse may want to travel. For this task, the subject was to lead the robot from a box marked on the floor with tape, along the dotted path through the obstacle course, and return the robot back to the starting box. We instructed the subjects to use one of the control methods to lead the robot through the obstacle course while avoiding the boxes and walls. We defined separate tasks for maneuvering the robot through the obstacles with its arms pointing forward and for maneuvering it with the arms pointed backward.

2) Bedside positioning task, Forward and Backward: The bedside positioning task was meant to simulate the scenario where a nurse may wish to move a robot into a patient's room and bring it to the patient's bedside in order for the robot to perform tasks such as patient transfer, bathing, or feeding. While doing this, the nurse would want to avoid hitting things including the doorway, patient bed, patient, or monitoring equipment inside the patient's room.

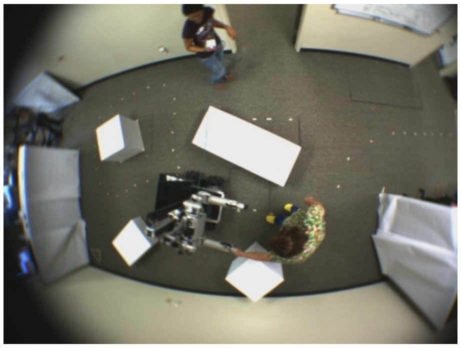
Figure 3(b) shows the experimental setup for the bedside positioning scenario. For this task, the subject led the robot into the patient room, led the robot to the patient's bedside, lowered the rails on the patient's bed, and positioned the robot's left and right end effectors within the two boxes marked on the patient's mattress. Positioning the end effectors in the boxes required that the arms be lowered to within 1 inch of the mattress.

We defined separate tasks for completing the positioning task forward and for completing it backward. For the backward task, the subject led the rear of the robot through the patient room doorway first. Then, when the robot was inside the room, the subject completed the remainder of the task in whatever orientation he wished.

C. Experimental setup

We performed the experiment in the Healthcare Robotics Lab in a carpeted area. The users completed the navigation tasks in a 8.5 m x 3.7 m space as shown in Figure 3(a). We placed four white boxes in consistent, predetermined positions in the navigation task area to serve as obstacles.

The users completed the forward and backward positioning tasks in a 4.3 x 3.7 meter simulated patient room as shown in Figure 3(b). We placed a fully functional Hill-Rom 1000 patient bed in the room with a patient care training manikin to serve as a simulated patient. To simulate potential obstacles



(a)

(b)

Fig. 3. **Experimental setup. (IRB approval and user permission obtained)** (a) A nurse (center) performing the navigation task forwards in the navigation task setup. The start box is out of view and just to the right of the image. (b) Bedside positioning task setup The boxes denote robot end effector placement.

one might find in a patient room, we placed an overbed table, an IV pole, a bedside table, and chairs near the bed.

D. Experimental design

We conducted the experiment using a 2 x 4, within-subjects factorial design. The two independent variables were: (1) the interface used to move the robot (DPI and gamepad interface) and (2) the task the user performed with the robot (navigation forward, navigation backward, positioning forward, positioning backward). Each subject used both interfaces to perform all four tasks (2 interfaces x 4 tasks = 8 trials per subject). We counterbalanced the order of the four tasks. For a given subject, the same ordering of the interfaces was used for each task. Across the subjects, this interface ordering was counterbalanced. After completing a task with both interfaces, we administered an intermediate survey for each interface to capture the subject's direct comparison between the two interfaces. Thus, in total, each subject completed 8 intermediate surveys, one for each trial.

We measured two objective variables for each trial: (1) time to complete each task and (2) number of collisions with obstacles, walls, or furniture. Using intermediate and final surveys, we measured several subjective variables as discussed in Section III-G. The surveys employed 7-point Likert scales, binary choice, 21-point scales (Raw Task Load Index (RTLX)), and open-ended questions [42].

E. Pilot study and power analysis

We conducted a pilot study in April 2009 with 8 subjects that compared earlier versions of the gamepad interface and the DPI. We used the results of this pilot study to improve the usability and performance of the two interfaces, and to select a target sample size for the full study. The subjects included 8 college students (7 male, 1 female, average age: 25.4 years) where half of the subjects had some previous experience designing robots. Overall, 87.5% of the subjects preferred to use the gamepad interface over the DPI, but several subjects indicated that they would have preferred the DPI if it were more sensitive.

Results of the subjective measures based on a 7-point Likert survey showed that users significantly preferred to use the DPI (M=6.5, SD=0.76) over the gamepad interface (M=5.63, SD=0.92) to maneuver the robot and position its end effector over a box marked on a table ($p<0.05$). We used these values to compute the omega-squared estimate of effect size (ω^2), which was relatively large, ω^2=0.21. To be conservative in our sample size estimate, we conducted our power analysis in the manner described in [28] using ω^2 =0.15 along with the parameters: power=.80 and number of groups a=8. With these parameters, we computed the conservative sample size estimate of n=12. We used this sample size as a guideline to recruit nurses for the larger study we present in this paper.

F. Hypotheses

We developed three main hypotheses for this study:

Hypothesis 1: Nurses will maneuver a robot in navigation and positioning tasks more effectively with a direct physical interface than a comparable gamepad interface.

Hypothesis 2: Nurses will find a direct physical interface more intuitive to learn and more comfortable and enjoyable to use than a comparable gamepad interface.

Hypothesis 3: Nurses will prefer to use a direct physical interface over a comparable gamepad interface to perform tasks in a nursing context.

G. Surveys

We administered a demographic information survey, a pre-task survey, eight intermediate surveys, and a final survey. In the pre-task survey, we asked the subjects about their computer, video game, and robotics experience. Following the completion of each task with both interfaces, we asked the subjects about their experiences with the intermediate survey shown below. Responses were limited to a Likert scale, except for the RTLX response.

1) I am satisfied with the time it took to complete the task using the interface.
2) I could effectively use the system to accomplish the task using the interface.
3) I was worried that I might break the robot using the interface.
4) The interface was intuitive to use to complete the task.
5) It was easy to navigate the robot around the obstacles using the interface./It was easy to position the robots hands on the patient bed using the interface.
6) It was enjoyable to use the interface.
7) I was worried about my safety while using the interface.
8) I am satisfied with the speed that the robot was moving while using the interface.
9) The interface was comfortable to use.
10) Overall, I was satisfied using the interface.
11) (RTLX)

TABLE I
SUBJECT 1 SAMPLE PROCEDURE.

Trial	Interface	Task
Pre-task Survey		
Learn how to use touching interface and practice		
1	Touching	Navigation, Forwards
Learn how to use gamepad interface and practice		
2	Gamepad	Navigation, Forwards
Intermediate Survey for Navigation, Forwards		
3	Touching	Navigation, Backwards
4	Gamepad	Navigation, Backwards
Intermediate Survey for Navigation, Backwards		
5	Touching	Bedside positioning, Forwards
6	Gamepad	Bedside positioning, Forwards
Intermediate Survey for Positioning, Forwards		
7	Touching	Bedside positioning,
8	Gamepad	Bedside positioning,
Intermediate Survey for Positioning, Backwards		
Final Survey		

We used the Raw Task Load Index (RTLX) survey to assess the user's workload with respect to the tasks [18]. We used the RTLX instead of the NASA TLX, since it requires less of the subject's time and studies have shown that it measures workload to a similar level of sensitivity [19].

We asked the users the following questions in the final survey. Questions 1 and 2 were measured on a 7-point Likert scale, while the remainder of the questions were either binary choices or open-ended.

1) It was easy to learn how to use the touching interface.
2) It was easy to learn how to use the gamepad interface.
3) Overall, which interface did you prefer to use and why?
4) Did you have any difficulties using the gamepad interface? If so, what were they?
5) Do you have any ideas to improve the gamepad interface? If so, what are they?
6) Did you have any difficulties using the touching interface? If so, what were they?
7) Do you have any ideas to improve the touching interface? If so, what are they?
8) Which interface was more comfortable to use overall?
9) Which interface was more easy to perform the navigation task with?
10) Which interface was more easy to perform the positioning task with?

H. Procedure

When participants came to the lab, we welcomed them and notified them that the primary experimenter would run the experiment by reading a script in order to keep the trials consistent between participants. We then administered the consent form, demographic survey, and pre-task survey.

After the users completed the initial paperwork, they performed the eight tasks depending on the counterbalanced order discussed in Section III-D. Table I shows a sample of the order of events performed during the study for Subject 1.

As illustrated in Table I, the subjects were instructed in how to use each interface just prior to its first use. The instruction consisted of an experimenter reading a script and gesturing. Each subject was also provided with an instruction sheet for reference while practicing. We asked the subjects

TABLE II
PRE-TASK SURVEY RESULTS

Gender	Male (3), Female (15)
Nursing Certification	Registered Nurse (16), Patient Care Assistant (1), Medical Assistant (1)
Education past high school	0 - 8 (M=4.28, SD=2.0) years
Ethnicity	White (12), African American (4), Hispanic (1), Other (1)
Age	23 - 58 (M=38.6, SD=12.2) years
Nursing experience	1 - 34 (M=12.4, SD=11.3) years
Personal computer experience	5 - 30 (M=16.9, SD=6.9) years
Time spent using a computer	3 - 60 (M=23.0, SD=14.9) hours
Time spent playing video games	0 - 4 (M=0.64, SD=1.19) hours

to practice controlling each of the degrees of freedom of the robot as well as a prescribed set of combinations of movements. The subjects took 5-10 minutes to practice each interface. Immediately after the subject learned how to use the interface for the first task, we explained the scenario and how to complete the first task. The subject then completed the task. We then taught the subject how to use the second interface, gave him time to practice, and then asked him to complete the same task. The user then completed the first set of intermediate surveys. After completing all the trials and intermediate surveys, we gave the subject the final survey.

The total experimental procedure took approximately 1.5 hours for each subject. We paid $30 USD to each subject to compensate for time and travel.

IV. RESULTS

We conducted the experiment with a total of 18 subjects from August 28, 2009 to Sept 18, 2009. We analyzed the objective and subjective measures using a within-subjects two-way analysis of variance (ANOVA). Only one of the dependent measures, time to complete the task, showed interaction effects between the independent variables. Consequently, we analyzed the main effects of the independent variables with respect to all dependent measures except time to complete the task. We have summarized the results of our analysis in four tables. Table III shows the main effect of interface type on the number of collisions. Table IV shows our analysis of the time taken to complete the tasks. Table V shows the main effects of interface type on the measures associated with the intermediate survey. Table VI shows the results from the final survey. We now discuss all of these results in more detail as they relate to our hypotheses.

Hypothesis 1 is supported by the results found for several dependent measures. Subjects had significantly higher RTLX scores when using the gamepad interface than with the DPI, which indicates that they experienced higher workload when using the gamepad interface to complete the tasks (See Table V). In addition, subjects' objective performance was better when they used the DPI, since they produced significantly fewer obstacle collisions than when they used the gamepad interface. Furthermore, subjects reported that they could more effectively use the DPI to accomplish their tasks than with the gamepad interface.

TABLE III
MAIN EFFECT OF INTERFACE TYPE ON NUMBER OF COLLISIONS

Dependent Measure	Gamepad	Touching	F-value: F(1,17)	p-value
# Collisions	M=1.7, SD=2.2	M=0.3, SD=0.6	22.19	<0.001

TABLE IV
SIMPLE EFFECTS OF INTERFACE TYPE ON TIME TO COMPLETE (SECONDS)

	Navigation, Forward	Navigation, Backward	Positioning, Forward	Positioning, Backward
Gamepad	M=172.0 SD=86.1	M=175.7 SD=76.6	M=98.8 SD=38.3	M=125.4 SD=36.4
Touching	M=99.1 SD=25.5	M=120.3 SD=28.9	M=90.3 SD=26.4	M=84.4 SD=20.6
p-value	p=0.002	p=0.007	p=0.44	p<0.001

TABLE V
MAIN EFFECTS FOR SUBJECTIVE INTERMEDIATE SURVEY (ROW ORDER MATCHES QUESTION ORDER) (7 POINT LIKERT EXCEPT FOR RTLX)

Dependent Measure	Gamepad	Touching	F-value: F(1,17)	p-value
Time	M=4.7, SD=0.3	M=6.1, SD=0.6	4.181	0.057
Effective	M=4.8, SD=1.5	M=5.9, SD=1.2	11.77	0.003
Break	M=3.1, SD=0.4	M=2.6, SD=0.4	4.30	0.054
Intuitive	M=4.1, SD=1.7	M=6.1, SD=0.7	38.33	<0.001
Easy	M=4.6, SD=1.7	M=6.6, SD=8.5	3.88	0.065
Enjoyable	M=5.1, SD=1.6	M=5.9, SD=1.1	6.44	0.021
Safety	M=2.1, SD=0.4	M=1.9, SD=0.4	1.152	0.298
Speed	M=5.1, SD=0.3	M=5.0, SD=0.3	0.027	0.871
Comfort	M=4.7, SD=1.4	M=5.9, SD=0.9	19.22	<0.001
Overall	M=4.7, SD=1.6	M=5.8, SD=1.0	9.79	0.006
RTLX	M=49.2 SD=21.4	M=36.6 SD=20.9	13.46	<0.002

TABLE VI
FINAL SURVEY RESULTS (BINARY EXCEPT FOR 7 POINT LIKERT FOR EASY TO LEARN)

	Gamepad	Touching	X^2 Value	p-value
Overall Preference	3 (16.7%)	15 (83.3%)	8.0	0.005
More Comfort	2 (11.1%)	16 (88.9%)	10.9	0.001
Navigation Pref.	3 (16.7%)	15 (83.3%)	8.0	0.005
Positioning Pref.	7 (38.9%)	11 (61.1%)	0.9	0.346
Easy to learn	M=4.6 SD=1.5	M=6.1 SD=0.9	N/A	<0.001

The ANOVA revealed significant interaction effects between interface type and task type for the time it took subjects to complete the tasks (F(3,48)=6.45, p=0.003). Our analysis of the simple effects of interface type for each task type revealed that users completed both of the navigation tasks as well as the positioning backward task significantly faster when using the touching interface. Although users took less time on average to complete the positioning forward task with the touching interface, the difference was not significant (see Table IV). These results also support hypothesis 1.

Hypothesis 2 is also supported by our analysis. Based on the subjective measures, subjects found the DPI significantly more intuitive, comfortable, enjoyable, and easy to learn than the gamepad interface (see Tables V and VI).

Hypothesis 3 is also supported. Table VI shows that a significant number of the nurses preferred to use the DPI overall, found it more comfortable to use, and preferred to use it for the navigation task. Although more than a majority preferred to use the DPI to perform the positioning task, the number was not significant.

Fig. 4. **Examples of user postures. (IRB approval and user permission obtained)** (a) Gamepad interface, positioning task. (b) Gamepad interface, navigation task. (c) and (d) DPI, navigation task.

We found no significant difference between the interfaces with respect to the nurse's perceived safety during the experiment, concerns about breaking the robot, nor perceptions of the robot's speed. On average, the nurses rated concern for their safety low at around a score of 2 for both interfaces.

V. DISCUSSION AND CONCLUSION

The results of both objective and subjective dependent measures show that the DPI was significantly superior to the gamepad interface for our subjects. In the future, we hope to perform further analyses of the data. We now briefly discuss factors that might influence how well these results generalize across all nurses, non-nurses, and various tasks.

Only two nurses reported that they had experience with robots, both with robotic toys. We would expect experience with robots to increase as robots become more common both in the workplace and at home. How this would impact a study such as ours remains an open question.

Video game experience serves as an interesting illustration of the potential impact of experience. Of the 18 nurses, six of them reported that they played video games. Of the three nurses who preferred to use the gamepad interface overall (see Table VI), two of them reported in the pre-task survey that they played video games. Intriguingly, even though these two nurses played video games and preferred the gamepad interface overall, they collided with obstacles more times when using the gamepad interface. One subject produced two collisions while using the gamepad interface and zero with the

DPI, while the other produced 22 collisions using the gamepad interface and only 3 using the DPI.

When controlling the robot, the nurses assumed several different postures, which may have affected their performance (see Figures 3(a) and 4). When using the gamepad interface, many users turned and oriented their bodies to match the robot's orientation, even when moving backwards. Nurses may have done this to ease the mental workload associated with mapping the gamepad interface to the robot's motion [4], [8]. A potential middle ground between these two styles of interfaces might be to mount a controller on the robot's body.

Another area that merits further investigation is the differences we found in the positioning and navigating tasks. While most users preferred using the DPI to perform the tasks overall, almost 40% of the nurses preferred to use the gamepad interface for the positioning task. This preference is surprising given that the DPI led to significantly fewer collisions overall and shorter time to complete in the positioning backward task. Several nurses reported that they could have more precise control over the fine movements necessary to complete the positioning task when using the gamepad interface. Based on their comments, the confined space in which the positioning task was performed (i.e., simulated hospital room) may have been a factor. Another potential factor is that the current DPI requires that the robot's arms be moved beyond the goal pose when rotating the robot, or moving the arms up or down. This can present problems when the user intends for the arms to make contact with a surface, such as the top of the bed.

Given the demonstrated success of the DPI, and the great potential for human-scale mobile manipulators in human environments, we anticipate that researchers and practitioners will implement a wide variety of DPIs over the next decade. With this study, we have evaluated a single point in a vast design space. We look forward to future explorations of this space by the robotics community, and hope that novel implementations and rigorous evaluations will go hand in hand.

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