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Full paper

A Direct Physical Interface for Navigation and Positioning of a Robotic Nursing Assistant

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Abstract

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). When a user is in close proximity to a robot, physical contact becomes a potentially valuable channel for communication. We define a direct physical interface (DPI) as an interface that enables a user to influence a robot's behavior by making contact with its body. We evaluated a DPI in a controlled laboratory setting with 18 nurses and compared its performance with that of a comparable gamepad interface. The DPI significantly outperformed the gamepad according to several objective and subjective measures. Nurses also tended to exert more force at the robot's end-effectors and command higher velocities when using the DPI to perform a navigation task compared with using the DPI to perform a positioning task. Based on user surveys, we identify various nursing tasks where robotic assistance may be useful and provide design recommendations specifically in the area of healthcare. This paper is based on 'Lead me by the hand: evaluation of a direct physical interface for nursing assistant robots', by Tiffany L. Chen and Charles C. Kemp, which appeared in the *Proceedings of the 5th ACM/IEEE International Conference on Human–Robot Interaction*. © 2010 IEEE [1].

Keywords

Healthcare robotics, nursing, direct physical interface, human–robot interaction, user study

1. Introduction

As robots become increasingly common in human environments, people will be presented with more opportunities to make contact with a robot's body and change its behavior. In human–human interactions, caregivers will often lead a child or older adult by the hand, and coaches in sports, physical therapists and choreographers all use physical contact to help people achieve desirable motions and postures.

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In the same way, direct physical contact may serve as an important form of communication between robots and humans. We define a direct physical interface (DPI) as an interface that enables a human to influence the behavior of a robot by making contact with its body. In this paper, we present a DPI that allows nurses to lead an anthropomorphic, omni-directional robot by the hand. We presented this DPI along with its evaluation with 18 nurses in our previous work [1]. In the current work, we present additional results from the evaluation performed in Ref. [1] regarding the measured forces that nurses applied when using the DPI to complete tasks. In addition, using surveys, we asked the 18 nurses what tasks they performed during their work day, as well as gained their perspectives on what nursing tasks a robot might be suited to perform. The results from these surveys allow us to better understand how robots might assist nurses and patients in healthcare.

1.1. A Healthcare Scenario

For this study, we have designed our 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.

There is a well-documented shortage of nurses and direct-care workers in the US and around the world [2, 3]. 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 the likelihood of [a patient] dying within 30 days of admission" and that "each additional patient per nurse was associated with a 23% increase in the odds of [nurse] burnout and a 15% increase in the odds of job dissatisfaction" [4]. Consequently, several studies have suggested that lowering the patient-to-nurse ratio would result in less missed patient care [3–5].

Nurses frequently experience work-related back injury [6, 7] due to the physical demands of manually handling patients. 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 [8–10]. 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.

2. Related Work

Several feasible interface methods exist for guiding robots that could potentially be used in nursing-related tasks. We expect DPIs to add value and be complementary to these and other interfaces.

2.1. 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 [11] and researchers have developed dancing robots that respond to physical interaction with a human dance partner [12]. Among other tasks, DPIs have been implemented for rehabilitation robots [13], for object transfer [14], to direct robot's attention during learning [15], to demonstrate tasks [16] and to distinguish interaction styles [17]. DPIs have also been implemented on robotic walkers to provide navigation assistance, obstacle avoidance and walking support for older adults [18, 19]. In addition, Argall and Billard have surveyed various forms of tactile human–robot interaction [20].

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 [21], Willow Garage's PR2 [22] and DLR's Justin [23] by making contact with their arms. Also, the nursing-care assistant robot RIBA is controlled via touch sensors on the robot's forearm and upper arm [9]. 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.

2.2. *Examples of DPIs for Navigation and Positioning*

We discuss a category of DPIs that enable a human to make physical contact with a robot's body for the purpose of directing the robot's motion — navigation, and positioning the robot's arms. Since physical contact is a main component of a DPI, it is natural to select force, torque and tactile sensors as the primary mode of input, as we see with several robotic systems controlled using a DPI in Table 1.

The particular control method or algorithm used to change the robot's motion can vary. Consequently, the user may need previous experience in order to operate a DPI that responds to pre-programmed tactile interactions as with the RIBA robot or may need knowledge of dancing in order to operate the MS DanceR system which relies on dance-step estimation using hidden Markov models (HMM). The DPI described in this paper only requires previous experience making physical contact with another person to move them in a general direction. Thus, DPI designers may wish to design a control method so as to take into account the previous experience of the target user, as well as the level of training that would be involved to show the user how to operate the DPI.

Several of the robots in Table 1 have a humanoid morphology. Furthermore, for each of the humanoid robots in Table 1, the contact points that the human uses to control the robot are mostly found on the arms or the end-effectors of the robot. Since humans frequently interact with other humans by touching their arms and hands, the DPI designers may have selected these contact points as intuitive and natural locations for moving the robot.

Each of the DPIs for the platforms listed in Table 1 allow the user to move the robot in the general direction in which the control input is applied. This design

Table 1.
Examples of DPIs used on various robots for navigation

Robot	Morphology	Interface sensing	Control	Movement	Contact point	Target user	Level of autonomy
Cody [1]	Humanoid	Force, joint angle	Proportional control	Holonomic	Arm, end-effector	Nurses	Full user control
RIBA [9]	Humanoid	Tactile	Intention, pulling direction	Holonomic	Arm	Nurses	Full user control; semi-automated lifting
Justin [23]	Humanoid	Torque	(not known)	Holonomic	Arm	General	Full user control
PR1 [24]	Humanoid	Torque	(not known)	Holonomic	End-effector	General	Full user control
PR2 [22]	Humanoid	Torque	(not known)	Holonomic	End-effector	General	Full user control
MS DanceR [12]	Humanoid	Force/torque	HMM (intention)	Holonomic	Arm, torso	Dance partner	Full user control
Skill Assist [25]	Ceiling-mounted Cartesian	Force	(not known)	Cartesian, passive rotation	Handle	Factory worker	Full user control
Romeo & Juliet [26]	Mobile manipulator	Force/torque	Motion/force	Holonomic	Object in end-effector	Construction worker	Full user control

feature is consistent with the recommendation that the control input device moves in the same global direction the robot moves as a result of the control input [27].

The human-scale mobile manipulators that have these DPIs tend to have omni-directional drive capabilities. The advantage of selecting this kinematic ability is that the user can direct the robot in any direction as opposed to being constrained by cart-like kinematics. Consequently, the omni-directional motion capability may reduce the mental and physical workload a user has to expend in order to navigate the robot to a specified position and orientation.

3. Implementation

In our study, we asked participants to control Cody 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.

3.1. System Description

Cody (Fig. 1) is a statically stable mobile manipulator weighing roughly 160 kg. The components of the robot are: Meka A1 arms, a Segway omni-directional base and a Festo 1-d.o.f. linear actuator. The arms consist of two 7-d.o.f. anthropomorphic arms with series elastic actuators and the robot's wrists are equipped with six-axis force/torque sensors.

3.2. Gamepad Interface

The gamepad interface consists of a Logitech Cordless RumblePad 2 game controller. As illustrated in Fig. 2, when the user tilts the left analog stick forward or backward the robot moves forward or backward, respectively. The velocity of the robot is proportional to 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, respectively. The left/right

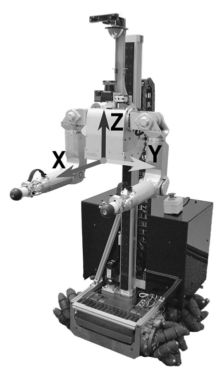


Figure 1. Mobile manipulator robot 'Cody' used in this study.

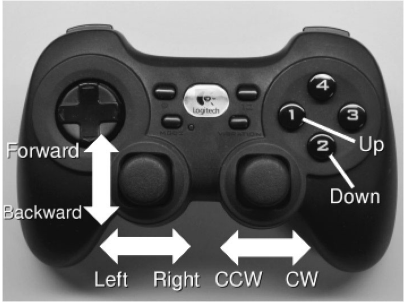


Figure 2. Gamepad interface.

velocities are capped at a maximum of 0.15 m/s. The maximum left/right velocities are lower than those for forward/backward because the authors felt that the user would be more prone to producing collisions between the robot and obstacles while moving the robot sideways compared with forward or backward. When the user tilts the right analog stick to the left or right, the robot rotates counter-clockwise (CCW) or clockwise (CW), respectively. 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 10.6 deg/s. To move the robot up or down along the linear actuator, the user must press the button that says '1' or '2', respectively. All motions can be performed simultaneously.

3.3. DPI

The DPI makes use of the Meka arms and the force/torque sensors at the wrists (Fig. 3). For both interfaces, the robot's arms maintain a single posture, which we refer to as the home position. Each of the torque-controlled arm joints acts like a damped spring with a low, constant stiffness. 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 Fig. 3, when the user applies sufficient force to either of the end-effectors and moves it, the robot responds. Pulling forward or pushing backward makes the robot move forward or backward, respectively. 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, respectively. The user can also grab the robot's arm and abduct or adduct it at the shoulder, which causes the robot to move sideways.

All of the following spatial quantities are defined with respect to the robot's coordinate frame shown in Fig. 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:

- $x_{\text{vel}} =$ the robot's forward/backward velocity.
- $y_{\text{vel}} =$ the robot's left/right velocity.

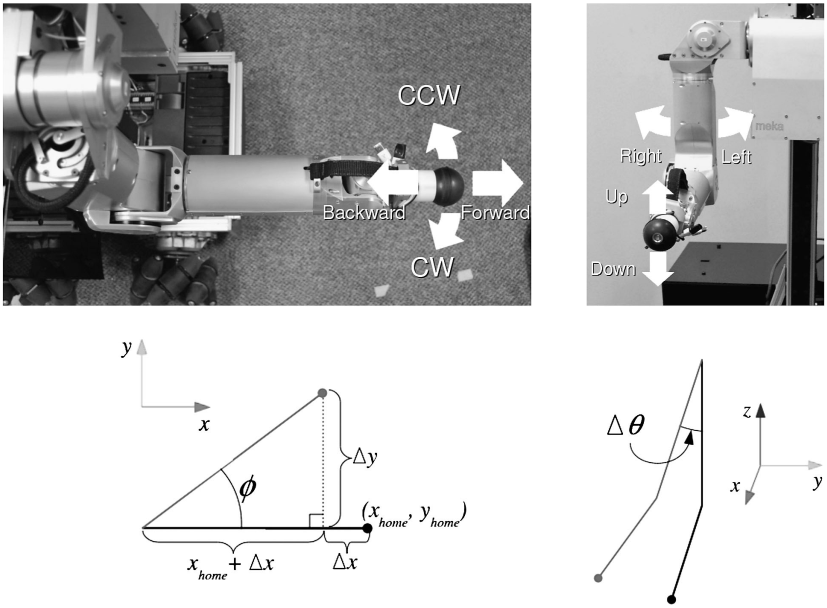


Figure 3. DPI (right arm). Left: overhead view. Right: front view. The black lines represent the arm's home position and the gray lines represent an example of a user-directed position. Note that in this example $\Delta x < 0$.

- $a_{\text{vel}} =$ the robot's angular (CW/CCW) velocity.
- $z_{\text{vel}} =$ the robot's up/down velocity along the linear actuator.

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

The user input consists of the forces applied in the x-direction and y-direction at the robot's wrist (f_x and f_y (N)), position changes of the end-effector (Δx, Δy and Δz (m)) with respect to the end-effector's home position (x_{home}, y_{home} and z_{home} (m)), and the angular displacement of the shoulder joint from its home position ($\Delta\theta$ (deg)) (see Fig. 3). In order to map these quantities to velocities, we use the following scaling factors:

$$
\begin{aligned}
x_{\text{vel}}^{\max} &= 0.35 \text{ m/s}, & f_x^{\max,\text{human}} &= 15 \text{ N} \\
y_{\text{vel}}^{\max} &= 0.15 \text{ m/s}, & \theta^{\max,\text{human}} &= 14.9 \text{ deg} \\
a_{\text{vel}}^{\max} &= 10.6 \text{ deg/s}, & \phi^{\max,\text{human}} &= 35.5 \text{ deg} \\
z_{\text{vel}}^{\text{down}} &= 1 \text{ cm/s}, & f_x^{\text{thres}} &= 1 \text{ N} \\
z_{\text{vel}}^{\text{up}} &= 3.6 \text{ cm/s}, & f_y^{\text{thres}} &= 2 \text{ N} \\
x_{\text{home}} &= 0.4 \text{ m}, & \Delta\theta^{\text{thres}} &= 5 \text{ deg}
\end{aligned}
$$

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

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:

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

$$x_{\text{vel}} = \begin{cases} 0, & |f_x| < f_x^{\text{thres}} \text{ and } |f_y| < f_y^{\text{thres}} \\ \operatorname{sgn}(f_x)\min(x_{\text{scale}}|f_x|, x_{\text{vel}}^{\max}), & \text{else} \end{cases} \tag{2}$$

$$y_{\text{vel}} = \begin{cases} 0, & |\Delta\theta| < \Delta\theta^{\text{thres}} \\ \operatorname{sgn}(\Delta\theta)\min(y_{\text{scale}}|\Delta\theta|, y_{\text{vel}}^{\max}), & \text{else} \end{cases} \tag{3}$$

$$a_{\text{vel}} = \begin{cases} 0, & |f_x| < f_x^{\text{thres}} \text{ and } |f_y| < f_y^{\text{thres}} \\ \operatorname{sgn}(\phi)\min(a_{\text{scale}}|\phi|, a_{\text{vel}}^{\max}), & \text{else} \end{cases} \tag{4}$$

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

We also smooth the control signals from the user by averaging the currently commanded velocity with the two previously commanded velocities (at 10 Hz) in order to reduce noise and smooth the velocity transitions. Smoothing the commanded velocity reduces jerkiness and the potential for undesired high-frequency oscillations.

4. Methodology

In this section we describe the experimental methods we used to test the performance of the two interfaces.

4.1. Participants

We recruited 18 nurses from metro Atlanta, Georgia, USA. To reduce bias, we stated that the nurses would be 'interacting' with a robot and did not elaborate on the experimental scenario in the recruiting announcement. See Table 2 for demographic information about the participants.

4.2. Task Description

During the experiment, we referred to the DPI as the 'touching interface' to make the name easier to remember for the participants. We asked the subjects to complete four tasks. We asked them to complete tasks using the robot moving in both the forward and backward directions in order to account for possible variations in the orientation with the robot that nurses might encounter when using it in their daily tasks. When using the wireless gamepad interface to complete a task, we instructed participants they could stand in any location.

Table 2.
Pre-task survey results

Variable	Values
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) h/week
Time spent playing video games	0–4 ($M = 0.64$, SD = 1.19) h/week

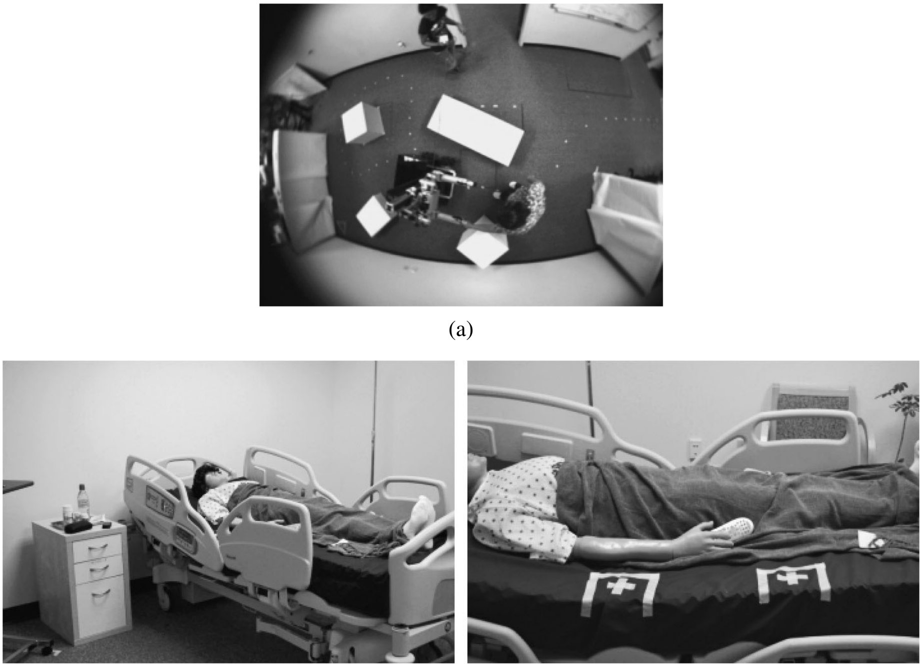
*4.2.1. Navigation Task (*Forward *and* Backward*)*

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 4a 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, through the obstacle course and return the robot back to the starting box. We instructed the subjects to use the selected control method to lead the robot through the obstacle course while avoiding the boxes and walls. We defined two separate tasks for maneuvering the robot through the obstacles. One task was defined when completing the course forward and another task was defined for completing it backward. For the *Navigation*, *Forward* task, the nurse led the robot so that the robot moved primarily in the positive x-direction along the path. Conversely, for the *Navigation*, *Backward* task, the nurse led the robot so that the robot moved primarily in the negative x-direction along the path.

*4.2.2. 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 4b 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. Position-



(a)

(b)

Figure 4. Experimental setup (Institutional Review Board approval and user permission obtained). (a) Nurse performing the navigation task forwards (overhead view). (b) Bedside positioning task setup. The boxes denote robot end-effector placement.

ing the end-effectors in the boxes required that the arms be lowered to within 1 in. of the mattress. We defined separate tasks for completing the positioning task forward and for completing it backward. For the *Positioning*, *Forward* task, the nurse led the robot so that the robot moved primarily in the positive x-direction through the doorway. Conversely, for the *Positioning*, *Backward* task, the nurse led the robot so that the robot moved primarily in the negative x-direction through the doorway. For each of the tasks, after the participant moved the robot through the doorway and into the room, the participant was permitted to rotate the robot to any desired pose in order to place the end effectors within the boxes marked on the mattress to complete the task.

4.3. 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 $\times$ 3.7 m space as shown in Fig. 4a. The users completed the forward and backward positioning tasks in a 4.3 m $\times$ 3.7 m simulated patient room as shown in Fig. 4b.

Table 3.
Experimental design

Interface	Task			
	Navigation, Forward	*Navigation, Backward*	*Positioning, Forward*	*Positioning, Backward*
Touching	18 nurses	18 nurses	18 nurses	18 nurses
Gamepad	18 nurses	18 nurses	18 nurses	18 nurses

4.4. Experimental Design

We conducted the experiment using a 2×4, within-subjects factorial design. The two independent variables were: (i) the interface used to move the robot (DPI or gamepad interface) and (ii) the task the user performed with the robot (*Navigation*, *Forward*; *Navigation*, *Backward*; *Positioning*, *Forward* or *Positioning*, *Backward*). Each subject performed all four tasks with both interfaces (2 interfaces $\times$ 4 tasks $=$ 8 trials per subject, see Table 3). 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.

We measured two objective variables for each trial: (i) time to complete each task and (ii) number of collisions with obstacles, walls or furniture. Using intermediate and final surveys, we measured several subjective variables as discussed in Section 4.5. The surveys employed seven-point Likert scales, binary choice, the Raw Task Load Index (RTLX) and open-ended questions. The RTLX is a self-reported, subjective measure of workload, and comprises six subjective 21-point scales that measure mental demand, physical demand, temporal demand, performance, effort and frustration level [28]. These scores are added to compute the RTLX score.

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.

4.5. Surveys

We administered a demographic information survey, a pre-task survey (see Table 2), eight intermediate surveys and a final survey. In the pre-task survey, we asked the subjects about their computer, video game and robotics experience. We also asked the subjects to provide a breakdown of the percentage of time they spent performing their nursing tasks in a typical work day. In addition, we asked them to what extent they enjoyed performing the tasks they reported on a seven-point Likert scale (1 = 'Strongly Dislike', 4 = 'Neutral', 7 = 'Strongly Enjoy'). We also asked them what nursing tasks they thought a robot could perform alone, what tasks they thought it could perform in cooperation with a human, and what tasks it should not perform. We made sure to ask these nursing task questions prior to any interaction with the robot or learning of the experimental scenario so as to reduce any bias the experiment may have placed on their responses. Following the completion of each task with both interfaces, we asked the subjects about their experiences with the intermediate survey:

(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).

We used the RTLX survey to assess the user's workload with respect to the tasks [28]. We asked the users the following questions in the final survey. Questions (1) and (2) were measured on a seven-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?

(5) Do you have any ideas to improve the gamepad interface?

(6) Did you have any difficulties using the touching interface?

(7) Do you have any ideas to improve the touching interface?

(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?

5. Results

In this section, we analyze the performance of the two interfaces and discuss the forces the nurses used with the DPI. We also analyze the nursing tasks that the participants reported that they performed as well as tasks they thought a robot could perform and the tasks they felt wary of a robot performing.

5.1. Performance Comparison of the Interfaces

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 Figs 5–10. Figure 5 shows the main effect of interface type on the number of collisions. Figure 6 shows our analysis of the time taken to complete the tasks. Figures 7 and 8 show the main effects of interface type on the measures associated with the intermediate survey. Figures 9 and 10 show the results from the final survey. We now discuss all of these results in more detail as they relate to our hypotheses.

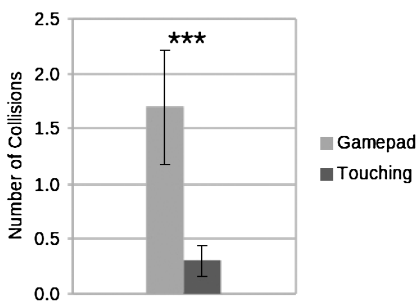


Figure 5. Main effect of interface type on number of collisions. Standard error bars shown. $^{***}p < 0.001$.

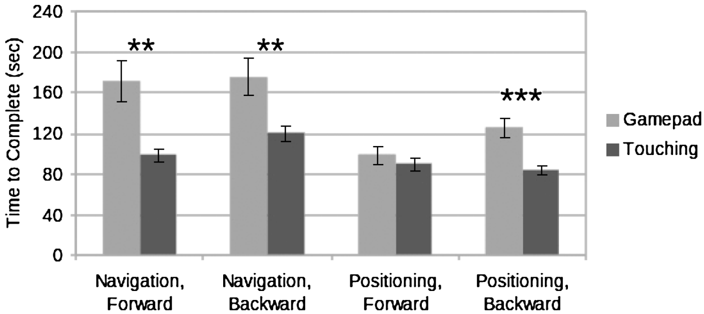


Figure 6. Simple effects of interface type on time to complete (s). Standard error bars shown. $^{**}p < 0.01$, $^{***}p < 0.001$.

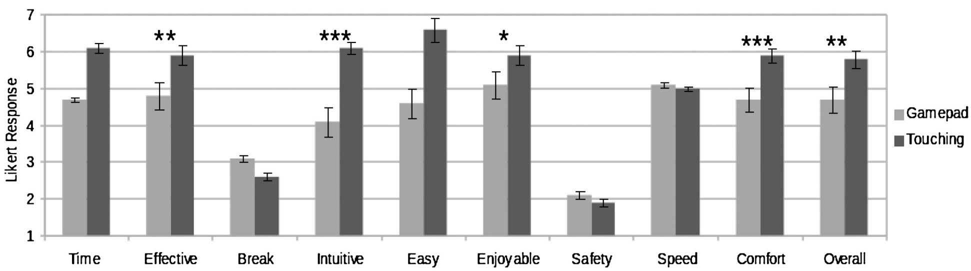


Figure 7. Main effects for subjective intermediate survey. Order matches question order in Section 4.5. Standard error bars shown. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

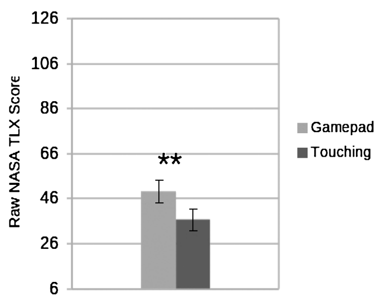


Figure 8. Main effects for subjective intermediate survey. RTLX response. Standard error bars shown. $^{**}p < 0.01$.

5.1.1. Hypothesis 1

Several dependent measures support Hypothesis 1. 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 (Fig. 8). In addition, subjects' objective performance was better when they used the DPI, since they produced significantly fewer obstacle collisions (Fig. 5). Furthermore, subjects reported that they could more effectively use the DPI to accomplish their tasks than with the gamepad interface.

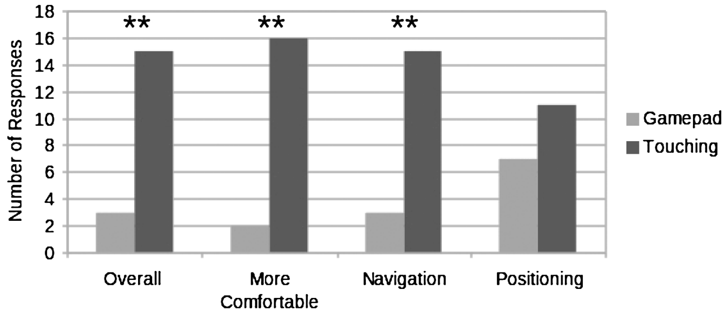


Figure 9. Final survey results (binary response). $^{**}p < 0.01$.

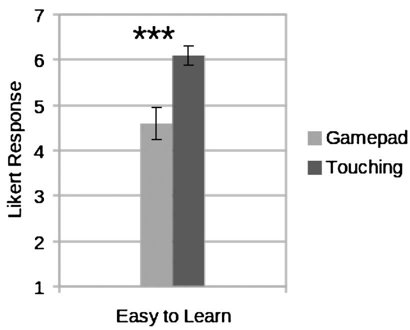


Figure 10. Final survey results. Easy to learn. Standard error bars shown. $^{***}p < 0.001$.

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 (Fig. 6). These results also support Hypothesis 1.

5.1.2. Hypothesis 2

The analysis also supports Hypothesis 2. Based on the subjective measures, participants found the DPI significantly more intuitive, comfortable, enjoyable and easy to learn than the gamepad interface (see Figs 7, 9 and 10).

5.1.3. Hypothesis 3

Hypothesis 3 is also supported. Figure 9 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.

5.2. Force Analysis of the DPI

The average measured magnitude of force the nurses exerted on the robot's end-effectors in the x–y plane is shown in Table 4 for each of the tasks involving the

Table 4.
Average magnitude of measured force applied in the x–y plane at the end-effector using the DPI

Task	*Navigation, Forward*	*Navigation, Backward*	*Positioning, Forward*	*Positioning, Backward*
Mean (N)	12.3	10.2	4.4	4.7
SD (N)	5.2	5.8	5.7	5.1

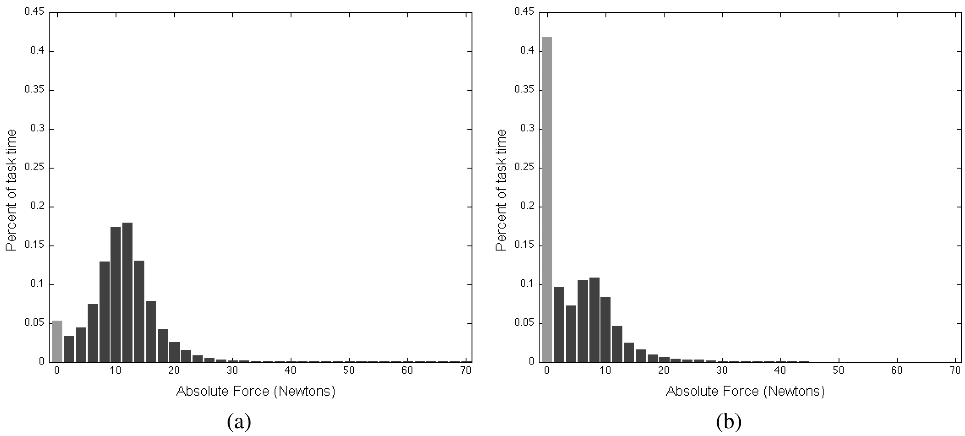


Figure 11. Average magnitude of measured force applied in the x–y plane at the end-effector using the DPI. (a) Navigation tasks. (b) Positioning tasks.

DPI. Forces at the end-effector whose absolute values were below the thresholds of: $f_x^{\text{thres}} = 1.0$ N or $f_y^{\text{thres}} = 2.0$ N were recorded as $|f_x| = 0$ N and $|f_y| = 0$ N, respectively. Overall, the measured forces at the end-effector in the x–y plane were more than 2 times greater when the nurses used the DPI to accomplish the navigation tasks compared with when they used the DPI for the positioning tasks. The navigation tasks involved leading the robot over a larger area than the positioning tasks, which may have caused the nurses to pull the robot's end-effectors to the maximum allowed force input so as to have the robot move at the maximum velocities, as opposed to the positioning tasks which involved more precise movements at lower velocities.

Furthermore, the plots in Fig. 11 show the percentage of time the nurses applied a range of measured forces at the end-effector in the x–y plane. The plots depict the general tendency for the nurses to exert measured forces at the end-effector below the $f_x^{\text{thres}} = 1.0$ N and $f_y^{\text{thres}} = 2.0$ N thresholds (shown in gray) for the positioning task over a larger percentage of the task time (42%) as opposed to the navigation tasks (5%). This tendency contributed to the lower overall average measured applied force while using the DPI for the positioning task.

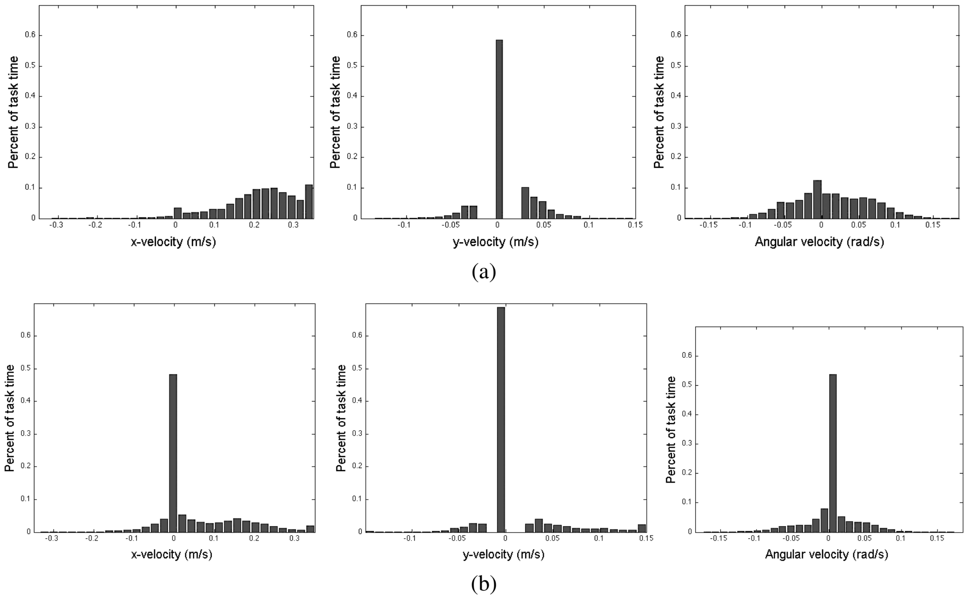


Figure 12. Measured velocities using the DPI. (a) *Navigation*, *Forward* task. (b) *Positioning*, *Forward* task.

Figure 12 shows the velocities the user commanded the robot to move while performing the *Navigation*, *Forward* and *Positioning*, *Forward* tasks. Similar velocity distributions are evident in the remaining two tasks (not shown), with the x-velocities being negated. Nurses tended to command higher x-velocities while performing the navigation tasks compared with the positioning tasks overall; specifically ($M = 0.2$ m/s, SD $= 0.1$ m/s) for the x-velocity for the *Navigation*, *Forward* and ($M = 0.05$ m/s, SD $= 0.1$ m/s) for the *Positioning*, *Forward* tasks. In addition, the nurses tended to command velocities closer to the maximum allowable x-velocity of 0.35 m/s while performing the navigation tasks. Figure 12a shows that nurses were commanding velocities very close or at this maximum. Although the nurses did command the robot to move sideways, the measured y-velocities were 0 m/s for more than 50% of the *Navigation*, *Forward* task and more than 60% of the *Positioning*, *Forward* task.

5.3. Nursing Task Analysis

In this section, we analyze the nurses' self-reported answers regarding what nursing tasks they performed throughout their day, as well as nursing tasks they felt a robot could perform and tasks they were wary of a robot performing.

Table 5 shows that almost all of the nurses (17 out of 18) reported that they charted or documented patient information. Fifteen nurses said that they perform some sort of task that involved moving patients such as transferring them from a patient bed to a chair, turning the patient over or holding them while another procedure was being performed. Thirteen nurses reported that they administered medicine to

Table 5.
Nursing tasks performed throughout the day

Task	Enjoyment		Number of responses
	M	SD	
Charting/documentation	3.8	1.6	17
Moving patients	4.0	1.5	15
Administering medicine	5.0	0.9	13
Assessment	5.3	1.2	12
Patient/family education	6.3	0.8	7
Bathing	3.8	1.6	6
Feeding	5.5	0.6	4
Staff communication	5.5	1.7	4
Bowel/bladder care	3.5	1.3	4
Monitoring vital signs	3.5	1.7	4
Socializing	7.0	0.0	3
Other information handling	6.7	0.6	3
Other patient care	5.3	0.6	3
Other	3.0	1.0	3
Blood work	7.0	0.0	2
Procedures	4.5	0.7	2
Other communication	4.0	1.4	2
Transfer/restock supplies	3.0	1.4	2

patients and 12 nurses reported that they performed patient assessments. Table 5 also shows the mean enjoyment rating of the nurses who responded for a particular task, where 1 is 'Strongly dislike', 4 is 'Neutral' and 7 is 'Strongly enjoy'. Of the tasks that had four or more responses, nurses rated patient and family education the most enjoyable task with an average score of 6.3, followed by patient feeding and communicating with staff, both with a score of 5.5, and patient assessment with score of 5.3. Nurses reported that they generally disliked performing bowel/bladder care and monitoring vital signs, both with a score of 3.5, followed by patient bathing with a score of 3.8, and moving patients with a score of 4.

The most frequently listed task that nurses felt robots could perform was moving patients as shown in Table 6. The nurses also listed janitorial work, retrieving or moving objects, bathing patients and feeding patients as other possibilities. Nurses generally felt that robots could be helpful for laborious tasks. Nurses stated that they were more wary of a robot performing tasks that involved decision making, extended nursing experience or tasks that involved high risk of medical injury. Such tasks included administering medicine, followed by patient assessment and blood work (e.g., inserting an intravenous line) (see Table 6).

In the open-ended responses of the final survey, several nurses made analogies between using the touching interface to other activities in their jobs and daily lives. One nurse reported that using the interface was similar to when she operates power

Table 6.
(Left) Tasks that nurses felt could be performed by a robot and (right) tasks that nurses were wary of a robot performing

Task	Number of responses	Task	Number of responses
Moving patients	16	Administering Medicine	9
Janitorial	7	Assessment	7
Retrieve/move objects	6	Blood work	5
Bathing	5	Feeding	2
Feeding	4	Touch patient	2
Transfer/restock supplies	4	Moving patients	1
Charting/documentation	3	Patient/family education	1
Monitoring vital signs	3	Monitoring vital signs	1
Dressing patients	3		
Deliver meal tray	3		
Administering medicine	2		
Errands	2		
Assessment	1		
Patient/family education	1		
Other information handling	1		

wheelchairs from a standing position, since she assists spinal cord injury patients everyday. Two other nurses also made connections with how they interacted with patients. One said that using the interface was similar to ambulating patients, while another said it was similar to when she 'guided' patients' hands to perform a task. One nurse even compared using the interface with using a lawnmower. No nurses made a comparison between the gamepad interface and another activity. In the final survey, 10 nurses reported being 'confused' remembering how to use the gamepad controls. Conversely, 10 nurses reported that the touching interface was more 'intuitive', 'natural' and 'made sense'. One of those 10 nurses reported being 'in tune' with the robot.

6. Discussion and Conclusions

The results of both objective and subjective dependent measures show that the DPI was significantly better than the gamepad interface for our subjects. Thus, a DPI may be a feasible interface to enable nurses to move mobile robots through a hospital environment. We expect that DPIs could complement more autonomous navigation methods used in robotics such as map-based navigation, while still offering nurses more direct control over the robot.

When controlling the robot, the nurses assumed several different postures, which may have affected their performance (see Figs 4a and 13). 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

(a)

(b)

Figure 13. Examples of user postures (Institutional Review Board approval and user permission obtained). (a) Nurses using the gamepad interface. (b) Nurses using the DPI.

workload associated with mapping the gamepad interface to the robot's motion [29, 30]. A potential middle ground between these two styles of interfaces might be to mount a controller on the robot's body.

The nurses were commanding the robot to move close to or at the maximum allowable x-velocity. Thus, the force sensitivity and robot velocities could potentially be tuned to better match the tasks. Specifically, the shape of the plots in Fig. 12 suggests that we might design the maximum allowable x-velocity to be higher.

More opportunities for physical interaction between humans and robots exist when robots interact both with patients and with nurses. For example, moving patients was listed as the second most frequently reported task that the nurses in our study performed and, on average, they rated it neutrally enjoyable. Thus, a robot could potentially perform patient moving tasks, and free up a substantial amount of time for nurses to perform other tasks that they may enjoy more and that involve more nursing judgement. Patient bathing also appears to be a candidate for physical human–robot interaction since five nurses suggested that a robot could perform this task and the nurses slightly disliked performing the task. However, two nurses listed that they would be wary of a robot touching patients and one was wary of a robot moving patients. Thus, there may be some debate among nurses as to whether a robot should be physically interacting with patients altogether. Furthermore, there may be some loss of social interaction between patients and nurses if a robot nurse assistant were to provide nursing care *in lieu* of human nurses.

From a roboticist's perspective, it is not readily clear what level of autonomy a DPI should incorporate, let alone a DPI used in a healthcare context. User experience, training and safety concerns may affect the designer's choice as to how much direct control to incorporate. Within highly cluttered healthcare 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.

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. We look forward to future explorations of this domain by the robotics community, and hope that novel implementations and rigorous evaluations will go hand in hand.

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