HAPTIC INTERACTION BETWEEN NAIVE PARTICIPANTS AND MOBILE MANIPULATORS IN THE CONTEXT OF HEALTHCARE

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HAPTIC INTERACTION BETWEEN NAIVE PARTICIPANTS AND MOBILE MANIPULATORS IN THE CONTEXT OF HEALTHCARE

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Dedicated to my family, fiancé, and friends, for their unending love and belief that I could accomplish anything.

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SUMMARY

Human-scale mobile robots that manipulate objects (mobile manipulators) have the potential to perform a variety of useful roles in healthcare. Many promising roles for robots require physical contact with patients and caregivers, which is fraught with both psychological and physical implications. In this thesis, we used a human factors approach to evaluate system performance and participant responses when potential end users performed a healthcare task involving physical contact with a robot. We performed four human-robot interaction studies with 100 people who were not experts in robotics (naive participants). We show that physical contact between naive participants and human-scale mobile manipulators can be acceptable and effective in a variety of healthcare contexts.

In this thesis, we investigated two forms of touch-based (haptic) interaction relevant to healthcare. First, we studied how participants responded to physical contact initiated by an autonomous robotic nurse. On average, people responded favorably to robot-initiated touch when the robot indicated that it was a necessary part of a healthcare task. However, their responses strongly depended on what they thought the robot's intentions were, which suggests that this will be an important consideration for future healthcare robots.

Second, we investigated the coordination of whole-body motion between human-scale robots and people by the application of forces to the robot's hands and arms. Nurses found this haptic interaction to be intuitive and preferred it over a standard gamepad interface. They also navigated the robot through a cluttered healthcare environment in less time, with fewer collisions, and with less cognitive load via haptic

interaction. Through a study with expert dancers, we demonstrated the feasibility of robots as dance-based exercise partners. The experts rated a robot that used only haptic interaction to be a good follower according to subjective measures of dance quality. We also determined that healthy older adults were accepting of using a robot for partner dance-based exercise. On average, they found the robot easy and enjoyable to use and that it performed a partnered stepping task well.

The findings in this work make several impacts on the design of robots in healthcare. We found that the perceived intent of robot-initiated touch significantly influenced people's responses. Thus, we determined that autonomous robots that initiate touch with patients can be acceptable in some contexts. This result highlights the importance of considering the psychological responses of users when designing physical human-robot interactions in addition to considering the mechanics of performing tasks. We found that naive users across three user groups could quickly learn how to effectively use physical interaction to lead a robot during navigation, positioning, and partnered stepping tasks. These consistent results underscore the value of using physical interaction to enable users of varying backgrounds to lead a robot during whole-body motion coordination across different healthcare contexts.

CHAPTER I

INTRODUCTION

Mobile manipulators, a specific class of robots, can navigate through human environments, manipulate objects, and have the ability to perform tasks closely with humans. Thus, these robots have the flexibility to perform myriad assistive and rehabilitative tasks and have the opportunity to provide healthcare assistance for humans in order to improve their quality of life.

What is common among many tasks in healthcare is that they frequently involve involve physical contact between the person providing care and the person receiving it. In fact, physical contact is essential to nursing [32]. Studies of nurse-patient interactions have observed that nurses frequently initiate contact with patients, both to perform tasks that require contact and to communicate with patients such as when providing emotional support [31]. For example, transferring a patient from a bed to a wheelchair requires that contact is made with a person's limbs and torso in order to position and transport the patient. Also, when giving a person a bed bath, contact must be made with the person's skin in order to cleanse it. Furthermore, when guiding a person during ambulation or during exercises involving whole-body motion, physical contact with the person's arms or hands must be made to lead and correct the person undergoing treatment.

If a robot were to perform these tasks, the robot would also need to make physical contact with people, initiated by the robot, human, or both. While substantial research has studied how robots can safely operate around people and handle unintended collisions [77], little is known about how a person will respond when a robot intentionally makes contact with the person's body and enters the person's intimate space [78] in a healthcare context. Further, it is not known which controllers would enable human-scale mobile manipulators to use force information from physical contact with humans to perform healthcare tasks effectively. Thus, the overall research question of this thesis is:

Can physical contact between naive participants and human-scale mobile manipulators be acceptable and effective within the context of healthcare?

In this chapter, we begin by motivating different user populations that robots could potentially assist. Then, we discuss the methodological approach of this thesis and four subsidiary research questions which provide evidence to support the overall research question. Finally, we provide an overview of the studies presented in this thesis.

1.1 Motivation

Assisting people with motor impairments

Robots have the flexibility to perform myriad tasks to provide functional independence for people with motor impairments and to reduce caregiver burden. In 2005 the U.S. Census Bureau estimated that more than 3.3 million Americans have motor impairments [25] which can prevent them from performing self-care tasks. People need to be able to perform several activities to live independently [168] and to achieve a high quality of life [193]. These activities include Activities of Daily Living (ADLs, e.g. feeding, toileting, transferring, dressing, and hygiene) [110, 109], Instrumental Activities of Daily Living (IADLs, e.g. housework, food preparation, and shopping) [110, 109], and Enhanced Activities of Daily Living (EADLs, e.g. hobbies and social activities) [155]. Many times, people with motor impairments rely on informal (e.g. family members) or formal (paid) caregivers to perform these tasks which places an emotional and/or financial burden on families. Similarly, increasing a sense of independence in older adults is also related to improvements in quality of life [164]. Robots have been developed to assist people with several types of ADLs, IADLs, and EADLs, but little research has been done regarding tasks involving physical contact such as bathing, toileting, and dressing [170].

Assisting People Who Provide Care for Others

Robots also have the potential to reduce the work burden of nurses and the potential for injury by helping them perform nursing tasks such as patient lifting. There is a 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 older adult population grows and prepares for retirement [89, 69]. In a study of the effects of high patient-to-nurse ratio, Aiken et al. found that each additional patient per nurse was associated with a 7% increase in patient mortality and a 23% increase in nurse burnout [5]. Consequently, studies have suggested that lowering the patient-to-nurse ratio would result in less missed patient care [69, 90]. Nurses frequently experience work-related back injury [86, 172] 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. Robots such as RIBA are being developed to assist with patient lifting [129]. In addition to patient transfer, nurses have identified several tasks involving physical contact for which robotic assistance would be useful including bathing, feeding, and dressing patients [34]. These suggestions for robotic assistance echo the understudied tasks in the literature stated by Smarr et al. [170]. A critical unaddressed issue for the success of these robots will be moving to and entering a patient's room and positioning the arms to lift a patient or to provide other care at the patient's bedside.

Helping older adults age in place by improving their health

Robots could also potentially serve as an assistive and rehabilitative robotic companion for older adults. People who are age 65 and over are projected to comprise 19.3% of the population by 2030 as the “baby boom” generation ages [3] and will increase demand on the healthcare system [136, 28]. Older adults experience age-related decline regarding cognition, sensation and perception, and movement control [60]. In particular, increased gait variability, which is correlated with balance, predicts falls in older adults [81]. Falls are the leading cause of injury in older adults and may result in injury such as fracture of the hip as well as institutionalization [7]. To compensate for decreased functional ability, some older adults move to assisted living or skilled nursing facilities in order to receive adequate care [125]. However, most older adults prefer to age in place in their own homes [66].

From a preventive perspective, robots have the potential to enable older adults to maintain their independence by regaining functional ability through therapeutic human-robot interaction as a form of exercise in their own homes or senior center. Physical exercise is commonly cited as an effective means to prevent cardiovascular disease, stroke, and diabetes [137, 122] and to improve postural and motor impairment [24] and functional performance [41] in older adults. However, many older adults face several barriers to physical exercise [163]. A robot could potentially serve as a motivating form of exercise by serving as a rehabilitative dance partner for older adults since partner dance in human-human interactions has been shown to improve gait and stability with people with Parkinson's disease and older adults [54, 74, 173, 119]. Thus, a robot could not only assist older adults in performing instrumental activities of daily living and activities of daily living, but also providing a means as preventive exercise to support aging in place [170, 13]. We gain motivation from previous work that shows that partner dance improves balance and gait for older adults [74, 119, 19], that dance is recommended for older adults to increase their range of motion [146], and that dance can confer mental and emotional benefits in addition to physical

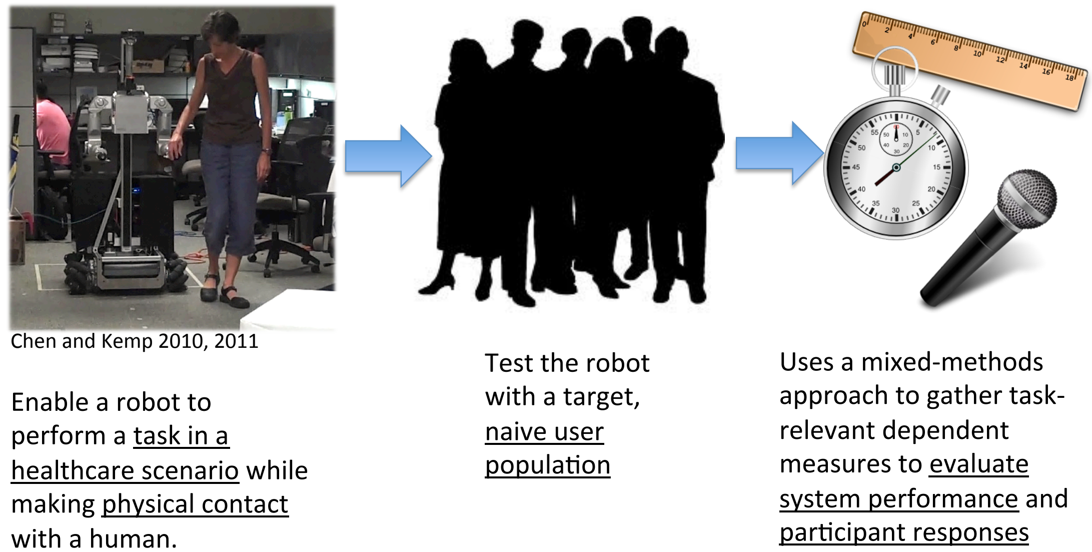


Figure 1: The approach used in this thesis.

benefits [104, 91].

1.2 Approach

To answer the overall research question, the approach of this thesis was to conduct four human-robot interaction studies where, in each study we: (1) enabled a robot to perform a task in a healthcare scenario while making physical contact with a human, (2) tested the robot with a target, naive user population, and (3) used a mixed-methods approach to gather task-relevant dependent measures to evaluate system performance and participant responses. This approach allowed us to determine the acceptability and the effectiveness of using physical contact between a human and robot during healthcare tasks. A diagram of this approach is shown in Figure 1.

The four studies we conducted in this thesis answered the following subsidiary research questions:

Study 1. What are people's responses to robot-initiated touch in a healthcare context?

Study 2. Can nurses use physical interaction to navigate and position a robot in

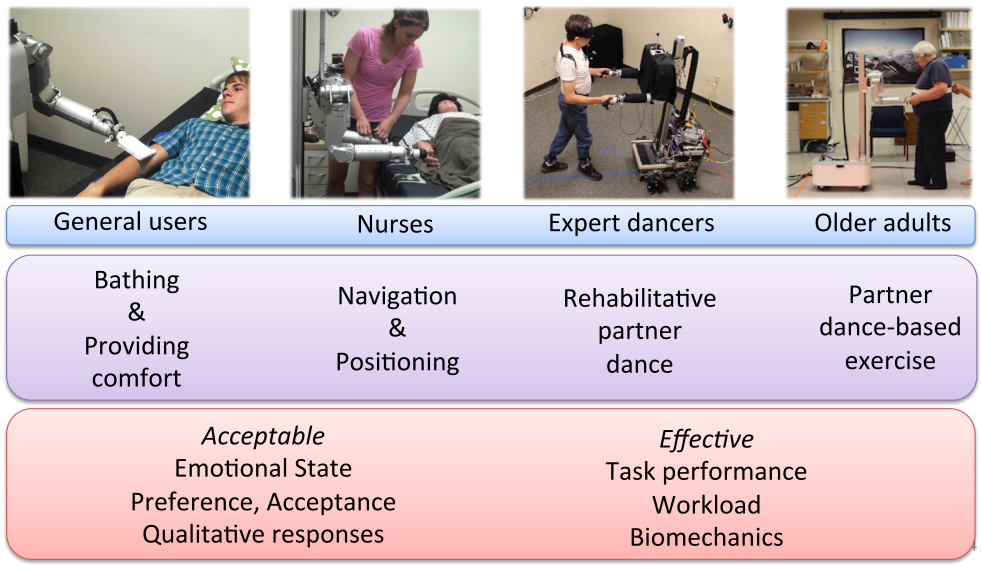


Figure 2: Overview of users, tasks, and measures used in this thesis.

hospital environments?

Study 3. Is it feasible to use an admittance controller to enable a robot to engage in rehabilitative partner dance with a human?

Study 4. Are older adults accepting of a robot for partner dance-based exercise?

These four studies investigated robot-initiated as well as human-initiated and cooperative physical contact between humans and robots. Figure 2 provides an overview of the users, tasks, and measures used in this thesis. Four different user populations were included in this work including general users, nurses, expert dancers, and older adults. Furthermore, these studies were conducted in different healthcare contexts. Together, providing answers to the four subsidiary research questions provided insight regarding to what extent haptic interaction is acceptable and effective across haptic interaction in healthcare in general.

The approach used in this thesis is commonly used in the field of human factors. Researchers and practitioners in human factors take into account human behavior and human characteristics when designing and evaluating human-machine systems (e.g., human-computer and human-robot systems). In doing so, the efficiency and performance of the entire system can be improved while making usage safe and satisfying for the human operators [148]. Proctor and Van Zandt [148] mention that considering human factors can prevent "waste of personnel and money, as well as danger to human life" during the development and deployment of human-machine systems. Furthermore, specific user characteristics such as education, training, age, and physical disability can affect how people use technology [76]. Thus, it has been suggested that human users be incorporated early and often throughout the development of the system, as is also practiced in user-centered design [148, 76].

In this thesis, we tested human-robot systems with people from actual user groups to enhance the applicability of the results to real-world deployment. Despite the benefits of involving users in the design process of human-robot systems, many times, robotics engineers develop robots in isolation from real users. This problem occurs in other fields as well perhaps due to lack of time or money or the belief that the engineer or designer is a sufficiently representative user [76]. Whatever the reasoning, there has been little work understanding people's responses to robots that make physical contact in healthcare scenarios. Furthermore, there are ethical concerns regarding people's psychological response to robots interacting closely with humans (e.g., fear, panic, and feelings of subordination to robots) [187]. Therefore, the results from the studies in this thesis provide valuable insight regarding the ethical implications of human-robot touch in healthcare as well as system usability and performance.

1.3 Overview of Document

In Chapters 2, 3, 4, and 5, we describe the results and methodologies of the studies in detail which are motivated individually by the healthcare context within which each is presented. Briefly, the results of the individual studies are provided here:

In Study 1 (Chapter 2), we conducted an experiment with 56 people in which a robotic nurse autonomously touched and wiped each participant's forearm. We analyzed the participants' physiological and self-reported emotional responses and custom questionnaire responses regarding the touch in either an instrumental or affective context. The perceived intent of the robot significantly influenced people's responses. If people believed that the robot intended to clean their arms, the participants tended to respond more favorably than if they believed the robot intended to comfort them, even though the robot's manipulation behavior was the same. Overall, participants had a favorable response to robot-initiated touch.

In Study 2 (Chapter 3), we defined 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 objective and subjective measures. Nurses also tended to exert more force at the robot's end-effectors and used higher velocities when using the DPI to perform a navigation task compared with using the DPI to perform a positioning task. Overall, the nurses were able to use physical interaction to effectively lead a robot through a navigation and positioning task in a simulated hospital environment.

In Study 3 (Chapter 4), we asked 10 expert dancers to evaluate the ability of a robot to generate whole-body motion during a forward/backward walking step. The robot used an admittance controller to generate motion. We varied the force gain of the controller and the robot's arm stiffness. The robot followed the participants with low lag (224$\pm$194 msec) across all trials. 60% of the participants said that the robot was a good follower. High force gain and high arm stiffness conditions achieved significantly better performance according to subjective and objective measures. Biomechanical measures such as human arm length, CoM-CoM distance, velocity, and forces correlated with the participants' subjective ratings which were internally consistent

(Cronbach's α=.92). Given the favorable ratings from the expert dancers during a partnered stepping task (PST), we determined that using an admittance controller to control the motion of a robot is feasible for use during human-robot rehabilitative partner dance.

In Study 4 (Chapter 5), similar to Study 3, we asked 16 older adults to engage in a PST with another robot that used an admittance controller to generate whole-body motion. The older adults in our study were accepting of using a robot for partner dance-based exercise evidenced by their responses to subjective questionnaires. We also identified facilitators and barriers to acceptance of a robot for partner dance-based exercise based on qualitative data. Using biomechanical force and motion capture data, video analysis, and subjective questionnaire responses, we determined that it is feasible to use an admittance controller for partner dance-based exercise for older adults.

Together, the answers to the subsidiary research questions allowed us to determine that physical contact between humans and mobile manipulators can be used across several different healthcare scenarios, with different user populations to produce useful and favorable interactions. In the Conclusion (Chapter 6), we discuss the implications of these findings.

CHAPTER II

STUDY 1: INVESTIGATION OF SUBJECTIVE RESPONSES TO ROBOT-INITIATED TOUCH

In this chapter, we enabled a robot to autonomously reach out and initiate contact with the forearm of 56 student participants. On average, participants had a favorable response to the first time the robot touched them. However, we found that the perceived intent of the robot significantly influenced people's responses. If people believed that the robot intended to clean their arms, the participants tended to respond more favorably than if they believed the robot intended to comfort them, even though the robot's manipulation behavior was the same. Our results suggest that roboticists should consider this social factor in addition to the mechanics of physical interaction. Surprisingly, we found that participants in our study responded less favorably when given a verbal warning prior to the robot's actions. The results of this study were published in [37, 35].

Overall, the results of this study suggest that autonomous robots that initiate touch with patients can be acceptable in some contexts. As a result, we recommend that patients' perceptions of a robot's intent of touch should be considered because the psychology of physical interaction is important, not just mechanics.

2.1 Introduction

Humans initiate contact with one another to achieve a variety of goals, such as facilitating communication and providing physical assistance. Robots have the potential to achieve similar goals by initiating physical contact with people, but this type of interaction is fraught with both physical and psychological implications. For example,

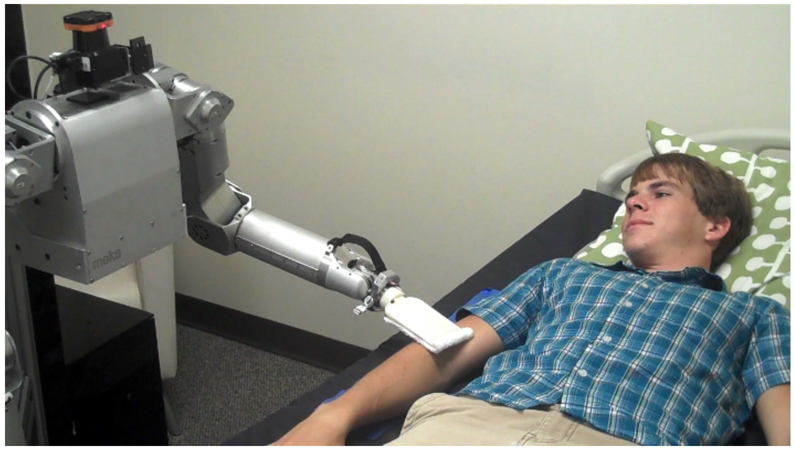


Figure 3: The robot Cody touches a subject during our experiment.

human skin is an especially important channel for social communication [128], and robot-initiated contact implies that the robot will enter into the person's intimate space [78].

While substantial research has studied how robots can safely operate around people and handle unintended collisions [77], little is known about how a person will respond when a robot intentionally makes contact with the person's body. This type of interaction is especially relevant to healthcare, since caregiving frequently requires that a caregiver initiate contact with the body of a care receiver who is awake and aware. For example, studies of nurse-patient interactions have observed that nurses frequently initiate contact with patients, both to perform tasks that require contact, such as cleaning a person's skin, and to communicate with patients, such as when providing emotional support [31].

2.2 Overview of Experiment and Main Results

So as to better understand how people respond to robot-initiated touch, we designed and conducted a 2x2 between-subjects experiment with 56 people (14 people per condition) in which a robotic nurse autonomously reached out, touched the participant's arm, moved across the arm, and then retracted. Depending on the condition, the robot verbally indicated before the physical interaction (*warning*) or after (*no warning*) that it intended to clean the participant's arm (*instrumental touch*) or provide comfort (*affective touch*). In order to assess participants' responses to these conditions, we took galvanic skin response (GSR) measurements throughout the experiment (described in Section 2.4.4), administered post-task questionnaires, and recorded responses to open-ended questions.

We designed the experiment to test the following two hypotheses:

- **Hypothesis 1**: Participants will find robot-initiated touch more favorable when it is perceived to be instrumental versus affective.
- **Hypothesis 2**: Participants will find robot-initiated touch more favorable when given a verbal warning prior to contact versus no verbal warning.

In agreement with our first hypothesis, we found that participants responded more favorably to the *instrumental touch* than to the *affective touch* conditions. In particular, more people agreed with the statement, "I would have preferred that the robot did not touch my arm." in the *affective touch* conditions. Nonetheless, all participants let the robot touch them again in a repeated trial. Because the physical behavior of the robot was the same for all trials, our results demonstrate that the perceived intent of robot-initiated touch can significantly influence a person's subjective response. As such, our results suggest that roboticists should consider this factor in addition to the mechanics of physical interaction.

In contradiction to our second hypothesis, we found that participants tended to respond more favorably to *no warning* than to *warning* conditions. Results from our post-hoc analyses suggest that participants may have become startled by the robot's voice during the verbal warning, and that the robot's reach towards the participant's arm may have served as a warning gesture. However, the underlying reasons for this result remain unclear.

We also report the results of post-hoc analyses that lend additional insight into the participants' responses to robot-initiated touch.

2.3 Related Work

This chapter builds upon our initial work communicated via a conference paper [37]. In this chapter, we provide additional results and analyses, including post-hoc analyses of participants' galvanic skin responses (GSR), attitudes towards robots, open-ended responses, and responses to a second trial. We also more thoroughly discuss related work, including research published after the submission of our conference paper.

2.3.1 Nurse-Patient Interaction

Nurse-patient interaction serves as an important source of inspiration for our experiment. It both serves as a motivating application for robots that initiate touch, and a well-studied example of the role of touch in human-human interaction.

Caris-Verhallen et al. observed two types of touch between nurses and patients that they defined as follows: *instrumental touch*, which is "deliberate physical contact" that is necessary in performing a task such as wound dressing; and *affective touch*, which is "relatively spontaneous" and "not necessary for the completion of a task" [31]. In an accompanying study of 165 nurse-patient interactions, researchers observed affective touch in 42% of the interactions and instrumental touch in 78% of the interactions [31]. McCann and McKenna report on observations of touching interactions between nurses and older adults in hospice [118]. Most of the observed nurse-initiated touches were on the extremities (arm, hand, leg, foot), and most touches (95.3%) were instrumental. Touches from nurses on the face, leg, and shoulders were perceived as uncomfortable by patients. Only instrumental touches on the shoulder and arm by a nurse were viewed as comfortable. The authors suggested that misinterpretation of a nurse's intention may have contributed to patient discomfort during some touches.

In our experiment, we make the same distinction between instrumental and affective touch. By using a robot, we have the distinct advantage of being able to control the physical interaction, and thereby investigate the role of perceived intent through a controlled-laboratory experiment.

2.3.2 Human-Robot Touch

We classify the initiation of haptic interaction between a human and a robot into three categories: robot-initiated touch, human-initiated touch, and cooperatively-initiated touch. We define robot-initiated touch as a haptic interaction that the robot initiates by making physical contact with the human. Similarly, we define human-initiated touch as a haptic interaction that the human initiates by making physical contact with the robot. We define cooperatively-initiated touch as being a haptic interaction for which the initiator of the touch is ambiguous. For this study, we also assume that the initiator of contact plays an active role during the interaction episode, while the other entity plays a primarily passive role.

Shaking hands [167] is an example of cooperatively-initiated touch, since both the human and robot can actively move towards each other. When people pet robots, such as Paro [95] or the Haptic Creature robot [195], it is an example of human-initiated touch, since the person actively moves towards a robot and makes physical contact with the robot's body. Within this study we focus on robot-initiated touch. Various robotic systems for healthcare involve robot-initiated touch, including facial massage [99], skin care [183], patient transfer [130], surgery [96], and hygiene [97].

There has been some prior work on studying people's responses to robot-initiated touch. For example, Bickmore et al. studied users' perceptions of and responses to affective touch performed by a virtual agent [15]. The virtual agent included a robotic component capable of pneumatically applying pressure to the user's hand. The user placed his or her hand in the robotic device and held it there. The pressure was initiated by the virtual agent to help convey empathy and comfort. They found marginal trends that suggested that touch increased participants' perceptions of having a working relationship with the agent, if the participants were receptive to touch by humans. The opposite trend was observed for participants who were not receptive to touch by humans.

There was also a video study that looked at the effect of human-robot touch and robot proactiveness on people's perceptions of a small humanoid robot's "machine-likeness" and dependability [40]. For reference, a "humanoid" robot "emulate[s] aspects of human form and behavior" [93]. Participants watched videos of a robot and a person interacting. Among other results, participants perceived the robot in the video to be less machine-like when it touched the person while offering to help the person.

Contemporaneous research reported by Nakagawa et al. in [133] is especially relevant to our study. They investigated how a robot making contact with and wiping a participant's hand affects the participant's motivation in a dull task. They compared this interaction with no touch, and the human touching the robot's hand. They found that participants performed the task significantly longer and with more activity when the robot touched and wiped their hands. Furthermore, participants felt that the robot was more friendly when touching them compared with no touch. They plan to use this interaction in healthcare applications, such as encouraging patients during rehabilitation. A number of factors may be responsible for the differences between their results and ours. We discuss these differences in the Discussion and Conclusions section (Section 2.8).

We are unaware of previous research that has directly investigated how the perceived intent of a robot influences a human's subjective response to robot-initiated touch. Likewise, there has been little work on determining cues that robots can use to improve subjective responses to robot-initiated touch, such as a verbal warning.

2.3.3 Robot Intention

Robot intention plays a critical role in our study. Within this section, we discuss several aspects of robot intention along with related work.

2.3.3.1 Must intentions be attributed to a robot?

With our experiment, we investigated how the perceived intent of a robot influences a person's response to robot-initiated touch. If no intent were attributed to the robot's actions, this inquiry would be inappropriate. Simple machines regularly make contact with people, such as restraining bars for amusement park rides, automated blood pressure cuffs, and car airbags. Likewise, more complicated machines, such as commercially available massage chairs, autonomously make patterns of contact with peoples' bodies. It seems likely that perceived intent usually does not play a role in these human-machine interactions. Rather, people perceive the devices as mindless mechanisms performing predefined actions.

One could potentially design healthcare robots to reduce the likelihood that people will attribute intentions to them. However, this may not be practical or even possible as healthcare robots become more versatile, perceptive, mobile, dexterous, and communicative in the course of their duties. People tend to attribute intentions, motivations, and emotions to agents that are viewed as being anthropomorphic. The degree to which an agent is viewed as possessing human-like qualities can affect how one predicts what the agent will do in the future as well as what its behaviors mean in the present [53].

Many characteristics can influence a person's tendency to anthropomorphize a machine and attribute intentions to it. People tend to anthropomorphize non-human agents when the agents seem similar to themselves, such as through motion or morphology [53]. For instance, Premack and Premack [147] demonstrated that people will anthropomorphize simple animated 2-dimensional shapes and attribute intentions to them if they move appropriately. Furthermore, mechanical devices such as robots are more readily anthropomorphized when they possess human-like faces and bodies [53, 84].

2.3.3.2 The Intentional Stance

Dennett posited that humans adopt the intentional stance when predicting the future behavior of other systems such as other people [48]. That is, by assuming another person is a rational agent that has beliefs about the world (e.g. there is milk in the refrigerator) and desires or goals of his or her own (e.g. he or she wants to drink milk), one can predict what that person intends to do (e.g. open the refrigerator door, pour a glass of milk, drink the milk, etc.) [48, 12].

Maselli and Altrocchi have stated that "perceived intent is an important determinant of response to another person, and thus attribution of intent is pivotal in understanding interpersonal behavior" [116]. Similarly, the perceived intent of a robot during human-robot interaction (HRI) may influence a person's response to the robot's actions.

2.3.3.3 Inferring Intent

Baird and Baldwin [12] emphasized the roles of high-level knowledge and low-level actions on perceptions of intent. For example, high-level knowledge that a person intends to tidy up a kitchen that has a sink full of dirty dishes could help an observer recognize that the person intends to clean the dishes. Likewise, observing low-level actions, such as a person directing his or her gaze towards dirty dishes, reaching for a sponge, and reaching for soap, could be used to infer the actor's intent to clean the dishes.

Within our experiment, the experimenters established a high-level context for the scenario by telling participants that the robot was a robotic nurse that would perform various nursing tasks. In conjunction with this context, the robot's speech served to communicate a high-level intention for the robot's actions of either comforting the participant or cleaning the participant's arm. Simultaneously, the robot's motions provided low-level intentions to the participants, such as reaching a hand out and touching the participant's body. We designed our experiment to study the effects of altering the perceived high-level intent of the robot, while keeping the low-level motion the same for all conditions.

2.3.3.4 Prior Research Involving Robot Intention

Researchers have investigated robot intentions in other contexts. Cakmak et al. considered how a robot can better communicate its intentions in order to improve object handoffs between robots and people [29]. In their study, the experimenter told participants that the high-level intention of the robot was to hand them an object while the experimenter varied the low-level spatiotemporal characteristics of the robot's motion. In our study, we vary the robot's high-level intentions while keeping its low-level actions constant. Wagner and Arkin enabled mobile robots to deceive other robots by giving false signals (heat signatures, sounds, and visual tracks) as to their locations in a game of hide-and-seek. The robots that were hiding communicated a false intent to the robots that were trying to seek them [188].

2.4 Implementation

In this section, we describe the robot we used in our experiment and the algorithm for the robot to safely make physical contact with a human participant's arm.

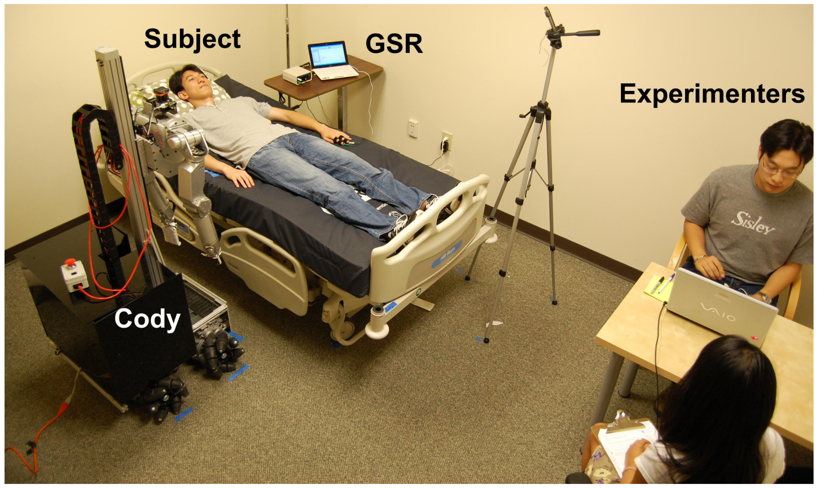


Figure 4: Experimental setup with a lab member in the patient bed. The two experimenters are shown seated in the bottom-right corner of the image.

2.4.1 The Robot

The robot Cody, shown in Figure 3,[1] is a statically stable mobile manipulator. The components of the robot follow: two arms from MEKA Robotics (MEKA A1), a Segway omnidirectional base (RMP 50 Omni), and a 1 degree-of-freedom (DoF) Festo linear actuator. The arms are anthropomorphic with series elastic actuators (SEAs) at each of their 7 joints, which enables low-stiffness actuation. The robot's wrists are equipped with 6-axis force/torque sensors (ATI Mini40). For this study, we used a custom 3D-printed, spatula-like end effector (7.8 cm x 12.5 cm) which resembles an extended human hand [97]. We cut a towel to fit the shape of the end effector and attached it to the bottom of the end effector. In our experiments, this towel makes contact with the participants' forearms. The towel's material can be interpreted as a cleaning surface or a compliant exterior for the robot's end effector.

2.4.2 Touching behavior implementation

For implementation details of the touching behavior, please refer to our previous work [97]. For reference, we show the algorithm used in [97] in Algorithm 1. The main

[1]We obtained IRB approval and participant permission for all of the photos in this study.

Algorithm 1 WIPE($pt_{init}, dir_x, dir_y, dist_x, dist_y$)

```
GoTo(pt_init + z_offset)
LOWER_UNTIL_HIT()
moves ← CEIL(dist_x/2cm)
for i = 0 to moves do
    for i = 0 to 2 do
        SURFACE_FOLLOW(arm, dir_y, dist_y)
        SURFACE_FOLLOW(arm, −dir_y, dist_y)
    end for
    SURFACE_FOLLOW(arm, dir_x, 2cm)
end for
```

difference between the previous implementation and the version used in this thesis is that the robot wiped a rectangular area on the person's arm in [97] but only wiped along a linear trajectory in the study presented in this chapter. Furthermore, in this chapter, the location above the person's arm to begin the behavior as well as the area to wipe were specified ahead of time by the researcher while in previous work, they were specified by a human operator using a selection interface.

During all of the robot's arm motions, the robot's joints were commanded to have low stiffness. For example, when in contact with a participant's forearm, the stiffness of the robot's end effector in the direction normal to the surface of the forearm was less than 60 N/m. For all of the robot's motions in the experiment, the commanded stiffness for the shoulder flexion/extension, shoulder abduction/adduction, shoulder internal/external rotation, elbow flexion/extension, and forearm pronation/supination motions were 20, 50, 15, 25, and 2.5 Nm/rad, respectively. We used position control for the abduction/adduction and flexion/extension motions at the robot's wrist. Even during position control, the wrist joints have significant compliance due to the passive compliance of the SEA springs and cables that connect the SEAs to the joints. For this study, we attempted to make the touching behavior consistent with both cleaning a person's forearm and providing comfort, so that there would be ambiguity about the purpose of the behavior.

When the robot is in its standby position, its arms and end effectors are pointing down towards the floor. The touching behavior begins by executing what we refer to as the "*Init*" action. During this action, the robot uses a preprogrammed joint trajectory that moves the left arm to a position where the end effector is 15.4 cm above the mattress surface and directly above the participant's forearm. The robot then moves its end effector downward until the force sensor on the wrist measures a force magnitude $\geq$ 2 N, indicating that the end effector has made contact with the arm. We designed the arm trajectory so that the "*Init*" action completed within approximately 7 seconds when tested on a lab member's arm. During the experiment, we recorded the time it took for the robot to perform the "*Init*" action. The overall mean time for the robot to complete the action across all participants was 6.91 seconds (SD=0.10 sec).

After making contact, the robot performs what we refer to as the "*Along*" action. During this action, the arm moves the Cartesian equilibrium point (CEP) of the end effector at approximately 4 cm/s. We designed the CEP to travel 14 cm to the left, and then 14 cm to the right along the participant's arm. A bang-bang controller attempts to keep the force magnitude measured by the force sensor on the wrist between 1 and 3 N by moving the CEP down towards the arm or up away from the arm. As a safety precaution, the robot terminates the touching behavior if the measured force magnitude exceeds 30 N. During the "*Along*" action, the robot exerted an overall mean force magnitude of 2.44 N (SD=0.18N) across all participants. We also designed this trajectory to be completed in approximately 7 seconds. The overall mean time of the "*Along*" action across all participants was 6.92 seconds (SD=0.02 sec), and the mean distance the end effector traveled to the left and right was 13.71 cm (SD=0.07 cm) and 13.61 cm (SD=0.02 cm), respectively.

To complete the touching behavior, the robot performs what we refer to as the "*Away*" action. During this action, the robot lifts its end effector upward, so that it moves away from the person's forearm. The robot then moves its arm back to the standby position. We designed this action to take approximately 7 seconds. The overall mean time for the robot to complete this action across all participants was 6.83 seconds (SD=0.08 sec).

Refer to Appendix C for design guidance regarding how to implement the robot behavior used in this study on other robotic platforms. Also refer to the code used for this study that we submitted as supplementary material to this thesis.

2.4.3 Safety

Ensuring the safety of a person while interacting with a robot is important during any HRI scenario. Studies in which a robot makes physical contact with a human require special care. We took several precautions when designing the robot's behavior and conducting the study to reduce the chance of injury. First, during the study an experimenter was always prepared to operate a run-stop button if undesirable contact with the robot were observed or anticipated. Second, the robot's arm operated with low joint stiffness and low joint velocities. Third, the robot attempted to keep the magnitude of the force against the participant's arm lower than 3 N.

For comparison, Tsumaki et al. reported that people experienced no pain when a skin care robot applied a downward force of 10 N [183]. Other researchers used a force magnitude threshold of 39.2 N with an oral rehabilitation robot [99]. Various factors could influence the force range that a person would find comfortable, including the contact surface over which the applied force is distributed, and the part of the person's body with which contact has been made. As such, these values provide a coarse comparison with other research.

During the debriefing after the experiment, participants generally reported that the force the robot applied was comfortable. No participants indicated any pain or discomfort during the interaction. Furthermore, in their open-ended responses, several participants reported that the touch was surprisingly light and gentle.

In accordance with the Georgia Institute of Technology Central Institutional Review Board (IRB), we read from a script in order to inform each participant of risks associated with the study, including the potential for undesirable contact with the robot. We also notified each participant that an experimenter would be prepared to use a run-stop button to stop the robot in the event of undesirable contact.

2.4.4 Galvanic Skin Response (GSR)

In order to provide an objective measure of the participants' arousal during their interactions with the robot, we measured their galvanic skin responses (GSR) using an S220 GSR Sensor from Qubit Systems in Kingston, ON, CA. Several researchers have employed GSR to characterize people's responses during HRI or to enable a robot to respond to a human's affective state [105, 120, 196, 177, 157].

When a person reacts to a stressful situation, the sympathetic nervous system is activated. This activation causes the sweat glands in the palms of the hands and soles of the feet to enlarge, which causes the skin to become more conductive. GSR is linearly correlated with arousal [107] and is generally associated with emotional response [20]. An increase in the voltage reading from the GSR sensor is associated with increased arousal. To use our off-the-shelf GSR sensor, we placed the participant's middle finger and index finger from his or her left hand on the sensor's two electrode plates and secured them with velcro. We attached leads to the electrodes with alligator clips and recorded the voltage reading using the proprietary software Logger Lite. We also recorded timestamps from a clock synchronized with the robot's actions.

We analyzed the GSR signal during the 28-second interval between the baseline recordings described in Section 3.4.4 and shown in Figure 7. During this time interval, we normalized the GSR signal for each participant to have a value between 0 and 1 inclusive using the following equation, as in [115]:

$$GSR_{norm}(t) = \frac{GSR(t) - GSR_{min}}{GSR_{max} - GSR_{min}}$$

2.5 Methodology

2.5.1 Experimental Design

		Warning Type	
		Warning	*No Warning*
Touch Type	*Instrumental*	7 men, 7 women	7 men, 7 women
	Affective	7 men, 7 women	7 men, 7 women

Figure 5: Experimental design.

We conducted a gender-balanced, 2x2 between-subjects experiment (see Figure 5). To test our hypotheses, we defined two independent variables: (1) the type of touch the robot executed (*instrumental* vs. *affective*) and (2) the warning condition (*warning* vs. *no warning*).

In each of the four treatment conditions, the robot executed the same touching behavior described in Section 2.4.2. The only difference between the *instrumental* and *affective* treatment conditions was what the robot said to the participant. The robot used the following utterances:

- *Instrumental, Warning utterance*: "I am going to rub your arm. I am going to clean you. The doctor will be with you shortly."
- *Instrumental, No Warning utterance*: "I have rubbed your arm. I have cleaned you. The doctor will be with you shortly."
- *Affective, Warning utterance*: "Everything will be all right, you are doing well. The doctor will be with you shortly."
- *Affective, No Warning utterance*: "Everything will be all right, you are doing well. The doctor will be with you shortly."

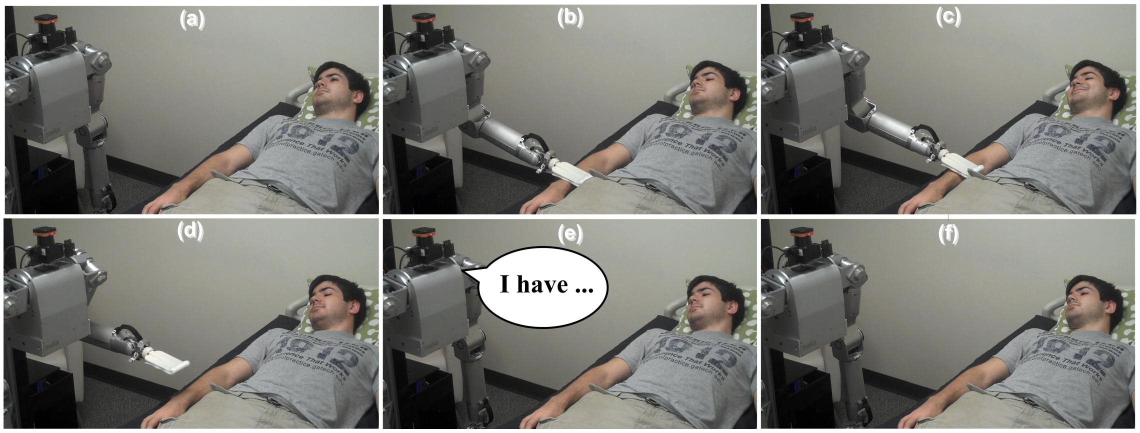


Figure 6: Cody touches a participant in the *instrumental, no warning* treatment. (a) Baseline. (b) *Initial* contact. (c) Moving *Along* the participant's arm. (d) Lifting *Away* from the participant. (e) *Speak*ing to the participant. (f) Baseline.

With this design, each participant experienced very similar physical interactions, but associated different intentions with the interaction, depending upon what the robot said. As we describe in detail in Section 2.5.3.4, we asked questions in order to exclude participants who did not interpret the robot's intentions correctly, which resulted in the exclusion of six people. We also controlled the length of time the robot spoke to be approximately 7 seconds for all verbal utterances.

Warning	Baseline	Speak	Initial	Along	Away	Baseline
No Warning	Baseline	Initial	Along	Away	Speak	Baseline
	2 min	7 sec	7 sec	7 sec	7 sec	2 min

Figure 7: Timing for *warning* vs. *no warning*.

For the *warning* and *no warning* treatment conditions, we changed the timing of when the robot spoke. Figure 7 illustrates the ordering and timing of the robot's action and speech in the *warning* and *no warning* conditions. For *warning*, the robot spoke before it touched the participant's arm. For *no warning*, the robot touched the participant's arm and spoke after the haptic interaction was over (i.e. once it was no longer in contact with the participant's body). We changed the grammatical construction of the utterances to be appropriate for these two cases.

2.5.2 Procedure

We recruited 63 students from the Georgia Tech campus through various student email lists, flyers, and word of mouth. We required participants to be at least 18 years of age, a United States citizen, and a native English speaker. We excluded six participants because they did not correctly interpret the robot's intentions (see Section 2.5.3.4) and one participant due to a software malfunction while collecting her questionnaire data. We assigned participants to each of the four treatment groups on a rolling basis according to gender.

In total, we included the data from 56 of the participants (28 males and 28 females) in the analysis for this study, ranging in age from 18-29 years (M=22.7, SD=2.7). The self-reported ethnicities of these participants were White (31), Asian (19), African American (2), Hispanic (2), Native Amer. / Pac. Islander (1), and Other (1). 87.5% of the participants were engineering students.

We performed our experiment in the Healthcare Robotics Lab in a 4.3m x 3.7m, climate-controlled simulated hospital room (see Figure 38). We placed a fully functional Hill-Rom 1000 patient bed, an I.V. pole, an overbed table, a living room chair, and a side table in the room. Participants filled out all paperwork and questionnaires within the simulated hospital room. We placed the robot 17 cm away from the edge of the patient bed.

The same two experimenters conducted all of the trials and remained in the room throughout the experiment to ensure the participant's safety. One experimenter, the first author, ran each experiment by reading from a script. While each trial was taking place, the experimenters sat at the far side of the room and looked at a computer monitor and at the robot, rather than at the participant (see Figure 38). We used a script and the same two experimenters for all trials in order to maintain consistency and avoid confounding factors.

When a participant arrived at the lab, the experimenters welcomed the participant and introduced themselves. Then, the participant signed a consent form, filled out a demographic survey, and filled out a pre-task questionnaire. Afterward, the experimenter explained that the robot was capable of performing several different simulated nursing duties, and that the robot would mimic doing so by gesturing with its arms and end effectors. It is important to note that the participants were unaware that the robot would reach out and make contact with them. Then, the experimenter asked the participant to lay down on the patient bed, and if a female participant was wearing a skirt, the experimenter offered her a blanket to cover her legs. The experimenter then asked the participant to place his or her right arm between two lines of tape marked on the mattress and to place his or her elbow directly on top of a third line of tape on the mattress. This arm placement ensured that the robot would make contact with the person's forearm. If the participant were wearing a long-sleeve shirt or sweater, the experimenter asked the participant to roll up his or her sleeve past the elbow or to remove the sweater, if possible. We asked the participant to place his or her left arm on the mattress and affixed a galvanic skin response (GSR) sensor to his or her fingers. We collected one minute of baseline data from this sensor and then asked the participant to fill out a brief questionnaire while laying on the bed (measures are detailed in Section 2.5.3).

We then asked the participant to keep his or her head facing a camera during the experiment. Then, we collected 2 additional minutes of baseline GSR data, initiated the robot interaction (described in Section 3.4.4), and collected another 2 minutes of baseline GSR data. We then asked the participant to get off the bed and fill out the post-task questionnaire for trial 1. Next, we asked the participant to lay down in the bed again and performed a repeated trial of the same interaction just experienced. Then, we asked the participant to fill out a post-task questionnaire for trial 2.

2.5.2.1 Posture selection

Because patients are typically in a reclined posture while a nurse performs a bed bath, we selected this posture for our experiment as shown in Figure 6. The reclined posture may have affected participants' emotional state during the experiment. Previous psychology research has shown that children in a supine position were more fearful than children who were sitting up [106]. Also, physical body posture, specifically slumped, hunched, and relaxed postures, can have an effect on one's emotional state [153]. In our study, we controlled posture across all conditions by asking all participants to recline in the patient bed.

2.5.3 Measured Variables

We measured several variables both before and after the participant interacted with the robot by administering a pre- and post-task questionnaire, respectively. In this section, we describe the measured variables we use in this study.

2.5.3.1 Emotional State

We measured the emotional state of the participants using the Self-Assessment Manikin (SAM) and the Positive and Negative Affect Schedule (PANAS). SAM comprises three 9-point scales that measure arousal, valence, and dominance (also referred to as level of control) using pictorial representations of these dimensions as described in [21, 108]. The Positive and Negative Affect Schedule (PANAS) comprises two 10-word mood scales, where each word is measured on a 5-point scale [191]. Individually, the two scales measure Negative Affect (NA) and Positive Affect (PA), where the lowest possible individual NA or PA score is 10 and the highest is 50. Both SAM and PANAS have been used extensively in psychology and HRI research to measure emotional state [158, 14, 157, 195].

We adapted the text from [21] and [191] for the SAM and PANAS questionnaires we administered. We administered the SAM questionnaire prefaced with the text, "Use these panels to rate your personal reaction OVERALL after the robot finished interacting with you:". Similarly, we administered the PANAS questionnaire prefaced with the text, "Indicate to what extent you felt the following way OVERALL after the robot finished interacting with you:".

2.5.3.2 Custom Likert-scale Questionnaire

In addition to assessing the participants' emotional response, we asked general questions about their experience using 7-point Likert scale questions where 1 = "Strongly Disagree," 4 = "Neutral," and 7 = "Strongly Agree". We asked the following questions pertaining to our two hypotheses:

LI1 I was confused as to why the robot was touching my arm.

LI2 It was enjoyable when the robot was touching my arm.

LI3 I was scared when the robot was touching my arm.

LI4 I felt reassured when the robot was touching my arm.

LI5 It was necessary for the robot to touch my arm.

LI6 I would let the robot touch me again.

LI7 I would have preferred that the robot did not touch my arm.

The questionnaire included additional questions unrelated to these hypotheses. For completeness, these questions and statistics of the responses to them can be found in Tables 8 and 9.

2.5.3.3 Negative Attitude Towards Robots Scale (NARS)

We also administered the "Negative Attitude towards Robots Scale" (NARS) which comprises three subscales: S1 which measures negative attitudes towards interactions with robots, S2 which measures negative attitudes towards the "social influence of robots," and S3 (an inverse scale) which measures positive attitudes towards emotions with robots [139]. NARS has been used to help explain differences found in other measures [182]. We administered NARS during the post-task questionnaire for trial 1 in order to avoid biasing participants prior to their interactions with the robot.

We used methods from [139] to perform our analysis using NARS. We divided the participants into subgroups according to the medians of each of the three NARS subscales S1, S2, and S3. If a participant had an S1 subscale score below the median S1 score, then that participant was placed in the "S1-Low" group. If a participant had an S1 subscale score above the S1 median score, then that participant was placed in the "S1-High" group. We repeated the same process to create the "S2-Low," "S2-High," "S3-Low," and "S3-High" subgroups. We verified that the high and low NARS subscale groupings produced significantly different NARS subscale scores ($p<.001$) for each of the subscales. The results of this verification are shown in Table 1. We used these groups as between-subjects factors in a post-hoc analysis discussed in Section 2.6.3.1.

2.5.3.4 Manipulation Check

We designed the first two questions of the post-task questionnaire for trial 1 to assess whether participants interpreted the robot's intentions correctly. First, we asked the participant to write down what the robot said to determine if the person correctly heard the robot's speech. Second, we asked the participant to write down why the robot was touching his or her forearm to determine if the person correctly understood the robot's stated intention. We excluded participants who did not pass both of these manipulation checks.

2.5.4 Expected Outcomes

Within this section, we describe the outcomes we would expect if our hypotheses were true.

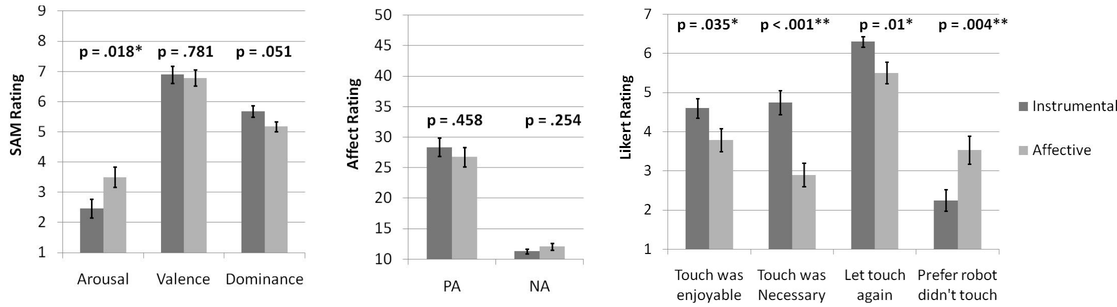


Figure 8: Main Effects of Touch Type: Participants' subjective responses according to SAM (left), PANAS (middle), and 7-point Likert scale questions (right). (**p <.0055, *p <.05, Standard error bars shown)

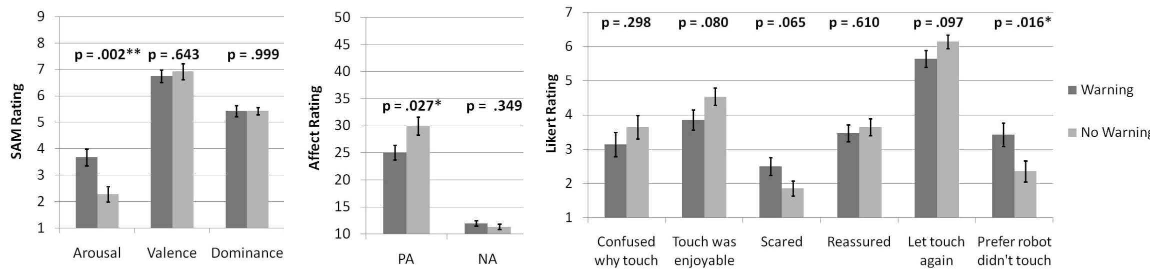


Figure 9: Main Effects of Warning Type: Participants' subjective responses according to SAM (left), PANAS (middle), and 7-point Likert scale questions (right). (**p <.0045, *p <.05, Standard error bars shown)

2.5.4.1 Hypothesis 1: Instrumental vs. Affective Touch

Overall, we expected participants to have a stronger preference for the robot not to touch them if the touch were affective as opposed to instrumental (LQ7). This is based primarily on the nursing findings described in Section 2.3.1. We also expected participants to experience lower arousal, higher valence, and higher dominance when the robot performs an instrumental touch compared with when it performs an affective touch. Additionally, we expected participants to have higher feelings of positive affect and lower feelings of negative affect when the touch is instrumental. We expected that they would enjoy the touching interaction more (LQ2), feel that the touch is more necessary (LQ5), and would be more willing to let the robot touch them again when the touch is instrumental (LQ6). These expected outcomes correspond with 9 dependent measures.

2.5.4.2 Hypothesis 2: Warning vs. No Warning

We expected participants to experience lower arousal, higher valence, and higher dominance when they receive a warning from the robot before it touches them, compared with when the robot touches them before speaking. We also expected participants to have higher feelings of positive affect and lower feelings of negative affect when they receive a warning. We expected participants to enjoy the interaction more (LQ2), to be less scared (LQ3), to feel more reassured (LQ4), and to be more willing to let the robot touch them again (LQ6) with a warning. We also expected that with a warning participants would be less confused as to why the robot was touching their arm (LQ1), and would be less inclined to prefer that the robot had not touched them (LQ7). These expected outcomes correspond with 11 dependent measures.

2.6 Results

We conducted a two-way, between-subjects analysis of variance (ANOVA) on the subjective data from trial 1 related to the two main hypotheses, and found no significant interactions between the independent variables of *touch type* and *warning type*. Thus, we only discuss the main effects of the independent variables.

Figure 8 shows the main effects of *touch type* on the 9 dependent measures relevant to Hypothesis 1. We denote dependent measures that were significant with α=.05 using a single asterisk, $*$. We denote dependent measures that were significant with the more conservative Bonferroni adjusted α=.0055 (.05/9) using two asterisks, $**$. The Bonferroni correction reduces the risk of finding significance by chance due to the multiple dependent measures associated with Hypothesis 1 (i.e., Type I errors - false positives).

Similarly, Figure 9 shows the main effects of *warning type* on the 11 dependent measures relevant to Hypothesis 2. We denote dependent measures that were significant with α=.05 using a single asterisk, $*$. We denote measures that were significant

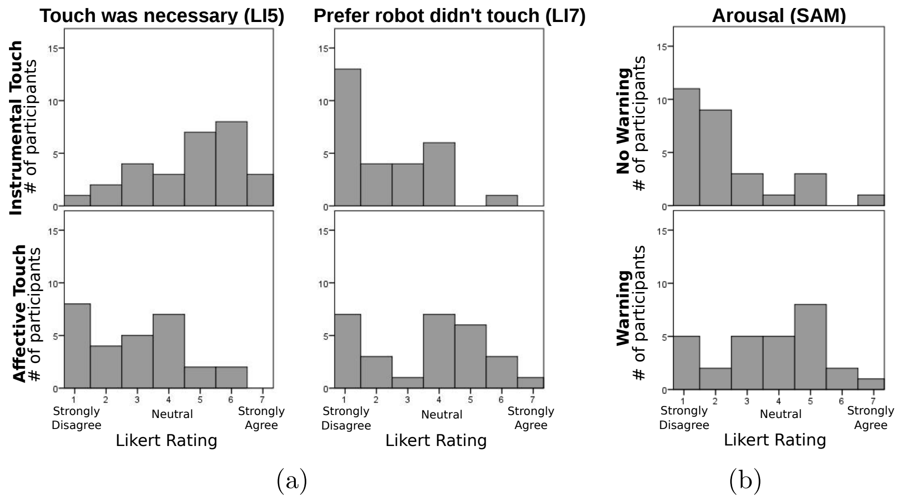


Figure 10: Histograms of Significant Dependent Measures According to Main Effect of (a) Touch Type, (b) Warning Type.

with the more conservative Bonferroni adjusted α=.0045 (.05/11) using two asterisks, **.

For completeness, Tables 8 and 9 show the main effects for all other Likert items from the post-task questionnaire. There were no significant interactions between the independent variables for these responses. Furthermore, none of these measures were significant with α=.05.

2.6.1 Hypothesis 1

With respect to the expected outcomes discussed in Section 2.5.4.1, the results were consistent and in support of Hypothesis 1. All 9 dependent measures changed in the anticipated directions, although the changes associated with four of the dependent measures were not statistically significant.

Two dependent measures were significant with the Bonferroni corrected α=.0055. Most importantly, more people agreed with the statement, "I would have preferred that the robot did not touch my arm." with affective touch than with instrumental touch (10 participants vs. 1 participant), and there was a statistically significant difference (F(1,52)=9.01, p=.004, $\eta_p^2 = 0.15$) in the responses to this question. This

Figure 11: Various facial expressions during the *Along* time interval.

clearly supports Hypothesis 1. Participants also reported that the instrumental touch was significantly more necessary than the affective touch (F(1,52) = 18.29, p<.001, η_p^2 = 0.26). On average, participants viewed the instrumental touch as slightly necessary with a score of M=4.8, SD=1.6 and viewed the affective touch as slightly unnecessary with a score of M=2.9, SD=1.6.

Three other dependent measures were only significant with α=.05. Participants were less aroused during the experiment when the robot performed an instrumental touch compared with when it performed an affective touch (F(1,52) = 5.92, p=.018, η_p^2 = 0.10). They also enjoyed the touch more (F(1,52) = 4.68, p=.035, η_p^2 = 0.08) and would be more willing to let the robot touch them again when the touch was instrumental as opposed to affective (F(1,52) = 7.05, p=.01, η_p^2 = 0.12). These results are also consistent with Hypothesis 1.

On average, participants were generally open to allowing the robot interact with them and touch them again, regardless of the touch type. As shown in Figure 8, participants reported on average that they would let the robot touch them again for both types of touch. Moreover, all 56 participants allowed the robot to touch them in the second trial.

2.6.2 Hypothesis 2

Surprisingly, with respect to the expected outcomes discussed in Section 2.5.4.2, the results support the contrary assertion that *no warning* results in more favorable subjective responses. 9 out of the 11 dependent measures relevant to Hypothesis 2 changed in the opposite direction from what we anticipated, although the changes associated with six of these dependent measures were not statistically significant. Only the mean rating of confusion changed in the anticipated direction, because people tended to be more confused in the no warning case, albeit not significantly. The average dominance was identical for the *warning* and *no warning* conditions.

Only one dependent measure was significant with the Bonferroni corrected α=.0045. Participants were significantly more aroused when the robot warned them prior to contact ($F(1{,}52) = 10.71$, p=.002, $\eta_p^2 = 0.17$), which is in contradiction to Hypothesis 2.

Two other dependent measures were only significant with α=.05. Participants had a higher positive affect rating when the robot did *not* warn them ($F(1{,}52) = 5.19$, p=.027, $\eta_p^2 = 0.09$). When the robot warned them, participants had a greater preference for the robot not to touch them ($F(1{,}52) = 6.26$, p=.016, $\eta_p^2 = 0.11$). These results are in opposition to Hypothesis 2. The changes associated with the remaining eight dependent measures were not significant.

2.6.3 Post-hoc analyses

In this section, we describe post-hoc analyses of participants' negative attitudes towards robots, PANAS scores, a repeated interaction with the robot, GSR, and open-ended responses about the interaction.

2.6.3.1 NARS

We investigated how participants' negative attitudes towards robots may have influenced the six dependent measures that showed a significant difference in the first trial (the dependent measures denoted with $*$ and $**$ in Figures 8 and 9).

First, we conducted a two-way analysis of variance (ANOVA) for *touch type* and each of the three NARS subscales (S1, S2, and S3). We found no significant interaction between *touch type* and any of the three NARS subscales. We also conducted a two-way ANOVA for *warning type* and the NARS subscales and found no significant interaction. Because we found no interactions, we collapsed across the *touch type* and *warning type* factors and analyzed the main effects of each NARS subscale separately. For each NARS subscale, we used t-tests to determine if the six dependent measures were significantly different for participants with high and low NARS subscale results (e.g., S1-Low versus S1-High).

Out of all the t-tests for the three NARS subscales and six dependent measures (3x6=18 t-tests), none of the tests were significant with a Bonferroni corrected significance level of $\alpha = .003$. However, one of the tests was significant with $\alpha = .05$ (Let touch again) while two other tests resulted in p-values of $p<.10$ (Prefer no touch, Postive Affect). Table 2 shows the results of these tests. Each of these differences was due to the S3 subscale, which measures positive attitudes towards emotions with robots. Although not significant, the results suggest trends that participants who had more positive attitudes towards emotions when interacting with robots (S3-High) were more willing to let the robot touch them again and had higher positive affect. Similarly, participants with less positive attitudes towards emotions when interacting with robots (S3-Low) preferred that the robot not touch them.

2.6.3.2 PANAS

We compared the PANAS scores from trial 1 with the norms for college students reported in [191]. We performed independent t-tests using the mean, standard deviation, and sample size (n=660) statistics for the college students who reported how they felt at the moment when they were filling out the questionnaire. The results of

Table 1: NARS subscale groupings according to S1, S2, S3 subscale scores. S1=Negative attitudes towards "situations of interaction with robots," S2=Negative attitudes towards the "social influence of robots," and S3=Positive attitudes towards emotions with robots.

Subscale	Median	Possible Range	Subgroup	M (SD)	t	p	Cohen's d
S1	10.5	6-30	Low(n=28)	8.3 (1.3)	-10.48	<.001	2.89
			High(n=28)	14.5 (2.8)			
S2	14	5-25	Low(n=27)	10.7 (2.1)	-11.11	<.001	3.03
			High(n=29)	16.8 (2.0)			
S3	9	3-15	Low(n=26)	6.4 (1.4)	-10.3	<.001	2.86
			High(n=30)	10.8 (1.7)			

Table 2: t-tests for selected dependent measures according to NARS subgroups. (Only results significant at the α = 0.10 level are shown). S3=Positive attitudes towards emotions with robots.

Subscale	Dependent Measure	Subgroup	M (SD)	t	p	Cohen's d
S3	Let touch again	Low	5.5 (1.4)	-2.54	.015	0.73
		High	6.3 (0.8)			
S3	Prefer no touch	Low	3.4 (1.8)	1.968	.054	0.52
		High	2.5 (1.7)			
S3	Positive Affect	Low	25.4 (7.1)	-1.875	.066	0.51
		High	29.4 (8.8)			

these comparisons across conditions are shown in Tables 3 and 4.

The PA scores for participants in the *warning* condition were significantly lower (p=.002) than the norm. This result is in line with the results found for Hypothesis 2, where the participants generally did not favor the *warning* condition. All other PA scores were not significantly different than the norm with α=.05 The NA scores for participants in all of the conditions were significantly lower than the norm, all with p<.0001. This result suggests that participants felt generally less negative than the norm for all experimental conditions. This result may be due in part to the fact that the participants were laying in a bed because low NA is associated with feelings of calmness and serenity [191].

The PA scale has been found to show a time-of-day effect [191] where PA scores tend to rise during the morning, remain steady during the day, and fall during the evening. While we did not explicitly control for the time of day, trials for the various conditions were distributed fairly evenly in time. For our study, 23 people participated in the morning (before noon), 22 participated in the afternoon (between noon and 6 pm), and 11 participated in the evening (after 6pm). Notably, participants in the *warning* and *no warning* conditions, for which we found a significant difference in PA, had almost the same distribution across these three times, only differing by one person in the morning, two people in the afternoon, and one person in the evening.

Table 3: Comparison of PA scores with the norm reported in [191]. PA score norm: M=29.7, SD=7.9, n=660.

Experimental Condition	n	PA M (SD)	t	df	p	Cohen's d
Instrumental touch	28	28.4 (8.0)	0.84	29	.41	0.16
Affective touch	28	26.8 (8.5)	1.77	29	.09	0.37
Warning	28	25.1 (7.0)	3.39	30	.002	0.59
No Warning	28	30.0 (8.8)	-0.18	29	.86	0.04

Table 4: Comparison of NA scores with the norm reported in [191]. NA score norm: M=14.8, SD=5.4, n=660.

Experimental Condition	n	NA M (SD)	t	df	p	Cohen's d
Instrumental touch	28	11.3 (2.0)	8.09	46	<.0001	0.66
Affective touch	28	12.1 (3.0)	4.47	35	<.0001	0.51
Warning	28	12.0 (2.6)	5.24	38	<.0001	0.53
No Warning	28	11.4 (2.5)	6.58	39	<.0001	0.64

2.6.3.3 Repeated Trial

We performed a two-way, repeated measures ANOVA on the dependent measures of PA, NA, Arousal, Valence, and Dominance for trials 1 and 2 of the experiment, because these were the only subjective measures that were collected for both trials. The purpose of this analysis was to determine whether the participants' emotional states would change as a result of a second robot-initiated touch interaction. All participants allowed the robot to wipe their forearms in the repeated trial.

We refer to the factor associated with the trial number as *Trial*. The results showed no significant interaction between the *Trial* and *touch type* or *warning type* factors. Thus, we analyzed the *Trial* factor separately. We show the effect due to the *Trial* factor on each of the relevant dependent measures in Table 5. The results show that participants' valence and PA scores significantly decreased from trial 1 to trial 2 (p<.001 and p<.0001, respectively), indicating that they became significantly less happy. Similarly, participants' NA scores increased (p=.07), although not statistically significantly so. Also, participants became somewhat less aroused from trial 1 to trial 2 with (p=.10), and their feelings of dominance did not significantly change.

We also compared the PANAS scores for trials 1 and 2 with the norms from [191] across all participants. The results from this analysis are shown in Table 6. The participants' PA scores were not significantly different than the norm after trial 1 (p=.07), but were significantly lower than the norm (p<.0001) after trial 2. Also, in trial 1, the participants' NA scores were significantly lower than the norm (p<.0001), and remained significantly lower than the norm after trial 2 albeit to a lesser degree (p=.01) than in trial 1. These results indicate that participants, on average, were less positive than the norm in trial 2 compared with trial 1, but were less negative than the norm in both trials.

Table 5: Main Effect of the *Trial* factor on participants' self-reported emotional state.

Dependent Measure	Possible Range	Trial 1 M (SD)	Trial 2 M (SD)	F(1,52):	p	η_p^2
Arousal	1-9	3.0 (1.8)	2.7 (1.7)	2.74	.10	0.05
Valence	1-9	6.8 (1.4)	6.3 (1.4)	16.11	<.001	0.24
Dominance	1-9	5.4 (1.0)	5.4 (0.9)	0.07	.79	0.001
Positive Affect	10-50	27.6 (8.2)	22.9 (7.1)	55.15	<.0001	0.52
Negative Affect	10-50	11.7 (2.5)	12.9 (5.4)	3.4	.07	0.06

Table 6: Comparison of PANAS scores from repeated trials with the norms reported in [191]. PA score norm: M=29.7, SD=7.9, n=660; NA score norm: M=14.8, SD=5.4, n=660.

Trial and Score type	n	Score M (SD)	t	df	p	Cohen's d
Trial 1, PA	56	27.6 (8.2)	1.85	64	.07	0.27
Trial 1, NA	56	11.7 (2.5)	7.85	106	<.0001	0.59
Trial 2, PA	56	22.9 (7.1)	6.82	67	<.0001	0.87
Trial 2, NA	56	12.9 (5.4)	2.53	65	.01	0.35

2.6.3.4 GSR

The results from analyzing the particpants' GSR suggest that the robot's first action served as a form of warning, whether it was spoken (*Speech*) or gestural (*Init*). After the participants had been warned via speech or gesture, these non-contact actions did not result in further ascents in arousal. In contrast, the actions associated with the *Along* interval, which involved contact with the participant's body, resulted in ascents in arousal regardless of the spoken or gestural warning.

Figure 12 shows the median of the normalized GSR across the participants for their first interaction with the robot according to treatment group. We omitted the GSR data from 10 participants due to errors in the recorded timestamps, from 5 participants due to erroneous measurements (excessive high-frequency content), and from 1 participant due to signal drop out during the interaction. Consequently, Figure 12 shows GSR readings from a total of 40 participants. Specifically, we used data from 10 participants each in the *Instrumental touch, Warning* and *Affective touch, Warning* groups, 8 participants in the *Instrumental touch, No Warning* group, and 12 participants in the *Affective touch, No Warning* group.

Statistically Significant Ascents

The GSR curves in Figure 12 are of a “type 3” pattern curve where there are not distinct peaks following each stimulus but are instead subsequent “ascents” [20]. This pattern may arise when stimuli are placed close enough such that a descent in the GSR is not produced between stimuli. The latency between the onset of a stimulus and the onset of a GSR response is typically between 1 and 2 seconds [20].

Due to our experimental design, participants began the human-robot interaction part of the experiment represented in Figure 12 in a relaxed state with a low-level of arousal and low GSR readings. From the GSR trends, we observe that the participants’ arousal tended to increase throughout the interaction.

Table 7 shows the results of pairwise t-tests comparing the normalized GSR values at the end and beginning of each interval for each treatment. Notably, during the *Along* interval the GSR signal had a significant ascent (increase in GSR) in all four conditions. This observation indicates that the instant of contact and motion along the forearm were arousing under all conditions, regardless of the interaction that had already taken place. In contrast, the robot’s retraction of its arm during the *Away* interval did not result in a significant change in GSR in any of the treatment conditions.

A significant ascent was associated with the first interval under all conditions. When the *Init* interval was the first action during the human-robot interaction (for the

No Warning condition), there was a significant increase in GSR during that interval across both of the *touch types*. This result was not observed for the *Init* interval under the *Warning* condition, where *Init* was not the first action of the robot, but instead occurred after *Speech*. The *Speech* interval corresponded with a significant increase in GSR for all four conditions. However, the ascent was much larger in the *Warning* condition (across both *touch types*), when the robot's utterance was the first action the robot performed, compared with the ascent in the *No Warning* conditions, where the robot's *Speech* was the last interval of the interaction.

Intervals with Similar GSR Change

We also compared intervals to one another. For our analysis of the *Init* and *Along* intervals, we combined the GSR data from the two *no warning* conditions, because these experimental conditions are the same prior to the *Speech* interval.

We performed three independent samples t-tests to compare the GSR difference for the combined *no warning* condition (M=0.32, SD=0.22), the *instrumental touch, warning* condition (M=0.28, SD=0.22), and the *affective touch, warning* condition (M=0.36, SD=0.17). We found no statistically significant difference in the GSR ascents associated with the *Along* interval under these three conditions. The results for these tests are as follows: *instrumental touch, warning* vs. *affective touch, warning*: $t(18)$=-0.97, p=.34, d=0.43; *instrumental touch, warning* vs. *no warning*: $t(28)$=-0.54, p=0.60, d=0.19; and *affective touch, warning* vs. *no warning*: $t(28)$=0.49, p=.63, d=0.20.

The GSR signal had a significant ascent in the first interval for all conditions. The first interval was *Speech* in the *warning* conditions and *Init* in the *no warning* conditions. The change in GSR signal for these two intervals was not significantly different (*Speech, Warning*: M=0.26, SD=0.20, *Init, No Warning*: M=0.33, SD=0.20,

$t(38)$=-1.2, p=.25, d=0.36). This result suggests that the robot's actions during the first interval resulted in comparable increases in arousal, regardless of whether the action was the robot speaking or the robot moving its arm.

Additionally, neither the *Speech* interval nor the *Init* interval was associated with an ascent when they occurred at other times during the interaction. The increase in GSR was significantly larger when *speech* was the first interval of the interaction as opposed to when it was the last interval (*Speech, Warning*: M=0.26, SD=0.20, *Speech, no warning*: M=0.08, SD=0.09, $t(38)$=3.5, p<.002, d=1.19). Similarly, the change in GSR was significantly larger when the *Init* interval was the first interval as opposed to the second (*Init, No Warning*: M=0.33, SD=0.20, *Init, warning*: M=0.05, SD=0.14, $t(38)$=-5.2, p<.001, d=1.66).

Many factors can influence GSR, including posture, age, temperature and lighting [20]. However, these factors were consistent across all trials.

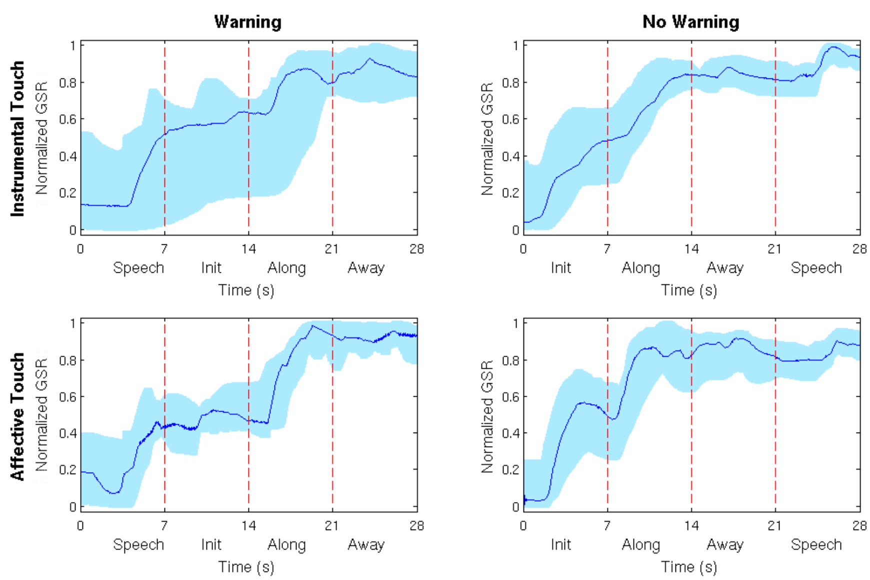


Figure 12: Normalized GSR across each treatment. Dark blue line shows median of normalized GSR signal. Light blue area shows data contained within the 25th and 75th percentiles. Red dashed vertical lines show timing of the *warning* and *no warning* conditions (shown previously in Figure 7). n=10 for *Instrumental touch, Warning* and *Affective touch, Warning*; n=8 for*Instrumental touch, No Warning*; and n=12 for *Affective touch, No Warning*.

Table 7: Pairwise t-tests of normalized GSR at beginning and ending of each interval for each treatment. The mean and standard deviation of the difference between the normalized GSR value at the end of the interval and the beginning of the interval is shown.

Interval	Treatment	GSR Difference M (SD)	t	df	p	Cohen's d
Init	*Instrumental, Warning*	0.04 (0.14)	0.93	9	.38	0.29
	Instrumental, No Warning	0.30 (0.21)	4.07	7	.005	1.43
	Affective, Warning	0.07 (0.15)	1.48	9	.17	0.47
	Affective, No Warning	0.36 (0.20)	6.27	11	<.0001	1.80
Along	*Instrumental, Warning*	0.28 (0.22)	3.97	9	.003	1.27
	Instrumental, No Warning	0.37 (0.27)	3.91	7	.006	1.37
	Affective, Warning	0.36 (0.17)	6.95	9	<.0001	2.12
	Affective, No Warning	0.30 (0.20)	5.2	11	<.001	1.50
Away	*Instrumental, Warning*	0.04 (0.09)	1.23	9	.25	0.44
	Instrumental, No Warning	-0.02 (0.09)	-0.56	7	.59	0.22
	Affective, Warning	0.002 (0.08)	0.06	9	.95	0.03
	Affective, No Warning	0.007 (0.14)	0.17	11	.87	0.05
Speech	*Instrumental, Warning*	0.26 (0.24)	3.37	9	.008	1.08
	Instrumental, No Warning	0.11 (0.11)	2.88	7	.02	1.00
	Affective, Warning	0.26 (0.17)	4.8	9	<.001	1.53
	Affective, No Warning	0.07 (0.07)	3.10	11	.01	1.00

2.6.3.5 *Experience with Robots*

26 participants (46%) responded "Yes" to the question "Do you have any experience with robots?" The examples of robots with which they reported having experience included toys, LEGO Mindstorms, iRobot Roomba, Boe-Bot, the Philips iCat, the Willow Garage PR2, an autonomous ground vehicle, and a bioreactor for tissue engineering. We compared the responses of participants who reported having robot experience (N=26) with the participants who reported having no robot experience (N=30). We first performed independent samples t-tests to compare their responses for each dependent measure used to test hypotheses 1 and 2 (12 measures total) and for each of the NARS subscales. No test was significant with α=.05. We then analyzed the effect size using Cohen's d. [58] recommends d=.41 be considered a minimum effect size of practical significance for social science data. Only one measure met this cutoff, which was question LI4 ("reassured") with d=.42 where those who reported no experience with robots felt slightly more reassured (M=3.8, SD=1.2) than those who reported previous experience with robots (M=3.3, SD=1.3). This suggests that experience with robots did not have a substantive effect on the results of our study.

2.6.3.6 *Open-ended Responses*

After the first touching interaction with the robot, we asked the participants to answer two open-ended questions in the post-task questionnaire. For our analysis, we read through all of the participants' responses for each of the open-ended questions. Then, we created categories for the types of responses people made. We present our results with respect to these categories. We also provide sample quotations from the responses to give the reader an idea of the types of comments the participants made.

Question #1: What would you suggest we change about the robot in order to make the interaction more comfortable?

We grouped the responses to question #1 according to comments concerning: (1) the robot's voice, (2) the robot providing a warning prior to touch, (3) the robot's movement, (4) the appearance of the robot, (5) the robot saying more, and (6) the design of the end effector of the robot.

21 out of the 56 participants mentioned that they wanted to change the robot's voice in some way. 13 out of these 21 participants (62%) were in the *Warning* treatment group. 9 out of these 21 participants wanted the voice to be more human-like, and 3 out of these 21 participants wanted the voice to be friendlier, while 3 other of these 21 participants simply wanted the voice to be "better" or to "improve" it with no other specific description as to how to improve it. No participants reported that the choice of the female voice should be changed.

15 of the 56 participants reported that they would like to have had some sort of warning prior to the robot touching them. 11 of these 15 participants (73%) were in the *no warning* treatment group. 3 of the 4 participants who were in the *warning* treatment group noted that when the robot warned them, its voice startled them. Specifically, 1 of these 3 participants mentioned that the speech was surprising, because the robot had been silent, while another 1 of these 3 noted that the robot had a "thundering voice" and that the volume of the voice should be lowered. Being startled by the robot's voice may have contributed to the participants' higher arousal ratings and our unexpected results. 1 of the 4 participants in the *warning* group suggested that the robot make an initial small movement before it touched the person.

21 of the 56 participants made suggestions to change some aspect of the robot's appearance. Specifically, 7 of these 21 wanted the robot to have a head or a face; 5 of these 21 simply wanted the robot to look more "friendly"; and 7 of these 21 wanted the robot to be less "metallic" looking or less mechanical. 11 of these 21 participants expressed that they wanted the robot to have more humanoid characteristics and

specifically mentioned some form of the word "human."

5 of the 56 participants indicated that they would have liked if the robot had spoken more. 4 of these 5 were in the *no warning* treatment group. 1 of these 4 participants suggested that the robot introduce itself, while 2 other of these 4 participants suggested that the robot should say more about the context of the situation and should give more indication of what was about to happen. 1 of these 4 participants simply suggested that the robot engage in "small talk." The single participant in the *warning* treatment group desired that the robot provide a longer explanation about the cleaning.

4 of the 56 participants made design suggestions for the robot's end effector. 1 of these 4 participants wanted the cloth on the end effector to be replaced by a more "human-like replacement" such as a rubbery material and a warming element. Another 1 of these 4 participants echoed the desire for a warming element if touch was involved. 2 of these 4 participants suggested to make the cloth softer and less rough.

1 of the 56 participants stated that: "I could see a robot performing tasks, not necessarily providing emotional support like comforting someone."

Question #2: What are your overall impressions of the experiment?

Many of the responses to question #2 were in line with the suggestions discussed already for question #1, and included suggestions to change the robot's voice and appearance, possibly to be more human-like.

1 participant stated that "I think that I would be comfortable having a healthcare robot interact with me in a doctor's office." On the other hand, another participant stated it was "not the same as having a human nurse" and another stated that she was "somewhat doubtful that interacting with the robot would be comforting in the

same way as with a human."

6 of the 56 participants noted that they were surprised how lightly the robot touched them and that it was more gentle than they had expected. 1 of these 6 participants stated that the light touch was "reassuring." This participant was in the *Instrumental touch, No Warning* treatment group.

On a similar note, 1 of the 56 participants stated that "I was surprised that I in fact felt more calm after interacting with the robot." This participant was in the *Affective touch, Warning* treatment group.

8 of the 56 participants noted that they expected to do more in the experiment or that the experiment would have more elements of interaction. 6 other of the 56 participants explicitly stated that they wanted more interaction with the robot.

9 of the 56 participants expressed confusion about parts of the experiment. Specifically, 5 of these 9 participants stated that they were confused about questions in the questionnaire. 1 of these 9 participants expressed that the robot's voice was difficult to understand. Although all 56 participants passed the manipulation check, 2 of the 9 participants stated that they were confused about why the robot was touching them. Of these 2 participants, 1 was in the *no warning, instrumental touch* group and 1 was in the *warning, affective touch* group. 1 of the 9 participants wondered whether there would be a second interaction immediately following the first.

5 of the 56 participants expressed negative feelings towards parts of the experiment. 1 of these 5 participants stated that he felt odd that the robot was trying to comfort him. Another of these 5 participants stated that he "felt weird to be laying on the bed," while another of these 5 participants felt uncomfortable during the period of waiting. Another of these 5 participants stated that being told not to move made her worried about doing something wrong during the experiment. The last of these 5 participants stated that the touch itself felt "weird" but that a warning would have made the touch less awkward. This participant was in the *Instrumental touch, No*

Warning treatment group.

Table 8: Main Effects of Touch Type on Likert items unrelated to Hypothesis 1.

Likert Item	Instr. Touch M (SD)	Affective Touch M (SD)	$F(1{,}52)$:	p	η_p^2
The robot was easy to understand.	5.7(1.2)	5.9 (1.2)	0.20	.66	0.004
I was confused as to why the robot was touching my arm.	3.0 (2.0)	3.8 (1.6)	3.25	.08	0.06
I was scared when the robot was touching my arm.	2.0 (1.2)	2.4 (1.4)	1.10	.30	0.02
I felt reassured when the robot was touching my arm.	3.6 (1.4)	3.5 (1.2)	0.26	.61	0.005
The robot cares about me.	3.2 (1.5)	2.9 (1.6)	0.60	.45	0.01
The robot was entertaining.	5.4 (1.6)	6.0 (1.3)	2.10	.16	0.04
When I first saw the robot, I thought it would hurt when it touched me.	1.9 (1.2)	2.5 (1.6)	2.2	.14	0.04
The robot looks very strong.	4.8 (1.6)	4.8 (1.5)	0	1	0
The robot looks friendly.	3.2 (1.5)	2.9 (1.3)	0.85	.36	0.02
Interacting with the robot would be more enjoyable if it looked more human-like.	4.9 (1.7)	5.0 (1.6)	0.03	.87	0.001

Table 9: Main Effects of Warning Type on Likert items unrelated to Hypothesis 2.

Likert Item	Warning M (SD)	No Warning M (SD)	$F(1{,}52)$:	p	η_p^2
The robot was easy to understand.	5.7 (1.2)	5.9 (0.9)	0.45	.51	0.009
It was necessary for the robot to touch my arm	3.9 (2.1)	3.8 (1.6)	0.03	.87	0.001
The robot cares about me.	2.8 (1.5)	3.3 (1.6)	1.22	.27	0.02
The robot was entertaining.	5.7 (1.5)	5.7 (1.5)	0	1	0
When I first saw the robot, I thought it would hurt when it touched me.	2.3 (1.6)	2.1 (1.3)	0.31	.58	0.006
The robot looks very strong.	5.1 (1.4)	4.4 (1.6)	2.55	.12	0.05
The robot looks friendly.	3.0 (1.5)	3.0 (1.3)	0	1	0
Interacting with the robot would be more enjoyable if it looked more human-like.	5.0 (1.6)	4.8 (1.6)	0.24	.63	0.005

2.7 Limitations

Further research will be required to determine the generality of our results. We carefully controlled factors such as the robot's appearance, the robot's motions, the location where contact was made on the person's body, and the person's posture. Any one of these or other factors, such as long-term interaction with the robot, the person's cultural background, or previous experience with robots could potentially have a significant influence on a person's response. For example, the participants in this study were predominantly engineering college students, which may limit generalization of our results to other populations.

Likewise, the participants were in a simulated scenario. Patients who actually require care or would benefit from comfort might respond differently. For instrumental touch, patients who require care might respond more positively, because the touch would truly be instrumental. For affective touch, it is unclear if people who would benefit from comfort would respond more or less favorably.

Additionally, participants were under informed consent, and, hence, knew they were part of an experiment. As such, the Hawthorne effect may have been a factor in our results. Because we carefully controlled the experiment, we would not expect this to be a confounding factor for our results based on comparisons across conditions, such as our finding that perceived intent can significantly influence a person's response to robot-initiated contact. On the other hand, participants' speculations about the nature of the experiment could potentially have influenced them to respond more positively to the interaction. That said, under the affective conditions, a large number of people (10 out of 28) agreed with the statement, "I would have preferred that the robot did not touch my arm." (see Figure 10). This demonstrates that many participants were willing to provide negative responses.

During recruitment, we specifically mentioned that participants would be interacting with a robot, but we did not indicate that the robot would make physical contact with them nor did we state that the robot would act as a nurse. Nonetheless, our recruiting method would be less likely to enroll people who are averse to interacting with robots.

2.8 Discussion and Conclusions

We have presented results from our study in which a human-scale robot using a compliant arm autonomously made contact with the forearms of 56 human participants without incident or reported discomfort. On average, regardless of the treatment, participants had a favorable experience in the first trial as indicated by measures such as valence, positive affect, and negative affect, as well as Likert items about perceived safety, fear of the robot, and willingness to have the robot touch them again. In general, these results suggest that robot-initiated touch can be a successful form of human-robot interaction in the context of healthcare. More specifically, in this study we investigated how two factors influence the response of participants to robot-initiated touch. We selected these factors based on their relevance to human-human interaction in the context of nursing.

2.8.1 Perceived Intent

Our study demonstrates that perceived intent can be a significant factor in how people respond to robot-initiated touch. For all trials in our experiment, the robot executed the same touching behavior, which resulted in consistent physical interaction with the participants. Significant variation in responses resulted from distinct interpretations of the robot's intentions rather than physical differences in the interaction. Specifically, participants responded less favorably when they believed the robot touched them to comfort them (affective touch) versus when they believed the robot touched them to clean their arms (instrumental touch). This was most evident in participants' agreement with the statement, "I would have preferred that the robot did not touch my arm." 10 participants from the affective touch conditions agreed with the statement versus 1 participant from the instrumental touch conditions, and the average response to this question was significantly different for affective touch and instrumental touch (p=.004).

In our study, the robot touched a relatively innocuous location on the participant's body. We would anticipate a stronger effect size if the robot were touching a more sensitive part of the body, such as during an actual bed bath. We would also expect the role of perceived intent to play a larger role during contact with more sensitive locations. For example, if a nursing robot made contact with a particularly sensitive part of a patient's body, the patient's response would likely depend on whether or not he or she believed the contact was a mistake, was intended to provide comfort, or was intended to achieve a medical goal.

Exploring ways to reinforce desired interpretations of robot-initiated touch could be a worthwhile direction for future research. In our study, we used the robot's speech, the actions of its arm, and the nursing scenario to convey intent. Many other cues, including high-level, low-level, implicit, and explicit cues, could plausibly be used to influence perceived intent. Alternatively, developing robots to which people are unlikely to attribute intentions may be an effective approach. As we discussed in the related work section (Section 2.3.3), however, this may not be feasible as healthcare robots become more advanced and less specialized.

2.8.2 Instrumental vs. Affective Touch

Studies of interactions between human nurses and human patients have found that patients respond more favorably to instrumental touch. Similarly, with our robot in a simulated healthcare task, participants responded much more favorably to instrumental touch than to affective touch. However, the extent to which this result would generalize to other robots in other scenarios remains an open question.

It may be possible to create a nursing robot from which people would welcome comforting touch and instrumental touch. For example, the robot's appearance and behavior might be altered to better match the tasks [67, 165]. As we described earlier, Nakagawa et al. have recently shown that a robot touching and wiping the hand of a participant can positively motivate the participant in a task [133]. Many factors may have led to the positive responses they observed. They used a small, cute, child-sized robot designed specifically for social interaction, while we used a human-scale mobile manipulator that we primarily designed to perform instrumental healthcare-related tasks. Their participants were seated upright and looking down at their robot, which was placed on a table. This dominant posture, similar to an adult interacting with a child, is in contrast to the supine posture of our participants who were looking up at the robot from a hospital bed. Cultural differences may also have been a factor, because their participants were from Japan while ours were native English speakers residing in the Atlanta area of the USA. Additionally, their robot asked the participants to first hold its right hand, which resulted in human-initiated touch prior to robot-initiated touch. In our study, the robot made first contact with participants.

All of these factors might make a difference in people's responses to robot-initiated touch, and some of them would be difficult or impossible for a roboticist to control. For example, robotic nurses may need to interact with people of many cultures who are in a supine posture. Likewise, the demands of instrumental tasks will place requirements on the robot's design, and may call for human-scale or larger robots.

Fortunately, with respect to the goal of instrumental touch, our results suggest that favorable responses can be achieved with a robot lacking strong social design elements. Participants from the instrumental touch conditions had a generally positive response to the first trial. Notably, only 1 participant out of 28 agreed with the statement "I would have preferred that the robot did not touch my arm." (see Figure 10). Whether or not the addition of social design elements would improve responses remains an open question. Some healthcare robots have integrated social design elements, such as the large teddy-bear-like RIBA robot that is designed for lifting patients [130]. One potential risk is that people might not respond well to some socially-oriented design choices in a large healthcare robot. The open-ended responses from our participants indicate that adding human-like characteristics may be beneficial.

2.8.3 Warning, Warning

We found that participants tended to respond more favorably when no verbal warning was given by the robot prior to contact. The open-ended responses and GSR data suggest that the movement of the robot as it reached out towards the person served as a form of gestural warning, and that it was preferred to the robot's spoken warning. The robot's unexpected physical movement and contact with the person after a long period of stillness may have been less jarring than the robot's unexpected speech after a long period of silence. It seems likely that factors such as the velocity of the arm movement and the loudness of the speech play a role in this type of interaction. As suggested in participants' open-ended responses, having the robot speak to the person ahead of time in a more natural manner, or otherwise reducing surprise, might lead to different results.

Another interpretation of our results could be that leaving the intent behind robot-initiated touch ambiguous while the interaction is occurring leads to more favorable responses. The robot explicitly stating its high-level intentions may have caused apprehension for the participants. This would seem to go against common bedside manner as practiced by human nurses. The speech prior to the robot's actions may have also resulted in a stronger tendency for participants to anthropomorphize the robot, which may have influenced their responses to the robot. Similarly, no warning may have resulted in participants perceiving the robot as more machine-like. Interestingly, in the open-ended responses, 11 participants who had not been warned stated that they would have liked to have been warned.

Further research will be required to confidently interpret these surprising results. For now, our results suggest that verbal warnings prior to contact should be carefully designed, if used at all, and that gesture can serve as a form of warning. When a robot should perform low-level communication of intention via gestures versus high-level communication of intention via speech remains an open question.

2.8.4 Negative Attitude Towards Robots Scale (NARS)

Our post-hoc analyses suggest that participants who have less positive attitudes towards emotions in interactions with robots as measured by NARS respond less favorably to robot-initiated touch. These results suggest that robot-initiated touch is related to emotional elements of interaction, and S3 subscale scores could be informative when a robot engages a person in such an interaction. However, we administered the NARS instrument after the experiment in order to avoid biasing the participants. As such, we found an association in the responses to NARS and other measures after the interaction, but we do not know if NARS responses collected prior to the interaction would have been predictive.

2.8.5 The Repeated Trial

Perhaps the most notable result from the repeated trial is that all participants allowed the robot to touch them again. Participants responded less favorably to the second interaction with the robot. It is likely that the nature of the repeated experiment resulted in people responding less favorably. The total experiment with both trials took approximately 45 minutes, included long periods of waiting, and involved filling out numerous questionnaires. In addition, the second trial was identical to the first, and consequently could have been less interesting to the participants.

2.8.6 Robot-initiated Touch for Healthcare and Medicine

Our results provide evidence that robot-initiated touch can be a practical form of human-robot interaction. Procedures associated with health and medicine often entail discomfort, such as when having blood drawn, receiving a bed bath, undergoing dental work, or being in the confined space of an MRI scanner. Our results suggest that robot-initiated touch can play a role in healthcare but that it need not be distressing for patients. However, further research will be required to generalize our results to real patients, including patients from other demographics who have not explicitly chosen to interact with a robot.

CHAPTER III

STUDY 2: A PHYSICAL INTERFACE TO NAVIGATE AND POSITION A ROBOT THROUGH HOSPITAL ENVIRONMENTS

In this chapter, 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. The results of this study were published in [36, 34].

Overall the results of this chapter suggest that nurses, with no robotics experience, could quickly learn how to effectively move ~160 kg robot using physical interaction. Consequently, physical interaction can serve as a valuable way for nurses to lead a robot.

3.1 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. 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 study, 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 [36]. In the current work, we present additional results from the evaluation performed in [36] 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 that 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.

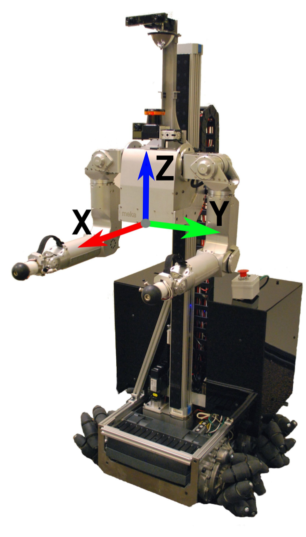


Figure 13: The mobile manipulator robot "Cody" used in this study.

3.1.1 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 U.S. and around the world [89, 69]. 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" [5]. Consequently, several studies have suggested that lowering the patient-to-nurse ratio would result in less missed patient care [5, 69, 90].

Nurses frequently experience work-related back injury [86, 172] 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 [142, 130, 80]. 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.

3.2 Related Work

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

3.2.1 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 (collaborative robots) have guided human movement through virtual fixtures [65], and researchers have developed dancing robots that respond to physical interaction with a human dance partner [178]. Among other tasks, DPIs have been implemented for rehabilitation robots [103], for object transfer [52], to direct robot's attention during learning [23], to demonstrate tasks [16], and to distinguish interaction styles [161]. DPIs have also been implemented on robotic walkers to provide navigation assistance, obstacle avoidance, and walking support for older adults [127, 151]. In addition, Argall and Billard have surveyed various forms of tactile human-robot interaction [10].

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 [6], Willow Garage's PR2 [192], and DLR's Justin [131] 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 [130]. 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.

3.2.2 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. Because 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 10.

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 HMMs. The DPI described in this study 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 10 have a humanoid morphology. Furthermore, for each of the humanoid robots in Table 10, the contact points that the human uses to control the robot are mostly found on the arms or the end effectors of the robot. Because 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 10 allow the user to move the robot in the general direction in which the control input is applied. This design 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 [8].

The human-scale mobile manipulators that have these direct physical interfaces 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.

Table 10: Examples of Direct Physical Interfaces used on Various Robots for Navigation.

Robot	Morphology	Interface Sensing	Control	Movement	Contact Point	Target User	Level of Autonomy
Cody [36]	Humanoid	Force, Joint angle	Proportional Control	Holonomic	Arm, End Effector	Nurses	Full User Control
RIBA [130]	Humanoid	Tactile	Intention, Pulling direction	Holonomic	Arm	Nurses	Full User Control; Semi-Auto. lifting
Justin [131]	Humanoid	Torque	(not known)	Holonomic	Arm	General	Full User Control
PR1 [194]	Humanoid	Torque	(not known)	Holonomic	End effector	General	Full User Control
PR2 [192]	Humanoid	Torque	(not known)	Holonomic	End effector	General	Full User Control
MS DanceR [178]	Humanoid	Force/ Torque	HMM (Intention)	Holonomic	Arm, Torso	Dance partner	Full User Control
Skill Assist [100]	Ceiling-mounted Cartesian	Force	(not known)	Cartesian, passive rotation	Handle	Factory worker	Full User Control
Romeo & Juliet [94]	Mobile Manipulator	Force/ Torque	Motion/ Force	Holonomic	Object in end effector	Construction worker	Full User Control

3.3 Implementation

In our study, we asked participants to control Cody (Figure 13, same robot used in Study 1) to complete a set of four tasks using two different interfaces: a gamepad interface and a DPI. The robot weighs roughly 160 kg. In this section, we will describe the robot used for this study and the implementation details for both of the interfaces.

3.3.1 Gamepad Interface

The gamepad interface consists of a Logitech Cordless RumblePad 2 game controller. As illustrated in Figure 14, 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 velocities are capped at a maximum of 0.15 m/s. The maximum left/right velocities are lower than those for forward/backward because 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.

3.3.2 Direct Physical Interface (DPI)

The DPI makes use of the Meka arms and the force/torque sensors at the wrists (Figure 15). 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

Figure 14: The gamepad interface.

that hold the wrist parallel to the forearm are position controlled with relatively high stiffness, and, consequently, do not bend significantly.

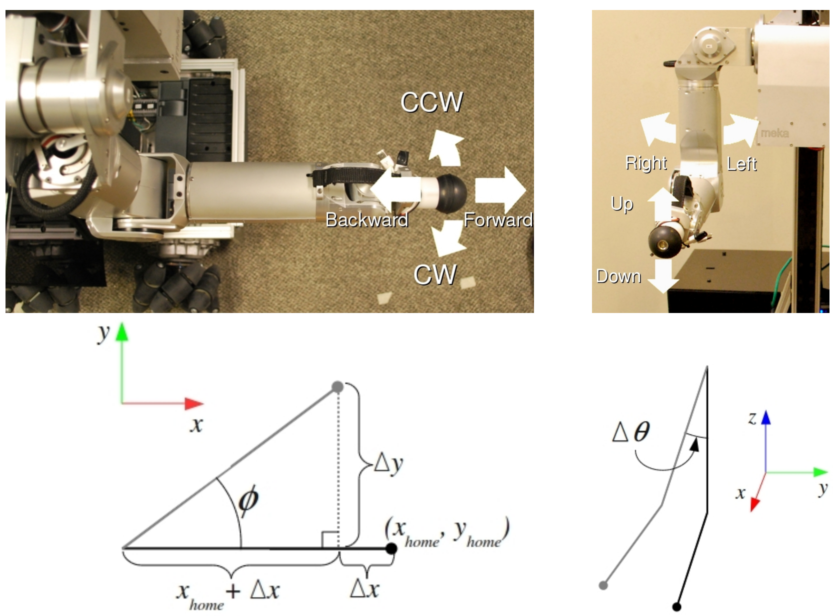


Figure 15: The Direct Physical Interface (right arm). Left: Overhead view. Right: Front view. The black lines represent the arm's *home position* and the gray lines represent an example of a user-directed position. Note that, in this example, $\Delta x < 0$.

As illustrated in Figure 15, 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 Figure 13. 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 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 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 degrees) (see Figure 15). In order to map these quantities to velocities, we use the following scaling factors:

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

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

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:

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

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

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

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

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

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.

Refer to Appendix C for design guidance regarding how to implement the robot behavior used in this study on other robotic platforms. Also refer to the code used for this study that we submitted as supplementary material to this thesis.

3.4 Methodology

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

3.4.1 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 12 for demographic information about the participants.

3.4.2 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.

3.4.2.1 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 16(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, 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.

3.4.2.2 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 16(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 *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.

3.4.3 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 x 3.7 m space as shown in Figure

(a)

(b)

Figure 16: Experimental setup. (IRB approval and user permission obtained) (a) A nurse performing the navigation task forwards. (Overhead view) (b) Bedside positioning task setup. The boxes denote robot end effector placement.

Table 11: Experimental Design

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

16(a). The users completed the forward and backward positioning tasks in a 4.3 x 3.7 meter simulated patient room as shown in Figure 16(b).

3.4.4 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 or gamepad interface) and (2) 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 x 4 tasks = 8 trials per subject, see Table 11). 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: (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 3.4.5. The surveys employed 7-point Likert scales, binary choice, the Raw Task Load Index (RTLX), and open-ended questions. The RTLX [79] 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. 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.

3.4.5 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. 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 7-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 shown below. While we didn't explicitly provide a definition of the term "comfortable" for the participants with respect to questionnaire items in this thesis, [39] defines it as "not causing any physically unpleasant feelings" and "allowing you to be relaxed".

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 robot's 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 Raw Task Load Index (RTLX) survey to assess the user's workload with respect to the tasks [79]. 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?
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?

3.5 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

Table 12: 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) hours/wk
Time spent playing video games	0 - 4 (M=0.64, SD=1.19) hours/wk

reported that they performed as well as tasks they thought a robot could perform and the tasks they felt wary of a robot performing.

3.5.1 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 five figures. Figure 17 shows the main effect of interface type on the number of collisions. Figure 18 shows our analysis of the time taken to complete the tasks. Figures 19 and 20 show the main effects of interface type on the measures associated with the intermediate survey. Figures 21 and 22 show the results from the final survey. We now discuss all of these results in more detail as they relate to our hypotheses.

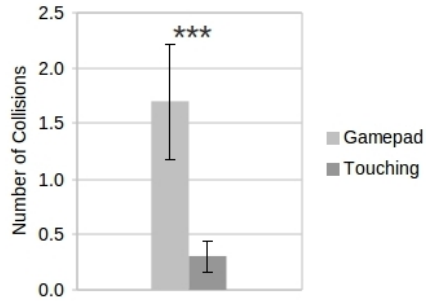


Figure 17: Main Effect of Interface Type on Number of Collisions. Standard error bars shown. ***$p<0.001$

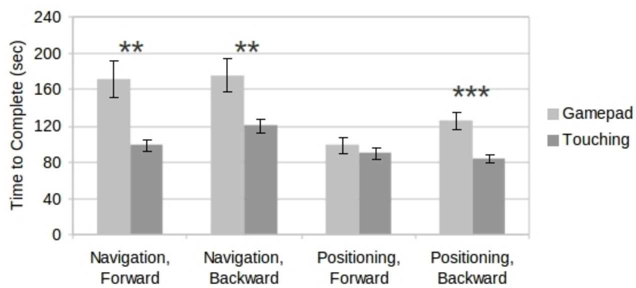


Figure 18: Simple Effects of Interface Type on Time to Complete (Seconds). Standard error bars shown. **$p<0.01$, ***$p<0.001$

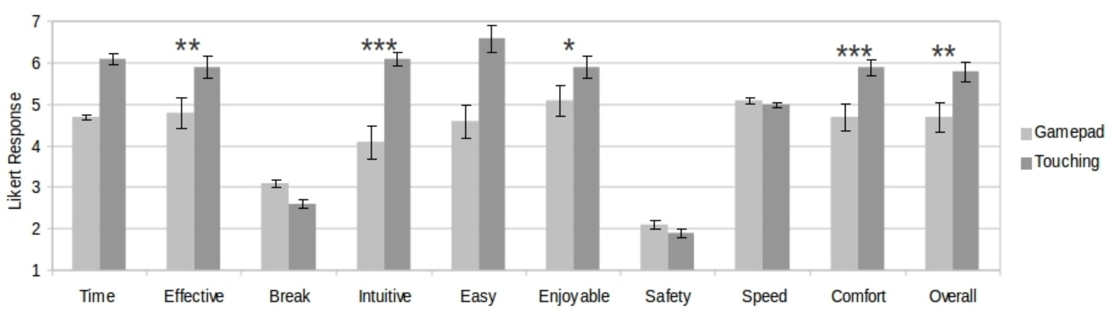


Figure 19: Main Effects for Subjective Intermediate Survey. Order matches Question order in Section 3.4.5. Standard error bars shown. *$p<0.05$,**$p<0.01$, ***$p<0.001$

3.5.1.1 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

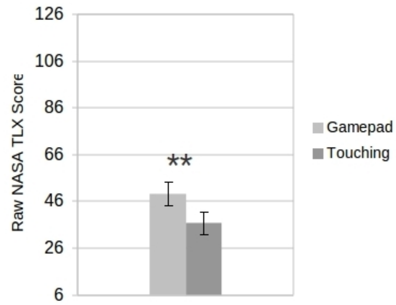


Figure 20: Main Effects for Subjective Intermediate Survey. RTLX response. Standard error bars shown. **$p<0.01$

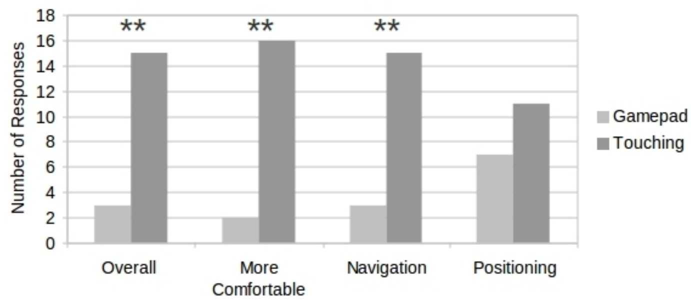


Figure 21: Final Survey Results. (Binary response) **$p<0.01$

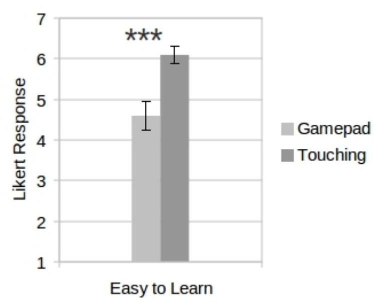


Figure 22: Final Survey Results. Easy to learn. Standard error bars shown. ***$p<0.001$

the tasks (Figure 20). In addition, subjects' objective performance was better when they used the DPI, because they produced significantly fewer obstacle collisions (Figure 17). Furthermore, subjects reported that they could more effectively use the DPI to accomplish their tasks than with the gamepad interface.

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 (Figure 18). These results are consistent with hypothesis 1.

3.5.1.2 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 Figures 19, 21, and 22).

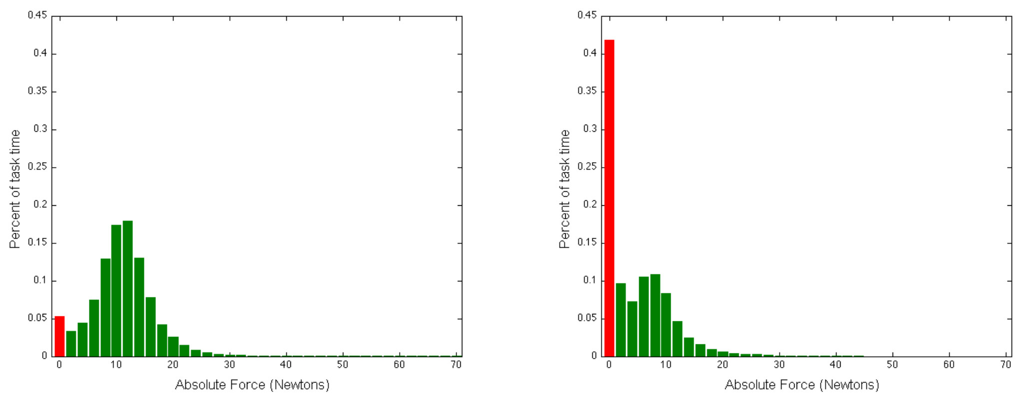
3.5.1.3 Hypothesis 3

Hypothesis 3 is also supported. Figure 21 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.

3.5.2 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 3.5.2 for each of the tasks involving the DPI. Forces at the end effector whose absolute values were below the thresholds of: f_x^{thres}=1.0 N or f_y^{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 two 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.

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



(a) (b)

Figure 23: Average magnitude of measured force applied in the x-y plane at end effector using the DPI. (a) Navigation tasks. (b) Positioning tasks

Furthermore, the plots in Figures 23(a) and 23(b) 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^{thres}=1.0 N and f_y^{thres}=2.0 N thresholds (shown in red) 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 24 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

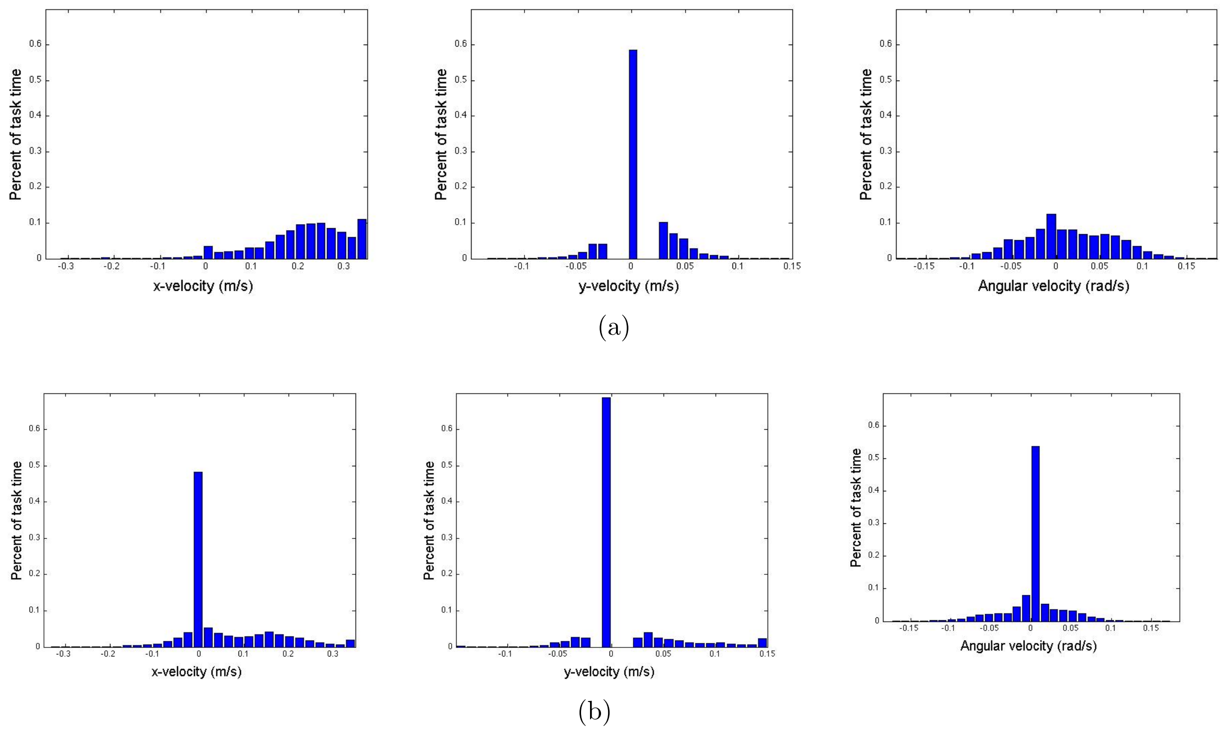


Figure 24: Measured velocities using the DPI. (a) Navigation, Forward task. (b) Positioning, Forward task.

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 24(a) 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.

3.5.3 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 13 shows that almost all of the nurses (17 out of 18) reported that they charted or documented patient information. 15 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. 13 nurses reported that they administered medicine to patients and 12 nurses reported that they performed patient assessments. The table 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 and 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 14. 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 14).

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 wheelchairs from a standing position, due to the fact that 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

Table 13: Nursing tasks performed throughout the day.

Task	Enjoyment Mean	Enjoyment Std Dev	Number of Responses
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

Table 14: Left: Tasks that nurses felt could be performed by a robot. Right: Tasks that nurses were wary of a robot performing.

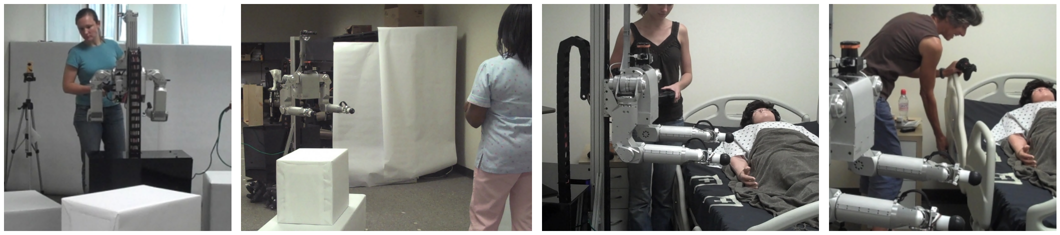
Task	Number of Responses
Moving patients	16
Janitorial	7
Retrieve/move objects	6
Bathing	5
Feeding	4
Transfer/restock supplies	4
Charting/Documentation	3
Monitoring vital signs	3
Dressing patients	3
Deliver meal tray	3
Administering Medicine	2
Errands	2
Assessment	1
Patient/family Education	1
Other information handling	1

Task	Number of Responses
Administering Medicine	9
Assessment	7
Blood work	5
Feeding	2
Touch patient	2
Moving patients	1
Patient/family education	1
Monitoring vital signs	1

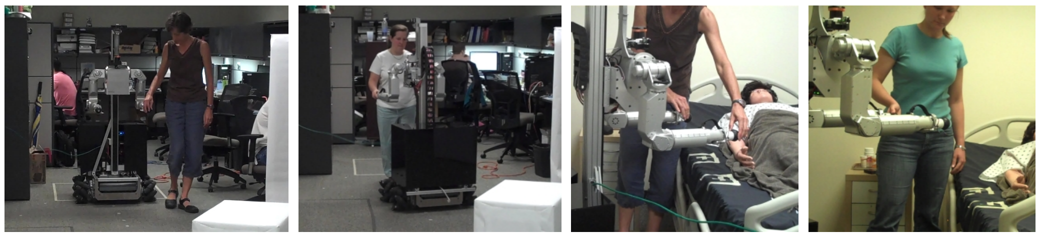
patients, while another said it was similar to when she "guided" patients' hands to perform a task. One nurse even compared using the interface with using a lawnmower. No nurses made a comparison between the gamepad interface and another activity. In the final survey, 10 nurses reported being "confused" 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.

3.6 Discussion and Conclusion

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



(a)



(b)

Figure 25: Examples of user postures. (IRB approval and user permission obtained) (a) Nurses using the gamepad interface. (b) Nurses using the DPI.

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 Figures 16(a) and 25). 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 [9, 45]. 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 Figure 24 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 because 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.

CHAPTER IV

STUDY 3: EVALUATION OF HUMAN-ROBOT PARTNERED STEPPING WITH EXPERT DANCERS

In this chapter, we asked expert dancers (N=10) to evaluate the ability of a compliant robot that used an admittance controller to generate whole-body motion to engage in a forward/backward walking step. We varied the admittance gain of the controller for the mobile base and the robot's arm stiffness. The robot followed the participants with low lag (224±194 msec) across all trials. 60% of the participants said that the robot was a good follower. High admittance gain and high arm stiffness conditions achieved significantly better performance according to subjective and objective measures. Biomechanical measures such as the hand to sternum distance, CoM-CoM distance, velocity, and forces correlated with the participants' subjective ratings which were internally consistent (Cronbach's α=.92).

Overall, the results of this chapter suggest that a simple admittance controller can be used to engage in partner dance and could also be used to engage users in exercise.

4.1 Introduction and Related Work

Partner dance is an effective rehabilitation intervention that relies heavily on haptic interaction between individuals. Partner dance has been shown to improve balance, gait, functional mobility, and functional autonomy in people with Parkinson's disease (PD) [70, 73, 19]. It can even be effective for people with severe PD, in part, because physical contact with a partner provides stability [70, 73]. Participants undergoing partner dance therapy expressed enjoyment, satisfaction, improved well-being, and interest in continuing the therapy [73].

In partner dance, such as waltz, foxtrot, and tango, partners communicate haptically through constant physical contact in order to generate coordinated, whole-body motion. This contact is made via a configuration of their hands and arms called their frame. Effective communication is crucial to the interaction because partner dance is often improvised without a set sequence of steps [126], and haptic interaction is sufficient to perform partner dance with complicated movements [62, 64]. As such, partner dance may serve as a useful paradigm for scientific inquiry into whole-body motor cooperation where explicit motor goals (e.g., direction, velocity, and distance to travel) are haptically communicated [162].

Robots may be able to play beneficial roles in partner dance therapy, such as serving as dance partners, performing assessments of participants, and acting as scientific instruments with which to conduct research. Robots for upper and lower extremity rehabilitation have successfully performed comparable roles, from helping people recover function [57, 85, 22] to performing diagnostic assessments [38].

Within this study, we focus on the goal of developing a rehabilitative robot dance partner. Specifically, we investigate the potential for a mobile robot with an omnidirectional wheeled base and compliant arms (i.e. a mobile manipulator) to engage in a simple partner dance with expert dancers. We build on Chapter 3 where we demonstrated that nurses could intuitively and effectively guide a robot by its end effectors. For this study, we use the same robot with a very similar admittance controller that commands the robot's mobile base velocity to be proportional to the forces applied to the robot's end effectors.

A key distinction from previous research is that we conducted a formal study in which experts dancers haptically interacted with our robot and evaluated its performance. Much of the prior research with dancing robots has focused on visual interactions and participants who were not expert dancers [166, 134, 123, 135, 11]. The more limited research that has looked at partner dance involving physical contact with humans has not involved formal evaluation with expert dancers [179, 180, 87, 189, 63].

We asked expert dancers to perform a simplified partner dance that we call the “partnered stepping task” (PST), which is a 1 degree-of-freedom (DoF) forward/backward walking step. We defined expert dancers as having 10 years of dance experience and 2 years of partner dance instruction experience. We focused on expert dancers for the following reasons: (1) effective rehabilitative partner dance has relied on expert dancers as instructors, (2) expert dancers can perform the cooperative motor task with high skill due to years of training, which can serve as a model for future robotic performance, (3) our expert dancers have been instructors and hence are uniquely qualified to evaluate and communicate the quality of dance [112], and (4) expert dancers allow us to characterize skilled interaction prior to working with non-experts with balance and gait disorders, whom we expect to be much more variable in their performance.

In addition to evaluating our robot’s performance using subjective measures, we identified objective biomechanical measures that correspond with favorable subjective dance experience. The biomechanical measures we identified can potentially help evaluate the performance of partner dance robots in the absence of expert dancers and quantify the effects of controller parameters on performance. We defined the PST in order to maintain consistency across participants, to measure the success of performing the task with the robot, and to provide justification for the set of biomechanical measures that we considered.

We also manipulated properties of the robot that might affect the haptic interaction during the PST to study their contribution to the interaction. In this work, we altered the robot’s arm stiffness and the admittance gain for the mobile base controller as part of a 2x2 within-subjects experiment. Varying properties of the robot also allowed the participants to evaluate varying degrees of the robot’s performance in order to create a range of values for correlation of the subjective responses and objective biomechanical measures.

With this work, we make several contributions. First, we defined the partnered stepping task (PST) and created a questionnaire to measure subjective dance quality. Second, we found that expert dancers were able to successfully perform the PST with a robot using only haptic interaction. Third, we found that a majority of expert dancers in our study interpreted the robot as following them well, and half found the robot to be fun to dance with. This is especially promising, given the straightforward controller for the robot's mobile base and the simplicity of the PST. Fourth, we identified biomechanical measures correlated with subjective dance quality for the PST, including the human's hand to sternum distance, inter-partner separation, velocity, and forces at the hands. Fifth, we found that high admittance gain resulted in better subjective and objective dance performance. Taken as a whole, these contributions make progress toward designing an effective dance partner robot to provide rehabilitative therapy for those with balance disorders.

4.2 Controller Design and Its Relationship to Other Human-Robot Dance Controllers

In this study, we use a simplified version of the controller that was used in Chapter 3. The original controller enabled naive users to lead a robot through complex environments with high subjective and objective performance. For our simplified version, we restricted the omni-directional robot to move forward and backward. The mobile base controller is a straightforward admittance controller that commands the velocity of the robot's base to be proportional to the sum of the forces applied at the robot's end effectors (see Section 4.3.1 for details). In addition, for two of the four conditions we tested, we commanded the robot's torque-controlled arms to have low proportional gains resulting in high compliance at the robot's end effectors. Together, the complete system can be interpreted as behaving like a damper in series with a spring with the robot's base motion emulating a damper and the robot's arms acting as a spring.

As we discuss in detail below, our controller is similar to controllers used for other robotic dance partners. Two notable differences with respect to some other controllers are the lack of a simulated mass element and the simplicity of our controller. In the context of this study, both design choices have advantages. First, our system stops moving in the event that the human loses contact with the robot's end effectors. This serves as a form of dead-man's switch that reduces the chance of our ∼160kg robot colliding with or running over participants. This may be an especially important consideration for naive users with impairments, which is our ultimate target population. Simulating a mass element would result in simulated inertia of the system and would require additional control elements to detect loss of contact and bring the robot to a halt. Second, while a number of research groups have developed elaborate controllers for human-robot dancing, careful evaluation of human-robot dance controllers through human studies has been limited. Our system is both simple and practical. The simplicity of our control system and the PST enabled us to focus our study on the relationship between biomechanical measures and subjective perceptions of dance. We varied key factors, such as the compliance of the robot's arms, while avoiding potentially confounding factors, such as using a hybrid controller with discrete states. The practicality of our system increases the relevance of our results, because there would be fewer impediments to producing and deploying the technology in clinically relevant settings. The present study the study presented in Chapter 3 suggest that even this simple controller can result in both task success and positive interactions, which is promising for the future of robot-facilitated partner dance therapy.

In previous work, Gentry et al. used a force controller to allow a PHANToM haptic device to lead human participants' hands through randomly sequenced trajectories [63]. A PD controller fed a force back to the user's hand through the device's stylus with respect to a reference position and velocity.

Holldampf et al. use vector fields to enable a human-scale robot to lead a human through previously recorded trajectories from human dance couples [87]. They also scaled the robot's trajectories based on forces measured at the hands to prevent the robot from dragging or pushing the human. The human interacts with the robot using an admittance-type haptic interface [144].

Takeda et al. issued velocity commands to the MS DanceR robot that were comprised of two velocity terms. The first term was a scaled version of pre-recorded velocities from human demonstrations. The second term was computed using a mass-damper model of forces at the robot's torso [179]. They demonstrate that the velocity generated from the second term allowed the robot to follow the human even if the robot's "stride length" scaling did not match the human's.

Wang and Kosuge modeled the dynamics of a human and MS DanceR robot as a connected pair of inverted pendulums. They used the model to minimize the interaction force [189]. Their results suggested that the inverted pendulum model was better able to reduce the interaction force compared with a virtual force from the human's estimated trajectory.

Bussy et al. [27, 26] enable the HRP-2 robot to carry a table with a human partner by using a trajectory-referenced admittance control law as well as a finite state machine to transition the robot's motion primitives when both leading and following.

Duchaine and Gosselin [49] found that using variable impedance control with force derivatives and a velocity controller resulted in better task performance during pick and place and drawing tasks between a human and robot compared with standard impedance control.

4.3 Implementation

This section describes the controllers used for this work. Our control system consists of a mobile base controller, which approximates a damper, as explained in Section 4.3.1 and robot arm controllers, which approximate springs, as described in Section 4.3.2. We also describe the robot's arm stiffness settings for the experiment as well as details of the motion capture system. For this study, we used the robot Cody which was also used in Studies 1 and 2.

4.3.1 Control of the Mobile Base

We used an admittance controller to control the motion of the robot's mobile base in response to forces applied to the robot's end effectors. The velocity commanded to the robot's base in the forward/backward direction $\dot{x}$ was computed using the equation

$$\dot{x} = c \cdot f_{tot} \tag{6}$$

where c is an admittance gain (using the terminology of [2]) and f_{tot} is the sum of the forces at the robot's end effectors in the forward/backward direction. The relationship between the force and velocity can be interpreted as a damper. The maximum commanded velocity was limited to 0.7 m/s in either direction, where 0.6 m/s is the minimum walking speed required for independent living [176]. We use a Kalman filter on the force sensor readings below 3N. We also averaged the three most recent commands for $\dot{x}$ in order to reduce noise and smooth velocity transitions. The *gain* setting was an independent variable in the experiment for this study where the admittance gain was set to $c = 0.01m/sN$ and $c = 0.02m/sN$ for the low and high gain settings, respectively (Section 5.4). The high gain setting was similar to the setting used with nurses in Chapter 3.

We used a digital voice recorder to characterize the time delay between the onset of an applied force at the end effector and the onset of motion of the robot's base. The average time delay for 5 trials for each of the treatment conditions were: *low gain, low stiffness*: M=171, SD=34 ms, *low gain, high stiffness*: M=157, SD=24 ms, *high gain, low stiffness*: M=125, SD=28 ms, and *high gain, high stiffness*: M=109, SD=6 ms.

4.3.2 Control of the Arms

We commanded the torque-controlled arms to maintain a bent elbow posture throughout the interaction (see Figure 26). We set the stiffness for the shoulder and elbow joints in order to attain a desired stiffness at the end effector in the forward/backward direction. This stiffness primarily resulted from the elbow stiffness and one of the shoulder joints. We set the pitch and yaw wrist joints to be in a high-stiffness position control mode for all four conditions to keep the end effectors parallel to the forearms.

At the high stiffness setting for the independent variable of *stiffness*, we attached a custom-fit, laser cut acrylic rig (see Figure 26) to Cody's upper arm in order to make the arms stiff in the forward/backward direction. In addition, we commanded high stiffness values at the shoulder and elbow joints. For the low stiffness setting, we removed the rig to allow the arm to rotate freely at the shoulder joint. In addition, we commanded low stiffness values at the shoulder and elbow joints. We placed a black t-shirt over the shoulders of the robot to cover the rig to disguise its presence or absence for the trials.

We measured the stiffness at the end effector for each of the conditions by displacing the end effector in the forward/backward direction while the robot was in the arm configuration used for the experiment. We measured the resultant forces at the end effector using the force/torque sensors and the displacements using the motion capture system. We took the slope of the line that best fit the force vs. displacement scatterplot under both stiffness conditions. We averaged the stiffness values from the left and right arms for each of the conditions where high stiffness was 2050 N/m

(R^2=0.91) and low stiffness was 543 N/m (R^2=0.94). While the high stiffness setting was several times higher than that of the low stiffness setting, it was not completely rigid and was still more flexible than an industrial manipulator, for example.

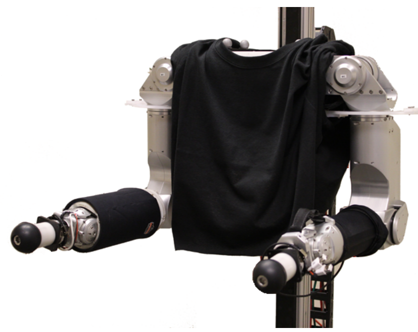


Figure 26: Acrylic rig used in the high stiffness condition.

Refer to Appendix C for design guidance regarding how to implement the robot behavior used in this study on other robotic platforms. Also refer to the code used for this study that we submitted as supplementary material to this thesis.

4.3.3 Motion Capture

We tracked the motion of the human expert dancer and robot using the NaturalPoint OptiTrack motion capture system and Tracking Tools software (Corvallis, OR). We tracked the position and orientation of iotracker (Vienna, Austria) rigid body targets, each comprised of four retro-reflective markers mounted on a base. We placed a rigid body target on the human's sternum, shoulders, hands, and shanks using elastic straps (Figure 27). We placed one custom made rigid body target on the robot's torso.

4.3.4 System Characterization

We experimentally measured the system gain and phase for the low gain, low stiffness treatment by applying sinusoidal velocity inputs at Cody's left end effector using a linear actuator at varying frequencies. We measured the force at Cody's end effector as the input and the velocity at the end effector as the output. The results of the analysis are shown in the Bode plot in Figure 28. We model the interaction between

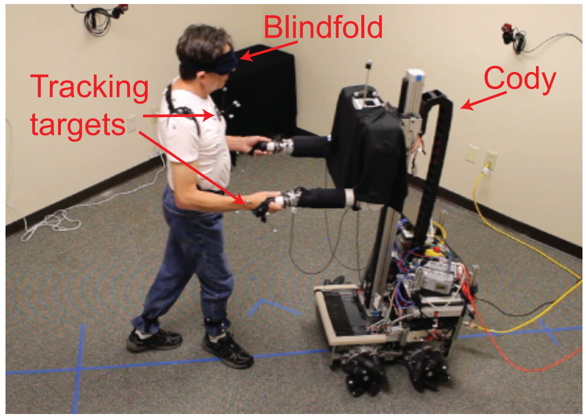


Figure 27: Experimental setup. An expert dancer leads the robot Cody during partnered stepping.

the linear actuator and the robot arm using a spring-damper model as shown in Figure 29. The values of the spring and damper constants are k = 543 N/m and b = 100 sN/m, respectively. The theoretical magnitude and phase plots of the transfer function of the spring-damper model are shown in Figure 28 using dashed lines. The damper dominates at low frequencies and the spring dominates at high frequencies. The empirical magnitude and phase plots are similar to the ideal ones across all frequency ranges.

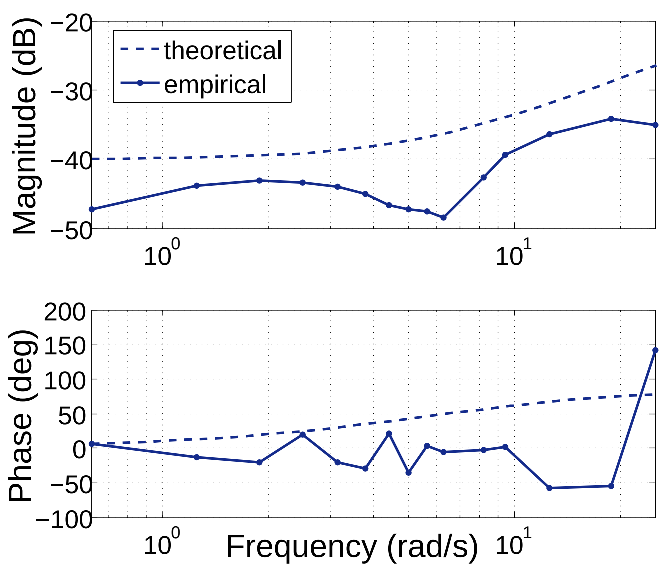


Figure 28: Bode plot for Low Gain, Low Stiffness. Input and output are force and velocity at the end effector, respectively. Empirical curve shows measured response of the robot. Theoretical curve shows the response of the ideal spring-damper model.

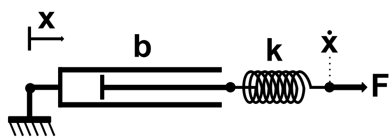


Figure 29: Model of the robotic system. The damper with damping coefficient b corresponds with the mobile base and the spring with spring constant k corresponds with the robot's arm. F and $\dot{x}$ are the force and velocity at the robot's end effector.

4.4 Methodology

This section describes the recruitment procedure, experimental design, experimental procedure, and the objective and subjective measures.

Table 15: Glossary of dance terminology. This glossary is used for terms in the Dance Quality Questionnaire (Table 16).

Term	*Definition*
Frame	A stable but flexible configuration of the arms and bodies of both the partners. In this experiment,the frame is comprised of the arms and bodies of you and the robot, connected at the hands.
Connection	Using the frame to transmit information through the hands in the form of direction, distance, and rotation, as well as intensity of movement, e.g., velocity and accent.
Timing	The coordination of movement to a pattern of beats that have a strong relationship with the phrasing tempi, and beats of a musical selection.

4.4.1 Recruitment

We recruited 11 expert dancers via word of mouth but only included the data from 10 participants (N=10) in our analysis because the robot's plastic arm rig broke while running the experiment with one participant. Several participants were acquaintances of one of the authors. We obtained informed consent from all participants according to our experimental protocol that was approved by the Institutional Review Boards of the Georgia Institute of Technology and Emory University. We required participants to meet the following inclusion/exclusion criteria: 18 years of age or older; 10 or more years of dance experience; 2 or more years of partner dance instruction experience; and no history of neurological disorders. We told participants that they would engage in partnered stepping and would interact with technology. We did not mention that the participants' partner would be a robot so as to avoid biasing participants. The demographics of the participants were: 4 female, M=43.5, SD=12.4 years of age, M=19.1, SD=13.4 years dance experience, and M=8.9, SD=6.3 years partner dance instruction experience.

4.4.2 Experimental Design

We conducted a 2x2 within-subjects design experiment with 3 repetitions of each treatment. We tested the independent variables of:

- *Gain*: high ($c = 0.02$ m/sN) vs. low ($c = 0.01$ m/sN)
- *Arm stiffness*: high (2050 N/m) vs. low (543 N/m)

We randomized the treatments in blocks of four and assigned three blocks to each participant for a total of (2 Gain) x (2 Arm stiffness) x (3 repetitions) = 12 trials per participant.

4.4.3 Procedure

The experiment took place at the Healthcare Robotics Lab (Atlanta, GA) in a 8.5 m x 3.7 m room while the initial paperwork and questionnaires took place just outside the room. An experimenter welcomed the participant and asked him or her to fill out a consent form, reimbursement paperwork, and a demographic information and pre-task questionnaire.

The experimenter told the participant that he or she would serve as the leader and that the robot would serve as the follower. The participant was instructed to interact with the robot performing a basic dance step, and to perform the step in a way that he or she was familiar with in partner dance. The experimenter instructed the participant on how to perform the task:

- Hold onto the robot's end effectors.

- Lead the robot backward 3 steps, starting on the right foot.
- Collect the feet together by skimming the left heel above the floor and without shifting weight onto the left foot.
- Lead the robot forward 3 steps, starting on the left foot.
- Collect the feet together. (end of once cycle)
- Repeat until four cycles are completed.
- Hold pose at the end of the last cycle until the experimenter says that it is ok to let go of the robot.

We instructed participants to step at 42 beats per minute while listening to music playing a synthesized drummed beat at 84 beats per minute. We allowed them to take whatever size step they were comfortable within boundaries marked on the floor. The distance between these boundaries was 2.6 m.

The participant practiced the dance step without the robot until he or she was comfortable. The experimenters adjusted the robot's height until the elbow height was comfortable. Then the participant practiced the dance step with the robot. During the practice, we set the robot's arm stiffness and gain settings corresponding with the first treatment in the randomization for that participant.

Once the participant was comfortable performing the task, the experimenter placed the markers on the participant. The experimenter stated that the participant would perform the task with the robot 12 times and that the robot may or may not respond differently each time. The experimenter asked the participant to read a hard copy of the dance quality questionnaire along with a glossary (Tables 15 and 16) and told the participant that he or she would be asked this questionnaire after each of the trials. The experimenter told the participant that his or her task was to focus on the interaction with the robot and to keep the questionnaire questions in mind.

Participants wore a blindfold and closed their eyes while wearing the blindfold for all of the trials. After the completion of a trial, the participant removed the blindfold and completed the dance quality questionnaire on a computer. We provided a hard copy of the glossary for reference next to the computer. We offered a snack and water to the participants during waiting times between trials.

After the participant completed the trials, the experimenter removed the tracking markers from the participant's body and then asked the participant to complete a final questionnaire and a final interview. The entire experiment took approximately 2.5 hours.

4.4.4 Defining the Partnered Stepping Task (PST)

For this work, we defined the PST as:

1. partners are human-scale and in upright, standing posture, facing each other,
2. partners are constantly physically coupled through the frame (involving the upper limbs and torso),
3. haptics is the primary mode of interaction between the partners (no visual or auditory cues),
4. the whole bodies (e.g. centers-of-mass (CoMs)) of both partners move during over-ground walking,
5. one partner is designated as the "leader" who initiates direction and velocity changes,
6. human participants in the task maintain a cadence that is synchronized with an external auditory signal,
7. the leader moves his or her CoM in the forward/backward direction (1DoF) with multiple steps,
8. the other partner (i.e., the robot) is designated as the "follower" who interprets and executes instruction cues from leader through haptics.

The PST is a representative task of partner dance because dance partners must step together in some agreement in order to effectively dance together. Further, Moore, a leading authority in ballroom dance technique, states that "To be able to walk properly in a forward and backward direction is the basis of ballroom dancing" [126].

In our experiment, items 1 and 2 of the definition of the PST would be satifised if the participants correctly executed the procedure in Section 5.4.2. Item 3 is satisfied due to the design of Cody's mobile base controller where only forces are used as input as well as the fact that the participants are blindfolded and do not receive auditory feedback from the robot. Furthermore, item 5 of the PST is satisfied because the participants are instructed to serve as the leader and the robot is only capable following by reacting to forces at the end effectors. Thus, if items 1, 2, 4, 6, 7, and 8 are satisfied during the execution of the interaction, the PST would be defined as successfully completed. We defined biomechanical measures that indicated satisfactory performance of several of these remaining items in Section 4.4.6.

4.4.5 Subjective Measures of Dance

To conduct an evaluation of our system with expert dancers, there is a need for subjective measures (e.g. a questionnaire instrument) to evaluate partner dance from the perspective of a partner through haptics. Although visually-based judging criteria of solo dance and partner dance exist from the perspective of a third party [184, 33, 112, 101], such an instrument focusing on haptic evaluation does not exist. In this work, based on consultations with experts and literature sources, we developed the dance quality questionnaire shown in Table 16. The questionnaire instrument incorporates questions regarding information that may be encoded in the haptic interaction.

Table 16: Dance Quality Questionnaire. Measured using 5-point scale. 1="Strongly Disagree," 3="Neutral," 5="Strongly Agree."

Type of skill	*Question* The robot...
Motor	maintained connection well.
Intent	was easy to communicate with.
	understood the direction in which I wanted it to go.
	understood the speed at which I wanted it to go.
	understood how far I wanted it to go.
Motor	was easy to move with.
Performance	maintained its frame well.
	responded with good timing to mine.
	was too heavy.
	moved in the direction in which I wanted it to go.
	moved at the speed at which I wanted it to go.
	moved how far I wanted it to go.
Motor	did not rush me.
Skill	gave me "just enough" space to move together well.

The questions are measured using 5-point Likert items where 1 = "Strongly Disagree," 3 = "Neutral," and 5 = "Strongly Agree." We also used the accompanying glossary of terms shown in Table 15 where we adapted some definitions from [17]. We administered a final questionnaire at the end to assess the participants' overall experience. The final questionnaire was comprised of the 5-point Likert items of: (1) The robot was fun to dance with. (2) I was dancing with the robot. and (3) The robot was a good follower.

4.4.6 Biomechanical Measures of Dance

We used kinematic and force data from each trial to objectively characterize measures of synchrony between the expert dancers and Cody that would correspond with successful performance of the PST. We computed the mean force (N) at the hands, the velocity (m/s) of the human and robot partner, CoM-CoM distance (distance between the centers of mass of human (sternum marker) and robot) (m), CoM-CoM variance (standard deviation of CoM-CoM distance) (m), human left hand to sternum distance (m), human left hand to sternum distance variance (standard deviation of human left hand to sternum distance) (m), per trial both when the human was walking forward and when walking backward. We performed a cross correlation between the trajectory of the human and the trajectory of the robot in order to compute the lag time (ms) of the robot behind the human for each trial.We determined the zero-crossings of the velocity of the right and left shank markers to determine when the participants placed their feet on the ground (shown as black circles in third plot of Figure 30). Using this information, we computed the average time between each of the participants' footfalls to measure the participants' average cadence (s) during each trial. We also computed the variability (standard deviation of cadence) (s), root mean square (RMS) (s), and the mean-squared error (MSE) (s) of the cadence.

We expected that these measures would be correlated with responses to the dance quality questionnaire (Table 16). Several of these measures may correspond with the objective in partner dance to move together while allowing the leader to have enough space to be comfortable initiating direction and speed changes (i.e., low variability of human hand to sternum and CoM-CoM distance, low lag). The leader may also wish to do so using a minimal amount of force.

Furthermore, several of these measures have been used in previous studies on human-robot partner dance [179, 189] as well as in a study on the regulation of interpersonal distance between a pair of humans in a forward/backward walking task [50]. We expect that these baseline measures will enable future comparisons with subjects who may have balance disorders (as done in [44, 143, 175]) or lower dance skill level.

4.4.7 Statistical Analyses

To determine the effects of the gain and robot arm stiffness factors, we conducted a two-way, repeated measures ANOVA with 3 repetitions on the responses to the dance quality questionnaire as well as the biomechanical measures. We did not correct for multiple comparisons. We also performed one-sample t-tests on the responses to the final questionnaire, comparing them with a response level of 3.

We also performed Pearson's correlations between the biomechanical measures and responses to the dance quality questionnaire. Correlations that were significant with α=.05 corresponded with a Pearson's correlation of $r(120)<-.18$ for significant negative correlations and $r(120)>.18$ for significant positive correlations which are denoted in Figure 32 as black and white colored squares, respectively.

We performed psychometric analyses on the responses to the dance quality questionnaire to assess its reliability and validity which are fundamental aspects of an accurate measurement instrument [181]. We computed a Cronbach's alpha value to measure the internal consistency of the 14-item dance quality questionnaire. We also computed intra-class correlation coefficients (ICCs) to measure the inter-rater reliability among participants as well as the test-retest reliability among the three repetitions of the treatments. For these values, we referred to the general cutoff of .8 as indicating good consistency and reliability [98, 59] but considered lower values as acceptable due to the low number of subjects.

4.5 Results

We present the results with respect to the contributions of this work and include suggestions for improvement of the interaction from participants.

4.5.1 Expert dancers successfully engaged in partnered stepping with a robot

Expert dancers interacted with the robot Cody according to the specifications of the PST in Section 4.4.4. Items 1 and 2 of the definition were satisfied by our observations that the participants completed the task procedure instructed to them in Section 5.4.2. Items 4, 7, and 8 were satisfied by our observation of the biomechanics

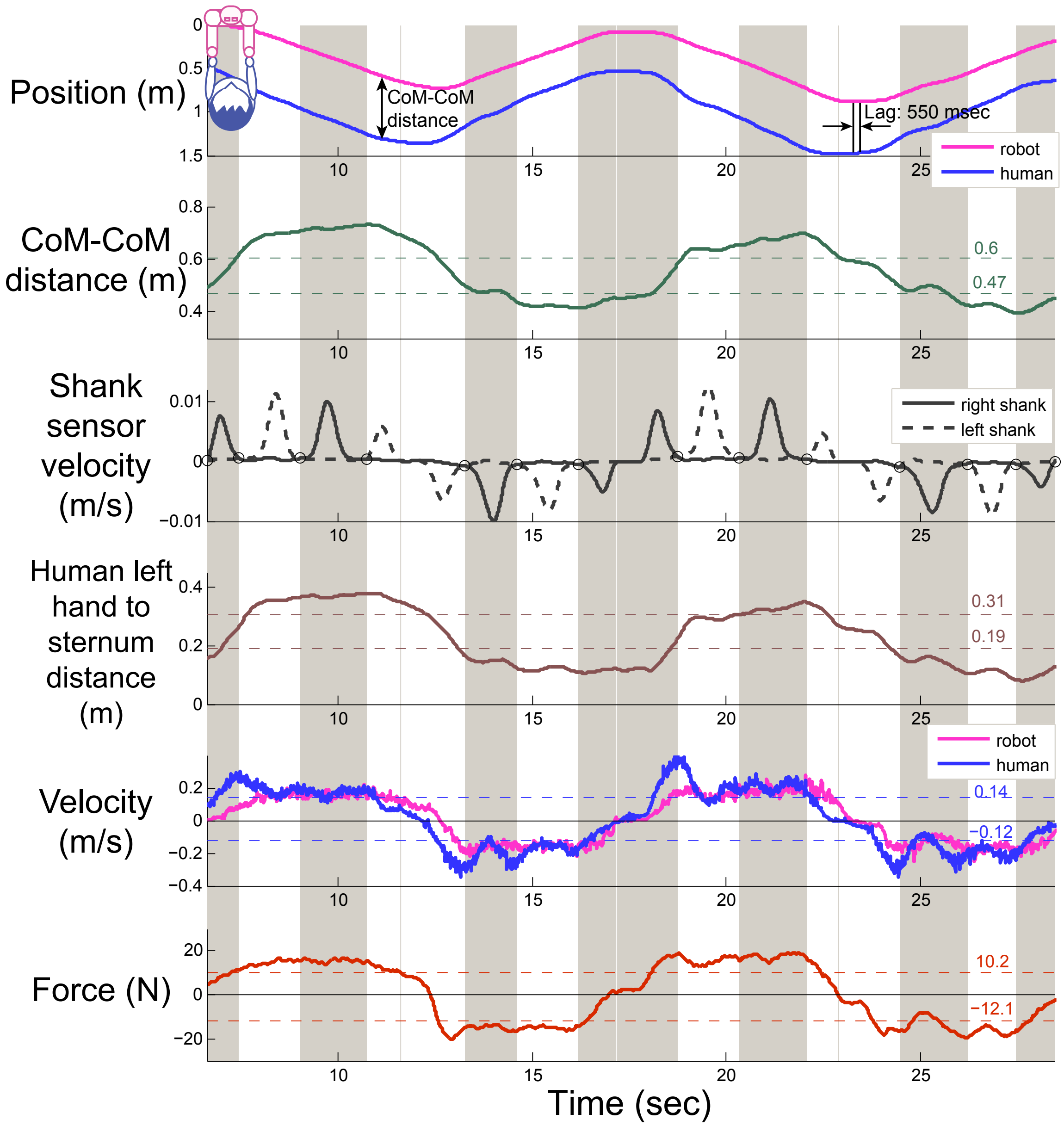


Figure 30: Biomechanics of human-robot partnered stepping. Example data from two cycles of one trial from one participant. Gray and white bars indicate intervals of time when right and left feet were on the ground, respectively. The experimental treatment for this trial was low gain, low stiffness.

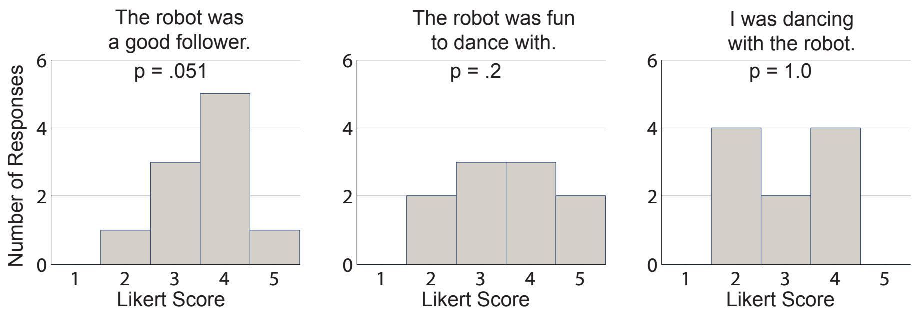


Figure 31: Final questionnaire responses regarding overall experience. Response level of 1="Strongly Disagree," 3="Neutral," 5="Strongly Agree." p-values show results from one-sample t-tests comparing with a response level of 3.

(example shown in Figure 30) that the CoMs of the human and robot moved in the forward/backward direction with multiple steps taken before each direction change. Furthermore, the average lag time of the robot behind the human was 224±194 msec across all conditions. This lag result was similar to results in [50] that reported average time lags ranging from 220 to 290 msec between human leader-follower pairs using visual cues. Also, the robot maintained a relatively consistent CoM-CoM distance as shown in the position trajectory in Figure 30 where CoM-CoM distance ranged from 0.39 to 0.72 m and averaged 0.54±0.06 m across all conditions with relatively low variance (standard deviation is 6cm). Item 6 was satisfied due to the participants averaging a time of 1.41±0.02 sec between each step across all conditions which is within one standard deviation from the expected 1.43 sec per step cadence of the external auditory signal played at 42 bpm.

4.5.2 Expert dancers viewed the PST with a robot to be fun, similar to dancing, and effective following (some of them)

60% of the participants agreed (responded with a response level of 4 or 5) that the robot was a good follower, 50% said that the robot was fun to dance with, and 40% said that the interaction with the robot was similar to dancing (Figure 31). While none of the distributions of responses were significantly greater than a response level of 3, these results are promising in that a majority felt that the robot was able to follow while at least a portion of the participants felt that the interaction was actually fun and similar to dance.

Participants generally agreed with the statement: "The robot was a good follower." (*M*=3.6, *SD*=0.8, Figure 31).

- The 6 participants who responded with a response level of 4 or 5 (60%) mentioned that the robot had good connection, speed, and timing.
- Of the 3 participants who responded with a response level of 3 (30%), 1 participant expressed the robot was slow to react or was too heavy, and had to "[work] hard."
- Only one participant disagreed (response level of 2) (10%). This participant stated that she had to make her frame more rigid or apply more force during some of the trials, and mentioned that the robot lagged or resisted too much to the direction or speed that she wanted.

Participants also responded favorably to the statement: "The robot was fun to dance with." (*M*=3.5, *SD*=1.1).

- 5 of the participants (50%) responded with a response level of 4 or 5. 3 of these participants compared the robot with a human in a positive way. For example, one participant stated: "I didn't quite expect a robot to follow as well/better than some human dancers." 2 participants mentioned that the experiment was "different" while 1 participant said it "engaged my curiosity."
- 3 of the participants (30%) responded with a response level of 3. 1 of these participants mentioned that the task was simple and allowed him to think about the robot's "reaction," while another participant said that the task "was neither fun or not fun" because the direction of the task did not vary and felt that the robot was "mechanical." The third participant stated that the interaction was "once in a lifetime" and "high-tech" but that the robot did not always follow smoothly.
- 2 of the participants (20%) disagreed (response level of 2) and both mentioned that the interaction or robot was "novel." 1 of these participants felt that the interaction

was “monotonous” but that the ”variety” of the interaction came from moving with the robot.

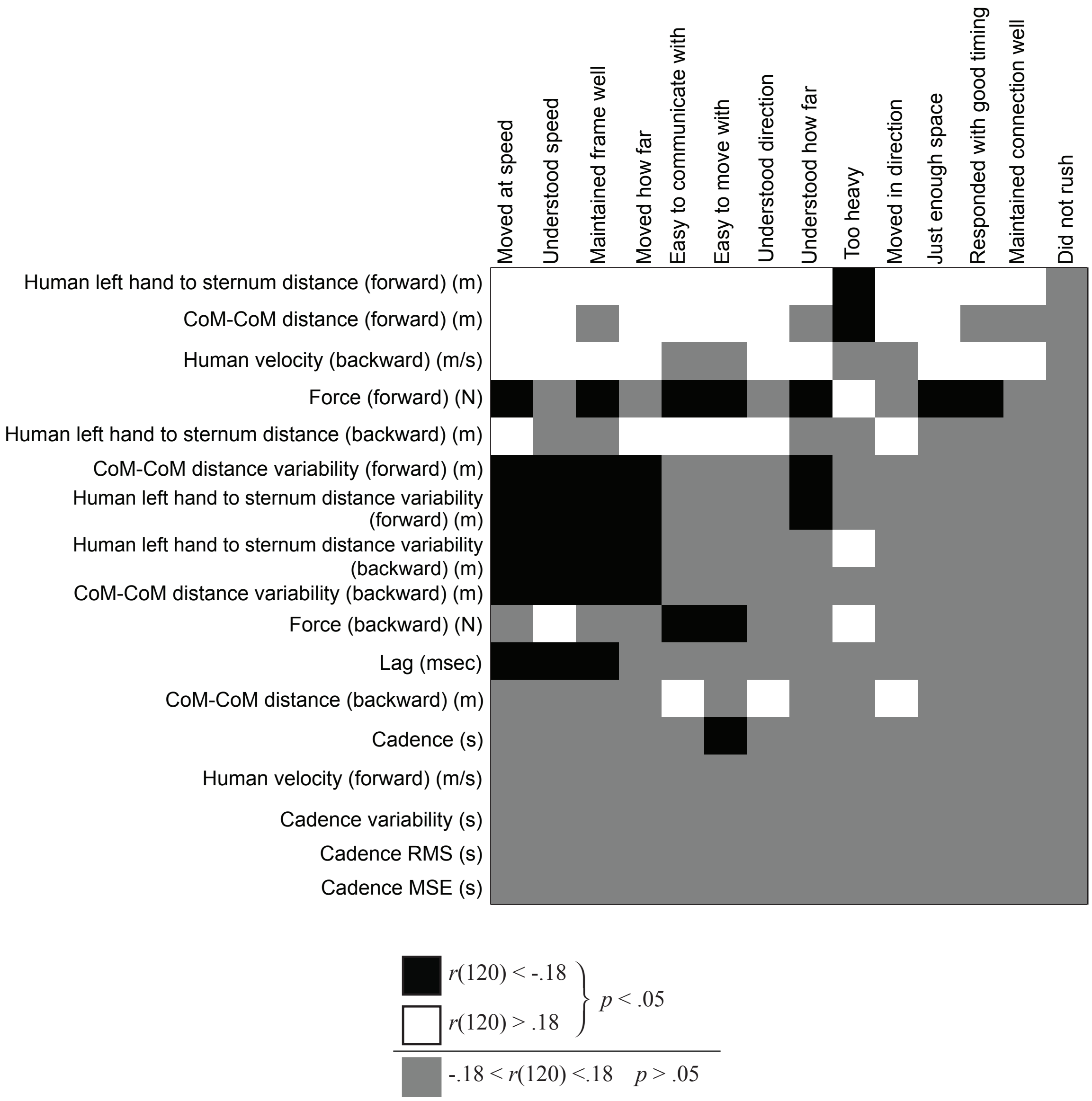


Figure 32: Correlation between subjective and objective measures. Biomechanical measures are listed on the rows and subjective measures are listed on the columns in descending order of number of significant correlations. Black and white boxes denote significant negative and positive Pearson's correlations coefficients, respectively. Gray denotes non-significant correlation.

The responses to the statement “I was dancing with the robot” were split as shown in Figure 31 (M=3.0, SD=0.9). 8 of the 10 responses mentioned that “dancing” requires timing with the beat of the music and the partners moving together. The consensus was that the interaction constituted "limited" dancing.

- Of the 4 participants (40%) that responded with a response level of 4 or 5, 2 of the participants mentioned the robot responded well to signals given. 1 of the participants mentioned that dance requires emotion, implying that it was lacking. 2 of the participants described the movement as "technically dancing."

- 2 of the participants (20%) responded with a response level of 3. 1 of these participants mentioned that because he was used to Argentine tango which is improvisational, the lack of variety in steps caused him to say that the interaction met the "minimum requirements".

- 4 of the participants (40%) responded with a response level of 2. 1 of these participants mentioned the lack of variety of movement while another participant felt a lack of "creativity and freedom" during the interaction and was not "enjoyable."

The responses to the dance quality questionnaire (shown according to the gain factor in Figure 33) indicated that the expert dancers rated the robot's subjective performance favorably on average. The response levels averaged above 3 for positively valenced questions and averaged below 3 for negatively valenced questions.

4.5.3 Biomechanical measures correlate with subjective dance quality

The dance quality questionnaire had excellent internal consistency (Cronbach's α=.92) across participants, treatments, and repetitions. Similarly, the test-retest reliability was good with an ICC of .80. The inter-rater reliability was acceptable with an ICC of .58 given the questionnaire's purpose of having consistency as well as providing differing insight among raters. These results indicate that the dance quality questionnaire can potentially serve as a reliable and valid instrument to measure dance performance.

Open-ended responses from the final questionnaire supported the validity of the dance quality questionnaire as developed from dancing literature and consultation with expert dancer Dr. Madeleine Hackney. 7 of the 10 participants (70%) stated that the glossary of dance terminology used in the dance quality questionnaire was "concise" or "well described." 2 other participants also agreed with the definitions, but mentioned that the definition of "connection" was more "complex" than the one used. 1 of these 2 people mentioned that emotional aspects of connection were omitted from the definition while the other mentioned that "tension" as well as frame are combined to "create a connection."

Overall, the results of the correlation analysis between the subjective responses and biomechanical data (Figure 32) consistently indicated that longer human hand to sternum distance, larger CoM-CoM distance, faster human walking speed, less force at the hands, lower variability of human hand to sternum distance, lower variability of CoM-CoM distance, less lag, and faster cadence are associated with more favorable ratings of subjective dance performance. These results were in line with our expected outcomes. These correlations supported the validity of the biomechanical and subjective measures.

4.5.4 High gain was rated more favorably by expert dancers

The subjective and objective measures of dance revealed significant differences according to the gain factor where high gain yielded better performance versus low gain. We did not observe significant differences in the subjective measures due to the stiffness factor, however, high stiffness yielded significantly lower lag time of the robot behind the human.Also, neither the gain factor nor stiffness factor had a significant effect on any of the cadence measures.

4.5.4.1 Gain

High gain resulted in significantly more favorable dance quality questionnaire responses (see Figure 33). According to measures of motor intent (Figure 33(a)), the high gain setting allowed the robot to communicate significantly better than the low

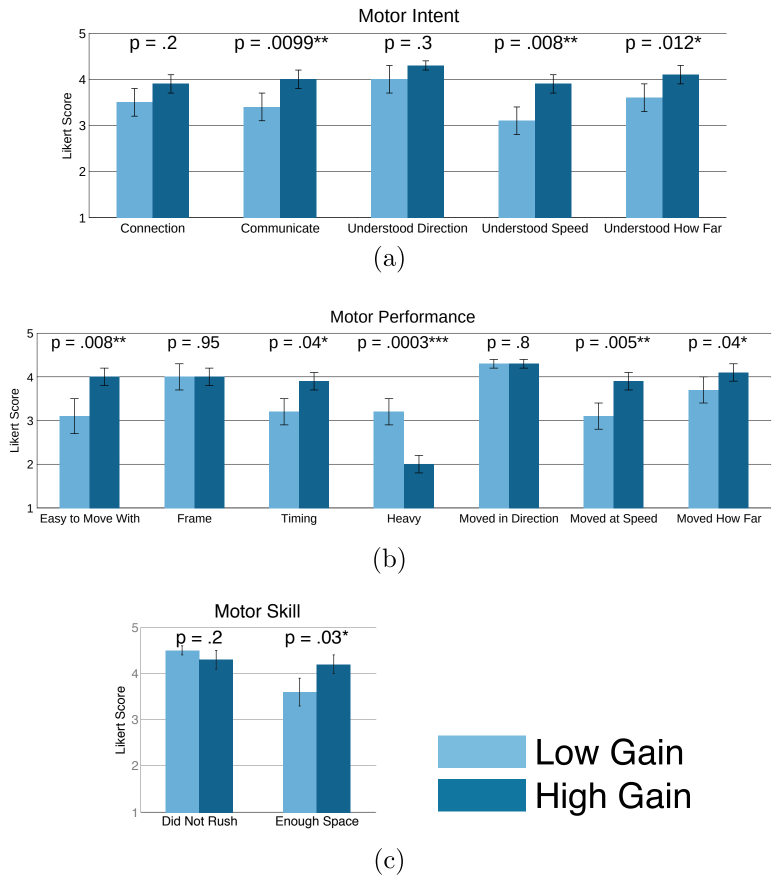


Figure 33: High admittance gain results in higher subjective dance performance. (a) Motor intent, (b) Motor performance, (c) Motor skill. Bars show mean and standard error. Response level of 1="Strongly Disagree," 3="Neutral," 5="Strongly Agree."

gain setting (F(1,9)=10.6, p=.01, η_p^2=0.54). Similarly, participants rated the robot better able to understand the speed at which they wanted the robot to go at the high gain setting compared with the low gain setting (F(1,9)=11.6, p=.008, η_p^2=0.56). Participants also felt that the robot was better able to understand the distance they wanted the robot to go when at the high gain setting (F(1,9)=9.8, p=.01, η_p^2=0.52).

According to measures of motor performance (Figure 33(b)), high gain also allowed the robot to be significantly easier to move with (F(1,9)=11.3, p=.008, η_p^2=0.56), move with significantly better timing (F(1,9)=5.7, p=.04, η_p^2=0.39), seem significantly less heavy (F(1,9)=31.8, p<.001, η_p^2=0.78), and be significantly better able to move at the speed (F(1,9)=13.7, p=.005, η_p^2=0.6) and the distance the human wanted the robot to go ($F(1{,}9)$=5.5, p=.04, η_p^2=0.38). According to one measure of motor skill (Figure 33(c)), the high gain setting allowed the robot to be significantly better able to give the human enough space ($F(1{,}9)$=6.8, p=.03, η_p^2=0.43).

The participants exerted significantly less force when interacting with the robot at the high gain setting versus the low gain setting (see Figure 35(a)), both when walking forward ($F(1{,}9)$=74.7, p<.001, η_p^2=0.89) and backward ($F(1{,}9)$=98.7, p<.001, η_p^2=0.92). In fact, the participants exerted 1.9x and 1.8x less force at the high gain setting when walking forward and backward, respectively. These ratios are similar to the 2x ratio of the high admittance gain (0.02 m/sN) to the low admittance gain (0.01 m/sN) setting. Furthermore, because the participants moved at similar speeds across the gain conditions, it seems that the participants were adapting their force input to maintain a constant velocity according to the robot's mobile base controller setting.

According to the objective measures, the robot lagged behind the human significantly less when at the high gain setting compared with the low gain setting (Figure 34(a)), ($F(1{,}9)$=17.7, p=.002, η_p^2=0.66).

The robot and human were significantly further apart from each other (larger CoM-CoM distance) when at the high gain setting when walking forward ($F(1{,}9)$=13.9, p=.005, η_p^2=0.61) and when at the low gain setting when walking backward ($F(1{,}9)$=5.5, p=.04, η_p^2=0.38). Similarly, the human's left hand to sternum distance was significantly longer when at the high gain setting when walking forward ($F(1{,}9)$=13.3, p=.005, η_p^2=0.60). Thus, there may be a relationship between the human's hand to sternum and CoM-CoM distance. The participants maintained a more consistent CoM-CoM distance when at the high gain setting as indicated by the significantly lower variability (standard deviation) ($F(1{,}9)$=7.6, p=.02, η_p^2=0.46) for backward walking. This trend was echoed where the variability of the human's left hand to sternum distance was significantly less variable at high gain for backward walking

($F(1{,}9)$=5.3, p=.046, η_p^2=0.37).

Experts rated higher gain as significantly more favorable according to several subjective measures of dance quality when performing the task. While this matched our expectations and common assumptions within the haptics community [30], we are unaware of previous work that has provided strong evidence for this in a controlled study in the context of dancing with a robot. Previous research has primarily focused on objective measures of tracking human motion with no clear relationship to subjective performance [179, 180, 87, 189, 63]. While higher admittance gain (lower damping coefficient) resulted in better subjective performance, increasing this gain can result in system instability. Predicting whether a gain will result in a stable human-robot interaction is an open question, although researchers have made some progress in this area [92].

4.5.4.2 Stiffness

None of the dependent measures from the dance quality questionnaire were significantly different due to the stiffness factor, which was surprising given the large difference in the settings. However, according to the objective measures, the robot lagged significantly less behind the human when at the high stiffness setting compared with the low stiffness setting (Figure 34(a)), ($F(1{,}9)$=18.3, p=.002, η_p^2=0.67). Also, the CoM-CoM distance was significantly larger at the high stiffness setting both when walking forward ($F(1{,}9)$=65.6, p=<.001, η_p^2=0.88) and backward ($F(1{,}9)$=12.0, p=.007, η_p^2=0.57). Similarly, the variability of the CoM-CoM distance was significantly lower for high stiffness when walking forward ($F(1{,}9)$=5.2, p=.048, η_p^2=0.37).

4.5.5 Expert dancers discuss benefits of the interaction and importance of other aspects of dance

Participants expressed a range of improvements to the robot or interaction. 4 people suggested improving the robot's performance regarding the "dampening," improving mobility, connection, and responsiveness. 3 people suggested to improve the rhythm, for example, by varying the time signature of the music. 1 participant suggested varying the direction of the interaction. 1 person mentioned that being able to adjust the robot's height made the interaction "[feel] good." One participant suggested making the frame more like a "hug" configuration, while another suggested to replace the robot's wheels with legs to "emulate humans more closely."

Regarding their impression on being blindfolded during the experiment, 7 participants emphasized that it allowed them to "focus solely on the physical connection," "sensation," or "the feeling of the movement." However, 1 person felt "awkward" while another felt that his "balance was compromised" but then said he wasn't overwhelmed. 2 people stated that they were not accustomed to being blindfolded while dancing and that "visual perceptions" were missed. 1 of these 2 people, in addition to a third person, stated that blindfolds are used as a teaching tool in partner dance, but usually for the follower.

When asked whether the interaction felt different when walking backward vs. walking forward, participants were generally split or indifferent. 2 participants thought walking backward was easier while 3 participants thought it was easier to move forward. 2 of the 3 people who felt it was easier to walk forward felt that there was more pressure or resistance which made the connection better or that it helped stabilize the participant. 3 people felt there was no difference.

We asked participants: "What types of people might stand to benefit from a robot like this and why?" 3 people mentioned that the robot could be used as a diagnostic tool to "measure improvement," for example, in strength and coordination. 1 person felt that it could be used to teach or train someone. Another participant felt that the robot might "make [exercise] more fun."

4.6 Limitations

The lack of significant differences among the measures according to the stiffness factor suggest that the difference in stiffness between the treatments was too small to achieve any significant effect. Future investigation on more extreme levels of robot arm stiffness may yield significant results. The extent to which our results would generalize to other forms of partner dance, participants from other demographics, robots acting as the leader, and human-human partner dance remains an open question.

4.7 Discussion and Conclusion

The results from this study demonstrated that Cody successfully followed expert dancers in partnered stepping according to subjective ratings by the participants as well as to biomechanics indicating motion synchrony between the partners. We demonstrated that an admittance controller that is not specific to a particular dance enabled cooperative motion such as during partner dance using only haptic interaction.

We were also able to alter the expert dancers' subjective dance experience with the robot by altering the robot's admittance gain setting. A high admittance gain setting for the robot's mobile base controller resulted in significantly higher subjective dance quality ratings as assessed by expert dancers. High admittance gain and high robot arm stiffness also improved the robot's objective performance according to lag time behind the human leader. Future work utilizing lower values of robot arm stiffness should be done to further understand the effects of arm stiffness on various measures of dance.

The correlation analysis between the subjective and biomechanical measures revealed that several biomechanical measures of synchrony could be used to objectively measure dance performance. Results indicated that the expert dancers more favorably rated their interaction with the robot when they were able to maintain longer and more consistent hand to sternum distance and inter-partner distance with the robot during the interaction. They also rated lower forces at the hands, lower lag time of the robot behind the human, and being able to step at a faster cadence as more favorable.

In this study, we lay a framework for evaluating partnered stepping with a robot dance partner using only haptic interaction. By using a subjective dance quality questionnaire, we allowed the responses of expert dancers to guide the evaluation of our robotic system, the identification of biomechanical correlates of favorable performance, and the comparison of admittance gain and robot arm stiffness properties as it relates to dance performance.

This work has contributed toward developing a robotic platform that can intuitively engage in rehabilitative human-robot partner dance with end users. By continuing to investigate this human-robot partnered stepping paradigm, we can develop an understanding of the role of haptic interaction during two-person, whole-body motor cooperation tasks.

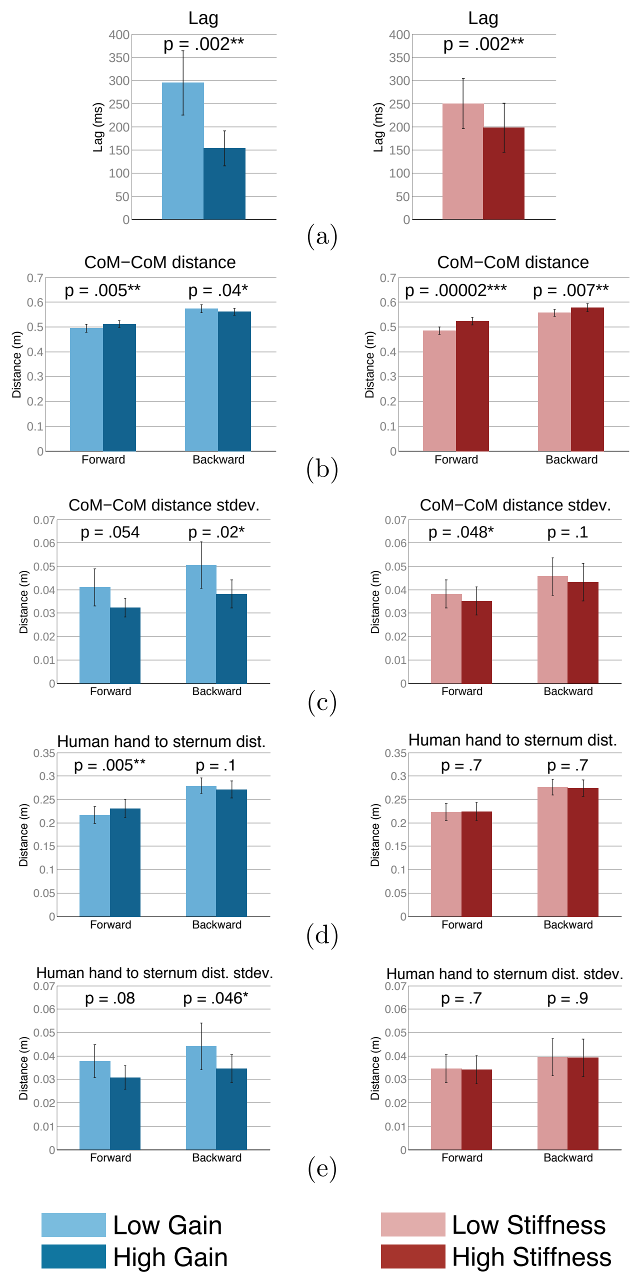


Figure 34: Biomechanical measures according to gain and stiffness. (a) Lag time of robot behind human, (b) CoM-CoM distance, (c) CoM-CoM distance standard deviation, (d) human left hand to sternum distance, (e) human left hand to sternum distance standard deviation. Bars show mean and standard error.

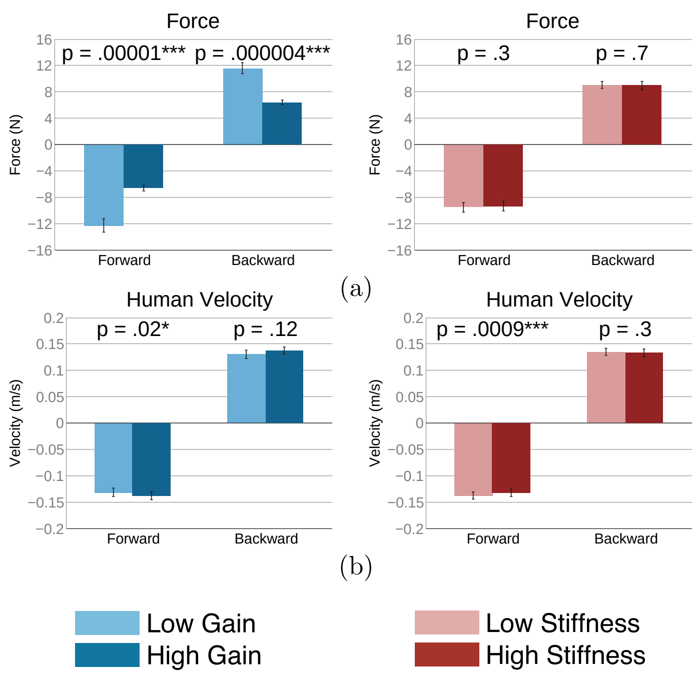


Figure 35: Humans adapt force input to maintain constant velocity. (a) Humans exert 1.9x and 1.8x less force at the high gain setting when walking forward and backward, respectively. (b) Humans maintain similar velocities across all conditions. Bars show mean and standard error.

CHAPTER V

STUDY 4: OLDER ADULTS' ACCEPTANCE OF A ROBOT FOR PARTNER DANCE-BASED EXERCISE

In this chapter, we conducted a study with 16 healthy older adults where they led a human-scale mobile manipulator during a partnered stepping task (PST). First, we found that older adults were accepting of a robot for partner dance-based exercise and that participants felt that the robot was particularly easy to use according to questionnaire responses. Second, by analyzing structured interview data using qualitative data analysis, we identified facilitators and barriers to robot acceptance. Lastly, we determined that using an admittance controller is feasible to enable older adults to engage in a PST with a robot by using biomechanical measures and video analysis.

Overall, the results of this study suggest that physical interaction between older adults and human-scale mobile robots can be effective and acceptable. Also, partner dancing with a robot should seriously be considered as a form of exercise for older adults and could provide a fun, engaging way to motivate older adults to adhere to exercise regimens.

5.1 Introduction

Older adults experience age-related decline regarding cognition, sensation and perception, and movement control [60]. In particular, increased gait variability, which is correlated with balance, predicts falls in older adults [81]. Falls are the leading cause of injury in older adults and may result in injury such as fracture of the hip as well as institutionalization [7]. To compensate for decreased functional ability, some older adults move to assisted living or skilled nursing facilities in order to receive adequate care [125]. However, most older adults prefer to age in place in their own homes [66, 1].

From a preventive perspective, robots have the potential to enable older adults to maintain their independence by improving functional ability through therapeutic human-robot interaction in their own homes or community living center. In this study, we propose to enable a robot to engage in partner dance with older adults in order to provide a potential therapeutic and preventive form of exercise. We gain motivation from previous work that shows that partner dance improves balance and gait for older adults [74, 119, 19], that dance is recommended for older adults to increase their range of motion [146], and that dance can confer mental and emotional benefits in addition to physical benefits [104, 91]. Previous work has also shown that a socially assistive robotic exercise coach can motivate and engage older adults to perform arm exercises while seated in a chair [56]. However, this previous work did not involve ambulation between the participants and a robot, which is the focus of the study in this chapter.

Robot dance partners could potentially confer the benefits of human-human partner dance while actively measuring a human's progress through a therapy regimen and potentially performing customized dance steps according to their partners' need. Robotic dance therapy might play a complementary role to human-human dance and need not entirely replace it.

Similarly, because walking backward and forward is a fundamental component of partner dance [126] and specifically Argentine tango [119], older adults could use a robotic dance partner in order to meet the recommended walking and balance improving activities recommendation by the American College of Sports Medicine (ACSM) and the American Heart Association (AHA) [137]. Specifically, walking has been shown to improve neuromotor performance such as balance and lower the risk of fracture in older adults [156, 154, 174]. Furthermore, ballroom dancing is listed as a moderate intensity sport or recreational activity on the Physical Activity Scale for the Elderly (PASE) [190].

However, it is not known whether robots can engage in partner dance with older adults. While there has been previous work developing human-scale robot dance partners that can follow or lead a human [178, 111, 189, 87, 160], they have not been formally evaluated by experts in dance, nor with target users such as older adults. The study in Chapter 3 has shown that a simple admittance controller can allow nurses to guide a robot through navigation and positioning tasks and that the same controller was evaluated by expert dancers to be a reasonable representation of partner dance (Chapter 4). In this study, we ask older adults to engage in a simplified partnered stepping interaction with a similar robot and controller design used in the previous study with experts.

Furthermore, it is not known to what extent older adults would be accepting of partner dancing with a robot in order to improve and maintain their health. Understanding facilitators and barriers to this particular interaction with robots will better inform how to design such a technology for older adults [171].

Thus, we have three research questions for this study:

- **Question 1**: Are older adults accepting of a robot for partner dance-based exercise?
- **Question 2**: What are facilitators and barriers of acceptance of a robot for partner dance-based exercise for older adults?
- **Question 3**: Is it feasible to use an admittance controller for partner dance-based exercise for older adults?

5.2 Related Work

In this section, we begin by describing barriers and motivators of exercise that older adults experience. We then discuss the physical and mental benefits of human-human partner dance. We also discuss socially assistive robots that have been used with older adults involving exercise. Then, we describe previous implementations of robots dancing with humans and how they relate and complement the work in this study. Finally, we describe the Technology Acceptance Model (TAM) which was adapted for use in the development of the materials in this study.

5.2.1 Older Adults' Barriers and Motivators to Exercise

Physical exercise is commonly cited as an effective means to prevent cardiovascular disease, stroke, and diabetes [137, 122] and to improve postural and motor impairment [24] and functional performance [41] in older adults. Furthermore, the American College of Sports Medicine (ACSM) and American Heart Association (AHA) recommend that older adults perform physical activities including walking or aerobics, muscle strengthening exercises, flexibility activities, and balance exercises to maintain and improve their health [137].

However, physical activity decreases with age [163] and 87% of older adults exhibit at least one of several barriers that can prevent them from achieving the recommended level of physical exercise [141]. Schutzer and Graves identify five barriers to exercise in older adults: (1) health, (2) environment, (3) physician advice, (4) knowledge, and (5) childhood exercise. For example, poor health status is a frequently cited barrier to exercise in older adults. Also, having lack of access to resources for exercise in the environment such as a park or recreation center also presents a barrier to exercise. Older adults are more likely to exercise if they are instructed to do so by their physician, but many times they do not receive this advice due to lack of time during a medical appointment or lack of reimbursement for counseling. Also, many older adults are unaware of the link between moderate exercise and health and feel that their everyday activities are sufficient to meet their physical activity needs. Lastly, older adults were more likely to exercise if they participated in a team sport as a child.

Conversely, Schutzer and Graves identify four motivators for exercise in older adults: (1) self-efficacy, (2) prompts, (3) music, and (4) demographics [163]. For example, self-efficacy, or, the belief that one is capable of performing an action in order to attain a desired outcome influences exercise behavior in older adults [152]. Prompts such as through paper mail and telephone calls have been shown to maintain exercise activity in older adults. The presence of music during exercise has been shown to improve exercise adherence in older adults by making the experience more enjoyable. Furthermore, older adults with demographics such as having a lower body mass, fewer chronic diseases, and being male as opposed to female subsequently had higher levels of exercise participation.

On a related note, although there is not yet a consensus for the definition of "motivation" in the rehabilitation community, rehabilitation professionals tend to agree that "motivation" is important in determining outcome (see [113] for a literature review). A qualitative study on interviews with stroke rehabilitation professionals regarding how they used motivation during clinical practice identified several causes of motivation. Those factors included: personality factors (e.g., optimistic vs. pessimistic), clinical factors (e.g., age, stroke, cognitive function), family factors, cultural factors, the rehabilitation environment (e.g., stimulating environment with socialization with other people), and the behavior of the rehabilitation professionals (e.g., labeling patients, having low expectations of patients) [114].

Robotics has the potential to reduce several of these barriers to exercise while enhancing motivators of exercise. Video game displays or social cues already have been used to keep patients motivated during robot assisted rehabilitation or exercise [102, 56]. In the future, a robot could be available in the home, a senior center, or residential care facility, providing access at all times to a form of exercise. A robot could also serve as a telepresence device to enable a physician to provide medical or exercise advice on a flexible schedule or for someone else to prompt the older adult. Furthermore, music is a fundamental element of partner dance which would serve to enhance the mood and motivate the older adult. Given these opportunities, we believe that partner dancing with a robot could become a motivational form of exercise for older adults to help them meet their recommended physical activity.

5.2.2 Benefits of Human-Human Partner Dance

Partner dance between humans has been shown to be an effective form of exercise to improve physical function in older adults. For example, McKinley et al. have shown that older adults at risk for falls achieved greater improvements in balance and gait when undergoing tango dance therapy compared with therapy involving only walking [119] while both therapy groups reduced their risk of falls according to these measures. Eyigor et al. have shown that Turkish folkoric dance improved the physical performance, balance, and quality of life in healthy female older adults [54]. Similarly, Hackney et al. showed that people with Parkinson's disease (PD) as well as older adults who completed tango dance therapy also experienced gains in measures of balance and gait compared with traditional strength/flexibility exercise [74] or no intervention [72]. Gomes da Silva Borges et al. found that older adults living in long-term care facilities improved their functional autonomy and balance when undergoing a ballroom dancing program compared with no intervention [19].

Aside from the physical benefits of partner dance for older adults, researchers have also discussed the emotional and motivational aspects of partner dance and dance, in general. Hackney and Earhart provide a brief review of the affective and behavioral benefits of participating in dance [71]. Specifically, they mention that the expression of emotions through movement involved in dance can improve mood which can in turn improve health [68]. Among older adults with dementia living in a care facility, researchers found that dance lifted spirits, reduced agitation, and increased bonding

[51]. Hackney and Earhart also mention that the interpersonal touch, connection, and community involvement associated with partner dance may serve as an entertaining diversion for those with physical and cognitive impairments. They also highlight the importance of adherence to a dance program in order for older adults to receive its full benefits as with any exercise or rehabilitation program. They report that in their previous work, participants responded favorably to tango dance therapy and were interested in continuing as evidenced in their low attrition rate [72, 73, 74, 75]. Other work has shown that an exercise program involving Korean dance movements was effective at increasing the functional status of older adults as well as motivating them to perform behaviors beneficial to their health [173].

While it is unknown whether the social and motivational benefits of dance will be seen in partner dance between humans and robots, this is a new and interesting area of investigation. Developing a robotic dance partner to provide partner dance therapy for older adults has the potential to confer the physical and mental benefits seen in previous human-human partner dance research. In Chapter 4, we have demonstrated that expert dancers evaluated a robot using a simple admittance controller to be a good follower in the context of partner dance. However, a critical unaddressed issue in both the partner dance therapy literature and robotic dance partner literature is whether older adults would be accepting of robotic partner dance exercise. Furthermore, it is not known what design aspects should be implemented on a robot in order to facilitate use of the technology.

5.2.3 Socially Assistive Robotic Exercise coaches for older adults

Fasola and Mataric provide a literature review of social robots that have been designed to assist older adults with providing information about exercise, discussing a user's activity levels, or demonstrating exercises [56]. Specifically, previous work by Fasola and Mataric has shown that a socially assistive robot (SAR) named Bandit was able to motivate and engage older adults in seated arm exercises [56]. Bandit demonstrated arm exercises and asked older adults to mimic his arm gestures. In turn, participants demonstrated arm exercises for the robot to mimic. Bandit also used facial expressions and verbal dialog to communicate. The participants completed four 20 minute sessions of exercise with Bandit over a two week period. The results of the study with Bandit provide support that robots can be used to engage older adults in exercises which could potentially be extended to other forms of social human-robot exercises such as partner dance.

At the same time, there are several differences between the work with Bandit and the work presented in this chapter. First, physical contact between the human and robot is a fundamental component of the partnered stepping interaction investigated in this study whereas Bandit did not make physical contact with participants when demonstrating the arm exercises. Participant ratings of the interaction may be dependent on the interaction modality. Second, whole-body motion coordination during walking is also a necessary aspect of partnered stepping. However, Bandit did not move its mobile base during the interaction and remained stationary throughout the study, aside from arm and facial movements. Third, Bandit's height is considerably shorter than the height of the robot used in our work (seated vs. standing height). These morphology, actuation, and task differences may also affect participant ratings of the interaction. Third, the primary focus of our work is to formally investigate older adults' acceptance of robotic partner dance. While the work with Fasola and Mataric found that participants rated the interaction with Bandit to be both enjoyable and useful, the work did not assess the interaction across other factors shown to predict technology acceptance such as perceived ease of use and intention to use the technology (as described in detail in Section 5.2.5). Furthermore, the hypotheses of the work with Bandit focused on on the performance of the system in comparison with a computer simulation representation of Bandit on a flat-panel display as opposed to acceptance of the robot.

We believe that the work in this study is complementary to previous work. However, to the best of our knowledge, we present the first user study evaluating the ability of a haptic controller to engage in partnered stepping with older adults and also the first to gauge the acceptance of older adults of partner dance as a form of exercise.

5.2.4 Dancing Robots

There have been many implementations of robots that dance either alone or with a human using visual interaction [166, 134, 123, 135, 11]. However, these interactions do not involve physical contact with a human partner, potentially making the implementation of and experience interacting with a full-body robotic dance partner vastly different in terms of safety, somatosensory and cognitive processing, and acceptance.

Regarding more relevant prior work, researchers have developed robots that make physical contact with humans for the purpose of engaging in partner dance [179, 180, 87, 189, 63]. However, none of these implementations were evaluated with expert dancers to establish the dance quality of the dance interaction with the robot. Furthermore, none of these robots interacted with older adults in order to gauge their acceptance or were used in the context of exercise or health improvement. Instead, the prior work had been primarily focused on the ability of the robotic dance partner to follow or lead a human according to performance goals such as minimum force at the hands or minimum trajectory error. In this study, we used a robotic implementation similar to that used in Chapter 4 where expert dancers rated a robot using an admittance controller as a good follower. We also will ask older adults to perform a partnered stepping task (PST), a simple, forward/backward walking task, which we also used in the previous study with experts.

Key distinctions from prior work are that we: (1) Asked older adults to engage

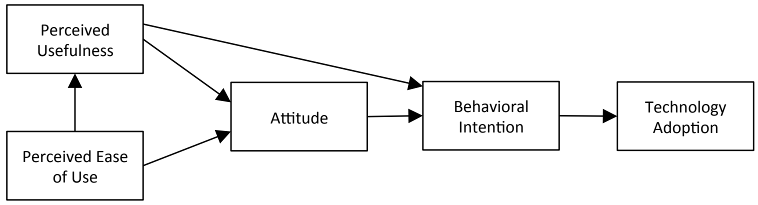


Figure 36: The Technology Acceptance Model (TAM). [47]

in a partnered stepping interaction with a robot, and (2) Assessed the acceptance of a robotic dance partner by older adults in terms of improving and maintaining their health. We believe that these two distinctions help advance work in the area of designing therapeutic robotic dance partners for older adults, as opposed to purely entertainment-based purposes.

5.2.5 Technology Acceptance Model (TAM)

The Technology Acceptance Model (TAM, Figure 36) was designed to explain computer usage behavior and has been used during the design and implementation of information technology (IT) in industry in order to improve use of the technology by IT employees [47]. TAM defines the causal linkages (correlations) between the perceived usefulness (PU) and perceived ease of use (PEOU) of a technology, the attitude (ATT) toward a technology, the behavioral intention to use (ITU) and the actual adoption (usage), of a technology [47]. More detailed definitions of these beliefs are given in Table 17. These beliefs or behaviors are also shown as boxes in Figure 36 and their empirically determined causal linkages are shown as arrows. Given these definitions and linkages, TAM was used not only to be predictive of user behavior but also to be explanatory so that researchers could identify areas of the technology that needed improvement [47].

In this work, instead of the acceptance of IT, we were interested in understanding the acceptance of a robotic dance parter by older adults in order to better design the robot to facilitate its adoption. In previous work, the PU and PEOU of robots have

Table 17: Definitions of constructs used in the Robot Opinions Questionnaire.

Construct	Definition
Perceived Usefulness (PU)	The user's subjective probability that using the technology will increase his or her performance. [46]
Perceived Ease of Use (PEOU)	The degree to which the user expects that using the technology would be free of effort. [46]
Attitude (ATT)	An individual's positive or negative feelings (evaluative affect) about using the technology. [46]
Intention to Use (ITU)	The strength of one's intention to perform a specific behavior to use the technology. [46]
Perceived Enjoyment (PENJ)	The extent to which the activity of using the technology is perceived to be enjoyable in its own right, apart from any performance consequences that may be anticipated. [185]

Table 18: Sources used for adaptation of questionnaire items for Robot Opinions Questionnaire.

Construct	Source(s)
Perceived Usefulness (PU)	[46, 171]
Perceived Ease of Use (PEOU)	[46, 171]
Attitude (ATT)	[88, 82]
Intention to Use (ITU)	[185, 186]
Perceived Enjoyment (PENJ)	[185, 186]

also been found to be important for predicting the intention to use robots by older adults [82]. Also, usefulness and ease of use were found to predict attitudinal and intentional acceptance of a robot for both younger and older adults [55]. Furthermore, TAM has been adapted for use when determining older adults' acceptance of a human-scale mobile manipulator to perform home-based tasks [171]. Similarly, we also adapt questionnaire items from TAM and other sources to measure older adults' acceptance of our robotic dance partner for the specific purpose of improving and maintaining their health.

Table 19: Robot Opinions Questionnaire.

PU	1. Using a robot for partner dance-based exercise would improve and maintain my health. 2. I would find a robot for partner dance-based exercise useful for improving and maintaining my health.¶ 3. Using a robot for partner dance-based exercise would increase my productivity in improving and maintaining my health. 4. Using a robot for partner dance-based exercise would make it easier to improve and maintain my health. 5. Using a robot for partner dance-based exercise would enhance my effectiveness in improving and maintaining my health. 6. Using a robot for partner dance-based exercise would enable me to improve and maintain my health more quickly.
PEOU	7. I would find a robot for partner dance-based exercise easy to use.¶ 8. I would find it easy to get a robot for partner dance-based exercise to do what I want it to do. 9. It would be easy for me to become skillful at using a robot for partner dance-based exercise. 10. Learning to operate a robot for partner dance-based exercise would be easy for me. 11. My interaction with a robot for partner dance-based exercise would be clear and understandable. 12. I would find a robot for partner dance-based exercise to be flexible for me to interact with.
ATT	13. Using a robot for partner dance-based exercise would be beneficial in improving and maintaining my health. 14. Using a robot for partner dance-based exercise to improve and maintain my health would be a good idea.¶
ITU	15. Assuming I had access to a robot for partner dance-based exercise, I would intend to use it.¶ 16. Assuming I had access to a robot for partner dance-based exercise, I predict that I would use it.
PENJ	17. I would find using a robot for partner dance-based exercise to be entertaining. 18. I would find using a robot for partner dance-based exercise to be enjoyable.¶ 19. I would find using a robot for partner dance-based exercise to be fun. 20. I would find using a robot for partner dance-based exercise to be pleasant. 21. I would find using a robot for partner dance-based exercise to be exciting. 22. I would find using a robot for partner dance-based exercise to be interesting.

Note: Questions adapted from sources in Table 18. All questions measured on a 7-point scale where 1 = "Strongly Disagree," 4 = "Neutral," 7 = "Strongly Agree."
¶Questions discussed in detail during the structured interview.

In this study, we adapt Likert questionnaire items from several sources to generate the Robot Opinions Questionnaire (Table 19). We use the Robot Opinions Questionnaire to measure the older adults' acceptance of the robot both before and after interacting with it. Table 18 shows the literature sources of the acceptance questionnaires that we adapt in this study.

Van der Heijden has shown that when the primary purpose of software is for entertainment that the perceived enjoyment (PENJ) and PEOU of that technology are stronger predictors of intention to use that technology than perceived usefulness [185]. In accordance with the previous research regarding software, PENJ has also been found to influence older adults' intention to use a robot [83]. Because partner dance with a robot could be construed as entertainment, we included questionnaire items regarding PENJ in addition to the constructs in the original TAM (see sources in Table 18).

5.3 Implementation

In this section, we describe the robot and controller we used for this study.

5.3.1 Robot

The robot DARCI (Dynamically Adapting Robot for Cooperative Interactions) is an M1 mobile manipulator from MEKA robotics (Figure 37). DARCI is comprised of two 7 degree-of-freedom (DoF) anthropomorphic arms, an omnidirectional base, and a 1 DoF linear actuator to allow the robot's torso to slide up and down. The arms have series elastic actuators (SEAs) at each of the joints, which enable low-stiffness actuation. To sense the forces at the robot's hands, two 6-axis force/torque sensors are mounted at the base of each end effector. Each end effector is comprised of a plastic cylindrical base with a spherical rubber ball placed at the distal end to provide a handle for the participant to grab onto. Similar end effectors were used in Chapter 3. The robot is statically stable and weighs ∼160kg. DARCI shares similarities with

Cody because they have the same degrees of freedom, have similar arms (DARCI's arms are an updated version of Cody's arms), have a similar Festo vertical linear actuator, and have an omnidirectional base. Furthermore, Meka, the company who commercialized DARCI, stated that "The M1 was inspired by the successful design of the Georgia Tech robot named Cody" [121].

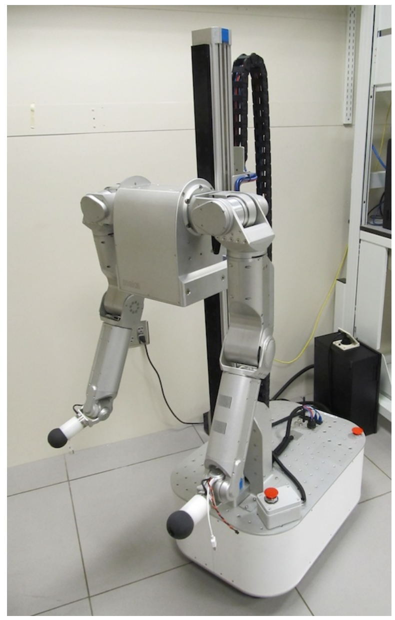


Figure 37: The robot DARCI used in this study.

5.3.2 Controller Design

The movement of the robot's base is controlled using an admittance controller similar to that used in Chapters 3 and 4. The sum of the forces f_{tot} applied at the end effectors by the human participant in the forward/backward direction is multiplied by the gain constant c in order to generate the velocity $\dot{x}$ commanded to the robot's base as shown in Equation 7.

$$\dot{x} = c \cdot f_{tot} \tag{7}$$

We set c to be $c = 0.04 m/sN$ which is larger than the higher gain setting $c = 0.02 m/sN$ used in Chapter 4. We set the maximum speed to be 0.6 m/s. We also averaged the 10 most recent commands for $\dot{x}$ in order to reduce noise and smooth velocity transitions.

5.3.3 Arm Stiffness

In our previous work, we found that higher arm stiffness of a robotic dance partner resulted in more favorable performance ratings from expert dancers (Chapter 4). Thus, we set the joints on both arms to the maximum allowed stiffness. In order to measure the stiffness at the end effector, we moved the end effector on the right arm sinusoidally in the forward/backward direction. We measured the forces and displacement of the end effector using the force sensors and Vicon tracking system during this movement. We determined the slope of the line that best fit the force vs. displacement scatterplot. The stiffness of the robot's right arm was 465 N/m (R^2=0.94). This stiffness is less than the low stiffness condition that we used for the robot Cody in our previous work with expert dancers as discussed in Study 3 (Chapter 4). These differences in stiffness are due to using different robot arm models for the Cody and DARCI platforms.

Refer to Appendix C for design guidance regarding how to implement the robot behavior used in this study on other robotic platforms. Also refer to the code used for this study that we submitted as supplementary material to this thesis.

5.4 Methodology

5.4.1 Recruitment

We recruited N=16 older adults using the Human Factors and Aging Laboratory Participant Database at Georgia Tech and via word of mouth. The participants were required to meet the following inclusion/exclusion criteria: (1) US Citizen or Permanent resident, (2) Fluent in written and spoken English, (3) 65-80 years of age, (4) Able to walk without an assistive device, (5) Able to use a pen to fill out questionnaires, (6) No history of falls within the last year, (7) No neurological disorders or injury, (8) No balance, vestibular, or dizziness problems, (9) No peripheral nerve injury, (10) No chronic lower back pain, numbness and/or tingling of the legs, feet, or buttock area, (11) No back or hip surgery and/or fractures within the past year, (12) No untreated anxiety disorders, and (13) No uncorrectable hearing or visual impairments.

Furthermore, we took care not to mention that the participants would be interacting with a robot, and, instead, would be "interacting with technology." We took this precaution so as to avoid recruiting participants who were biased against or in favor of interacting with a robot. The participant demographics are shown in Table 20.

We administered the Mini-Mental State Examination (MMSE) and excluded participants who had a MMSE score of less than 24 which could indicate mild cognitive impairment [61]. We did this to ensure that the participants would be able to understand the instructions for the task and the questions we asked. We excluded 2 participants since they achieved MMSE scores of 21 and 22. We also excluded the data from one participant due to a robot arm failure during the initial experimental setup prior to the participant seeing or interacting with the robot. We compensated these three participants prorated for the time they participated. These three participants are not included in the total count of N=16.

5.4.2 Procedure

We performed the experiment in the Georgia Tech Neuromechanics Lab in a climate-controlled, windowless room (see Figure 38). We asked participants to complete questionnaires in an office located near the lab as well as at a desk located inside of the experiment room.

The main experimenter read a script when conducting the experiment in order to maintain consistency between participants and also spotted the participants by

Table 20: Demographic information of participants.

Gender	9 female (56%), 7 male (44%)
Age	65 - 79 years, M = 71.5, SD = 5.0 years
Ethnicity	13 white (81%), 3 black (19%)
Education past high school	3 some college/Associates (19%), 5 BA/BS (31%), 6 Masters (38%), 2 Doctoral (13%)
Marital status	6 married (38%), 5 divorced (31%), 4 single (25%), 1 widowed (6%)
Type of housing	13 house/apartment/condo (81%), 3 senior housing (independent living) (19%)
Type of transportation	14 drive own vehicle (88%), 1 public transportation (6%), 1 no response (6%)
Income	3 \$10,000-19,999, 1 \$20,000-29,999, 2 \$30,000-39,999, 2 \$40,000-49,999, 3 \$70,000-99,999, 3 >\$100,000, 1 not willing to answer, 1 no response

walking behind them during each trial. We provide details on how the experimenter spotted the participants later in this document. Another experimenter assisted the main experimenter with checking the filled out questionnaires for completeness, running the robot commandline scripts, collecting video data, operating the run-stop button, and managing the robot's power and data cables during the trial.

When a participant arrived, the main experimenter greeted the participant and introduced him or her to the experimenters and guided the participant to a conference room. The experimenter offered the participant a snack and bottle of water. The participant read and signed a consent form and a personal health information form. Each participant also filled out reimbursement forms, demographic, and health questionnaires (adapted from [43]), and a dance experience questionnaire. They also filled out questionnaires regarding their balance confidence (Activities-specific Balance Confidence (ABC) scale [145]) and their technology experience (modified from [42]). Then, we administered the MMSE to determine their cognitive functioning ability. We also administered a questionnaire to measure the older adults' self-reported

Table 21: Participants' previous dance experience.

Years of general dance experience	0-55 years, M = 13.8, SD = 19.6 years
Types of general dance experience	Ballroom, jazz, salsa, swing, line dance, ballet, tap, slow two-step, modern, fox trot
Partner dance frequency	4 never (25%), 6 rarely (38%), 5 occasionally (32%), 1 moderate (6%)
Partner dance enjoyment†	M = 4.9, SD = 1.9

†Measured on a 7-point scale where 1 = "Strongly Disagree," 4 = "Neutral," 7 = "Strongly Agree."

Note: Years and Types of general dance experience are from N=10 participants who reported having any dance experience.

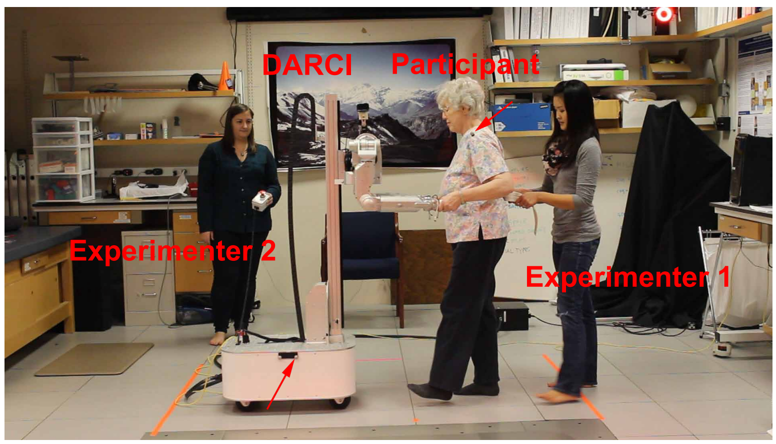


Figure 38: Experimental setup. Red arrows denote locations of tracking markers used in biomechanical analysis. Experimenter 1 holds gait belt placed on participant. Experimenter 2 holds run-stop button.

physical activity (Physical Activity Scale for the Elderly (PASE) [190]) and a questionnaire to determine the participants' familiarity with robots (adapted from [124]. See Tables 21, 22, and 23 for the results.

Then, the main experimenter told the participant that the information that he or she provides would help in research on what older adults think about interacting with robots and performing tasks together. The main experimenter also told the participant that "There are no right or wrong answers" and that researchers want to know what the older adults think to help design robots better. These types of statements were repeated at multiple stages of the experiment to encourage the older

Table 22: Participants' health information.

Self-reported health rating‡	$M = 3.9$, $SD = 0.8$
Self-reported health in comparison to others‡	$M = 4.1$, $SD = 0.7$
Health satisfaction§	$M = 4.3$, $SD = 0.6$
How often health problems stand in the way of doing other things‖	$M = 1.9$, $SD = 0.9$
Self-reported need to exercise more†	$M = 5.4$, $SD = 1.6$
Number of prescription medications taken	$M = 2.0$, $SD = 1.9$
Number of non-prescription medications taken	$M = 0.6$, $SD = 0.8$
Mini-Mental State Examination (MMSE)	26 - 29, $M = 27.9$, $SD = 1.1$
Physical Activity Scale for the Elderly (PASE)	63.2 - 208.7, $M = 115.4$, $SD = 40.7$
Activities-specific Balance Confidence scale (ABC)	80.7-94.9%, $M = 89.7\%$, $SD = 4.0\%$
Reported health conditions	6 Arthritis, 6 Hypertension, 4 Diabetes, 1 Heart Disease 1 Other

‡Measured on a 5-point scale where 1 = "Poor," 3 = "Good," 5 = "Excellent."
§Measured on a 5-point scale where 1 = "Not at all satisfied," 3 = "Neither satisfied nor dissatisfied," 5 = "Extremely Satisfied."
‖Measured on a 5-point scale where 1 = "Never," 3 = "Sometimes," 5 = "Always."
†Measured on a 7-point scale where 1 = "Strongly Disagree," 4 = "Neutral," 7 = "Strongly Agree."

Table 23: Participants' Technology Experience and Robot Familiarity.

Robot Familiarity††	$M = 0.25$, $SD = 0.58$
Technology Experience‡‡	$M = 12.9$, $SD = 3.8$

††Number of robots previously used out of a possible 13 robots.
‡‡Number of technologies previously used out of a possible 18 technologies.

adults to provide their honest opinion. The participant took a 5-minute break.

The main experimenter then led the participant to the room in the Neuromechanics Lab that contained the robot. The experimenter introduced the robot as a "mobile manipulator" and explained the basic function of its mobile base, vertical lift, compliant arms, and hands. The experimenter stated that "This robot is designed to help people who may need assistance" and that the participant should "think of how [he or she] could benefit from the use of this robot in [his or her] home or in a senior center where [he or she] might have access to it." The experimenter instructed the participant to think of how he or she could benefit from the robot either now or in the future.

The experimenter then gave the participant an opportunity to walk around the robot and look at it from all sides. After that, the experimenter led the participant to a desk located in the room where he or she completed the Robot Opinions Questionnaire, prior to interacting with the robot (see Table 19). We will refer to this instance of the Robot Opinions Questionnaire as the *Pre* version. The experimenter then led the participant back toward the robot and explained that although the robot was capable of performing many tasks, the participant would only perform one of those tasks called "partnered stepping" with the robot. The experimenter described the definition of partnered stepping (see definition of the Partnered Stepping Task below). The experimenter explained that people can use partner dance, such as tango, waltz, salsa, or foxtrot, as a form of exercise or for entertainment purposes, or both. The experimenter mentioned that the PST was a more simplified version of partner dance and was intended to give the participant an idea of what the more complex partner dance would be like. The experimenter noted that the robot was capable of moving side-to-side and rotating, but that only forward/backward walking would be focused on. The experimenter reminded the participant to imagine having a robot like the one they were interacting with in his or her own home or a senior center.

The experimenter instructed and demonstrated how to complete the partnered stepping task. The experimenter demonstrated the task by stepping at 42 beats per minute while listening to music playing a synthesized drummed beat at 84 beats per minute as done in our previous study with expert dancers (Chapter 4).

- Hold onto the robot's hands.
- Lead the robot backward 3 steps, starting on the right foot.
- Collect the feet together by tapping the left foot next to the right foot.
- Lead the robot forward 3 steps, starting on the left foot.

- Collect the feet together by tapping the right foot next to the left foot.
- Repeat until 4 cycles are completed.
- Hold pose at the end of the last cycle until the experimenter says that it is ok to get go of the robot.

The experimenter noted that she would tell the participant when to start and stop so as to allow the participant to focus on the interaction between himself or herself and the robot. The experimenter told the participant that the steps need not be performed exactly right, although preferred, and that he or she could take whatever step size was most comfortable. The experimenter then guided the participant through three practice trials to learn the steps without interacting with the robot. One participant asked to perform a fourth practice trial to be comfortable with the steps.

The experimenter then placed a gait belt around the waist of the older adult. A gait belt is a device widely used in nursing. A nurse holds onto the belt to prevent a patient from falling while walking or to provide a grasping point for patient transfer [149]. Likewise, in this experiment, the gait belt provided the experimenter with something to grab onto to prevent the participant from falling in the event that he or she lost his or her balance. The experimenter held the slack of the gait belt in her left hand and held her right hand underneath the gait belt at the center of the participant's back. The experimenter visually followed or "spotted" the participants by walking backward and forward according to the participants' self-selected gait while placing as little force as possible on the gait belt. While the gait belt was used with a population of healthy older adults, the experimenters used the device out of an abundance of caution to ensure the safety of the participants and would recommend that others working with older adults utilize the same device when performing similar tasks with a robot. When asked during a pilot study of this experiment with two older adults, neither pilot participant stated that they felt the experimenter touching or pulling on them during the task. These comments along with the experimenter's experience with the participants support that the amount of physical contact from the experimenter was negligible and allowed the participants to focus on the task and the haptic interaction with the robot. Anecdotally, none of the participants mentioned negative comments regarding the physical contact the experimenter made with the gait belt.

To track the motion of the participant's torso, the experimenter placed a tracking marker on the participant's left shoulder. We then adjusted the robot's height until the participant felt that it was comfortable. We kept the height constant for all of the trials. We asked older adults to hold onto the robot's end effectors in a symmetrical "practice frame" (see Figure 38) for increased stability, and ease of use, similar to the frame used in [71]. The participant then completed one practice trial while interacting with the robot. Two participants requested to perform one additional practice trial with the robot.

The experimenter told the participant that he or she would complete three trials of the same setting that they experienced during the practice trials. After each trial, we administered the NASA TLX questionnaire [79] to measure workload and the Partnered Stepping Questionnaire I (Table 24). After the participant completed all three trials, we administered the Partnered Stepping Questionnaire II (Table 25). Then the experimenter led the participant back to the conference room and administered a *Post* task copy of the Robot Opinions Questionnaire as well as the Final Questionnaire (Table 26).

The experimenter then performed a structured interview based on the participants' questionnaire responses (see end of Section 5.4.3 for details). We recorded the participants' verbal responses using an audio recording device. The experimenter then gave the participant a copy of the experiment debriefing, consent form, and personal health information authorization form. The experimenter then thanked the participant and escorted them out. The entire experiment took approximately 2.5

Table 24: Partnered Stepping Questionnaire I.

1. The robot was easy to communicate with.
2. The robot was easy to move with.
3. The robot was too heavy.
4. The robot moved in the direction in which I wanted it to go.
5. The robot moved at the speed in which I wanted it to go.
6. The robot moved how far I wanted it to go.
7. The robot did not rush me.
8. The robot gave me "just enough" space to move together well.
9. Please tell us anything else about your experience. (open-ended)

Note: Questions 1-8 measured on a 7-point scale where 1 = "Strongly Disagree," 4 = "Neutral," 7 = "Strongly Agree."

hours.

5.4.3 Subjective Measures

In this section, we describe the questionnaires we used throughout the experiment to quantify the participants' subjective experience with the robot.

We administered the Partnered Stepping Questionnaire I (shown in Table 24) after completing each of the trials with the robot. The questionnaire contained Likert items regarding the participants' experience with the robot and were measured on a 7-point scale where 1="Strongly Disagree," 4="Neutral," and 7="Strongly Agree." We used this questionnaire to detect whether the participants felt that the robot's performance changed after they gained more experience using the robot after each trial.

As stated previously, we administered the Partnered Stepping Questionnaire II (shown in Table 25) after completing all 4 of the trials with the robot. We used this questionnaire so that the participants could assess the robot's overall performance. The questions were also measured using Likert items on a 7-point scale as with the Partnered Stepping Questionnaire I.

We administered the Robot Opinions Questionnaire (shown in Table 19) after

Table 25: Partnered Stepping Questionnaire II.

1. The robot was a good follower.¶
2. The robot was fun to interact with.
3. I was dancing with the robot.¶
4. I felt that the robot and I were a team.
5. I felt a social connection with the robot.¶

Note: All questions measured on a 7-point scale where 1 = "Strongly Disagree," 4 = "Neutral," 7 = "Strongly Agree."
¶Questions discussed in detail during the structured interview.

seeing the robot but before interacting with the robot (*Pre*) and then again after interacting with the robot (*Post*). We pseudo-randomized the ordering of the questions. First, we randomized the ordering of the questions. Then, we arranged the questions so that the attitude and intention to use questions were asked first in order to capture their initial reaction to the robot and to avoid being biased by the other questions. Then we shifted questions down the list to ensure that no consecutive questions were from the same construct.

In order to understand the reasoning participants used to respond to the questionnaire items, we conducted a structured interview. During the interview, we referred back to a subset of the questions in the Robot Opinions Questionnaire *Post*, Partnered Stepping Questionnaire II, and the Final Questionnaire (denoted with ¶ in Tables 19, 25, and 26). When we referred back to these questions, we stated: "For the question (state question), you responded (state participant's rating). Please tell me more about your response." We also asked other interview questions related to design aspects of the robot such as its appearance.

5.4.4 Qualitative Data Analysis

We used qualitative data analysis techniques to systematically categorize the participants' responses to the structured interview [159]. First, the primary experimenter

Table 26: Final Questionnaire.

1. I would use a robot for partner dance-based exercise for entertainment purposes outside of improving and maintaining my health.
2. I would prefer to dance with a human for partner dance-based exercise instead of a robot in order to improve and maintain my health.¶
3. I would be more physically active if I had access to a robot for partner dance-based exercise.
4. I would be more motivated to exercise if I had access to a robot for partner dance-based exercise.¶
5. I would be concerned with my safety when using a robot for partner dance-based exercise.¶
6. I would use a robot for partner dance-based exercise to learn new dance moves.
7. I would be concerned that using a robot for partner dance-based exercise would replace social interaction with other people.
8. I would be comfortable making physical contact with a robot for partner dance-based exercise.
9. I would recommend using a robot for partner dance-based exercise to my friends.
10. I would prefer to use my current exercise routine over using a robot for partner dance-based exercise.¶

Note: All questions measured on a 7-point scale where 1 = "Strongly Disagree," 4 = "Neutral," 7 = "Strongly Agree."
¶Questions discussed in detail during the structured interview.

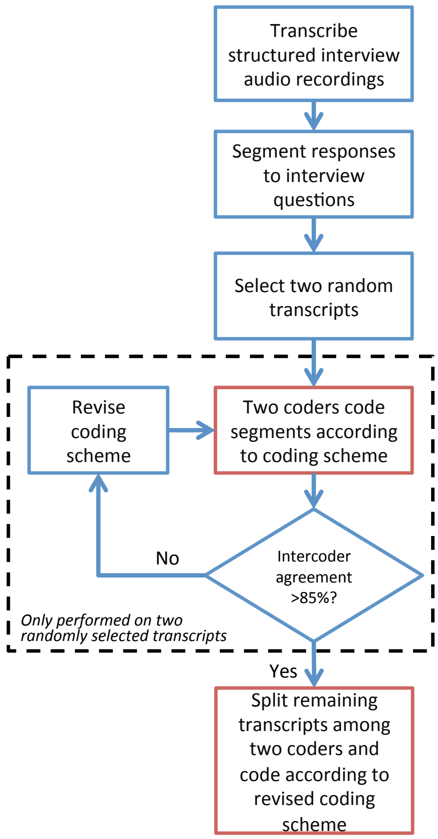


Figure 39: Coding process for qualitative data analysis.

developed an initial "coding scheme," or list of categories using a top-down/bottom-up approach. The top-down approach involved referring to previous literature on robot acceptance and exercise in older adults, and extracting relevant categories according to those topics (e.g., task, robot, human, environmental characteristics and exercise motivation). Then, using the bottom-up approach, the primary experimenter included more specific categories that fell underneath the top-down categories (e.g., "Robot motivates/would motivate user to exercise"). Each of these specific categories is called a "code." This process was performed for both potential facilitators (i.e., aspects that would encourage technology adoption) and barriers (i.e., aspects that would discourage technology adoption).

We provide a diagram of the procedure we used in order to process the interview data in Figure 39. Next, we transcribed the participants' responses to the structured interview questions verbatim from audio recordings of the interviews. We loaded the transcripts into MAXQDA 11 which is a software tool used by psychologists and other professionals to analyze qualitative data [117]. We parsed the transcripts into "segments" where a segment was defined as a participant's response to an interview question. Then, we randomly selected two transcripts and "coded" (categorized) the segments according to the initial coding scheme. A primary and secondary coder (primary experimenter and labmate) coded the segments of these same two transcripts. During the coding process, a coder categorized a segment as containing any number of facilitators or barriers according to coding scheme. The primary and secondary coders completed two rounds of coding the same two randomly selected transcripts. After each round, the coders resolved discrepancies by adding, removing, and refining codes to the scheme. The third round of coding resulted in 88% intercoder agreement where 85% intercoder agreement is an acceptable minimum in qualitative research [159]. After agreement was reached, the coding scheme was finalized and not changed any further. The remaining 14 transcripts were divided evenly among the primary and secondary coder to code individually according to the final coding scheme (shown in Appendix A).

5.5 Results

In this section, we begin by describing the background information of the participants. Then we discuss the results with respect to the three research questions presented in Section 5.1.

5.5.1 Participant Background Information

Participants were from a relatively diverse background with 81% white and 19% black participants with varied levels of education and income (Table 20). Most participants lived in their own homes (81%) while the others lived in independent senior housing (19%).

10 participants reported having any kind of dance experience, which was variable, ranging from 0 years to 55 years (Table 21). When we asked all the participants if they enjoyed partner dance, their average response was 4.9 where 4="Neutral" and 5="Slightly Agree." Participants had low experience with robots and moderate technology experience (Table 23).

Participants reported themselves to be in good health (Table 22). Their physical activity levels (PASE) were in line with reported PASE norms [138] when separated by gender (males: M=134.8, SD=54.1 and females: M=100.3, SD=18.0). They had an average of 89.7% confidence in their balance in doing the activities listed in the ABC questionnaire where higher than 80% is associated with highly functioning, physically active older adults [132]. Of the 12 participants who reported having an exercise routine in the Final Questionnaire, their exercises included: doubles tennis, walking, stretching, stationary bike, weights or weight machines, aerobics classes, golf, tai chi, racewalking, swimming, treadmill, line dancing. Some of these participants visited fitness centers or a senior gym.

5.5.2 Research Question 1: Older Adults are Accepting of a Robot for Partner Dance-based Exercise

By analyzing the participants' responses to the *Pre* and *Post* Robot Opinions Questionnaires, we determined that older adults are accepting of a robot for partner dance-based exercise. In this section, we discuss the statistical analysis for Research Question 1 in detail.

We computed a Cronbach's α value to measure the internal consistency of the responses to each of the constructs in the Robot Opinions Questionnaire (PU, PEOU, ITU, ATT, PENJ, for both *Pre* and *Post* tests for a total of 10 Cronbach's α values). Each of the Cronbach's α values was between .86 and .99, indicating excellent internal consistency for each of the constructs. These results allowed us to average across the Likert ratings for each of the constructs. The medians and ranges for these averages are reported in Table 27.

Table 27: *Pre* and *Post* Acceptance Results.

	Pre					**Post**				
Construct	**Mdn**	**Range**	Z	r	p	**Mdn**	**Range**	Z	r	p
PU	5.8	3-7	3.05	.76	.002**	6	1.2-7	2.51	.63	.012*
PEOU	4.3	2.8-6	2.63	.66	.009**	6	3.7-7	3.42	.85	<.001***
ATT	6	4-6.5	3.37	.84	<.001***	6	1.5-7	2.46	.62	.014*
ITU	6	3-7	3.30	.82	<.001***	6	1.5-7	2.38	.59	.017*
PENJ	5.3	3.7-6.3	3.05	.76	.002**	5.8	1.7-7	2.61	.65	.009**

Note: All tests are Wilcoxon signed-rank tests with a test score of 4 = "Neutral." Refer to Table 19 for complete questions.
*$p<.05$, **$p<.01$, ***$p<.001$

Table 28: Comparing *Pre* vs. *Post* Acceptance Results.

Question	**Pre Median**	**Post Median**	Z	r	p
PU	5.8	6	0.57	.14	.57
PEOU	4.3	6	3.24	.81	.0012**
ATT	6	6	-0.43	.11	.66
ITU	6	6	-0.31	.08	.76
PENJ	5.3	5.8	1.43	.36	.15

Note: All tests are Wilcoxon signed-rank tests. Refer to Table 19 for complete questions.
**$p<.01$

Although parametric statistical inference tests were used in previous chapters, non-parametric tests are used in this chapter per the recommendations in [140] regarding analysis of data from Likert scales. The recommendations acknowledge that while parametric t-tests are robust to normality assumption violations, non-parametric tests do not have a distribution assumption and are better suited for samples under N=30, as in the present study.

The results of the Wilcoxon signed-rank tests (test score of 4 = "Neutral") for the responses to the *Pre* and *Post* Robot Opinions Questionnaire are shown in Table 27. The data show that the participants had acceptance ratings that were significantly above a neutral response to the $\alpha = .05$ level (denoted with (*)), across all 5 constructs of acceptance, for both the *Pre* and *Post* acceptance measurements. These results indicate that the participants were accepting of the robot for parter dance-based exercise both before as well as after interacting with the robot. For the *Post* responses to the Robot Opinions Questionnaire, the median responses to each of the 5 constructs of acceptance were either 5.8 or 6 where 5 = "Slightly Agree," and 6 = "Agree" on the 7-point scale. Histograms of the *Post* responses to the Robot Opinions Questionnaire are shown in Figure 40.

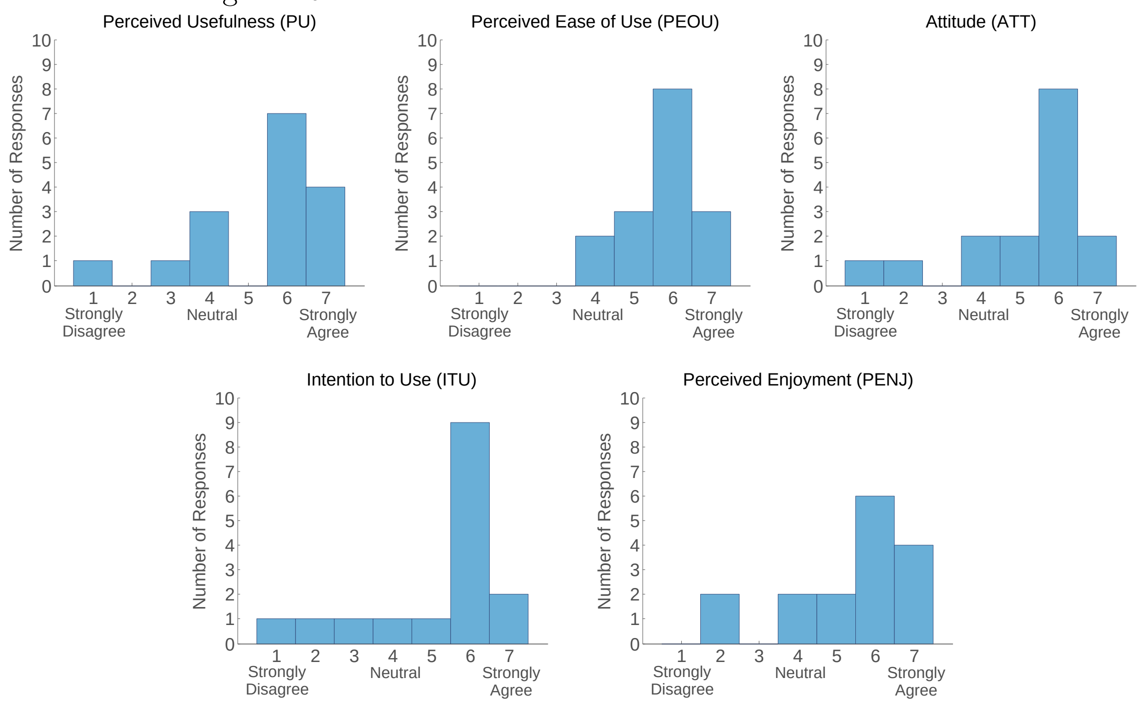


Figure 40: Histograms of responses to Robot Opinions Questionnaire (POST, overall scale) asked during interview.

The results of the *Pre* vs. *Post* Wilcoxon signed-rank tests are shown in Table 28. The table displays only the median responses for the *Pre* and *Post* responses for conciseness. Refer to Table 27 for the data ranges. The results show that the participants' acceptance levels did not significantly increase or decrease to the α = .05 level, except for the Perceived Ease of Use construct. Participants' PEOU significantly increased from the *Pre* (Mdn = 4.3) to the *Post* (Mdn = 6) responses to the Robot Opinions Questionnaire.

5.5.3 Research Question 2: Facilitators and Barriers Provide Insight on Acceptance

By performing a qualitative data analysis on the participants' responses during the structured interview, we identified several facilitators and barriers to older adults' acceptance of a robot for partner dance-based exercise. Of note, participants found the robot easy to use which supports the findings for Research Question 1. Furthermore, participants generally mentioned more facilitators than barriers.

Tables 29 and 30 show facilitators and barriers, respectively, that participants mentioned during the structured interview. Specifically, the data in these tables are only from the interview responses when asking participants to elaborate on their Likert responses to the five questions of the Robot Opinions Questionnaire *Post* denoted by a ¶ in Table 19. The counts in Tables 29 and 30 show the number of participants who mentioned a specific facilitator or barrier at least once over these five questions.

Table 29: Facilitators of Robot Acceptance of a Robot for Partner Dance-based Exercise.

Rank	**Facilitator**	**# of people who mentioned**
1	Robot is easy to use	11
2	Robot is enjoyable	8
3	Robot motivates/would motivate user to exercise	6
3	Robot would improve health (general)	6
4	Robot performed task well (general)	5
5	Can use robot when human partner is not available	4
5	Robot provides/would provide a means to exercise	4
5	User likes to dance | User wants to learn how to dance	4
6	Robot does exactly what it is told	3
6	Robot is/would be always available	3
6	Task was simple | easy to learn	3

Note: These are facilitators mentioned by at least three people during structured interview regarding participants' responses to questions in Table 19 denoted with ¶ (Robot Opinions Questionnaire *Post*).

Regarding the facilitators, the most notable result is that 11 out of the 16 participants mentioned that the robot was easy to use. This result supports the finding

Table 30: Barriers of Robot Acceptance of a Robot for Partner Dance-based Exercise.

Rank	Barrier	# of people who mentioned
1	Task does not provide exercise | would not improve health	5
2	Robot does not do/teach new dance moves/exercises	4
2	Robot is not enjoyable	4
2	Task was too simple | boring	4
3	User does not need/want robot (general)	3

Note: These are barriers mentioned by at least three people during structured interview regarding participants' responses to questions in Table 19 denoted with ¶ (Robot Opinions Questionnaire *Post*).

in Research Question 1 that the robot was perceived to be significantly easier to use after interacting with the robot. For example, one participant stated that the robot was "light to the touch," and that "as I moved, the robot moved with me, with no trouble at all," while another participant said that was "very easy to do so, to control it" and that "there was no problems [*sic*] whatsoever."

While 8 participants stated that the robot was enjoyable (facilitator), 4 mentioned that it was not (barrier). For example, some participants stated that "I thought it was great fun, and it would encourage me to do more dancing," or that "it would encourage me to exercise more and it was fun...I enjoy walking more than I do lifting weights." At the same time, another participant stated "what could be more exciting about putting dishes in the dishwasher, am I supposed to get excited about that? I consider the robot like a dishwasher."

6 participants mentioned that the robot would motivate them to exercise. For example, one participant stated: "because of the reliability that it would be there for me whenever I look at it, that would encourage me more, 'hey, let's dance!'" One participant said that the robot would "try to encourage you instead of like a piece of furniture" by engaging in spoken dialog and saying: "'don't be lazy!' or 'oh I know you'll feel better when you're finished.'"

Several participants mentioned that the robot would improve their health (6) and would provide a means to exercise (4). For example, one participant stated that "if I didn't use a robot or have self-imposed exercises, my health would decline," and another stated that the robot "is good for the eye-hand coordination and the brain coordination with the physical body." One participant stated: "I would use [the robot] on a daily basis, while I'm watching the news... I don't have an exercise machine, but [the robot] would be my exercise machine, to dance... to raise the heart rate." However, 5 participants stated that the task performed would not provide exercise or improve health. For example, one participant said: "I don't find that exercising at all, it was very little...compared to what I do." For reference, this participant said that he walks 1-3 miles per day as exercise.

Participants expressed that the robot performed the task well (5) and did exactly what it was told (3). For example, one participant said: "It just simply followed my instructions." One participant even compared the robot with his girlfriend: "It never fought me, it never tried to move in the direction like my old girlfriend, wanting to go in a different direction than I wanted to go."

3 participants mentioned that the robot would always be available and 4 specifically mentioned that they could use a robot when a human partner was not available. For example, one participant stated: "Consider if...you have bad weather out, and you can't get to any place where you're going to get exercise. The robot would be there to take up your interest." Another mentioned that if his girlfriend was not able to accompany him to their dance class, "if I could buy a robot to teach me at home, I would do that."

4 participants expressed that they either liked to dance or would want to learn how to dance. For example, one participant stated: "I love dancing so...if it were only the robot would be available to dance then we would dance [*sic*]." On the other hand, 3 participants simply expressed that they did not want or need a robot. For example, one participant stated: "if I had a stroke, then I might find someplace to

do this. I have not had a stroke so I think it's too slow and I would not participate with it."

Regarding the task, 3 participants stated that the task was simple or easy to learn while 4 expressed dissatisfaction with the task's simplicity. For example, one participated stated: "I didn't feel as though it was difficult for me to grasp what was necessary to do. I didn't feel confused or uncomfortable in any way." This participant expressed concern that technology that was too complicated would not be adopted by people older than he was. On the other hand, another participant stated "I couldn't do that for a long period of time, it's boring."

Along similar lines, 4 participants mentioned that the robot did not do or teach new dance moves or exercises. For example a participant said: "I would go out of my way to use [the robot], you know, if it included learning dances and new steps. I think that would be very enjoyable."

In summary, participants expressed a wide variety of facilitators and barriers when discussing their responses to the Robot Opinions Questionnaire *Post*. Roughly speaking, more participants mentioned facilitators than barriers, which captures the general favorable acceptance ratings discussed in Research Question 2. Some comments were regarding the design of the task or robot, while other comments discussed users' personal preferences or exercise habits. As such, the facilitators and barriers can help guide future designs of a robot for partner dance-based exercise for older adults across multiple dimensions.

5.5.4 Research Question 3: Older Adults Successfully Engaged in PST with a Robot

In order to determine the feasibility of using an admittance controller for partner dance-based exercise with older adults, we assessed determine whether the participants were able to complete the task with the robot as instructed and whether the participants rated the robot as performing the task well. To assess performance of the participants and robot, we discuss several objective task measures. Also, we refer to the responses to the Partnered Stepping Questionnaire II (Table 25) to determine the participants' subjective assessment of the robot's performance. While we asked the participants to perform the task preferably in the way the experimenter instructed, we informed them that it was more important to focus on the interaction between them and the robot.

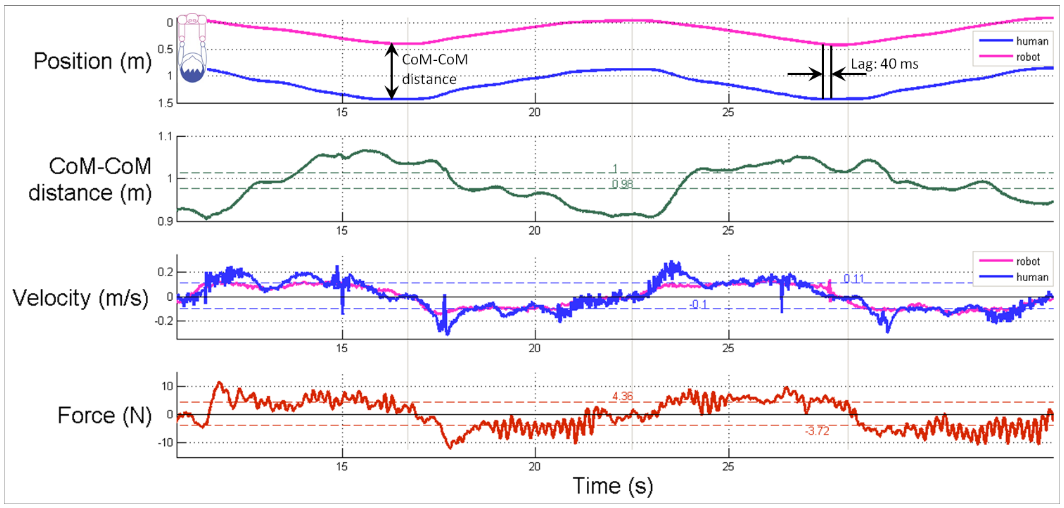


Figure 41: Overall biomechanics. Example data from two cycles of one trial from one participant.

In this section, we will refer to several of the biomechanical measures computed from the force and motion capture data. Figure 41 shows an example of the biomechanics collected and computed for one trial for one participant (2 out of the 4 cycles shown). We computed the average CoM-CoM distance (distance between the markers on the robot and human denoted by red arrows in Figure 38), the standard deviation of the CoM-CoM distance, velocity of the human and robot, and force for each trial, both when the human was walking forward and when the human was walking backward.

We found that participants were able to complete the task close to what was instructed by the experimenter. After the completion of the experiment, we viewed the video recordings of the trials and manually counted the number of steps the participants took as well as the number of cycles they completed during a trial. Participants performed *M*=25.4, *SD*=3.2 steps per trial, where 24 steps per trial was the preferred performance. They completed *M*=4.2, *SD*=0.5 cycles per trial where 4 cycles was the preferred performance. As result, they performed an average of *M*=6.1, *SD*=0.3 steps per cycle where 6 steps per cycle was the preferred performance. Extra cycles and steps performed by the participants were due to the experimenter allowing a participant to complete an additional complete cycle if a participant misstepped during a trial (e.g., shuffled feet or paused) or due to experimenter miscount. Participants traveled an average distance of *M*=0.9, *SD*=0.2 m per cycle which indicates that they performed the steps in a way that resulted in translating their CoM position during overground walking as instructed (i.e., as opposed to stepping while staying in one place). In addition, all participants maintained physical contact with the robot's hands throughout each of the trials. Furthermore, no participants fell during the experiment and no adverse events occurred, precluding the need to push the run-stop button.

Across all trials, the participants and robot maintained a CoM-CoM distance of *M*=0.98, *SD*=0.05 m when walking forward and *M*=1.04, *SD*=0.04 m when walking backward. The standard deviation, a measure of variation, of the CoM-CoM distance across trials was *M*=0.05, *SD*=0.03 m both for when walking forward and when walking backward. For reference, these CoM-CoM standard deviation values are toward the upper range of the average CoM-CoM standard deviation values among the treatment conditions in our previous study with expert dancers (Study 3, Chapter 4). Because the study with experts was completed using a different robot and experimental setup, we make this comparison only to provide a sense of the quality of the interaction between the older adults and the robot given the range of the biomechanical measure found when expert dancers performed a similar task.

The average force applied to the robot's hands across all trials was M=-4.7, SD=1.0 N (forward) and M=4.9, SD=1.0 N (backward). Also, the average robot velocity was M=-0.08, SD= 0.02 m/s (forward) and M=0.09, SD=0.02 m/s (backward). Similarly, the average velocity of the participants was M=0.11, SD=0.02 m/s (forward) and M=0.11, SD=0.02 m/s (backward). These data indicate that the participant applied forces to the robot's hands which resulted in motion of the robot's base similar to the velocities of the participants.

Considered as a whole, these objective task measures indicate that participants performed the task close to what was instructed by the experimenter. Participants applied forces to the robot's hands while maintaining constant contact with the robot and completing the steps of the PST. The participant and robot moved together during overground walking at similar speeds and maintained a relatively consistent amount of distance separation between them.

Table 31: Partnered Stepping Questionnaire II Results.

Question	**Median**	**Range**	Z	r	p
1. Good follower	6	4-7	3.54	.89	<.001***
2. Was fun	6	2-7	2.65	.66	.008**
3. Was dancing	5.5	2-7	2.34	.59	.02*
4. Were a team	6	2-7	2.41	.60	.02*
5. Social connection	4.5	1-7	0.35	.09	.73

Note: All tests are Wilcoxon signed-rank tests with a test score of 4 = "Neutral." Refer to Table 25 for complete questions.
*p<.05, **p<.01, ***p<.001

The results of the Wilcoxon signed-rank tests (test score of 4 = "Neutral") for the responses to the Partnered Stepping Task Questionnaire II are shown in Table 31. The responses to questions that were significantly above or below neutral with the α = .05 level are denoted with an (*). The results show that participants said that the robot was a good follower, was fun to interact with, that the interaction was like dancing, and that the participants felt that they and the robot were a team. Thes responses to these questions had a median score of 5.5 or 6 where 5 = "Slightly Agree" and 6 = "Agree." These responses indicate that the participants felt that the robot generally performed the task well. For reference, histograms for the responses to the Partnered Stepping Task Questionnaire II that were referred to in the interview are provided in Figure 42.

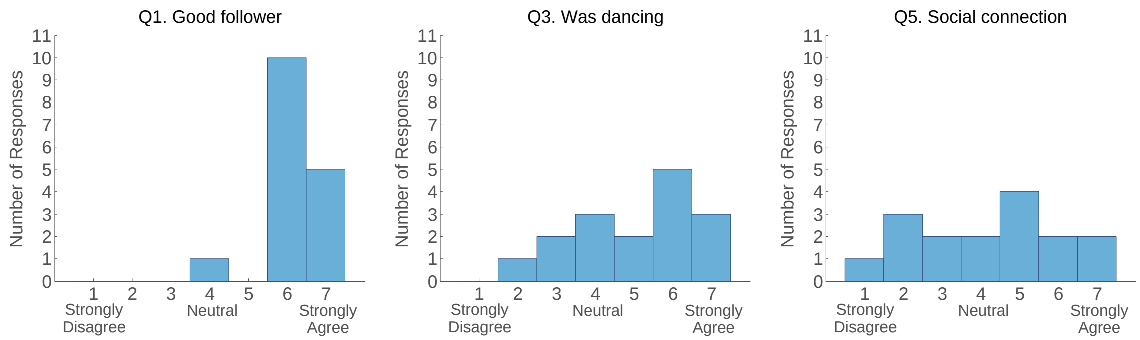


Figure 42: Histograms of responses to Partnered Stepping Questionnaire II questions asked during interview.

In summary, regarding Research Question 3, it is feasible to use an admittance controller for partner dance-based exercise for older adults. We found that older adults were able to complete a partnered stepping task while interacting with a robot using an admittance controller. The participants also rated the robot as performing the task well. Because walking has been shown to be an effective form of exercise for older adults to improve and maintain their health [156, 154, 174], this controller design provides exercise for older adults in the form of overground walking. Although the speeds the participants traveled were lower than the comfortable gait of older adults when walking alone (range of average comfortable walking speeds is 1.28 to 1.36 m/s for older adults in their 60s and 70s [18]), the speeds were similar to the average speed that expert dancers used (0.13 m/s) in our previous work with Cody (Study 3, Chapter 4).

5.5.5 Extended Results

This section contains results that are outside of the research questions for this study. The facilitators and barriers mentioned in response to the remaining interview questions are found in Appendix B, and are left for future analysis.

Table 32: Final Questionnaire Results.

Question	**Median**	**Range**	Z	r	p
1. Use robot for entertainment	5.5	2-7	1.99	.50	.047*
2. Prefer to dance with human	6	3-7	3.00	.75	.003**
3. Would be more physically active	5	1-7	0.71	.18	.48
4. Would be more motivated to exercise	5	1-6	1.46	.37	.14
5. Would be concerned with safety	2	1-6	-2.91	.73	.004**
6. Would use to learn new dance moves	3	2-7	-0.58	.14	.57
7. Concerned would replace social interaction with people	2	1-5	-3.10	.78	.002**
8. Comfortable making physical contact	6	2-7	2.40	.60	.02*
9. Would recommend to friends	6	1-7	2.06	.52	.04*
11. Prefer current exercise routine	5.5	4-7	0.16	.04	.87

Note: All tests are Wilcoxon signed-rank tests with a test score of 4 = "Neutral." Refer to Table 26 for complete questions.
*p<.05, **p<.01

The results of the Wilcoxon signed-rank tests (test score of 4 = "Neutral") for the responses to the Final Questionnaire are shown in Table 32. The responses that were significantly above or below a neutral response to the $\alpha = .05$ level are denoted with a (*). The results suggest that the participants would be willing to using the robot for entertainment outside of health purposes, would prefer to dance with a human rather than a robot, would not be concerned with safety when interacting with the robot, would not be concerned that the robot would replace social interaction with people, would be comfortable making physical contact with the robot, and would recommend the robot to friends. In addition to the Robot Opinions Questionnaire results, these results also indicate that the participants had generally positive attitudes toward using the robot. At the same time, the participants expressed that they woud prefer human interaction for partner dance-based exercise. For reference, histograms for the responses to the Final Questionnaire that were referred to in the interview are provided in Figure 43.

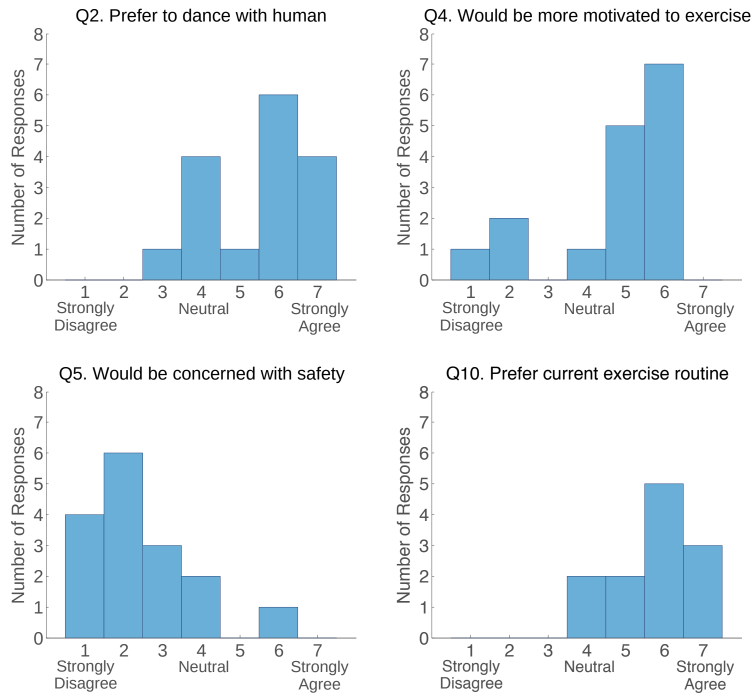


Figure 43: Histograms of responses to Final Questionnaire questions asked during interview.

We conducted a Friedman's ANOVA on the NASA RTLX scores to evaluate the differences in workload across the three trials. The test was significant ($\chi^2(2, N{=}16)$ = 10.2, p = .006), indicating differences in workload across the three trials. We performed *post hoc* pairwise Wilcoxon signed-rank tests and controlled for Type I errors using the Least Significant Difference (LSD) procedure. The workload for trial 2 (Median = 19.5, Range: 6-64) was significantly lower than the workload for trial 1 (Median = 23.0, Range: 9-59) (Z = -2.20, r = .55, p = .03). Workload for trial 3 (Median = 17.0, Range: 6-58) was not significantly different than the workload for trial 2 (Z = -.79, r = .20, p = .43). These results suggest that the participants' workload decreased after their first trial but did not change after their second trial.

We performed a Friedman's ANOVA for each of the questions in the Partnered Stepping Questionnaire I (Table 24) to determine the differences in these measures across the three trials. Only one of the tests (Q3. "The robot was too heavy.") was significant ($\chi^2(2, N{=}16) = 9.08$, $p = .011$). We performed pairwise Wilcoxon signed-rank tests and found that the participants found the robot to be significantly more heavy in trial 2 (Median = 2.0, Range: 1-5) compared with trial 1 (Median = 2.0, Range: 1-4) (Z = -2.23, r = .56, p = .03). There was no significant difference between the participants' rating for trial 2 and trial 3 (Median = 2.0, Range: 1-5) (Z = -0.14, r = .03, p = .89).

5.6 Limitations

It is unclear whether the findings regarding older adults' acceptance can generalize to long-term acceptance of partner-dance based exercise robots as there has not been previous work modeling long-term usage [169]. The results of this work support that older adults would be at least willing to try out the technology which is a positive first step for the development of this technology.

We conducted the study using a relatively small sample size of N=16 which limits the generalizability of our findings to the general older adult population. Furthermore, this study was performed in the US in the Atlanta metro area which may limit the generalizability to other cultures or demographics. Nonetheless, the findings regarding acceptance and the facilitators and barriers of acceptance give roboticists and human-robot interaction designers an initial guide for the future design of therapeutic robotic dance partners and other areas of inquiry.

Although the participants were already accepting of a robot for partner dance-based exercise prior to interacting with it, their perceived ease of use of the system increased after interacting with it. Participants might have perceived that physically interacting with the robot would be more difficult than they expected. This finding opens up interesting questions regarding older adults' perceptions of physical interaction with robots.

While the results of this study are promising, human-robot partner dance has not yet been shown to result in the same physical and mental benefits as human-human dance. There is ongoing neuromechanical research trying to understand how human-human dance improves balance and gait. In the future, the results from human studies can be used to program robots to help human dance partners achieve specific motor rehabilitation goals. Notwithstanding, it is feasible that a robotic dance partner that could simply get older adults moving and walking, even at slow speeds, and could enable older adults to perform at least a portion of their recommended physical activity. For now, these are still open questions that warrant future research.

5.7 Discussion and Conclusion

In this work, we have demonstrated that older adults can lead a human-scale mobile manipulator during a partnered stepping task using only physical interaction. To our knowledge, this is the first user study of its kind to be performed. Specifically, participants rated the robot as easy to use and performed the task well. As such, the simple admittance controller that was used to control the robot serves as a tangible example for other control engineers to build upon in the future. Also, this haptic controller could potentially be used to enable older adults to navigate and position a robot's mobile base for other tasks. For example, older adults could use this type of physical interaction to demonstrate a new task for a robot or just to move it to another location.

We also determined that older adults are accepting of a robot for partner dance-based exercise. We found this result to be supported both before and after older adults performed a partnered stepping task with a robot. These results suggest that (1) older adults would be willing to try partner dancing with a robot to improve their health and (2) physically interacting with a robot to perform a partnered stepping task did not decrease their already high level of acceptance. In fact, their perceived ease of use of the robot increased. These results are promising because we have identified human-robot partner dance as a type of exercise that older adults would be willing to use to improve their health. Further, older adults seem to be open to using physical interaction to command a robot and may even find it surprisingly easy or intuitive to use.

We also identified facilitators and barriers that older adults mentioned to acceptance of a robot for partner dance-based exercise. In line with our findings regarding acceptance, older adults found the robot to be easy to use and enjoyable, and felt that it could be used to improve their health by motivating them to exercise. This type of robot could be also used to teach older adults how to dance as a hobby. At the same time, participants expressed the desire for a more varied dance step routine and to make the interaction more fun. These data may assist in developing design changes to improve acceptance and meet the older adults' expectations for a robot for partner dance-based exercise.

The results of this work indicate that human-robot partner dance as a form of exercise and physical HRI with older adults are promising areas of further investigation. We imagine that the ability to engage in therapeutic partner dance will be just one of many tasks that a human-scale multipurpose robot could perform. Through continued work in this area, we can develop a robot that can enable older adults to improve their health and life richer, fuller lives.

CHAPTER VI

CONCLUSION

In this thesis, we conducted four human-robot interaction studies where 100 naive users participated in an interaction with a robot involving physical contact in a healthcare context. By using a human factors approach to evaluate haptic human-robot interactions with potential users, the results of this thesis are more relevant to real-world healthcare scenarios. Appendix C provides design guidance regarding how other robotics designers can reproduce the interactions used in this thesis on their own robot platforms.

Through the four studies, we have answered four subsidiary research questions where we determined that: (1) The perceived intent of robot-initiated touch significantly influenced people's responses, (2) Nurses performed navigation and positioning tasks with a robot better with physical interaction and was more intuitive and easy to use compared with a gamepad, (3) Expert dancers rated a robot using a simple admittance controller to be a good follower during a partnered stepping task, and (4) Older adults were accepting of a robot for partner dance-based exercise and could perform a partnered stepping task with a robot. We found that participants were able to effectively complete tasks with robots according to measures of task performance, workload, and biomechanics. Furthermore, participants found physical interaction with robots to be acceptable according to measures of emotional state, preference, acceptance as well as qualitative interview responses. Thus, with respect to the overall research question of this thesis, we conclude that **physical contact between naive participants and human-scale mobile manipulators can be both acceptable and effective within the context of healthcare**.

6.0.1 Advancing the Understanding and Usage of Physical Contact in HRI

The most surprising result of this work is that participants were generally positive toward physically interacting with a robot across various contexts with people of varying expertise and demographics. For example, in Study 1, participants reported favorable valence and positive affect ratings and willingness to let a robot initiate contact with them again. In Study 2, nurses preferred using a physical interface to navigate and position a robot compared with a standard gamepad interface. In Study 4 with older adults, participants were accepting of a robot for partner dance-based exercise across each of the 5 measures of acceptance used (perceived usefulness, perceived ease of use, attitude, intention to use, and perceived enjoyment). Prior to this work, there was a dearth of research in understanding people's responses to physical contact with a human-scale mobile manipulator. Thus, at the outset of this work, it was unclear whether participants would express severe aversion to letting a robot enter their intimate space to touch them or being in continuous contact with a robot during partner dance, for example. Contrary to this concern, the findings in this thesis consistently show that people are open to using physical interaction with robots. These results speak to the potential for other types of human-robot touch to be acceptable in healthcare and warrants future research.

In Studies 2, 3, and 4, participants consistently found that they could easily and effectively navigate or position a robot by making physical contact with its body. For example, in Study 2, nurses clearly found using physical contact to move a robot to be superior to a gamepad with respect to intuitiveness, ease of use, workload, and overall preference. In Study 3, a majority of the expert dancers said that the robot was a good follower during partnered stepping. In Study 4, older adults found the robot even easier to use than they had perceived prior to interacting with a robot during partnered stepping. They also expressed that the robot performed the task well.

Because little training is required to learn how to use a physical interface such as those used in Studies 2, 3, and 4, haptic interaction can provide a pragmatic and effective form of interaction between naive participants and robots in other tasks involving whole-body motion. These findings suggest that users from various backgrounds and demographics can quickly become skillful at using physical interaction to move a robot. The ability to quickly learn and retain the ability to move and position a robotic nurse can free up time for users to learn other robot functionalities or perform other care tasks which might make nurses and other caregivers more efficient when providing care for others.

6.0.2 Limitations

While the experimental setups for each of the four studies of this thesis were meant to mimic real-world scenarios, they were not performed with real patients or end users in real hospital environments, private homes, or independent living facilities for older adults. Responses to robot-initiated contact may be dependent on to what extent a user is actually in need of care. Also, real-world environmental considerations such as large amounts of clutter or small hallways or living spaces may place constraints on the navigable areas available for robotic nurse assistants or robotic partner dance companions.

The robotic dance partner implementation in this thesis may not yet be able to accommodate users with different balance and gait ability or other needs. For example, users with Parkinson's disease or amputees may benefit from added stability provided by the robot or the customization of the interaction parameters. The robot's arm stiffness could be increased or the controller gains could be adjusted by a physical therapist, another potential user. Extra safety precautions may also need to be considered (e.g., a ceiling mounted harness). In sum, a clinician's perspective as well as the perspective of motor impaired users should be incorporated into the design of future prototypes of a robotic dance partner if it were to be used with populations with special needs.

Also, the findings of this work may not generalize to other cultures as human responses to touch from other humans may be culturally dependent [150]. As such, research in haptic HRI across different cultures should be performed to understand the generalizability of social haptic HRI findings.

6.0.3 Future Directions

Although the focus of this work was on haptic interaction between humans and robots, we believe that our findings can complement other areas of HRI design.

From the results in Study 1, we conclude that it is important to understand how to reinforce desired interpretations of robot-initiated touch in different healthcare contexts. We found that a robot could successfully use verbal utterances to declare the intent of its touch (i.e., instrumental vs. affective) but that verbal warnings should be carefully designed. HRI researchers can consider using other intention cues such as gaze, deictic gestures, and motion timing schemes in conjunction with verbal utterances to effectively "warn" participants of upcoming robot-initiated contact.

In Study 2, we provided evidence that nurses can use physical contact in the form of an admittance controller to effectively and intuitively navigate a robot through cluttered hospital environments. On the other hand, robots such as the Aethon Tug already autonomously navigate the halls of hospitals to deliver medicine, food, and linens to assist nurses with their jobs [4]. The ability to use physical contact to guide a robot to desired locations and positions can be incorporated along with a map-based autonomous navigation system. There may be situations, especially those that involve physical contact with patients such as patient lifting, where a nurse may wish to quickly override a robot's autonomous path plan. Studying under what scenarios manually guided or autonomous navigation would be better suited for nurse efficiency and patient safety would make contributions to the field of shared autonomy in HRI as well as healthcare.

Older adults in Study 4 mentioned that a robot for partner dance-based exercise would motivate them to exercise and improve their health, but that it should perform or teach new dance moves and be less boring. Future work could potentially combine the exercise benefits of human-robot partner dance with the promising results found by Fasola and Mataric in the field of socially assistive robotics [56]. They found that a SAR could motivate older adults to perform exercises by demonstrating exercises and engaging participants in interactive games. These motivating elements could be incorporated when demonstrating new partner dance moves to older adults to encourage fun and exercise program adherence.

In conclusion, this thesis provides evidence that physical contact can be both acceptable and effective between naive users and human-scale robots in real-world healthcare scenarios. The results highlight the importance of considering people's psychological responses to robot-initiated touch in addition to the mechanics of performing a healthcare task involving physical interaction. People of varying demographic and professional backgrounds generally had favorable responses to physical interaction with a robot during the performance of healthcare tasks. Furthermore, physical interaction enabled naive participants to complete navigation, positioning, and partnered stepping tasks with a robot with relative ease and enjoyment. Thus, physical contact can serve as a valuable means to enable people to perform tasks involving whole-body motion coordination with human-scale robots. Given the general purpose functionality of mobile manipulators, haptic human-robot interaction can be used to enable robots to perform other healthcare tasks effectively with humans. Expanding the repertoire of tasks that robots can perform with humans can only serve to increase the potential of robots to improve people's quality of life.

APPENDIX A

STUDY 4: CODING SCHEME

Facilitators

1. Environmental characteristics
   (a) Physical environment
      i. Senior center is/would be large enough to accommodate robot
      ii. Other
   (b) Social environment
      i. Others could benefit from using robot
      ii. Robot could be used in private
      iii. Watching others perform task with robot would be enjoyable
      iv. Other
   (c) Other
2. Human characteristics
   (a) User needs
      i. Exercise
         A. Robot helps/would help establish exercise routine
         B. Robot motivates/would motivate user to exercise
         C. Robot provides/would provide a means to exercise
         D. Other
      ii. Robot could perform chores or other tasks

iii. Robot would improve health (general)

iv. Other

(b) User wants, personal preferences, and enjoyment

i. Robot is enjoyable

ii. User likes to dance | User wants to learn how to dance

iii. User needs/wants robot (general)

iv. Other

(c) Other

3. Partnered Stepping Task (PST) characteristics

(a) Music was good (general)

(b) Task became easier with more repetitions

(c) Task was similar to dance

(d) Task provides exercise | would improve health

(e) Task was simple | easy to learn

(f) Other

4. Robot characteristics

(a) Robot appearance

i. Robot does not have to look humanlike

ii. Robot looks friendly | does not look intimidating

iii. Robot task performance is more important than appearance

iv. Robot's appearance is good (general)

v. Other

(b) Robot capability

i. Amount of strength used to control robot was good (general)

ii. Robot adapted/would adapt to user, task, or environment

iii. Robot could do/teach new dance moves/exercises

iv. Robot did/would not step on user's feet

v. Robot does exactly what it is told

vi. Robot is capable of social interaction/connection

vii. Robot is customizable

viii. Robot is easy to use

ix. Robot never gets tired

x. Robot performed task well (general)

xi. Robot provides/would provide a means to practice dance moves

xii. Robot speed was good

xiii. Robot would perform task better than a human

xiv. Robot's height was good | Adjusting height is useful

xv. Other

(c) Robot convenience

i. Can use robot when human partner is not available

ii. Robot is/would be always available

iii. Other

(d) Robot is not a human | Robot is better than a human (general)

(e) Robot is safe

(f) Other

Barriers

1. Environmental characteristics

(a) Physical environment

i. Robot should be able to traverse carpets and rugs

ii. User's home is too small to accommodate robot's size

iii. Other

(b) Social environment

i. Using robot publicly is not desirable

ii. Other

(c) Other

2. Human characteristics

(a) User needs

i. Exercise

A. Robot does not/would not motivate user to exercise

B. Robot does not/would not provide a means to exercise

C. Other

ii. Robot would not improve health (general)

iii. Other

(b) User wants, personal preferences, and enjoyment

i. Robot is not enjoyable

ii. User does not like to dance (general)

iii. User does not need/want robot (general)

iv. Other

(c) Other

3. Partnered Stepping Task (PST) characteristics

(a) Music

   i. Music was boring

   ii. Should be able to change the music

   iii. Other

(b) Task became harder with more repetitions

(c) Task does not provide exercise | would not improve health

(d) Task was difficult | was not easy to learn

(e) Task was not similar to dance

(f) Task was too simple | boring

(g) Other

4. Robot characteristics

   (a) Robot appearance

      i. Robot should be smaller

      ii. Robot should have a face | facial characteristics

      iii. Robot should have flashing lights/LEDs

      iv. Robot should have legs | different wheels

      v. Robot should look more humanlike (general)

      vi. Robot should wear clothes

      vii. Robot's appearance is not good (general)

      viii. Other

   (b) Robot capability

      i. Amount of strength used to control robot could be improved

      ii. Robot did not do exactly what it was told

iii. Robot did not perform task well (general)
iv. Robot did/would not adapt to user, task, or environment
v. Robot does not do/teach new dance moves/exercises
vi. Robot height could be improved
vii. Robot is not capable of social interaction/connection
viii. Robot is not easy to use
ix. Robot should be able to talk
x. Robot speed could be improved
xi. Robot would not be able to do/teach new dance moves/exercises
xii. Robot would not perform task as well as a human
xiii. Other

(c) Robot could break or malfunction

(d) Robot is expensive

(e) Robot is not a human | Human is better than robot (general)

(f) Other

Conditionality statement

1. User does not need/want now, but may need/want in future
2. Other

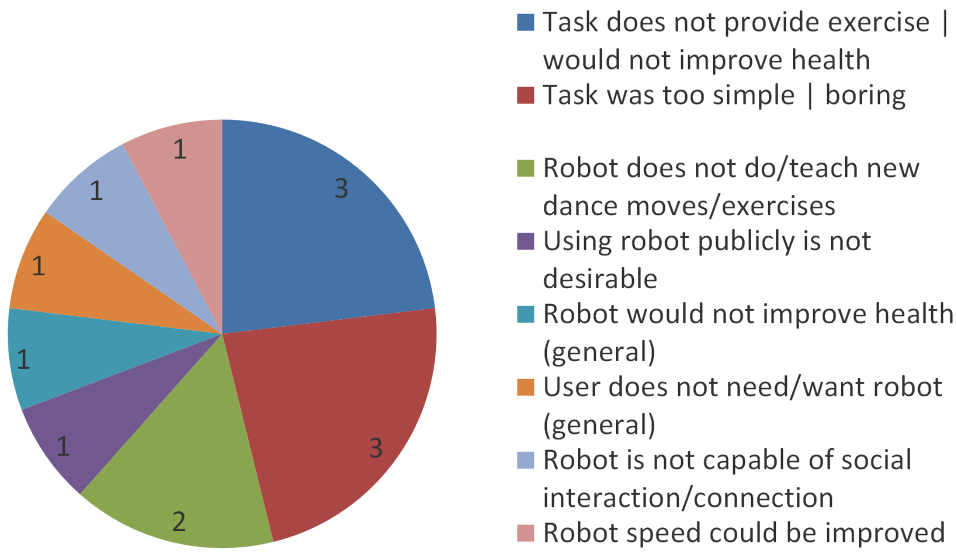
Unable to respond to question

1. Already responded in a previous question
2. Nothing to say | No
3. Unsure of robot capability | Do not have experience with robots
4. Other

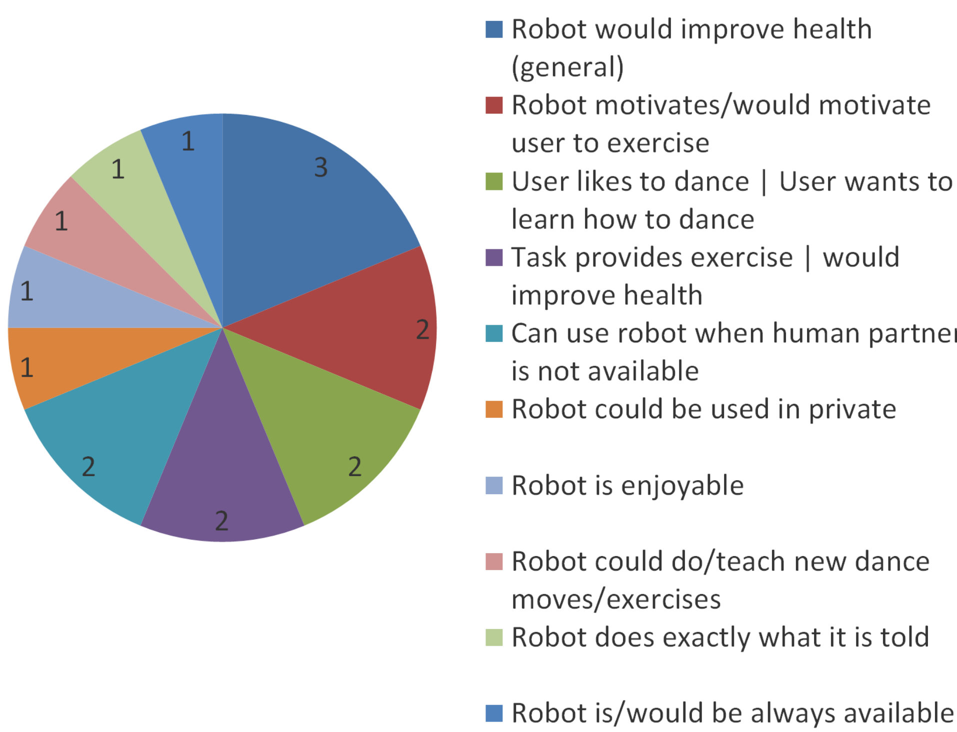
APPENDIX B

STUDY 4: EXTENDED CODING RESULTS

This appendix contains the results of the qualitative data analysis in Study 4. Each of these figures shows the facilitators and barriers that participants mentioned in response to a question of the structured interview. Please refer to Tables 19, 25, and 26 to see the question wording when specified. For each figure, each number label represents the number of participants who mentioned each of the individual codes (by color).

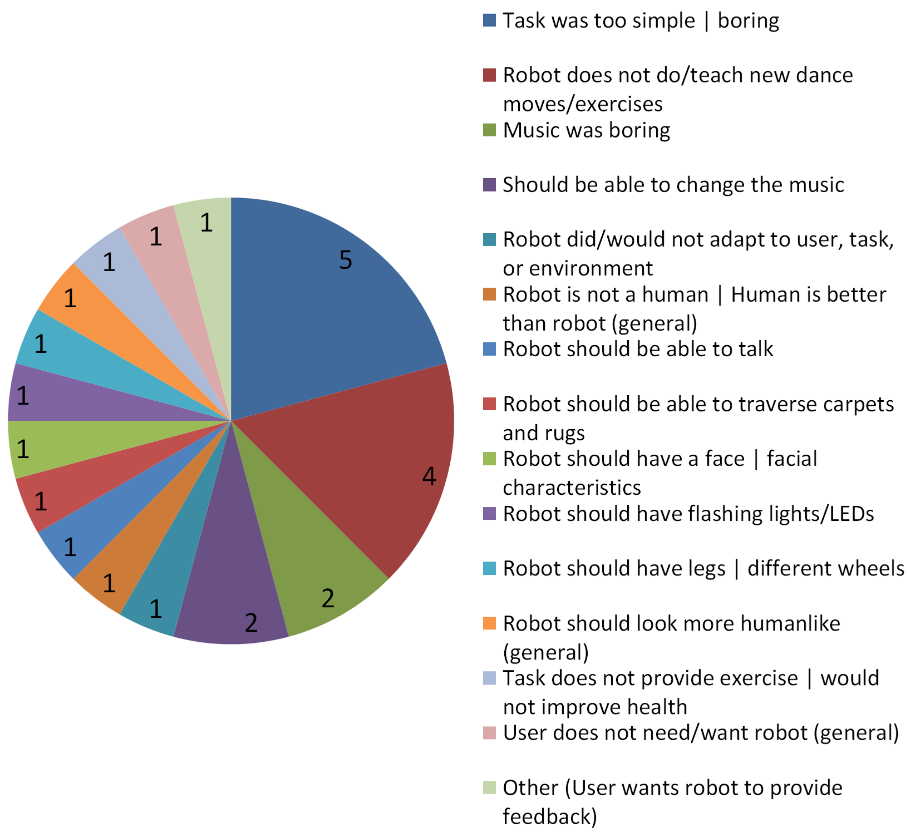


(a) Barriers

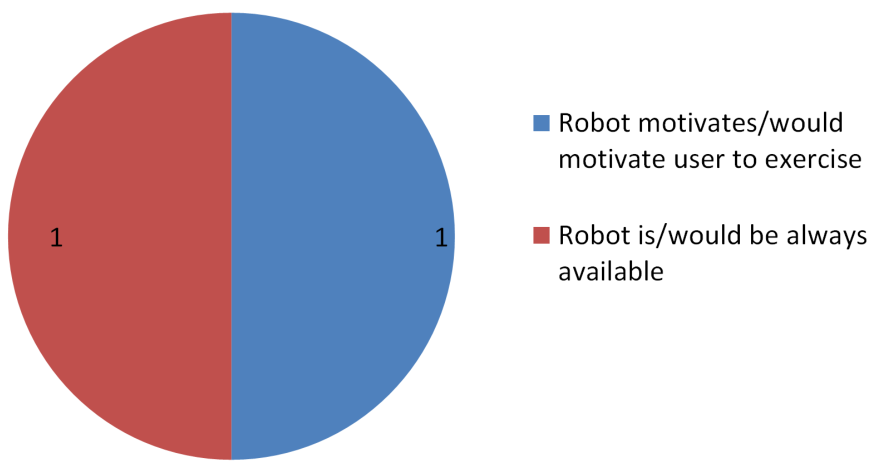


(b) Facilitators

Figure 44: Followup to participants' responses to Robot Opinions Questionnaire *Post*, Question 2.

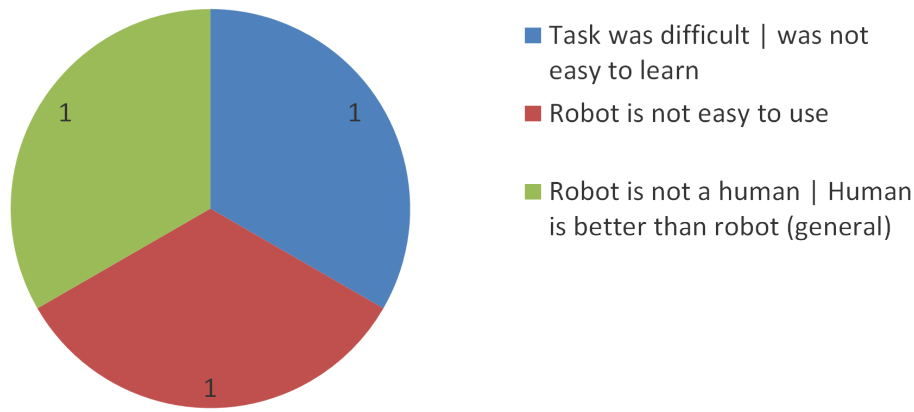


(a) Barriers

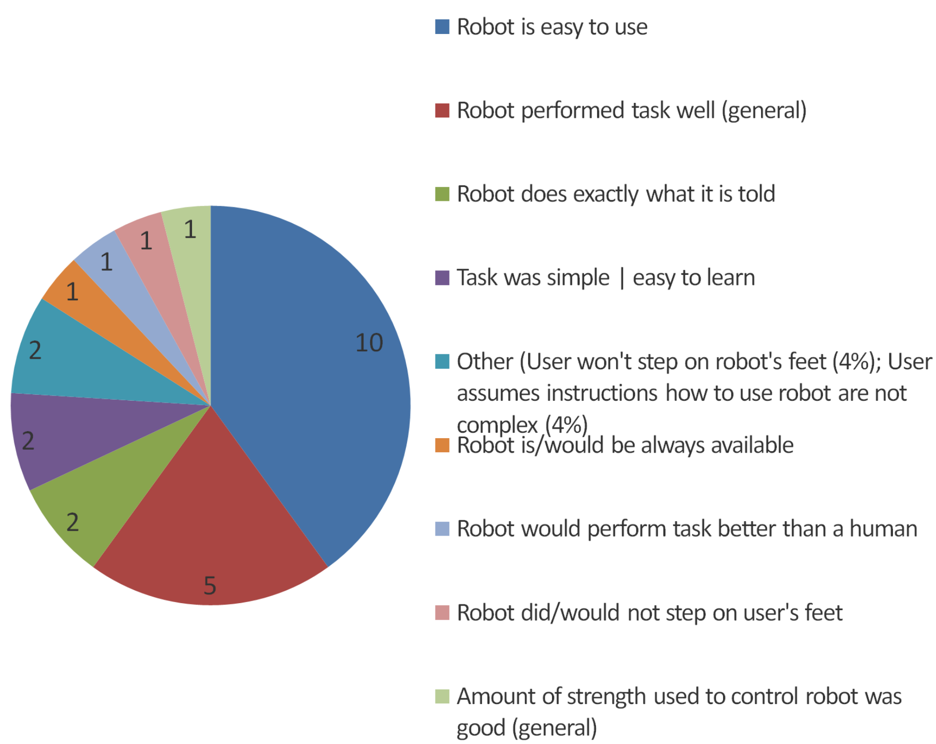


(b) Facilitators

Figure 45: Question: "What features or capabilities of a robot for partner dance-based exercise would make it more useful?"

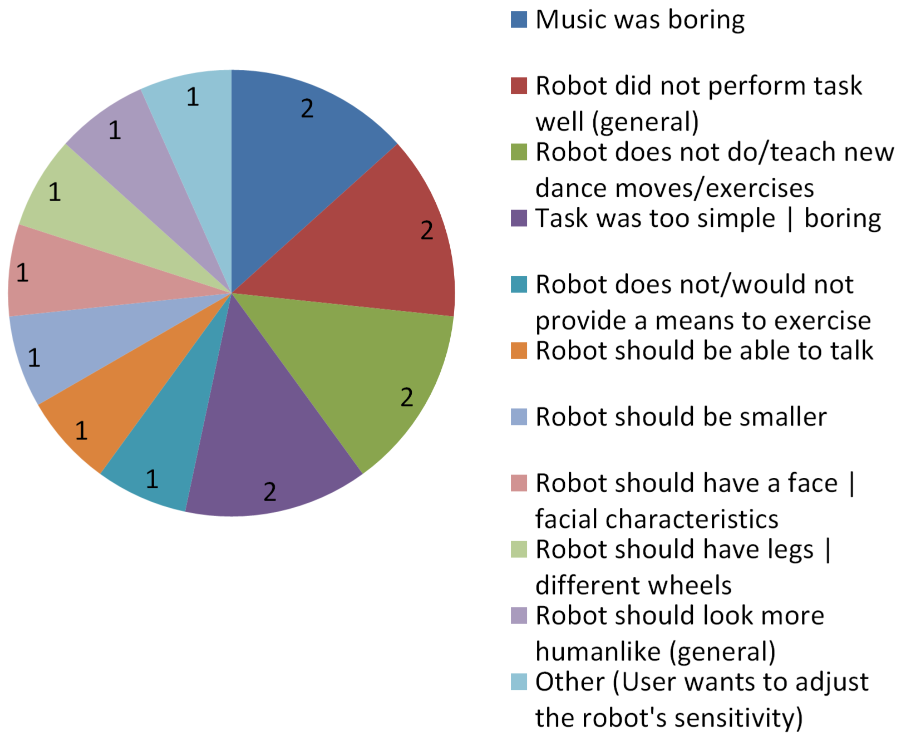


(a) Barriers

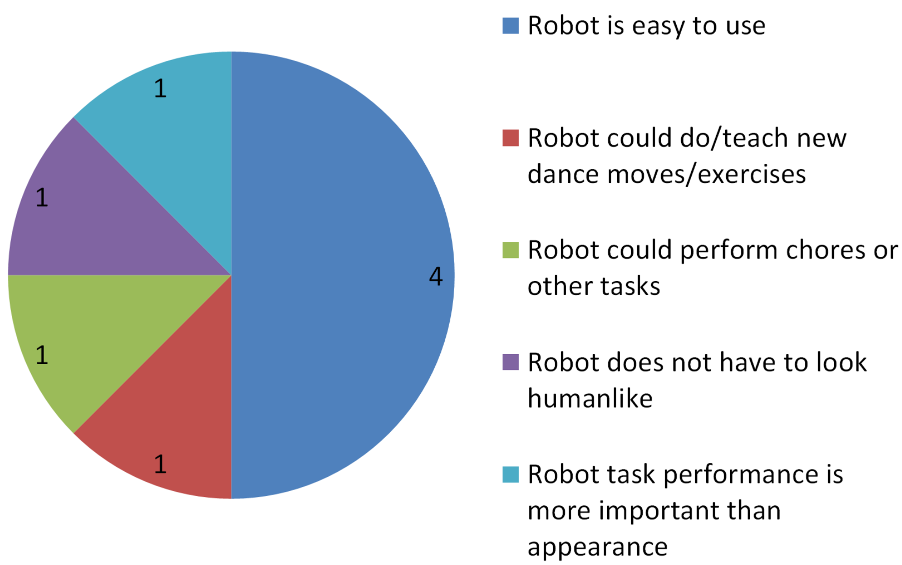


(b) Facilitators

Figure 46: Followup to participants' responses to Robot Opinions Questionnaire *Post*, Question 7.

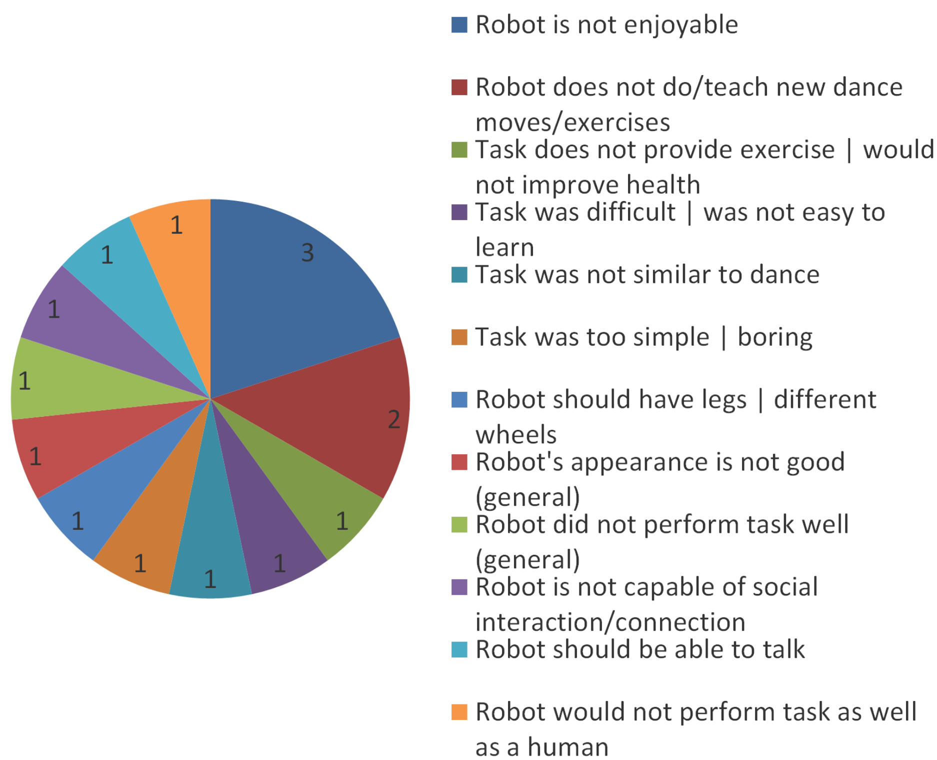


(a) Barriers

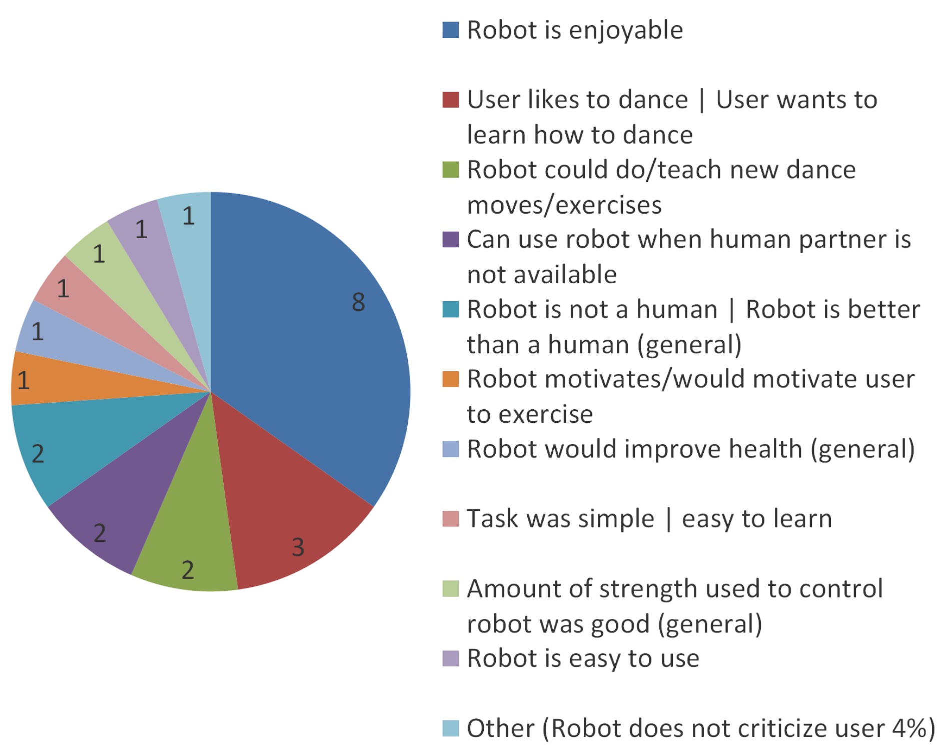


(b) Facilitators

Figure 47: Question: "What features or capabilities of a robot for partner dance-based exercise would make it easier to use?"

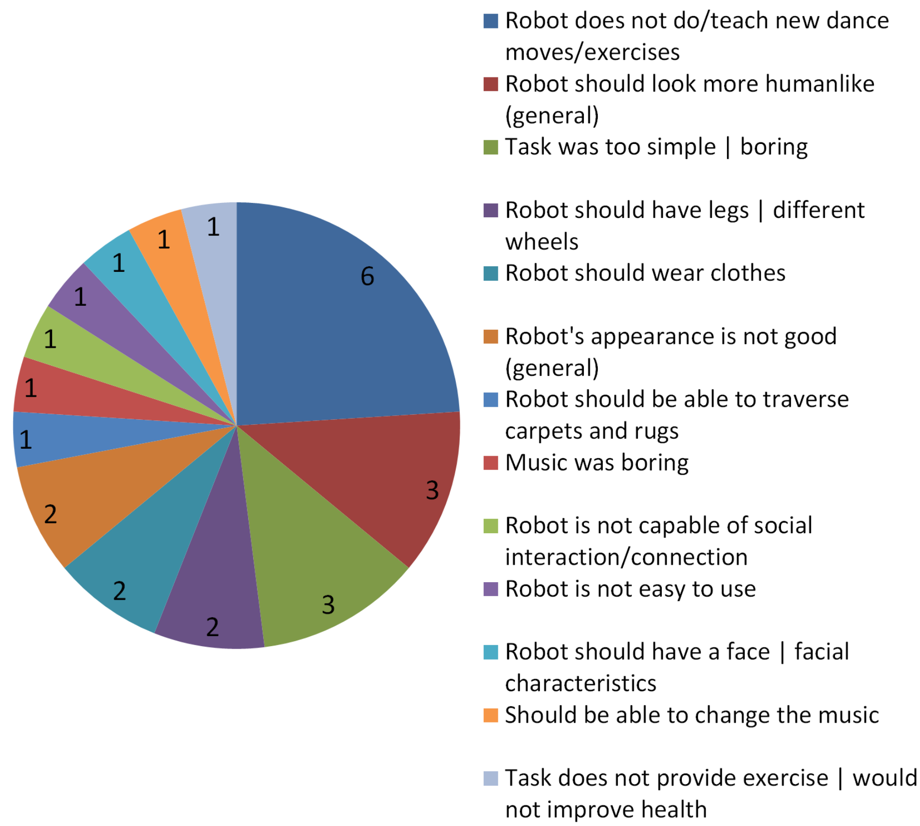


(a) Barriers

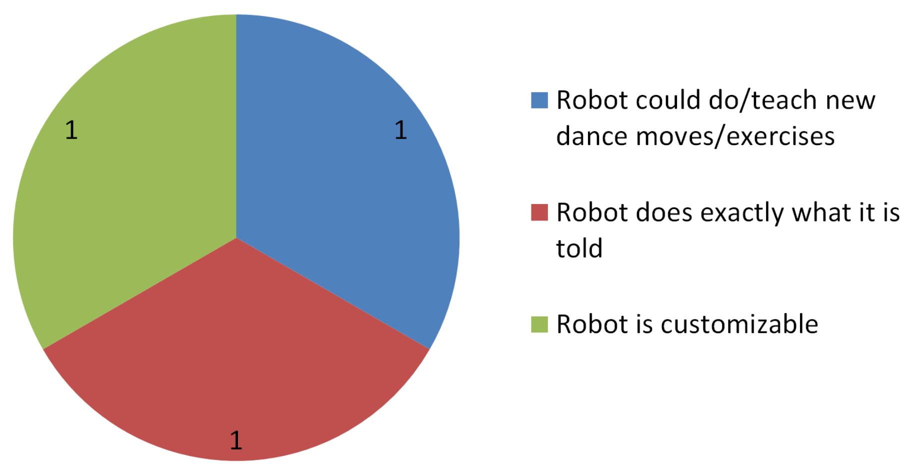


(b) Facilitators

Figure 48: Followup to participants' responses to Robot Opinions Questionnaire *Post*, Question 18.

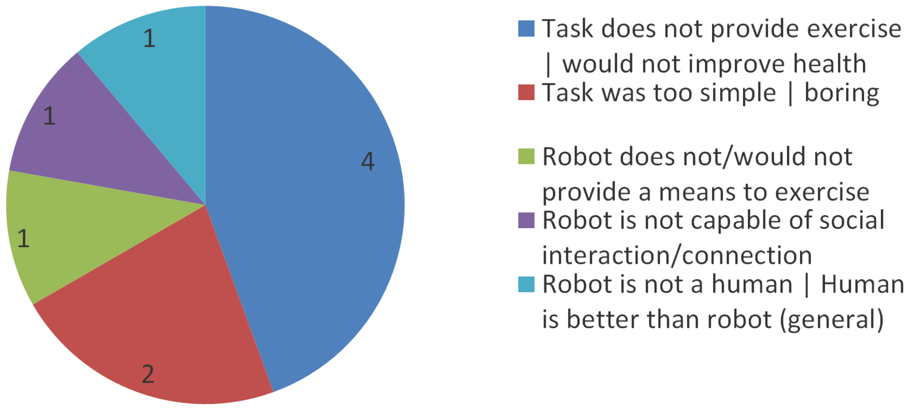


(a) Barriers

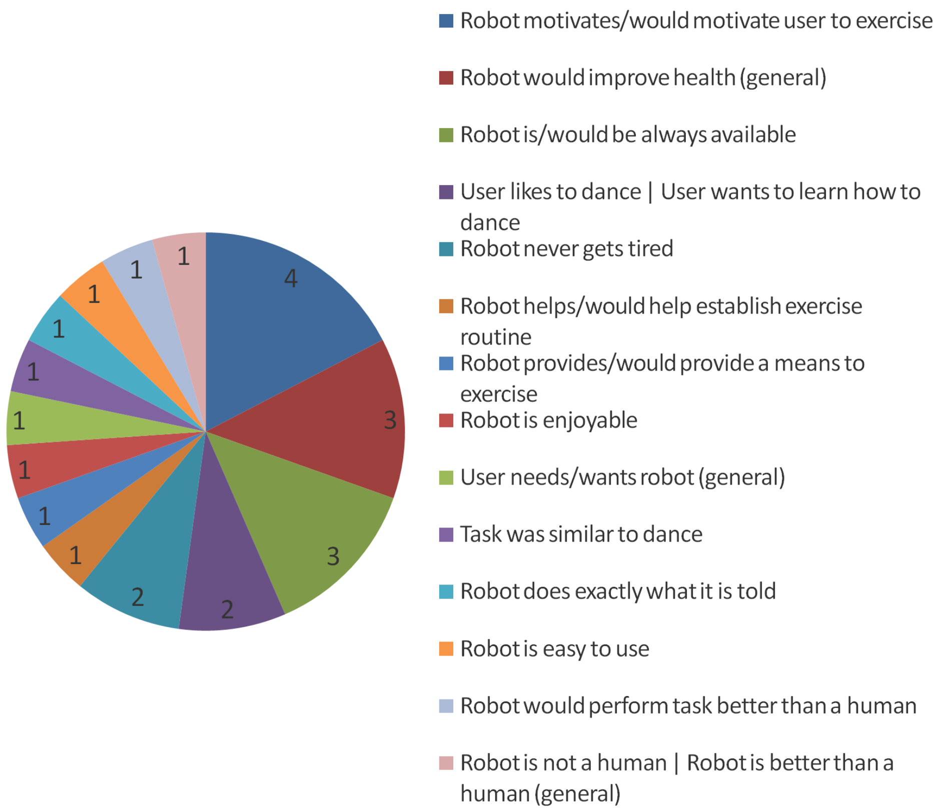


(b) Facilitators

Figure 49: Question: "What features or capabilities of a robot for partner dance-based exercise would make it more enjoyable?"

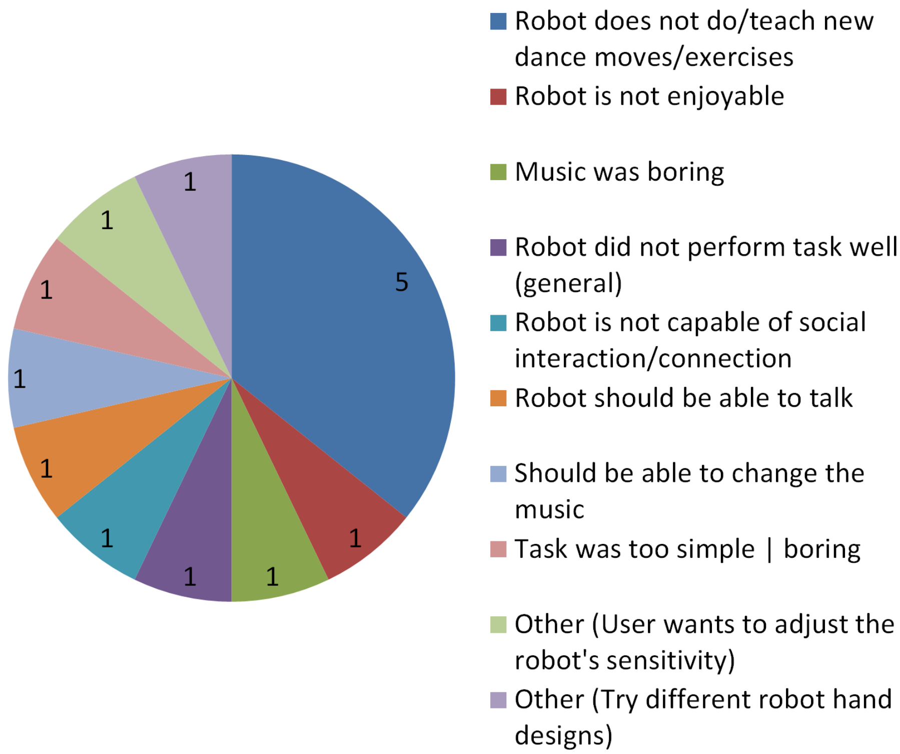


(a) Barriers

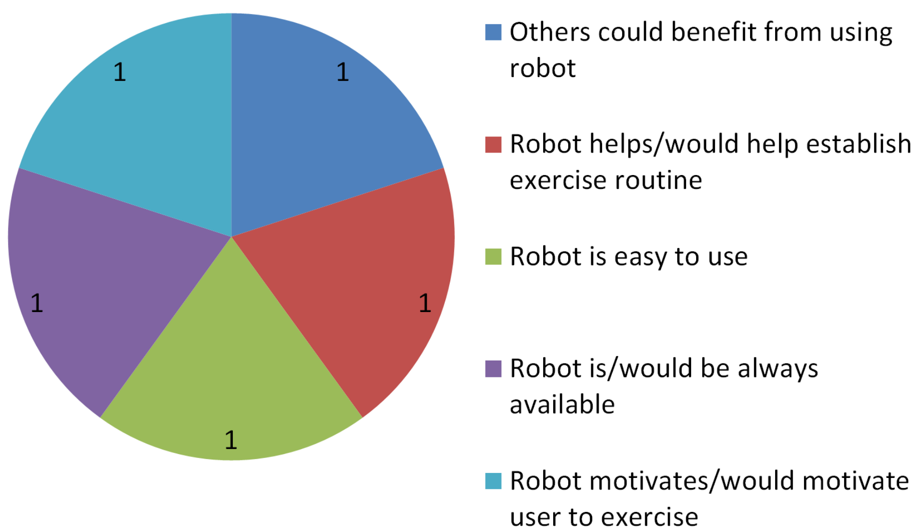


(b) Facilitators

Figure 50: Followup to participants' responses to Robot Opinions Questionnaire *Post*, Question 14.

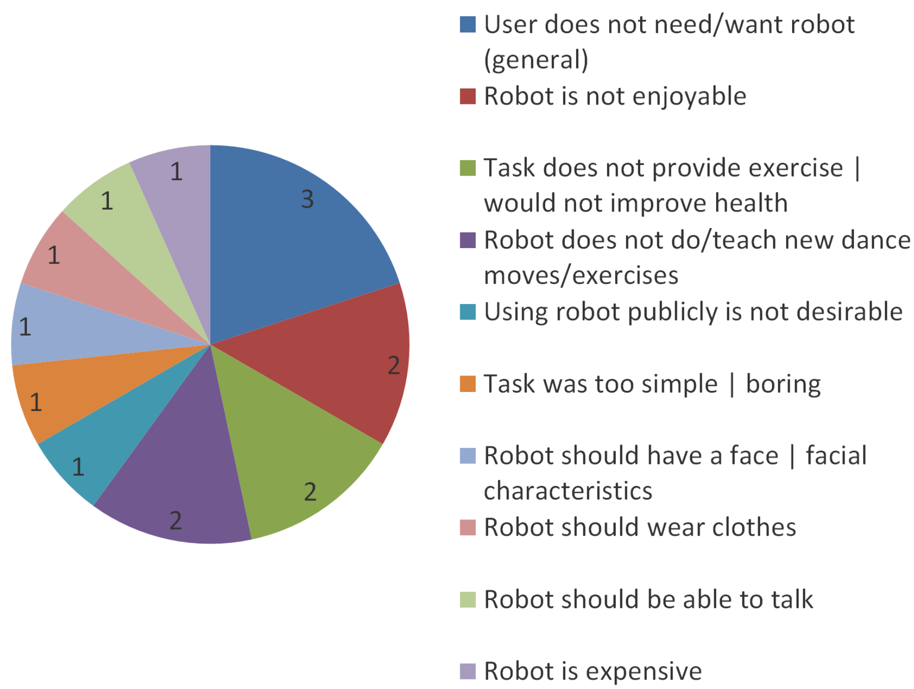


(a) Barriers

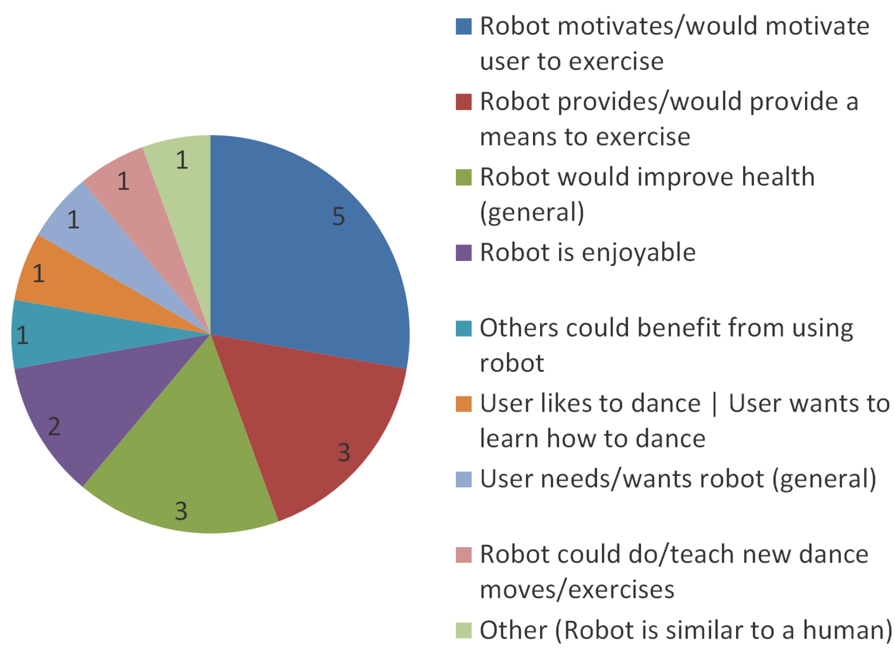


(b) Facilitators

Figure 51: Question: "What features or capabilities of a robot for partner dance-based exercise would make it a better idea?"

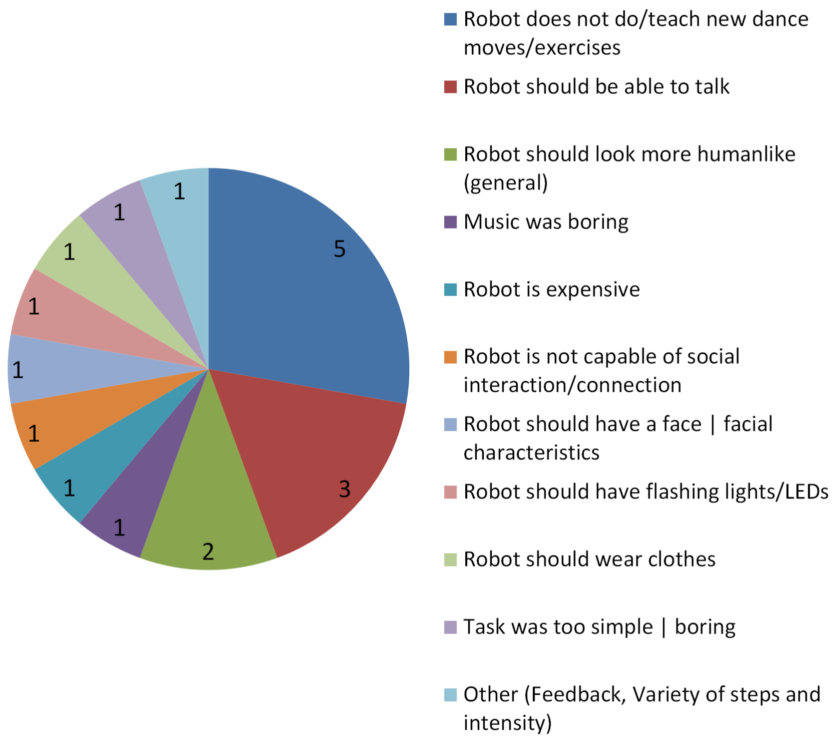


(a) Barriers

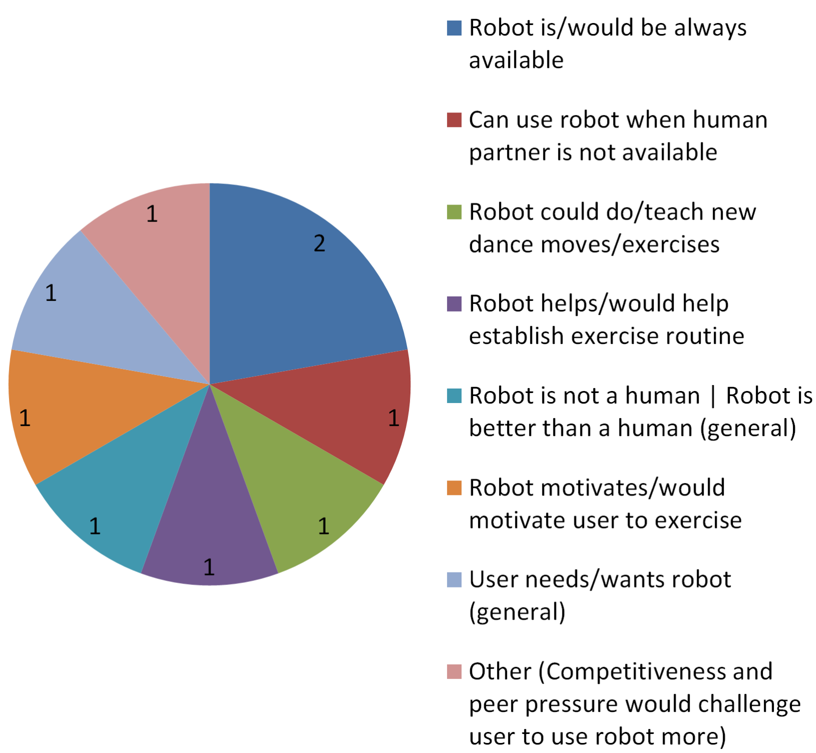


(b) Facilitators

Figure 52: Followup to participants' responses to Robot Opinions Questionnaire *Post*, Question 15.

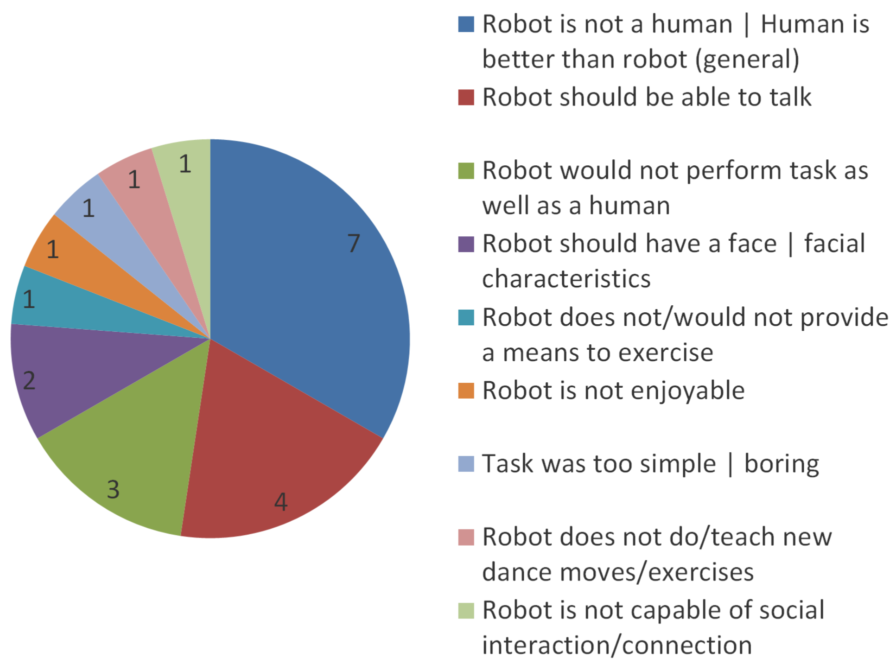


(a) Barriers

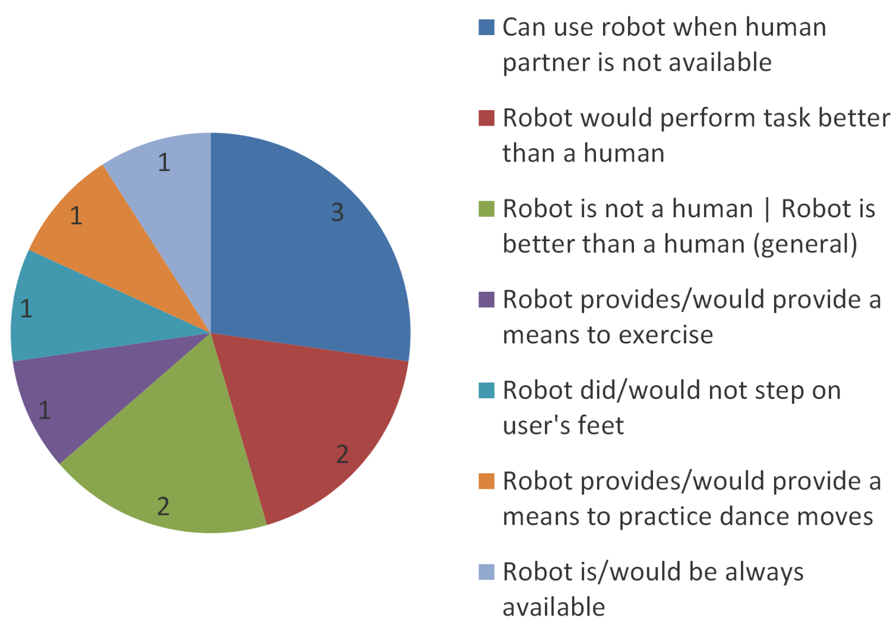


(b) Facilitators

Figure 53: Question: "What features or capabilities of a robot for partner dance-based exercise would make you more likely to use it?"

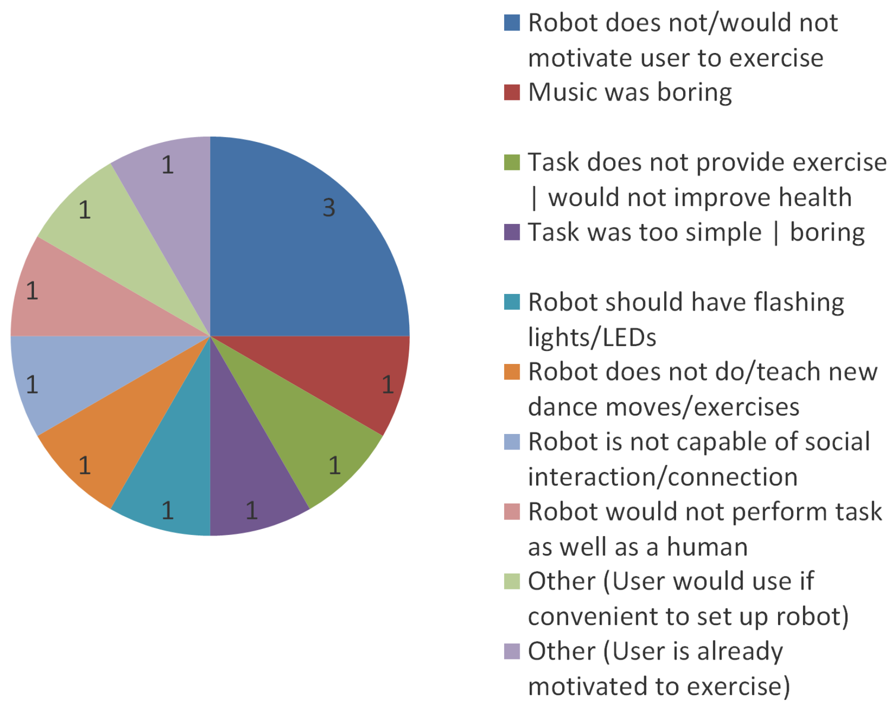


(a) Barriers

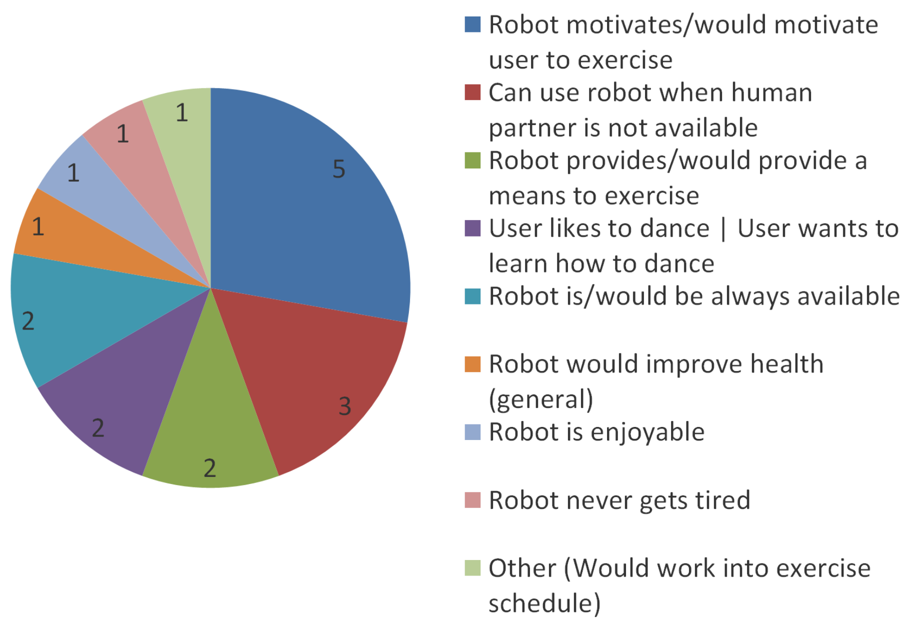


(b) Facilitators

Figure 54: Followup to participants' responses to Final Questionnaire, Question 2.

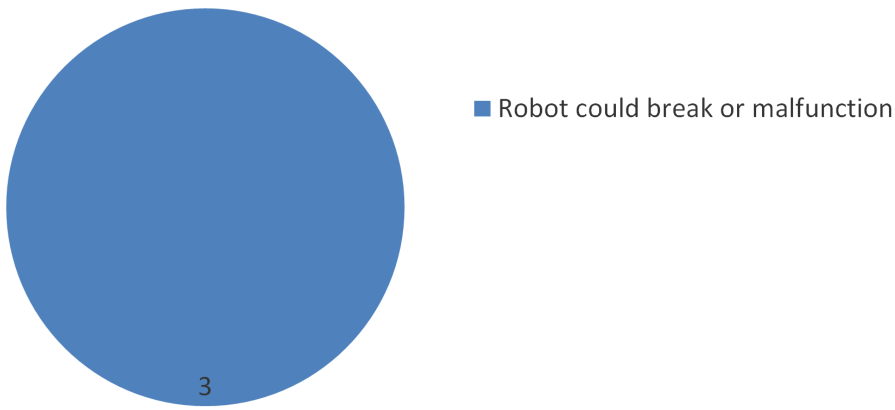


(a) Barriers

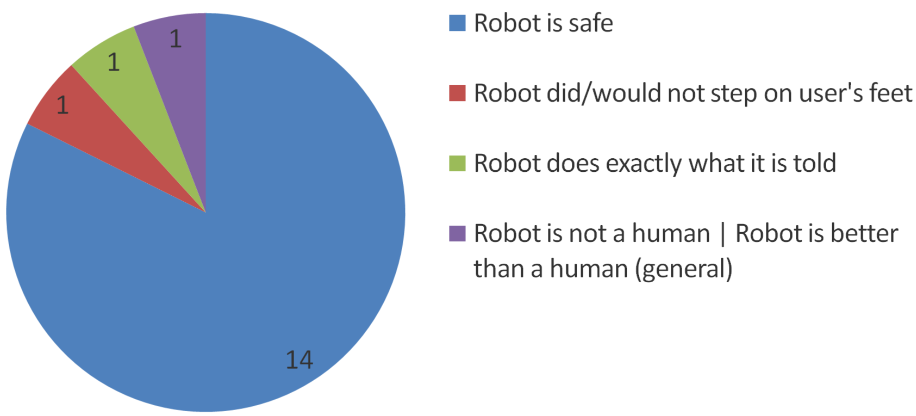


(b) Facilitators

Figure 55: Followup to participants' responses to Final Questionnaire, Question 4.

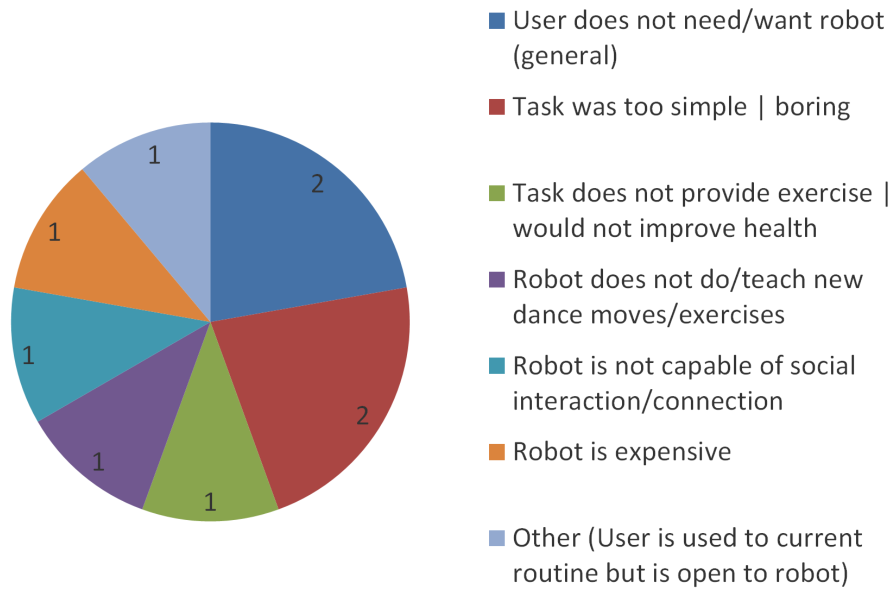


(a) Barriers

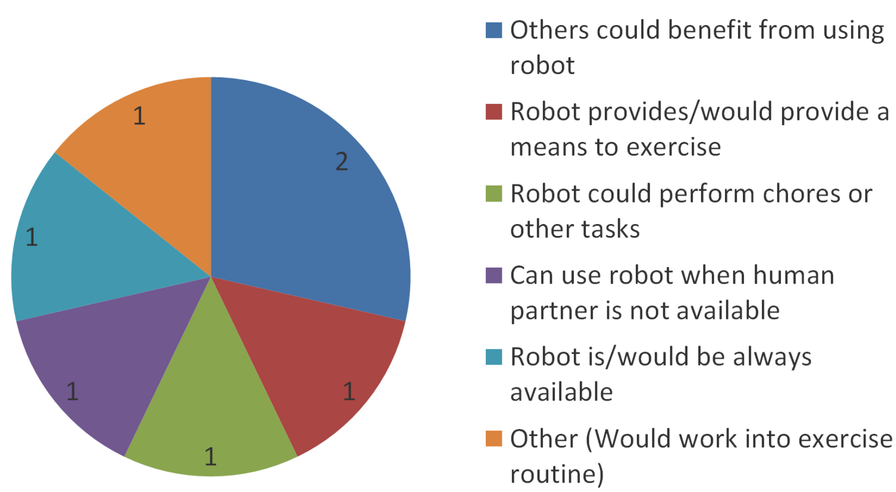


(b) Facilitators

Figure 56: Followup to participants' responses to Final Questionnaire, Question 5.

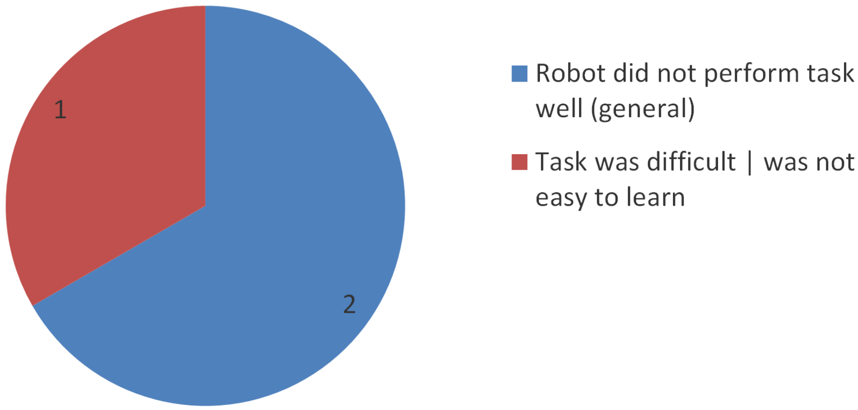


(a) Barriers

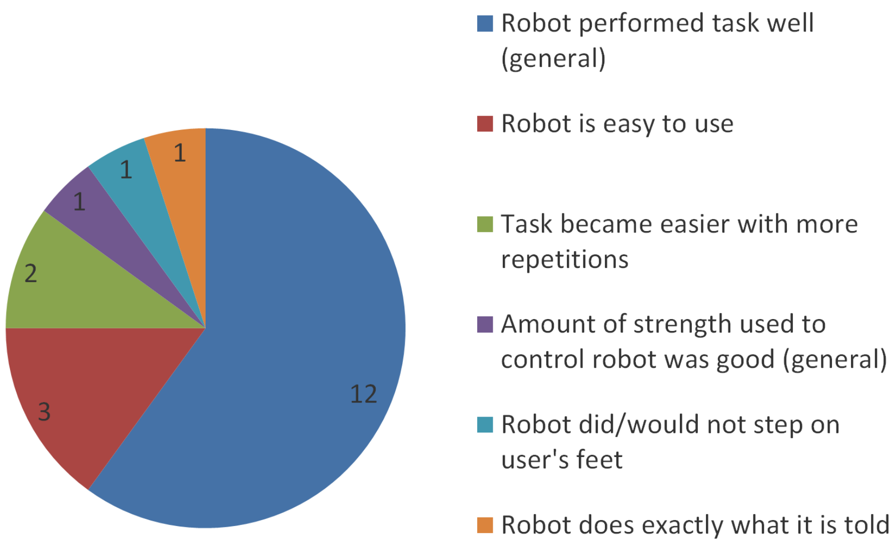


(b) Facilitators

Figure 57: Followup to participants' responses to Final Questionnaire, Question 10.

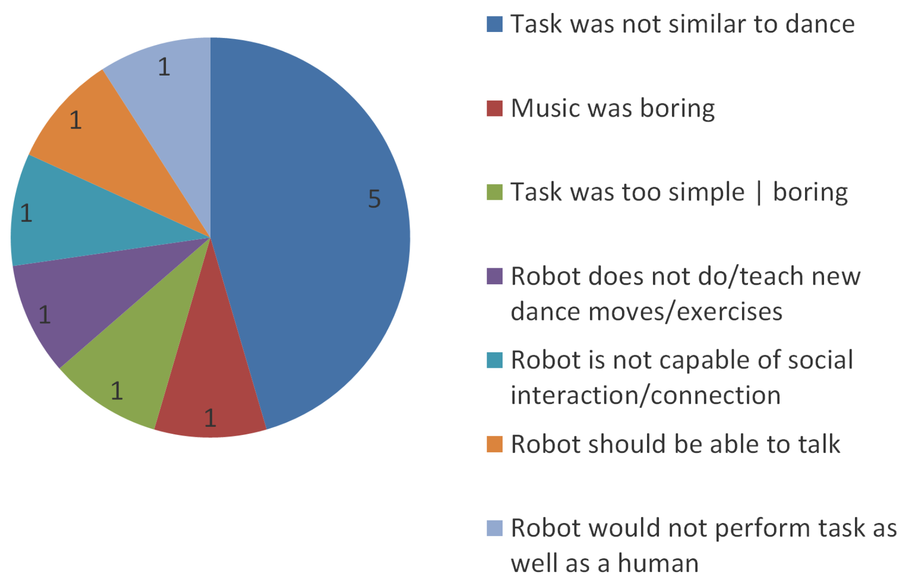


(a) Barriers

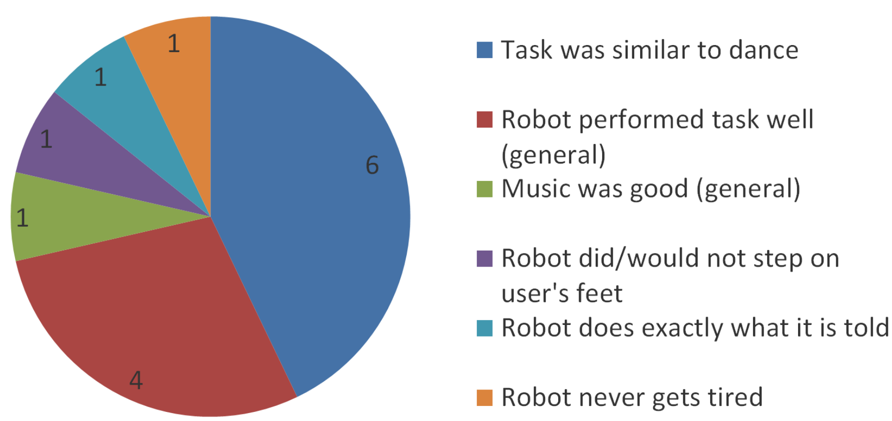


(b) Facilitators

Figure 58: Followup to participants' responses to Partnered Stepping Questionnaire II, Question 1.

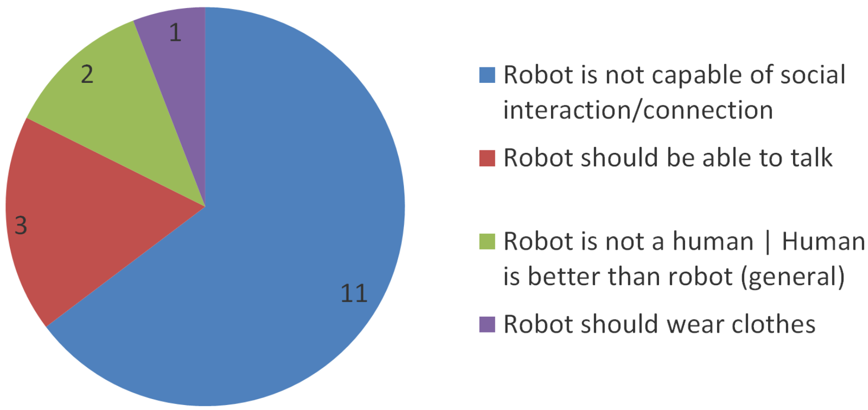


(a) Barriers

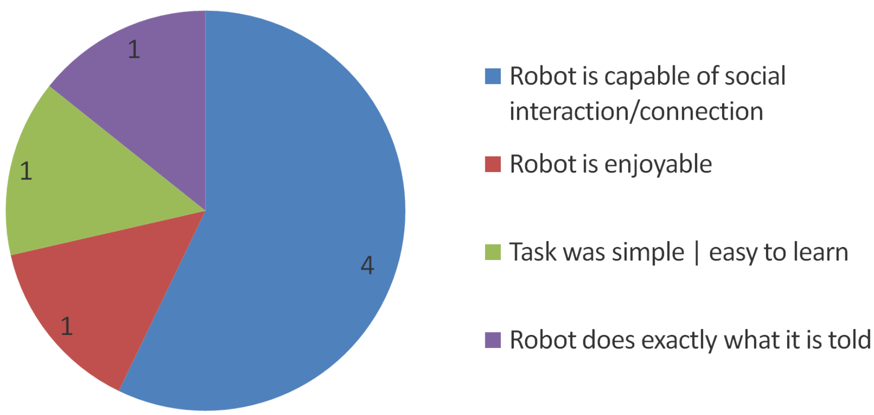


(b) Facilitators

Figure 59: Followup to participants' responses to Partnered Stepping Questionnaire II, Question 3.

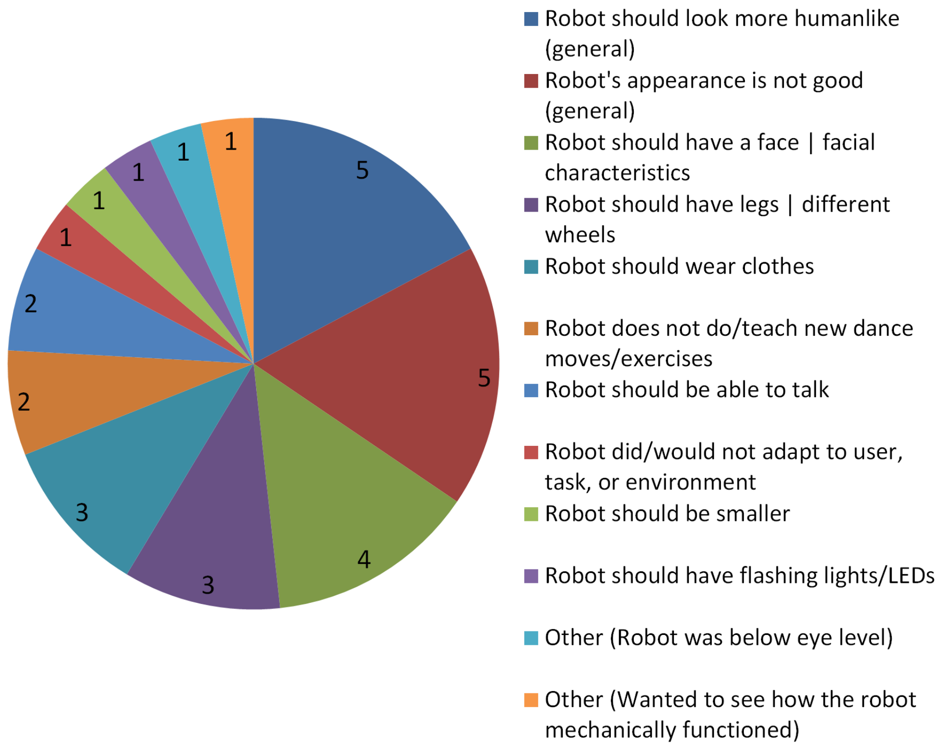


(a) Barriers

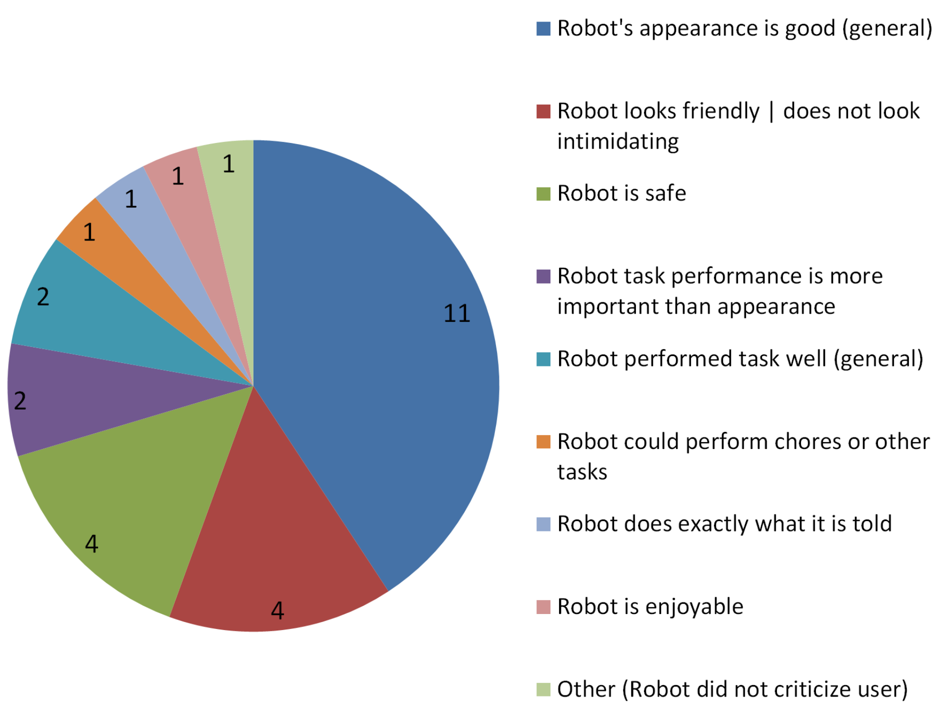


(b) Facilitators

Figure 60: Followup to participants' responses to Partnered Stepping Questionnaire II, Question 5.

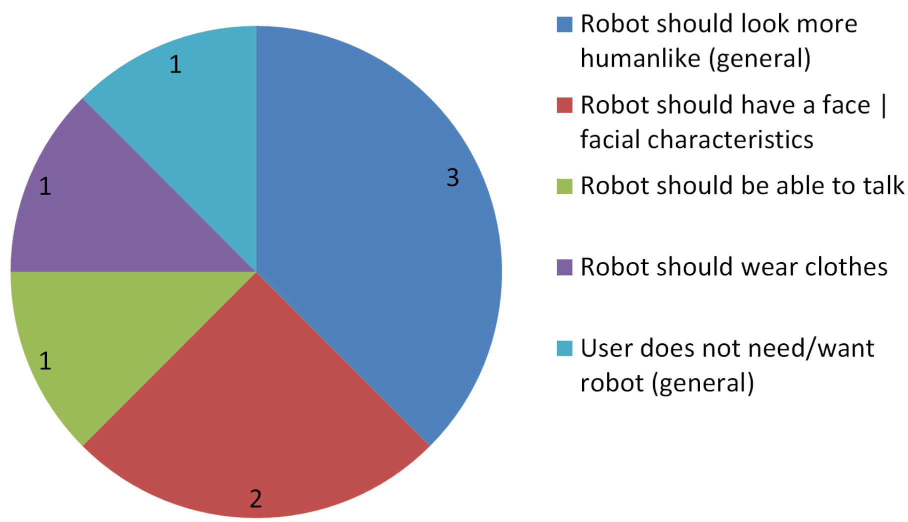


(a) Barriers

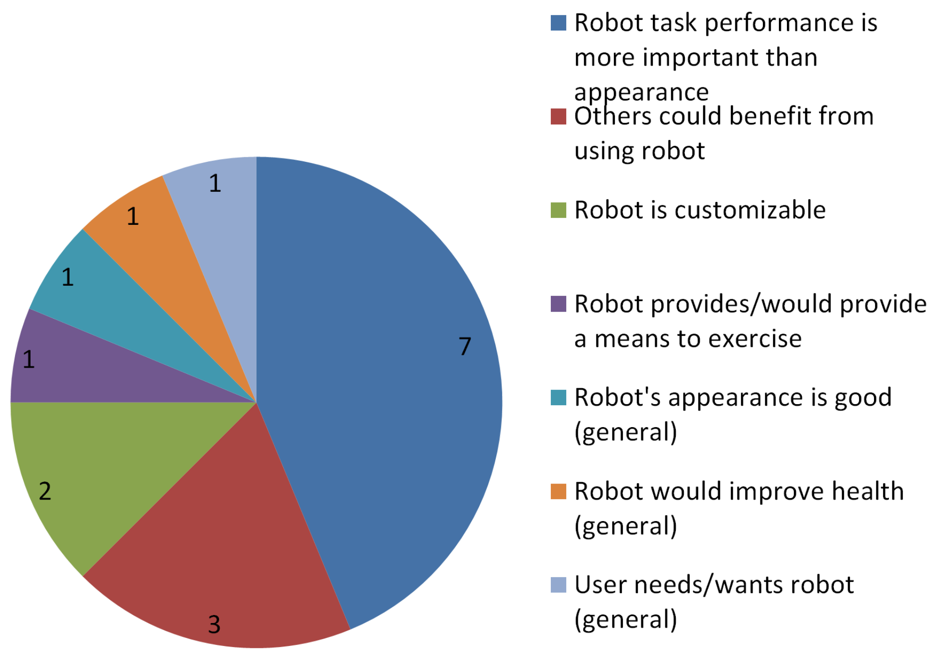


(b) Facilitators

Figure 61: Question: "What were your impressions about the robot's appearance?"

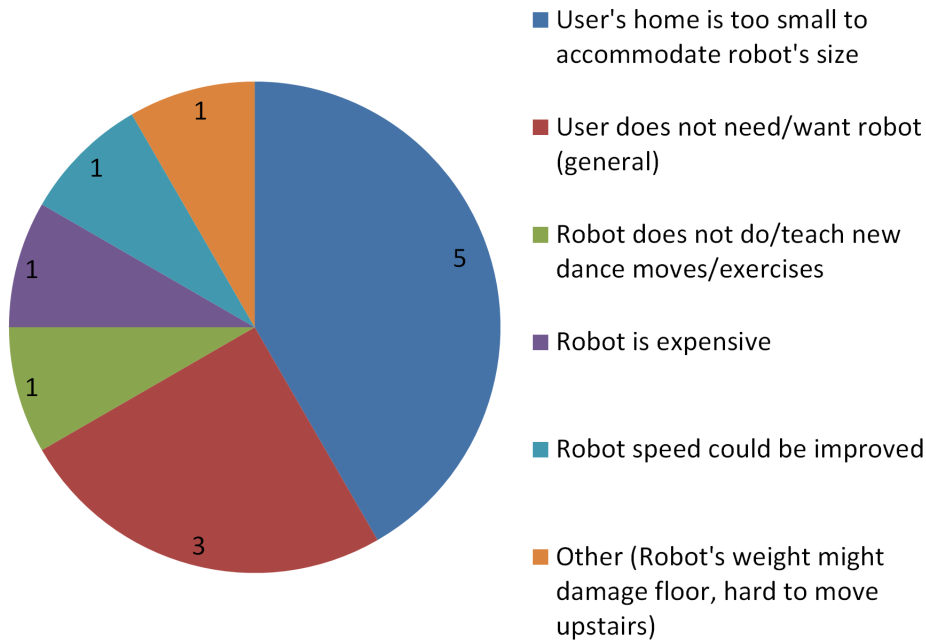


(a) Barriers

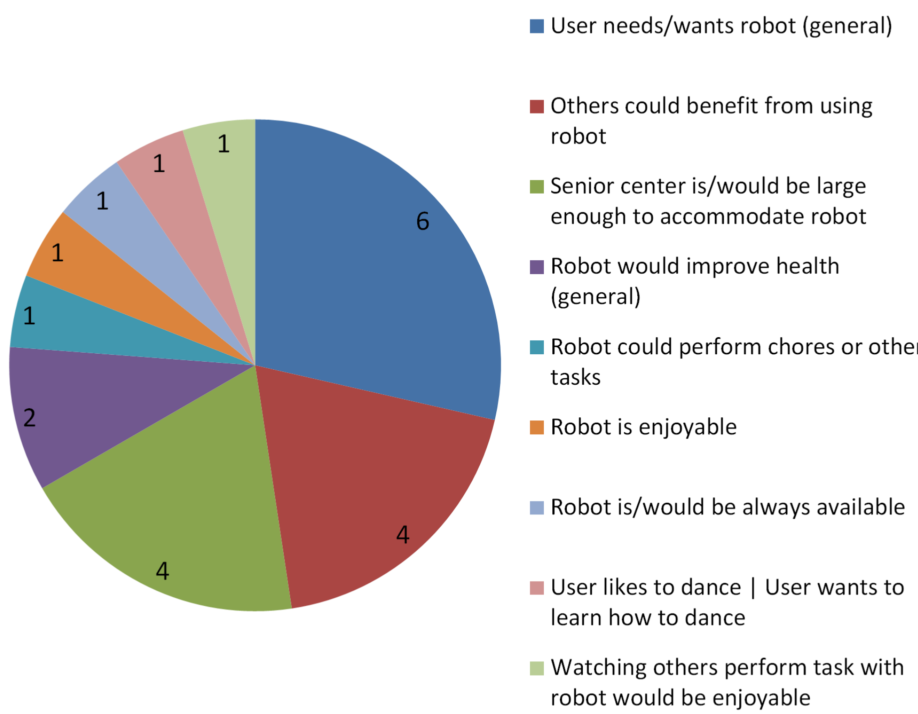


(b) Facilitators

Figure 62: Question: "How important is the robot's appearance to have a robot like this in your home or senior center? Why or why not?"



(a) Barriers



(b) Facilitators

Figure 63: Question: "If someone gave this robot to you today, would you want it in your home or senior center? Why or why not?"

APPENDIX C

DESIGN GUIDANCE FOR HAPTIC HUMAN-ROBOT INTERACTION IN HEALTHCARE

In this appendix, we provide guidance regarding how robotics designers can implement the algorithms used in this thesis on different robot platforms. We provide guidance on the design of the tasks performed in this thesis: (1) wiping the skin of a human arm and (2) whole-body motion coordination. For each task, we describe the design parameters and processes that were used to produce the acceptable and effective haptic human-robot interactions in this thesis. Then, we discuss specific implementation details that can be used to adapt the design parameters for different robotic platforms (e.g., different morphology, different haptic sensing elements). Refer to the code submitted along with this thesis as supplementary material for the specific implementation used.

Task 1. *Wiping the skin of a human arm*
Refer to Study 1 (Chapter 2) for the specification of the bang-bang controller used in that study. The following design guidance refers to that specification.

1. Controller design

    (a) Force range: After the robot makes contact with the human's skin, it moves across the human's skin while maintaining a normal force with the skin within a specified force range using bang-bang control. [Force range used: 1 to 3 N (Study 1)]

    (b) Path length: After the robot makes contact with the human's skin, it moves across the human's skin according to a distance specified by the path length parameter. [Path length value used: 14 cm (Study 1)]

2. Physical contact attributes

   (a) End effector: The end effector of the robot that will make contact with the human's skin has a soft covering that does not chafe or abrade the human's skin.

   (b) Robot arm stiffness: The robot's arm is compliant (low stiffness) in order to take into account contours of the human's skin surface. [Robot arm stiffness setting used: 20, 50, 15, 25, and 2.5 Nm/rad (shoulder flexion/extension, shoulder abduction/adduction, shoulder internal/external rotation, elbow flexion/extension, and forearm pronation/supination motions) (Study 1)]

3. Parameter tuning

   (a) Force range: The force range is set such that it specifies sufficient force required to maintain contact with the human's skin and to remove any undesired debris from the human's skin while maintaining the safety and comfort of the human. The control engineer determines the distance that the robot will move along the normal axis, either toward or away from the human skin, to maintain the desired force range.

   (b) Path length: The path length is either specified *a priori* by the control engineer, or during the interaction by a human operator.

   (c) Robot arm stiffness: The stiffness at each of the robot's joints must be tuned such that the robot is able to maintain contact given the force threshold while maintaining comfort of the human.

(d) Pilot testing: The controller is tested first with a phantom apparatus (e.g., a compliant tube that resembles the shape of a human arm) and then with human participants during pilot studies. Proper protections for human subjects must be arranged (e.g., with the Institutional Review Board (IRB) of a university) prior to conducting pilot studies. After each testing session, force range and path length parameters and robot arm stiffness settings are modified per the design guidance discussed above.

In Study 1, it was assumed that the human's arm was placed such that the surface normals to the arm were aligned with gravity. When this assumption will most likely not be true, the robotics designer must detect the direction of the surface normals using an alternative sensing method (e.g., computer vision). Also, the robot had a low stiffness arm that allowed it to "follow" the contours of the human's arm. If low stiffness actuation is not available, then any other surface following implementation can be used, as long as the force threshold is comfortable for the human user (e.g., 2N of normal force). However, the safety associated with using low stiffness arms would be lost and hence, should be avoided.

Task 2. *Whole-body motion coordination*

Refer to Studies 2, 3, and 4 (Chapters 3, 4, and 5) for the specifications of the admittance controllers used in those studies. The following design guidance refers to those specifications.

1. Controller design

   (a) Direction: The robot moves its mobile base in the same direction in which force is applied to its body by the human.

   (b) Magnitude/Gain: The robot moves its mobile base in a speed that is proportional to the force or joint angle change that is applied to the robot's body by the human. [Magnitude/gain values used: 0.02 m/sN (forward/backward motion), 0.01 m/s·deg (sideways motion), 0.3 1/s (rotation) (Study 2); 0.01 and 0.02 m/sN (forward/backward motion) (Study 3); 0.04 m/sN (forward/backward motion) (Study 4)]

2. Physical contact attributes

   (a) Location: The location(s) on the robot's body upon which the human is expected to make contact is/are comfortably reached by the human while in a standing posture.

   (b) Robot arm stiffness: The location(s) on the robot's body upon which the human is expected to make contact is/are physically compliant (are low stiffness).

3. Parameter tuning

   (a) Magnitude/Gain: The magnitude/gain of the admittance controller are manually tuned until the desired responsiveness is achieved.

   (b) Smoothing: The last 0.10 sec of the raw velocity commands are averaged to smooth velocity transitions. This time window can be shortened or lengthened until the desired velocity smoothness is achieved without sacrificing response time.

   (c) Robot arm stiffness: The stiffness at each of the robot's joints must be tuned so that the human can comfortably apply forces to the robot without undue energy expenditure. In turn, the magnitude/gain parameter may have to be adjusted to take into account the comfortable range of joint angle positions expected to be used by the human. [Robot arm stiffness settings used: 2050 N/m (high stiffness), 543 N/m (low stiffness) (Study 3); 465 N/m (Study 4)]

(d) Pilot testing: The controller is tested first with an able-bodied population of convenience (e.g., co-workers, students) and then with end users (e.g., nurses, older adults) during pilot studies. If available, expert users such as expert dancers or physical therapists should be consulted throughout the design process and also used during pilot testing. Proper protections for human subjects must be arranged (e.g., with the Institutional Review Board (IRB) of a university) prior to conducting pilot studies. After each testing session, controller magnitude/gain and smoothing parameters and robot arm stiffness settings are modified per the design guidance discussed above.

Different forms of haptic sensing can be used to implement the design guidance outlined above. For example, tactile sensors or buttons can be placed on any location on the robot's body that is comfortably accessed by the human. As long as the location of the tactile sensor on the robot's body is known, the axis upon which the human is applying the force can be resolved in order to determine the direction in which the robot should travel. Haptic sensors that have a non-linear response to the amount of force applied can also be used as long as their characterization is known. With this information, the control engineer can modify the magnitude/gain term to respond appropriately to command velocities that are proportional to the force that is input by the human. As used in Study 2, the robot's end effector position, shoulder angle, and the forces applied at the wrist were used as different types of input to the controller. As long as the direction of the velocity of the robot's base matches the direction in which the human moves the robot's body, and the magnitude of the velocity is scaled according to the magnitude of the input, then the type of input signal can vary.

It is recommended that a robot with compliant arms or locations of contact are used. The compliance of the robot arms used in this thesis modified the total system response when coupled with the admittance controller. Alternatively, the robotics designer can add a spring element to the controller in series with the damping element as prescribed by the admittance controller.

Users of differing heights and postures can also be accommodated by carefully selecting the location of expected contact. For example, if the primary user of the robot is a child, then the arms, and hands of the robot can still be used as locations of contact as long as the robot matches in height with the child. If the robot is a small, floor-based or tabletop robot, then the expected location(s) of physical contact on the robot's body must be placed so that a person seated on the floor or at a table can comfortably reach them.

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