Robot, Uninterrupted: Telemedical Robots to Mitigate Care Disruption

Sachiko Matsumoto
University of California, San Diego
La Jolla, CA, USA

Pratyusha Ghosh*
University of California, San Diego
La Jolla, CA, USA

Rabeya Jamshad*
University of California, San Diego
La Jolla, CA, USA

Laurel D. Riek
University of California, San Diego
La Jolla, CA, USA

ABSTRACT

Emergency department (ED) healthcare workers (HCWs) are interrupted as often as once every six minutes, increasing the risk of errors and preventable patient harm. As more robots enter hospitals, and the ED, they must support HCWs in managing interruptions, and ideally mitigate their harmful effects, without disrupting ED communication. However, interruption-mitigation strategies, particularly for mobile telemanipulator robots (MTRs), are not well understood. In this work, we explore interruption-mitigation and reorientation methods for MTRs in the ED. We conducted a study where ED HCWs teleoperated an MTR in a realistic hospital simulation environment. Our findings revealed insights on how MTRs might support multitasking in environments with frequent task switching, and the place of autonomy in safety-critical spaces. Conflicting opinions about the appropriateness of different MTR behaviors highlighted challenges and ethical dilemmas that influence the integration of MTRs in the ED. This work will support the implementation of interruption-mitigation strategies on MTRs, enabling them to better support people in fast-paced, interruption-driven environments thus reducing the risk of errors in these situations.

CCS CONCEPTS

• **Computer systems organization → Robotics**; • **Human-centered computing → Interaction design**; • **Social and professional topics → Medical technologies**.

KEYWORDS

Human robot interaction, Robotics, Healthcare robotics, Interruptions, Teleoperation, Telemedicine, Emergency Medicine

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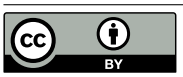

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Figure 1: The Stretch robot from the footage recorded in the simulation center.

1 INTRODUCTION

Emergency medicine (EM) is a complex, uncertain, high-stress, fast-paced environment. EM HCWs must engage in multiple tasks concurrently, including complex and rapid decision making, all while being interrupted every six minutes [23, 56, 86]. Critically, teams must make decisions and perform multiple tasks in which their performance is directly connected to patient harm or death.

EDs are polychronic work environments [12], where HCWs must account for concurrent work by others, which happens at different time scales. Interruptions are a double edged sword. On one hand, they help maintain fluid information flow in the ED, aiding patient care and ED logistics [89, 91].On the other hand, decades of human factors research shows that interruptions can lead to preventable patient harm, increased stress, and lower patient satisfaction [91].

Recently in response to the Covid-19 pandemic, researchers have investigated using robots in the ED, particularly telemedicine robots to support HCWs [44, 50, 72]. Many robots currently used in patient-facing telemedicine are fairly simple mobile telepresence robots (e.g., a tablet on wheels) [72]. These robots are incapable of conducting full patient exams, as HCWs often need to physically interact with patients to make a diagnosis [50]. Thus, MTRs may be better suited for many ED tasks that require physical interaction.

However, MTRs increase risk for patient harm as they may interact with patients, collide with people or walls, or drop or break objects. Thus, it is particularly important that MTRs are well-designed to be usable and useful to both HCWs and patients. Understanding interruptions and interruption-mitigation is also important in other safety-critical contexts where MTRs could help teams of people, like disaster zones and nuclear power plants [37, 58].

To avoid preventable patient harm and adding to HCW burden, MTRs must support HCWs during interruptions. While human-robot interaction (HRI) researchers have investigated strategies to mitigate robot-caused interruptions [4, 7, 8, 22], we still do not understand MTR methods to mitigate interruptions caused by other people. If MTR designs do not account for this, they could exacerbate the negative effects of interruptions. In particular, it is unclear what actions, if any, an MTR should take while a HCW attends to an interruption. Its autonomous behaviors will impact patient safety and ED workflow, so it is important that they are well-designed. Additionally, we do not yet understand how MTRs can help reorient HCWs to the task they were performing before the interruption.

In our research, we explored HCWs' strategies for dealing with interruptions in the ED and how an MTR can assist HCWs in managing interruptions. We investigated what behaviors ED HCWs think robots should engage in when the HCW is interrupted (e.g., stopping, continuing the task, handling the interruption in some way). Furthermore, as errors can happen due to task-switching [74, 95], we investigated the possibility of robots helping HCWs reorient after interruptions. We also explored how willing ED HCWs are to engage with different types of interruptions, given the type of task they are performing (similarly to [26]).

We conducted a study with ED HCWs. First, we conducted information-gathering interviews to understand the clinical decision-making process when handling interruptions. We also discussed desirable MTR behaviors that could mitigate the impact of interruptions in different scenarios. Based on these interviews, we created a realistic MTR prototype, which enabled clinicians to experience the simulated teleoperation of the MTR in a medical center. We then used the prototype to conduct a study that explored how MTRs might support HCWs when they are interrupted, and help reorient them when they return to their original task.

Our contributions are three-fold. First, we explore the roles of MTRs in the ED during physically interactive patient care tasks, focusing on how MTRs can mitigate interruptions from other people. These mitigation strategies may lower HCW cognitive load and increase task completion, thus reducing preventable patient harm.

Second, our work informs the HRI community on broader implications of appropriately designing MTR behaviors for integration into HCW workflow. We highlight efficiency trade-offs, technology limitations, and ethical tensions when designing MTR behaviors that support HCWs. Our analysis on suitable robot behaviors also takes into account the level of autonomy, patient and HCW safety, trust, and the potential for robot failures. Third, to support reproducibility in the HRI community, we provide access to our MTR prototype: https://github.com/UCSD-RHC-Lab/MTR-Sim. This could help researchers rapidly test and validate interruption-mitigation strategies for MTRs. Through these contributions, we encourage HRI research in MTR-mediated interruption-mitigation in the ED, as well as other interruption-driven, safety-critical environments.

2 BACKGROUND

2.1 Robots in Healthcare

In light of outbreaks like Covid-19, HCWs may experience increased stress [62, 76], adversely affecting the ability for healthcare systems to respond. Thus, research efforts in robotics have focused on integrating robots in to clinical spaces to help HCWs with their workload, facilitate access to care, and minimize risk to the clinical workforce [2, 3, 24, 31, 33, 36, 63, 66, 72, 73, 78, 96].

Telepresence robots are one type of robot explored during the pandemic [21, 72], as well as other contexts like collaborative teams [77, 88], school and work [5, 46, 59, 60, 67, 80], and personalization [29]. They are mobile robots that incorporate video conferencing, providing operators with an embodiment in a remote location.

MTRs are another kind of robot used in hospitals. These robots are remotely controlled by a clinician, and are similar to telepresence robots with the addition of a manipulator to effect changes in the remote environment. They have been used to perform care tasks such as cleaning, item delivery, and monitoring vitals [39, 47].

However, deploying robots in hospitals, particularly in EDs, poses unique challenges which must be addressed for successful integration into existing workflows. Prior work suggests that robots in the ED must be designed to navigate crowded hallways and avoid collisions, account for the complex care needs of high acuity patients, widely ensure robots' safety and usability, and account for differences in workflow and physical environments at different EDs [50, 78, 82–84]. Therefore, despite MTRs' potential to support HCWs' work, their behavior must be carefully designed to facilitate the interruption-prone, time and safety-critical workflow of the ED.

2.2 Interruptions in the ED

Workflow interruptions are key characteristics of EDs [1, 14, 26, 27, 30, 38, 40, 91–93]. When interrupted, HCWs typically assess their workload and prioritize tasks based on criticality. They may multitask or stop the current task to attend to the interruption, and then reorient back to the original task after the interruption [1, 93].

These interruptions adversely affect patient care outcomes in the ED [38, 93], resulting in more clinical errors and lower task completion [74, 94]. Additionally, highly interruptive environments increase fatigue and stress, and decrease critical thinking and situational awareness among HCWs, potentially causing delays in care [26, 91, 93]. Patient satisfaction may also be adversely affected [38].

EDs utilize many strategies to manage interruptions and mitigate their negative impacts [13, 64]. For instance, reducing interruptions [6, 11], facilitating asynchronous communication, and using technology to facilitate information access may reduce care disruption [42]. Cognitive strategies, such as mental rehearsal of the original task or use of environmental cues, may also support recollection and reorientation upon task resumption [64]. However, it is unknown whether these strategies are feasible and effective longitudinally in different types of EDs [13], and we do not understand what effect MTRs may have on these strategies. Thus, our work explores suitable MTR interventions for managing interruptions in the ED.

2.3 Interruptions in HRI

HRI researchers have investigated the effects of interruptions on trust and reaction times, as well as in safety-critical environments where multitasking is required [34, 49, 98]. Researchers also explored methods to facilitate task re-engagement or corrective actions after interruptions [79, 87]. In most studies, participants were required to attend to interruptions, whereas in real life, they often have a choice whether or not to switch their attention. Therefore,

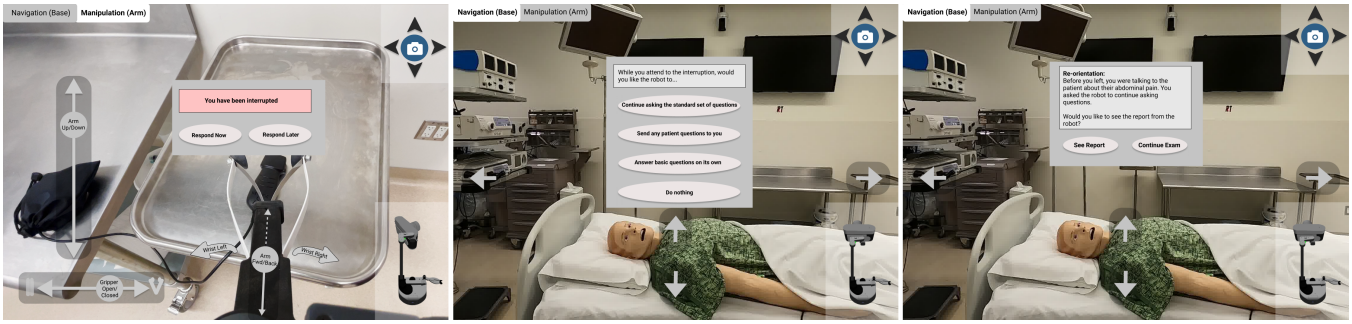

Figure 2: We showed ED HCWs various interruption prompts they could respond to in the Figma prototype. *Left*: The prompt indicating an interruption. When this prompt appeared, an experimenter acting as an HCW verbally explained the interruption to the operator. *Middle*: When interrupted, the operator could choose one of several behaviors for the robot to perform. *Right*: Reorientation prompt that appeared when participants who asked the robot to continue the patient interview returned from the interruption.

in our study, we allowed HCWs to choose when to attend to interruptions, and explored the factors that influenced those decisions.

HRI researchers have also explored replicating human-human interaction behavior in robots when interrupting individuals to engage in social interactions. Some work proposed models to predict people's interruptibility, and explored social behaviors to assist with interruptions [4, 7, 8, 18, 22, 28, 35, 68–70]. Researchers also examined preferred robot behaviors when a robot interrupted one task to attend to another [20]. While there have been several studies exploring how robots can handle interruptions themselves or appropriately interrupt others, to our knowledge, there is a distinct lack of research in the HRI field on how robots can mitigate the effects of interruptions when people are interrupted by other sources.

3 METHODOLOGY

We conducted a qualitative study to explore how robots can assist HCWs in mitigating the impacts of interruptions in the ED. We conducted this study as a realistic, online simulation via Figma, where a remote clinician participant teleoperated our MTR (Stretch) and was periodically interrupted. We then collaboratively explored interruption-mitigation strategies robots could provide, including reorientation methods, with clinicians. This study was declared exempt by the UC San Diego IRB, under protocol number 804926.

3.1 Robot

Our study used the Stretch from Hello Robot [43] (Fig. 1). It is a mobile manipulator, with a non-holonomic base, an arm, and a head camera, each with two degrees of freedom, as well as a wrist and gripper with one degree of freedom. While having eight degrees of freedom enables the Stretch to perform a wide variety of tasks, it can also make controlling the robot complex.

3.2 Prototype Design

Though the Stretch has an off-the-shelf web-interface, we engaged in an iterative design process to develop a more intuitive control interface. The original interface involved significant mode switching [19], which can place substantial physical and cognitive load on operators [85, 97]. To limit the number of modes and windows, our redesigned interface had two modes: navigation mode and manipulation mode, similar to those described in [43] (Fig. 2). While this somewhat limits concurrent robot motions, operators tend to perform manipulation only after navigating to an appropriate location [43]. In navigation mode, the operator controls the robot base via four arrow buttons. In manipulation mode, they control the robot arm, wrist, and gripper via sliders and buttons. In both modes, the operator has access to camera controls to pan and tilt the robot's head camera. Additionally, we added a small 3D model of the robot, which showed the direction of the camera, to help operators orient.

We used this interface to create a realistic simulation of teleoperating the MTR in Figma [71], a tool for UI/UX design. In collaboration with a HCW, we recorded footage of an experimenter teleoperating the robot in a medical simulation center and interacting with a patient simulator. We chose an ultrasound as the task because it requires use of many of the robot's capabilities, and includes tasks that HCWs commonly perform. We overlaid our interface design on this footage to develop the Figma prototype. With this prototype, operators could pretend to control the robot to perform an ultrasound. When they clicked buttons on the interface, the screen would change as if the robot had moved in that direction.

3.2.1 Incorporating ED Interruptions. To better understand how MTRs might support HCWs during and after interruptions, we conducted a literature review and engaged two EM physicians (1 male, 1 female) in semi-structured information-gathering interviews over Zoom. They had 1.5 and over 20 years of experience in EDs, respectively, and little experience with robots.

We asked the physicians how they made decisions about common types of interruptions we found in our literature review, including communication of patient information and broader ED information, consultation requests, and physical assistance requests.

We then introduced the clinicians to the capabilities of MTRs, and presented them with the ultrasound scenario we intended to use in the prototype. We divided the ultrasound into four sub-tasks (Fig.3) and asked how they would prioritize interruptions during each sub-task. We also asked how they thought the robot might help them mitigate the effects of interruptions during each sub-task, and how the robot could help them re-orient after an interruption.

We extensively discussed insights from the interviews and our literature review. We found that HCWs tend to prioritize based on task criticality, ED throughput, task stage, and professional relationships. The physicians also emphasized that robot behaviors that facilitate efficiency, communication, and reorientation would be helpful in mitigating the impact of interruptions.

Using these insights, we updated the prototype to include three interruptions of varying time-sensitivity and urgency that HCWs

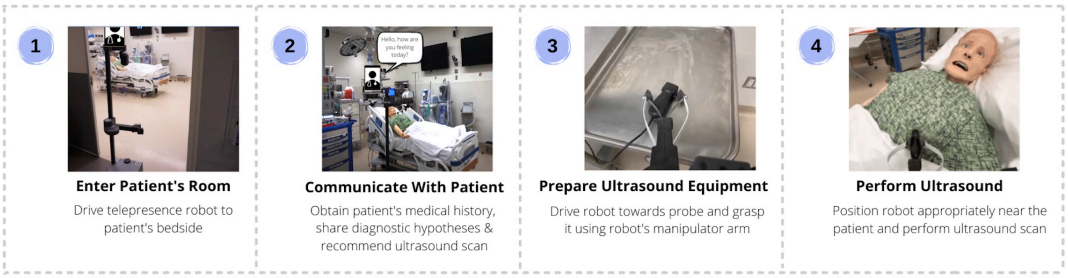

Figure 3: The ultrasound task had four parts: enter the room, talk to the patient, prepare equipment, and perform the scan.

could choose to attend to or ignore. We randomized the order in which they occurred. In the *Discharge Interruption (DI)*, HCWs could discharge a patient who was under observation for four hours after an allergic reaction. This interruption would likely be of lower urgency since the patient was stable, but could still be a priority because discharge is important for patient throughput in the ED.

In the *Consultant Interruption (CI)*, HCWs could take a call about a patient with a leg fracture from an orthopedic consultant, who would not be available for the next two hours. While this interruption also did not incorporate a high-acuity patient, it might cause a greater sense of urgency because deferring the interruption could delay a patient's care for several hours. The third interruption, the *Patient Interruption (PI)*, was a patient with an infection whose blood pressure had suddenly dropped and who may have sepsis. This interruption might result in the greatest sense of urgency because it involved potentially life threatening symptoms.

We also integrated options for robot behaviors that might be useful to HCWs in mitigating the impact of these interruptions. If HCWs attended to the interruption, the robot could continue the primary task, answer simple patient questions, send patient questions to HCWs, or do nothing. If HCWs chose for the robot to send them questions, 20 seconds into the interruption, a prompt would appear with a question from the patient, and they could respond to the question. Otherwise, the robot would not disturb them during the interruption.

After the interruption, HCWs saw a pop-up with text reminding them what they had been doing and updates based on the robot behavior they chose during the task (Fig. 2). Depending on the chosen robot behavior, certain reorientation prompts also included reports from the robot that HCWs could view if they wanted to (such as patient history data gathered by the robot). The Figma prototype also updated the simulation based on the choice of MTR behavior that HCWs made, allowing the clinicians to get a realistic idea of what help from the MTR may look like during task interruptions.

We incorporated these interruptions via a pop-up on the screen at three points in the simulation (see Fig. 2). The first interruption was during the *Interview Task (IT)*, when HCWs first talked to the patient. The next interruption occurred during the *Grasping Task (GT)*, when HCWs were picking up the probe. The last interruption happened during the *Ultrasound Task (UT)*, as they were about to start the ultrasound. These tasks represent scenarios where participants were engaging in interpersonal interaction, physical manipulation without direct patient interaction, and physical interpersonal interaction via the MTR, respectively, three distinct task contexts during which HCWs might be interrupted.

3.3 Main Study

We recruited 12 participants (1 female, 11 male)[1] via email and word of mouth. Participants were EM physicians with an average age of 38 years and between 1 and more than 20 years of experience (mean=9 years) in medicine at different types of hospitals, including teaching, non-teaching, for-profit, non-profit, urban, and rural hospitals. They generally had limited experience with robots. Prior to participating, participants were asked to sign consent forms. If they had not done so, their consent for participation and video recording was obtained before commencing the study and they sent the consent forms after completing the study. To preserve the anonymity of our participants we refer to them as P1-P12.

Durign the study, one experimenter (*E1*) explained the study to participants, answered participants' questions, and conducted the interview. Another experimenter (*E2*) acted as the primary patient, and a third experimenter (*E3*) acted as various HCWs in the ED who interrupted the participant.

First, *E1* introduced the study, the MTR's capabilities, and the prototype to participants. Participants completed a tutorial with a simple pick-and-place scenario to gain familiarity with the interface in the prototype. Once participants completed the tutorial, *E1* explained the main study, the roles of the experimenters, and how interruptions would occur. Participants then began the main study.

Participants clicked through the prototype to teleoperate the robot in the simulation. We asked them to perform an ultrasound on the primary patient, which included four sub-tasks, similar to the division in our information-gathering interviews.

In the simulation, participants were interrupted three times, as described in Sec. 3.2.1. When participants were interrupted, *E3*, acting as another HCW, explained the nature of the interruption.

After hearing about the interruption, participants could ignore the interruption and continue with the task or attend to the interruption. If they attended to the interruption, they chose one of the four behaviors for the robot described in Sec. 3.2.1.

While attending to interruptions, participants saw a black screen with an image of people talking. *E3*, acting as an HCW, relayed information to them, based on a prepared script, and asked them questions related to the interruption for approximately one minute.

After they completed the simulation, we conducted semi-structured interviews with participants to better understand their reasoning behind the decisions they made during the interruptions and their thoughts on how the robot reoriented them after interruptions.

[1]Women are underrepresented in EM, representing about 27.6% of active ED physicians in the U.S. [45]. Despite efforts to reach out to women ED physicians at two medical facilities, we were unable to increase the number of female participants in our study.

At the end of the interview, we asked them to complete the SUS questionnaire [9] and a demographic form.

3.4 Data Analysis

We analyzed the transcripts collected from our interviews using reflexive thematic analysis (RTA) [15]. We chose this method as we sought to have a more nuanced understanding of participant concerns and ideas for possible robot behaviors. RTA granted us greater flexibility and sensitivity in understanding participant insights. First, three researchers independently critically explored the data, and came together to discuss our initial codes. Over several rounds of discussions, we refined the codes and grouped them into broader themes based on their shared patterns of meaning. Finally, based on the finalized themes, we reflected on the implications of these findings in relation to our overall research goals. Since the focus is on reflexive understanding of the data rather than coder consensus, in line with the RTA methodology [16] and most qualitative papers in the HCI/CSCW communities [55], we did not calculate inter-rater reliability.

We calculated the mean SUS score to evaluate the usability of our interface prototype, and analyzed the different task prioritization choices the physicians made during interruptions in the simulation.

4 FINDINGS

4.1 Managing Interruptions in the ED

Participants discussed the chaotic and dynamic nature of the ED, including the many tasks they need to complete, the multitude of interruptions they face, and their decision making process for managing interruptions. One participant described their method for managing tasks as "mildly controlled chaos" (P8). Participants also explained the adverse effects of interruptions in the ED, such as disrupting their ability to provide care to patients, damaging their relationship with patients, and delaying care down the line.

Most participants emphasized the importance of patient acuity and risk. For example, only 3/12 participants chose to attend the interruption involving patient discharge, while 11/12 participants chose to attend to the patient with unstable vitals. Since answering consultant calls tends to be a "rate-limiting step" (P8) in patient care, and delaying it can be detrimental to patients, all participants chose to attend to the interruption involving an incoming consultant call. These choices reflect how ED HCWs prioritize tasks, where high acuity patients and minimizing patient care delays take preference over discharging stable patients and ED throughput.

Additionally, participants considered the state of their task when the interruption occurred. For instance, participants were less inclined to take interruptions when sterile or performing a procedure. They were also less willing to attend to a second interruption if they had already interrupted the primary patient's care once.

4.2 Autonomy for Improving HCW Workflow

Participants felt that MTRs should have some degree of autonomy in order to be useful. They envisioned how an autonomous MTR could facilitate their workflow and help them complete tasks.

Reorientation Cues: Participants generally felt that the reorientation cues we incorporated into the study were "great" (P6, P8) and "useful" (P2). They thought the cues could help them reorient after they returned from the interruption. One participant noted that "cues like that are invaluable in reducing your spin up time because [...] you don't have to go back far in your train of thought to rebuild the decision momentum" (P5). Some participants observed that such cues would likely be more helpful if they were away from the task for a substantial period of time, whereas they may not need the cues if they only left the task briefly. One participant clicked through the reorientation cues without reading them, but indicated during the interview that they would consider looking at them in the future. They expressed how the cue would need to contain useful, succinct, organized information or else they would "click through it just like anything else that I click through" (P7).

Facilitating Multitasking and Efficiency: Some participants appreciated how a robot with autonomous capabilities might facilitate multitasking. They were interested in the idea of the robot performing certain tasks for them while they attended to other tasks. They felt this could help save them time or save time for another person who would otherwise need to do those tasks. They believed using the robot to multitask in this way could help reduce the amount of time patients spend in the ED and make the ED more efficient. One participant noted they "enjoyed" controlling the robot, but "the degree that you're able to get more out of the robot without a lot of manual input from me [...] that's efficiency, that's time I get back" (P6).

Participants expressed interest in autonomous assistance with a variety of tasks. Many liked the idea of a robot taking a patient's history or asking billing questions. Some also suggested the robot could autonomously navigate to certain areas, prepare tools for procedures, update patient vitals, or provide translation services. One participant suggested the robot could order labs, perform minor procedures, or administer certain medications to patients.

Participants also ideated how the robot could assist with critical patient care. Some imagined being able to quickly and easily access multiple different patients. One participant considered having multiple robots for critical patients so they could "flash from one robot to like another robot and [...] look at [the critical patient]" (P8). They also wanted to be able to see information like labs and imaging for the patient.

Several participants also thought that autonomous robot navigation could reduce their transit time. Rather than walk or drive the robot themselves, the robot could navigate on its own while they performed other tasks. One participant suggested that the robot could alert them when a patient's blood pressure dropped and then autonomously navigate to the patient's room. Then, "all I have to do is click a button and I'm now in that robot" (P5).

Participants also discussed how the robot could facilitate certain less safety-critical patient care tasks, such as changing a TV channel or ordering food. The robot might also be able to alert the appropriate HCW if the patient asked for someone, which could potentially relieve nurses of taking messages from patients to physicians.

Robot as Information Gatherer and Coordinator: Many participants thought the robot could gather information in various ways. For instance, they indicated that it was helpful that the robot could continue the patient interview when they were interrupted. When interrupted while conducting the patient interview during the simulation, 8/9 participants who chose to attend to the interruption wanted the robot to continue asking the patient a standard

set of questions. The robot acting as an "extension" (P1) of the HCW in this way could improve their workflow by collecting and recording data. With this information from the robot, they thought they would likely be able to complete the patient interview more quickly than without the robot's assistance.

Participants also suggested the robot could gather patient questions while the HCW attended to the interruption. During the simulation, two participants opted for the robot to send them the patient's questions while they were away from the room to attend to an interruption. This could enable the HCW to know "what [the patient] is thinking, [...], what they want to know, [...] what [the HCW] didn't address [...] before [they] left the room" (P1).

More broadly, the robot could collect and distill information from different sources to help coordinate care in the ED. Participants suggested that "tying the team together" (P3) and ensuring everyone is aware of what is happening with a patient could be a useful role for the robot. The robot might also help reduce the number of interruptions HCWs face, acting as "an interface [...] like distilling everything that I need to see [...] kind of a Cliff['s] Notes version" (P6). One participant suggested that the robot could collect multiple interruptions at different points in time, summarize the information, and alert the HCW "at the appropriate times," which might feel more like an "update" than an "interruption" (P6).

Shared Autonomy for Robot Control: Participants expressed concern about their ability to operate the robot. One participant worried, "I feel like I'd probably drop stuff and run [the robot] into the wall [...] I just worry about messing it up" (P11). Several participants wanted full autonomy or shared autonomy for manipulation and pick-and-place tasks in the interest of time-efficiency and robot safety. For instance, one participant said trying to pick up the ultrasound probe "was a little bit tough" and reminded them of the "grabber game that you do in arcade[s]," so they thought it would be "useful" if the robot could do it autonomously (P2).

4.3 Robot as Information Provider and Advocate

Participants discussed how they could use the robot an extension of themselves while attending to an interruption. During the simulation, two participants wanted the robot to answer some frequently asked questions for the patient while they attended to an interruption. Another observed that "a lot of times patients don't know what's going on, and the more they know, the happier they are" (P12), so the robot could provide information. For example, the robot could update the patient about their lab results. One participant suggested the robot could also help the patients remember their medical history so that they may better communicate with HCWs during patient interviews.

Participants also suggested that the robot could advocate for the patient and assist them throughout the visit. One participant noted, "a lot of people can't get somebody to come in with them to the ED," so knowing the robot was there to assist them could be "helpful" (P3). They thought the robot might help patients remember questions they want to ask, since patients sometimes have difficulty with this given all the other information they need to process.

However, some participants wondered if patients might be put off by the robot. One participant thought patients might be frustrated by the rigidity of the robot, wondering how people would react if the question was "how long [has] your [...] pain been going on [...] and [the pain had] been going on for two weeks, but it's been worse over the last week" (P11). Another participant thought some patients might be frustrated interacting with the robot, but could be more likely to accept it if it clearly acted as an advocate for them.

4.4 Concerns around Robot Usage

While participants generally felt that the robot had the potential to be useful, many also voiced concerns about its autonomous features and the robot's potential impact in the ED.

Appropriate Robot Usage: While robots could potentially assist HCWs in a variety of ways during and after interruptions, participants also discussed when they should not use the robot. Many participants indicated they were comfortable with the robot performing relatively low-risk tasks such as asking questions to a patient or doing an ultrasound. On the other hand, some participants preferred to perform certain tasks in person, even if a robot was available: "I'm gonna go check on someone I think is unstable and I'm going to go in person for that [...] that's universal, whether or not I have access to a robot [...] I didn't feel comfortable letting the robot do that for me, I want to go there in person" (P11).

Safety Concerns around Full Autonomy: Participants valued the potential for the robot to assist with patient requests, but also brought up concerns about the robot handling these requests autonomously. One participant illustrated how a seemingly simple request for a glass of water or help lowering their bed could become complex (P4). If the patient needed to be put under general anesthesia, they would not be allowed to eat or drink anything, so complying with this request could delay their care. Similarly, a patient having difficulty breathing might not be allowed to lower their bed, as it could make it even harder to breathe. Thus, to help with these requests, the robot would either need to consult with an HCW before complying or have enough medical awareness to know whether requests could delay care or harm the patient.

The robot would also need social awareness to handle requests on its own. One participant provided an example of a patient asking for their bag. If the patient was becoming "physically aggressive"' and then wanted their bag, it is "sort of a judgment thing" (P4). It is possible the robot should not acquiesce to their requests because their bag might contain a weapon.

Effects on Cognitive Load: Participants were unsure if an MTR would reduce their cognitive load. Controlling the robot required a lot of time and effort, so some "[didn't] think it would change [their cognitive load] too much" (P4).

Participants suggested they might attend to more interruptions and task-switch more frequently when using a robot. "I would probably be more inclined to interrupt my [...] history taking or physical exam to do a task really quickly if that task is in the room with me" (P10). Others indicated that the MTR might help them task switch quicker or more efficiently, such as by allowing them to switch between multiple patients' information in different tabs.

Participants also were concerned about the robot adding more interruptions to their work. For instance, if the robot sent patient questions to the HCW while they were attending to another task, it might add "choppiness" to their workflow (P12).

ED Integration: Some participants were wary of the challenges inherent in integrating the system into the ED. They highlighted older computers that might not be able to run the robot's interface software and the difficulties for an autonomous robot in the dynamic, safety-critical ED environment. As one participant observed, "I think it would be tough to have it move autonomously, just because the environment is so constantly changing, even the same room might be organized in a different way very frequently" (P4). Some participants also expressed doubt that a robot could autonomously perform tasks requiring high dexterity or personalized procedures, such as ultrasounds. Another participant noted that technology often takes several rounds of iteration before it becomes effective: "I think it has a potential to do good, but I highly doubt that it's going to be a [...] really effective thing to us on the first go round just because [...] every single piece of technology that we've ever developed [...] it has [challenges like], the battery runs out or [...] it gets lost" (P7).

4.5 Control Interface Feedback

Participants found the realistic prototype interface fairly usable, giving an average SUS score of 69 (std=10, min=55, max=82.5).

Depth Perception Challenges: A common challenge participants faced in teleoperating the MTR was limited depth perception. Participants struggled to understand the physical space that the robot occupied in the world with respect to other objects. They suggested that more familiarity with "what the robot [...and] arm look like, how tall [it] is" (P3), a wider field of view, and 3D information could help overcome some limitations with depth perception.

Control Modalities for Robot Teleoperation: Participants suggested other modalities for teleoperating the robot. Some participants recommended capitalizing on people's experience with video games for robot control, "Have you looked at [...] a twin stick? [...] probably half the people who [...] use these things [robots] play video games" (P5). Other participants recommended using keyboard controls or haptic interfaces.

Supporting Face-to-Face Patient Communication: While some participants felt the "patient interaction [was] not significantly different for [...] the history," (P12), others expressed concern that the "interface [...] would be like a barrier between myself and [...] patient interaction" (P10). Several participants liked that the patient could see their face on the robot, with one noting they "still think that eye contact is important in telehealth" (P1). They also wanted the patient to be informed about when the robot was performing a task autonomously or was being manually controlled.

5 DISCUSSION

5.1 Concerns about Automation

Our participants saw value in the robot having some degree of autonomy to reduce burden on HCWs, which aligns with prior work in the field [72]. However, the type of autonomy robots could employ varied, according to our participants. For example, one participant did not want the robot answering patient questions, while another was comfortable with the robot assisting HCWs caring for a time- and safety-critical patient with a heart attack. The appropriateness of a robot performing different kinds of tasks will likely depend on the capabilities and affordances of the robot.

Appropriate tasks for MTRs will likely shift as technological capabilities and perceptions of technology change. Given current MTR capabilities, many scenarios common in the ED are still challenging. For instance, MTRs could likely deliver a blanket to a patient, but could not perform physical patient examinations, as some participants envisioned. As robot end effector dexterity and tactile feedback improve, MTRs may become capable of such tasks, but concerns around safety and trust in the robot may still make these tasks inappropriate.

The appropriateness of robot behaviors may also vary with the characteristics of the individual ED where the robot is located, including the physical ED environment and the characteristics of the people it interacts with, including patients, HCWs, and family members [50]. [10] also argued that the usability of telepresence robots in hospitals can be limited because of factors including HCW training curve and lack of effort to facilitate adoptions of new practices. More research is needed to determine which factors are most important when determining robot behavior appropriateness, as well as how these factors interact.

If a robot acts fully autonomously in the ED, it must be aware of potential safety concerns for HCWs, patients, and itself. Patients sometimes act aggressively towards HCWs. One participant referred to this, noting they might break a sterile field if there was a physical threat to their colleague. Another participant highlighted how the robot may need discretion even for seemingly straightforward tasks. For instance, if a patient who is acting aggressively asks for their bag, the robot should not necessarily comply, since their bag could contain a weapon. Similarly, other work indicates that it is possible people may act aggressively towards the robot itself [41, 75]. In such situations, it is not clear what steps, if any, the robot should take to deescalate the situation. Thus, the robot must either have enough understanding of the situation to make such distinctions or check with an HCW to determine what is allowed, potentially adding to the number of interruptions the HCW faces.

To navigate these complex environments in the ways participants described, robots must have adequate situational awareness, social awareness, and in-depth medical knowledge. Individually, these competencies are difficult for autonomous systems, even in relatively static environments, like factories or laboratory settings. In dynamic, chaotic environments like the ED, where the robot will frequently need to adapt to new, unanticipated situations, robustly designing such systems is even more challenging. Robots may not recognize novel situations that reduce their social or situational awareness, which could hamper their ability to act appropriately, potentially leading to workflow disruption or patient harm. If robots can recognize such situations, it is not clear how they can best respond to their reduced capability to minimize disruption and harm.

Furthermore, competing priorities may necessitate the robot making ethical choices that robot creators may not anticipate. In the case of an aggressive patient requesting their bag, the robot might know the person is agitated, but may not have enough social awareness to know whether they intend harm, or the situational awareness to know what their bag contains. The robot could give the bag to the patient, potentially putting other people at risk, or refuse the request, denying the patient access to their own property and reducing their autonomy. It is not clear which choice the robot should make or how the robot should make the choice.

Despite these challenges, it is important that robots have some degree of autonomy to enhance usability. Our participants strongly indicated that the robot should be active while they attended to interruptions. "Wasting time, having [the robot] do nothing [...] doesn't make a lot of sense to me" (P5).

5.2 Multitasking

Research indicates that interruptions lead to more errors and higher rates of task incompletion. Thus, much prior work explores ways to reduce interruptions. However, task-switching and interruptions are integral to how EDs currently function [74]. To coordinate their activities and perform tasks they need to, HCWs must frequently task-switch. Structural changes to the healthcare system might reduce the task load and task-switching of HCWs, but such changes are unlikely to occur soon, and may take years to implement.

Reflecting this reality, several participants imagined how the MTR might help them "multitask" during interruptions. They appreciated the robot continuing the task they were performing when they were interrupted. In this type of multitasking, the robot might act as an "extension" of the HCW, performing tasks in parallel with them. If properly implemented, such robot behaviors may reduce HCW task load and ensure that interrupted tasks are completed in a time-efficient manner.

To be effective, the robot must quickly and thoroughly update the HCW about its task progress in a way that is appropriate to the context of the situation [52]. Otherwise, such activity may add to the HCW's cognitive load as they attempt to understand what the robot did while they were away. Furthermore, robots must effectively coordinate with other HCWs in the ED as part of a larger team, which can be challenging [51, 53, 54] Researchers have explored various methods for robots to provide information and updates to teammates, such as using legible motion [25], incorporating gestures [17], and developing shared situational awareness [48, 65]. However, more work is needed to apply such strategies to chaotic environments where modeling tasks, human teammates, and their knowledge may be more difficult.

Additionally, robot designers must carefully consider how the robot should behave if it experiences a failure while autonomously completing tasks. It may need to alert people about this failure, without adding to interruptions or disruptions in doing so. Roboticists should try to design the robot transparently so people are aware of when these failures might occur. Otherwise, failures may decrease users' trust in the robot [90].

Participants also described how an MTR could enable them to task switch more efficiently. One participant suggested they may task switch more frequently using an MTR. While it could enable HCWs to attend to different tasks more quickly, the system must be carefully designed to ensure this does not increase cognitive load or the potential for errors. ED stakeholders must therefore also consider their goals for integrating robots in the ED workflow, balancing the competing priorities of reducing HCW cognitive burden and enabling HCWs to complete all of their care tasks.

Participants suggested that the robot could help coordinate care in the ED, which could help mitigate interruption impacts. Grundgeiger et al. [32] suggested that responsibility for making sure interrupted tasks are completed might lie on multiple people or the unit as a whole. If the robot could help coordinate tasks, it could keep track of interrupted tasks that need to be completed, and potentially enable other people to be aware of and complete those tasks. However, if poorly designed, this could force HCWs to interact and coordinate with the robot in addition to other HCWs and patients, potentially adding another challenge to their workload. Thus, such a system would need to be thoughtfully designed to avoid possibly adding to certain HCWs' task load or cognitive burden.

5.3 MTRs as Mediators

Many participants discussed the potential for the robot to serve as an advocate for patients. This is an interesting idea and ties into other work in the HRI and HCI communities. Technology, and robots in particular, have the potential to help mediate relationships. For instance, in Moharana et al. [57], participants suggested that robots might take on roles that caretakers found stressful in their relationship with a person with dementia. Similarly, an MTR might be able to assist patients in interactions they find stressful during their stay in the ED, like speaking up when they are concerned about their health and not feeling heard.

However, some people may feel put off by the robot attempting to act as a mediator. For instance, it is possible a robot mediator in acute care could reduce communication transparency, especially since even small changes to communication can affect patient perceptions of interactions [50, 81]. [61] also discussed how telepresence robots may inhibit effective emotional and social interactions, would require transparency about robot actions and user intent, and should communicate any privacy concerns to interactants. Thus, the possibility of robot mediation in acute care is complex, and requires additional research to understand more fully.

5.4 Limitations and Future Work

Our study has a few limitations. The participants were all physicians. This was due to the fact that our study focused on physician-specific tasks. However, we plan to include other interprofessional HCWs, such as nurses and respiratory therapists, in future work. We also would have liked to consider interruption management from the patient's perspective. However, we first needed to understand, via this study, what types of tasks would be appropriate for the robot to do, from the physicians' perspective, before involving patients. Second, while our study was conducted using fairly high fidelity simulation, it would of course be better to run our study with a physical robot. Once we complete development of our robot, we plan to validate our proposed behaviors on a physical robot.

5.5 Conclusion

We presented new roles for MTRs, focusing on interruption management and preventable harm reduction. Such robots could help enhance patient care, particularly in under-resourced areas with limited access to medical specialties. We also described HCW preferences and concerns for robot-mediated task-reorientation and interruption management in the ED. These contributions could enable robots to integrate into emergency spaces with less disruption, promote patient safety, and assist HCWs with their high task load. This work serves as a basis for further study into robot–mediated task management in dynamic, chaotic environments.

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