

# Coordinating Clinical Teams: Using Robots to Empower Nurses to Stop the Line

ANGELIQUE TAYLOR, University of California, San Diego, USA

HEE RIN LEE, University of California, San Diego, USA

ALYSSA KUBOTA, University of California, San Diego, USA

LAUREL D. RIEK, University of California, San Diego, USA

Patient safety errors account for over 400,000 preventable deaths annually in US in hospitals alone, 70% of which are caused by team communication breakdowns, stemming from hierarchical structures and asymmetrical power dynamics between physicians, nurses, patients, and others. Nurses are uniquely positioned to identify and prevent these errors, but they are often penalized for speaking up, particularly when physicians are responsible. Nevertheless, empowering nurses and building strong interdisciplinary teams can lead to improved patient safety and outcomes. Thus, our group has been developing a series of intelligent systems that support teaming in safety critical settings, Robot-Centric Team Support System (RoboTSS), and recently developed a group detection and tracking system for collaborative robots. In this paper, we explore how RoboTSS can be used to empower nurses in interprofessional team settings, through a three month long, collaborative design process with nurses across five US-based hospitals. The main findings and contributions of this paper are as follows. First, we found that participants envisioned using a robotic crash cart to guide resuscitation procedures to improve efficiency and reduce errors. Second, nurses discussed how RoboTSS can generate choreography for efficient spatial reconfigurations in co-located clinical teams, which is particularly important in time-sensitive situations such as resuscitation. Third, we found that nurses want to use RoboTSS to “stop the line”, and disrupt power dynamics by policing unsafe physician behavior, such as avoiding safety protocols using a robotic crash cart. Fourth, nurses envisioned using our system to support real-time error identification, such as breaking the sterile field, and then communicating those errors to physicians, to relieve them of responsibility. Finally, based on our findings, we propose robot design implications that capture how nurses envision utilizing RoboTSS. We hope this work promotes further exploration in how to design technology to challenge authority in asymmetrical power relationships, particularly in healthcare, as strong teams save lives.

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\*\* Angelique Taylor and Hee Rin Lee contributed equally.

Authors' addresses: Angelique Taylor, University of California, San Diego, 9500 Gilman Dr. La Jolla, USA, amt062@eng.ucsd.edu; Hee Rin Lee, University of California, San Diego, 9500 Gilman Dr. La Jolla, USA, heerin@eng.ucsd.edu; Alyssa Kubota, University of California, San Diego, 9500 Gilman Dr. La Jolla, USA, akubota@eng.ucsd.edu; Laurel D. Riek, University of California, San Diego, 9500 Gilman Dr. La Jolla, USA, lrieck@eng.ucsd.edu.

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## 1 INTRODUCTION

Patient safety is a critical issue in the healthcare system as preventable medical errors (PMEs) lead to 400,000 preventable patient deaths per year in hospitals alone [17, 33]. 70% of these errors are the result of communication and collaboration breakdowns that occur in safety-critical team settings. Nurses are uniquely positioned to identify and prevent such errors as they are frontline healthcare workers and primary advocates for patients [60, 79]. However, strict hierarchical structures and asymmetrical power dynamics between physicians and nurses often result in penalties for nurses who speak up to “stop the line” of behavior that causes medical errors [60]. Thus, providing nurses with a mechanism to promote open and honest communication within clinical teams can empower them to prevent behavior that causes patient safety lapses and errors.

Studies show that empowering nurses is one way to enable them to “stop the line” when they observe patient safety risks [60, 68]. For example, empowering nurses leads to increased job commitment, which results in positive work behavior and improved patient outcomes [21, 43, 44]. Furthermore, nurse empowerment promotes improved communication with higher ranking team members, thereby redistributing power dynamics in clinical teams [62].

Prior research in Computer Supported Cooperative Work (CSCW) demonstrates the potential for robots to shift power dynamics among clinical team members. For example, introducing surgical robots into the operating room (OR) changes team communication, as the surgeon becomes physically separated from the team, which leads to increased autonomy of the remaining team members [65]. In particular, robots can help redistribute power from higher ranked team members to lower ranked ones in the clinical hierarchy. It also changes how teams make decisions [64] and their spatial arrangements [62]. In this paper, we build upon this concept to explore how embodied, mobile robots, which able to learn, sense, and interact within groups, may be able to empower nurses.

For the past few years, our group has been developing a series of intelligent systems that work with interprofessional teams in safety critical settings [24, 27, 42, 76]. In this work, we explore the use of our Robot-Centric Team Support System (RoboTSS), comprised of a series of modules which have the ability to engage in group detection, tracking, motion forecasting, and interaction (See Fig. 1). The vision is that RoboTSS can be used to support teams in real world environments.

In this paper, we explore how the group interaction module of RoboTSS can be designed to empower nurses and support them in interprofessional teaming. We engaged in a three month long, collaborative design process with nurses who work across five US-based hospitals, and across six clinical disciplines, including: progressive care, pediatrics, critical care, and anesthesia. We conducted a series of semi-structured interviews with them, where we explored their experiences of teaming and the possibilities of using RoboTSS to support their work.

The main contributions of our work is fivefold. First, our participants envisioned using a robotic crash cart during resuscitation scenarios that can autonomously navigate to a patient’s bedside, walk a team of providers through a procedure (e.g., resuscitation code), and automatically open drawers of the crash cart. This relieves clinicians themselves of manually moving the crash cart to the patient’s room; instead, they can immediately go to the patient’s bedside and start working.

Second, we found that nurses envisioned using RoboTSS to generate choreography for efficient spatial reconfigurations in co-located, unstructured clinical teams. Co-located, unstructured teams (e.g., resuscitation teams) often work in safety-critical, time-sensitive environments. Thus, it is challenging for clinical teams to spatially position themselves in a cohesive way such that all team members work effectively throughout the procedure.

Third, we found that nurses want to use RoboTSS to challenge authority by reconfiguring the power distribution in teams. For example, nurses identified ways they could use the system

to “stop the line,” and disrupt power dynamics by policing unsafe physician behavior, such as avoiding safety protocols and checklists. Although checklists were developed to empower nurses, asymmetric power dynamics between nurses and physicians impede this critical process from being appropriately performed. Participants suggest that introducing robots as a neutral third party can support nurses.

Fourth, our study reveals that nurses envisioned using RoboTSS to support real-time error identification, such as breaking the sterile field, and giving robots the burden of communicating those errors to physicians, which relieves nurses of that responsibility.

Finally, we propose new design implications that capture how nurses envision how RoboTSS might support and empower them in clinical teams. We extrapolated these design implications from our findings while considering two primary means of empowering nurses: 1) by challenging authority, and 2) by improving team collaboration to reduce nurse workload. Our proposed design implications capture design concepts that can empower nurses, the team settings for which these concepts were designed, as well as the level of hierarchy in the team setting.

We hope this work promotes further exploration in how to design technology to improve interprofessional teamwork, particularly in healthcare, as strong teams save lives.

## 2 BACKGROUND

This section provides an overview of the areas involved in this paper in order to provide context for the narratives that are discussed in later sections. These areas include the impact of clinical teams on patient safety, nurse empowerment, human-robot teams in healthcare, and computational methods for group perception.

### 2.1 How Clinical Teams Impact Patient Safety

Healthcare teams are critical across many care settings, including hospitals, nursing homes, surgical centers, home care, etc. [15]. In this paper, we focus our work on care delivery within hospital settings. Even within hospitals, there are many types of teams across many units. We focus specifically on clinical teams working on either resuscitation (e.g., within emergency departments (ED) or intensive care units (ICU)), and performing surgical procedures (e.g., within ORs). These teams are interprofessional (e.g., physician, nurses, respiratory therapists, technicians), and vary in their structure and organization, e.g., ORs and ICUs are highly structured, EDs are more dynamic.

PMEs are the third leading cause of death in the United States, 70% of which occur as a result of team failures [11, 17, 33]. These errors are a direct result of poor communication, poor collaboration, and mistakes made during patient care, which causes patient harm, and in some cases, patient death [33, 57]. Such errors are exacerbated by the hierarchical nature of clinical teams.

Hierarchical culture is inherent in many clinical teams as many are composed of providers with various levels of expertise and experience (e.g., physician, nurse, certified nursing assistant (CNA)). In general, clinicians with more education are higher in the clinical hierarchy and have more power when working in teams. Such hierarchical culture leads to communication challenges for team members that rank lower in the clinical hierarchy. For instance, nurses are the primary advocate for patients while they are being treated at the hospital, so they are uniquely positioned to speak up for them when they observe safety risks. Yet when nurses advocate for patients to higher ranked team members, they are often penalized and confronted, which discourages them from speaking up the next time they observe a safety lapse [60].

Many interventions exist to mitigate these challenges, including checklists [2, 25] and interprofessional team training programs (e.g., TeamSTEPPS [40]). While these interventions have made major improvements in patient safety, they suffer from low adoption rates, receiving particular criticism from those at the top of traditional hierarchical structures [20]. In this work, we explore

how our team-focused technology (RoboTSS) might help to scaffold these existing interventions, by providing a potential means to level hierarchies (as has been shown possible in VR [70]) with the added benefit of the “cool factor” of robots to support adoption.

## 2.2 Nurse Empowerment and Patient Safety

A series of studies in the nursing literature found that due to the unique proximity of nurses to patients, nurse empowerment enhances patient safety and outcomes, reduces death rates, and shortens length of stay within hospitals [30, 43, 60, 67, 68]. These studies consider nurse empowerment as an organizational issue [60, 68]; therefore, they employ frameworks from organizational studies, such as Kanter’s organizational empowerment theory [38]. Okuyama et al. [60] focused on nurses’ speaking up behavior for patient safety and examined ways to embolden them to report behavior that jeopardizes patient safety. These studies consider nurse empowerment as an issue of team communication effectiveness, particularly due to asymmetrical power dynamics between physicians and nurses.

Another group of studies found that nurse empowerment issues originated from US healthcare reforms that have continued since the 1990s [9, 16, 30]. As budgets were cut, private organizations began managing healthcare systems in ways that adversely affected nurses. As a part of downsizing labor forces in hospitals, nurse staffing levels were reduced, workloads increased, and responsibilities expanded. Consequently, under these adverse working conditions, nurses experienced more emotional exhaustion and stress. This group of studies define empowerment as an issue of “the extent to which nurses possess the power to influence the behavior around them” which is a more holistic approach to empowerment [68]. This research considers the level of autonomy of nurses as well as their communication issues, which ultimately leads to concerns of their overall job satisfaction (e.g., workload, job security).

Several educational interventions have been designed to encourage nurses to speak up, including technology-based interventions (c.f., [18, 71]). For example, Robb et al. [70, 71] used virtual teammates in clinical settings to support clinicians lower in the clinical hierarchy (e.g., nurses). Studies such as these motivate our study on using technology to support nurse empowerment through a collaborative design process with nurses. Additionally, to increase the voices of nurses within the research process, our study enables nurses to define their challenges in team settings rather than to focus on speaking up as a main topic of this study.

## 2.3 Healthcare Robotics

Healthcare robotics is a new area of research that explores using robots to address challenges in the healthcare [69]. Robots have the potential to help people with motor, cognitive, and sensory impairments, such as by providing mobility or limb support (e.g., smart wheelchairs, robot prostheses), therapeutic support (e.g., robotic pet therapy, robots for autism), and sensory augmentation (e.g., smart canes). They can also be used to support cognitive and mental health.

Within the context of nursing, robots can reduce the physical strain and injury that nurses experience from lifting patients [54, 58] and delivering materials [23]. They can also assist nurses with reception tasks in hospitals (e.g., desk reception) [1]. Other robots are used for telemedicine [32, 46] and surgery [62, 75]. The aforementioned robots can help fill care gaps, which result from a shortage in the healthcare workforce and the growing number of patients that need medical care [69, 74].

One of the most commonly studied robots in co-located clinical team settings are surgical robots, which are remotely operated by a surgeon. Researchers have investigated how surgical robots change team communication [65], decision making [64], and spatial arrangement of surgical teams



Fig. 1. The trajectory of our team support system, RoboTSS. From left to right, our system includes group detection (RoboGEM), group tracking (RoboGEM 2.0), group motion forecasting, and robot group interaction methods. The goal of this study is to continue our work on robot group interaction by designing robots to support and empower nurses.

[62]. For example, Pelikan et al. [62] found that surgical robots shift power from the surgeon to the rest of the team by redistributing roles and tasks.

In order for robots to work effectively and be well-adopted in healthcare, there are several robot adoption factors that must be taken into consideration [69]. These factors include the *safety and reliability* of robots, ensuring they are safe around users and being robust to real-world clinical situations. *Usability and acceptability* concerns ensure that stakeholders, who have varying levels of technical literacy, are able to fully utilize the robot and are accepting of its functionalities during day-to-day tasks. However, in order for stakeholders to take advantage of a robot’s capabilities, it must be shown to be *clinically effective*, i.e. provide a clear benefit to users. Furthermore, *cost effectiveness* is an important factor as not all clinical settings are well-resourced to purchase expensive equipment, nor do most individuals. Finally, it is important that a robot in healthcare has sufficient *capability and function* for it to carry out its intended functionality in dynamic, real-world environments.

Many of the aforementioned factors are taken into consideration while designing robots for healthcare applications. However, there is a lack of work done to integrate robots into face-to-face teaming situations during high stress, dynamic, safety-critical situations in which many PMEs take place (e.g., resuscitation). Thus, we are interested in exploring how robots can work alongside clinicians to improve clinical teaming. Additionally, we explore mechanisms to empower nurses in such settings.

## 2.4 Computational Methods for Group Perception

The goal of our work is to design intelligent systems to support and empower nurses as they work in interdisciplinary teams. In order for us to design systems to work in teams, we require group perception methods that enable such systems to perceive teams in their environment. This enables the system to identify where their team members are located as well as where they may potentially relocate to in the immediate future. Therefore, we provide a brief review of our group perception methods as they enable intelligent systems to identify and track team members over time.

Over the past two years, we developed RoboTSS, an intelligent robotic system that enables robots to support teams. RoboTSS has four modules: group detection, group tracking, group motion forecasting, and robot group interaction modules (See Fig. 1). Our group detection system, *Robot-Centric Group Estimation Model* (RoboGEM), is unsupervised and works well on ego-centric (i.e. first-person), real-world data, where both pedestrians and the robot are in motion at the same time [76]. RoboGEM outperforms the current top-performing method by 10% in terms of accuracy and

50% in terms of recall, and it can be used in real-world environments to enable robots to work in teams [77].

Our group tracking system expanded the scope of RoboGEM by adding a new tracking algorithm and improving its group detection method (RoboGEM 2.0). RoboGEM 2.0 performs well in crowded environments using a tracking-by-detection approach and, to the best of our knowledge, is the first tracking method to leverage deep learning. This provides a more robust affinity representation than prior work (which employs hand-crafted feature representations), and can be used for group data association. RoboGEM 2.0 is based on the intuition that pedestrians are most likely in groups when they have similar trajectories, ground plane coordinates, and proximities. It also includes new methods for group tracking that employ Convolutional Neural Network feature maps for group data association, and Kalman filters to track group states over time. We are currently developing a new group motion forecasting method using inspiration from characteristic crowd movement patterns in the computer vision literature (c.f. [83]).

In this paper, we aim to utilize RoboTSS to support clinical teams in our continued development of the robot group interaction module. Through a collaborative design process with nurses, we enable them to envision how RoboTSS can support and empower them. Then, we analyze data collected from interviews, and we propose design implications that capture how nurses envision utilizing RoboTSS which takes the team setting and degree of team hierarchy into consideration.

### 3 METHODOLOGY

#### 3.1 Collaborative Research Methodology

This paper employs a collaborative research methodology [50] inspired by collaborative ethnography [45] and participatory action research [22]. These approaches allow researchers to be more reflexive about their own biases and enable participants to be collaborators rather than informants. This also helps researchers and participants negotiate research processes and goals. Our collaborative research approach is also inspired by a co-creation method [81] and a more recent participatory design method [6], in which participants actively advocate for themselves throughout the design process rather than physically designing artifacts. Based on those studies, participants shaped our research questions which evolved throughout our research process.

Due to the lack of existing research in collaboratively designing robot algorithms, we developed our collaborative research methodologies through a negotiation process with participants. A growing number of robot design research investigates how to adopt participatory design methodologies to co-design the appearance of robots and their interaction behaviors [10, 14, 48, 53, 56]. However, robot algorithms are black-boxed, and novice research participants have limited knowledge about algorithm development processes [83]. Even outside of robotics, researchers found that algorithms, in general, are not easy to co-design with lay people due to the technical complexity behind them [4]. In particular, robot algorithms are difficult to illustrate and they are not physically tangible; therefore, we explore our own study methodology rather than simply adopting existing co-design techniques such as sketching [39].

One important issue in a robot co-design process is incorporating perspectives of participants who do not have much experience with technically complex robotic technologies. Due to the wide technical knowledge gap between roboticists and lay people, prior research has not addressed incorporating users' input into decision making processes of robotics research compared to other technologies [47, 51, 52]. As a result, participant perspectives are less often reflected in robot research processes [49]. Roboticists, having more influence than users in the development process, could reflect stereotyped representation of participants in their research due to their unconscious biases [47]. Our collaborative methodologies consider power issues between researchers and

participants. For example, our collaborative research methodologies enabled participants to shape our study design and research goals (e.g., addressing their main issues through our research) rather than asking them to contribute physical designs (e.g., sketches, rapid prototyping).

For example, participants had the power to shape our research agenda, recruitment plans, and research procedure. Our original research question was how RoboTSS can support teams in healthcare settings; however, in our early interviews with an anesthesiologist and a nurse, the question evolved to how RoboTSS can empower nurses. When changing our research agenda, we also dove into existing nurse empowerment literature both in the healthcare field [30, 43, 67] and in robotics [70, 71]. As our research agenda evolved, our recruitment plan also changed. We originally planned to recruit various healthcare professionals including physicians, nurses, and anesthesiologists, but our first three interviews with an anesthesiologist and two nurses led us to exclusively focusing on nurses. This is why we interviewed one anesthesiologist participant and six nurse participants in our study. The altered research question also changed our research procedure.

In the first version of our interviews, we did not have a specific question list for participants, but instead, we employed collaborative map making consistent with [50]. We provided three research keywords that we are interested in (team, robot, workplace). Then, we asked participants to share any 10-13 words that are relevant to those three keywords and explain the meaning of each word. The initial procedure aimed to enable participants to frame those three keywords from their perspectives. That procedure helped us find the importance of nurse empowerment in our initial interviews. However, based on the feedback from the interviews, we found that this open-ended approach broadened our research scope unnecessarily, especially after we decided to focus on nurse empowerment issues. As a result, we altered our methodology so that we can focus on nurse empowerment without ambiguity in our interview questions.

Although we focused on nurse empowerment as a main theme in our final study, our goal was to analyze nurses' issues from their perspectives rather than testing a hypothesis. Our efforts enabled us to find that issues surrounding nurse empowerment are not only about speaking up, but also about increasing team efficiency and reducing workload. We describe the finalized research procedure below.

### 3.2 Procedure

Through a collaborative research process, we conducted an in-depth, semi-structured series of interviews with seven healthcare professionals from across the United States over a three-month period (See Table 1). To make our research process as collaborative as possible, we invited participants to discuss any team-related challenges that they wanted to share. Enabling participants to have as much control as possible over our research process was imperative to understanding how our system can support and empower them. Thus, to help participants feel comfortable expressing their ideas, we explained to participants that we sought to learn from their experiences in healthcare.

We described the goal of our research, a high-level description of prior perception work that can be used in healthcare, and how our group perception system works. We conducted interviews both face-to-face and remotely (e.g., via Skype), depending on the participant's preference and their proximity to our team. We recorded audio of the interviews with the participant's permission. We told participants that our goal is to learn about the challenges they encounter in team-related tasks. After that, we introduced RoboTSS to them as a system that enables robots to work in teams with groups of people by using sensors to detect and track groups. Then, we showed participants a video demonstration of RoboTSS running on a mobile robot that roamed around a public park, observing and identifying groups of people with bounding boxes drawn around them (See Fig. 1, left-most image).

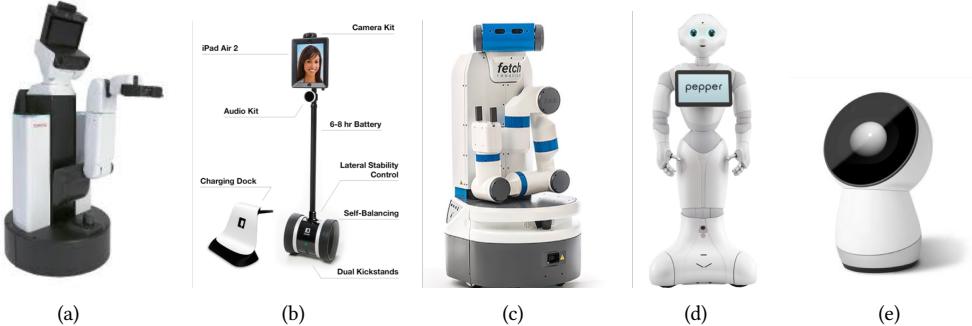


Fig. 2. The robots that we showed participants during the interviews. From left to right: (a) Toyota Human Support Robot, (b) Double Telepresence Robot, (c) Fetch robot, (d) Pepper, and (e) Jibo.

Because many healthcare providers are not familiar with modern robotics technology, we showed participants pictures of several robots similar to ones currently used for healthcare applications [69]. These robots demonstrate a range of feasible functionalities and include the Toyota Human Support Robot, Double Telepresence robot, Fetch robot, Pepper, and Jibo (See Fig. 2). We discussed each robot's level of mobility, manipulation capability, sensing capability, and potential settings in which they are used. An example description of a robot that we discussed with participants is as follows, "This is the Toyota Human Support Robot. This is a mobile robot, and it is designed to be very safe because it is supposed to work in people's homes. It has a RGB-D sensor [color and depth camera] up here [in the robot's head]. It has a sensor in its gripper as well, and this manipulator can come out and reach things, manipulate things, place things in different places. It can also raise up. The head tilts and it can kind of explore a space. It can speak to you. It can also understand verbal language as well."

To enable participants to freely express their ideas about robots, we also briefly described current computer vision, robotics, and machine learning challenges that have been addressed in the literature, including methods for object and people tracking, navigation, and object manipulation. This gave participants an idea of previous challenges that have been addressed using robots and other intelligent systems, and enabled them to think about how to apply these same methods to challenges that they face in teams.

In the next part of the interviews, we asked participants open-ended questions, to encourage them to freely discuss their challenges as healthcare providers. Some of these questions included: What are some team-related challenges that you face on a day-to-day basis? What are some examples of breakdowns in team performance? How might RoboTSS be useful for improving team collaboration? Do you think it might be useful for robots to help improve team dynamics? If so, how?

### 3.3 Analysis Process

Two researchers followed grounded theory to analyze the data [13]. One is a computational HRI researcher, and the other is a human-centered design researcher. After each interview, the two researchers reviewed the other's analyses/notes and discussed interesting themes from the interviews. As we explained in 3.1, throughout this initial analysis process, we discussed what types of participants we need to saturate our data on nurse empowerment. As a result, we had one anesthesiologist and six nurses. Initially, we wanted to include various healthcare professionals.

Table 1. Demographics of research participants which includes their pseudonym, age, specialty, credentials, years of experience, and the types of hospitals that they have worked in. The hospital types include: teaching (T), non-teaching (NT), for-profit (FP), non-profit (NP), and urban (U).

Pseudonym	Age	Specialty	Credentials	Experience	Hospital-Type
Jessica	28	Anesthesiology	Nurse Anesthetist, DNP	5 years	T, NT, FP, NP, U
Andrew	44	Anesthesiology	Anesthesiologist, MD	15 years	T, NT, FP, NP, U
Lauren	38	Critical Care	Registered Nurse, BSN	10 years	T, NP, U
Danielle	35	Critical Care	Registered Nurse, BSN	11 years	T, NT, FP, U
Steve	29	ICU Step Down, Progressive Care	Registered Nurse, BSN	0.5 years	T, FP, U
Sarah	28	ICU, Travel Nurse	Registered Nurse, BSN	5 years	T, NT, NP, U
Rebecca	28	Pediatrics, Neonatology	Registered Nurse, BSN	5 years	NT, NP, U

However, as we focused more on nurse empowerment, we recruited more nurses and examined their perspectives within our analysis process for deeper analysis.

After all interviews were complete, the audio recordings were transcribed. The researchers coded the audio recordings to find emerging themes through an inductive coding process using NVivo. They compared the codes, and identified overlapping themes among participants. This process initially yielded 455 codes, which we organized into a coding hierarchy following grounded theory. In developing our coding hierarchy, we iteratively reviewed our transcripts until all relevant data was represented in the hierarchy to comprehensively explain new emerging concepts. Thus, we updated the coding hierarchy iteratively. The resulting hierarchy had three overarching themes which we report in Section 4. These include: 1) Robots as a Neutral Party to Challenge Hierarchical Culture (Section 4.1), 2) Robotic Crash Carts for Coding Situations (Section 4.2), and 3) Concerns about new robotic technologies (Section 4.3).

### 3.4 Participants

We recruited six nurses and one anesthesiologist. The anesthesiologist provided an outside perspective of nurse empowerment and advocated for them which enriched our understanding of nursing challenges in hospital settings. He also provided a perspective of someone higher in the hospital hierarchy and how they perceive nurse empowerment challenges. Participants were selected to give perspectives from a wide range of expertise and specializations including: the ICU, critical care, progressive care, pediatrics, neonatology, and anesthesiology. Five participants were female and two were male. Their ages ranged from 28-44 years old (mean age: 32.9 years old). All participants earned a bachelor's degree at a minimum, and their experience working in healthcare ranged from 6 months to 15 years (mean 7.4 years). Three participants are clinical educators, and work within a university medical simulation center. We employ pseudonyms to represent our participants to preserve their privacy and individuality.

## 4 RESULTS

Participants discussed the two main challenges they face in hospital settings, as well as how RoboTSS may be useful in addressing them. The first challenge is the hierarchical culture of hospital settings and the associated asymmetric power dynamics when interacting with higher-ranking healthcare professionals (Section 4.1). Participants envisioned how RoboTSS might alleviate this problem by serving as a neutral third party to redistribute power to those lower in the hierarchy.

The second challenge they discussed was effective teaming during code situations, one of the most common team activities for nurses (Section 4.2). To mitigate this problem, participants envisioned integrating RoboTSS with their existing crash cart to facilitate these situations through choreography generation for clinical teams, supplies management, decision support, and chart production.

Additionally, participants discussed some concerns they had regarding the integration of robots into hospitals (Section 4.3). These concerns include robot understanding of situational context, robots acting as additional social actors, and robots impeding on provider and patient privacy.

#### 4.1 Robots as a Neutral Party to Challenge Hierarchical Culture

All participants envisioned their robots can challenge power issues both with 1) physicians and 2) administrators in their institutions.

**4.1.1 Challenge asymmetric power dynamics with physicians.** Six out of seven participants illustrated that the strong hierarchical culture of hospitals impedes their efforts to ensure patient safety and provide the best care to their patients. The nurse participants expressed the most frustration with physicians, in particular.

Steve, a new nurse who has been working in a hospital for six months, explained his frustration with his inability to help patients to the extent that he initially imagined, as follows:

“There are a lot of times where doctors will try and maybe tell you to do something that you are not able to do, legally. I had one that told me to do this certain procedure. I’m like ‘I’m pretty sure I don’t do that.’ He said, ‘Oh, well, just find out who can.’ I went through the whole system and I was like, ‘Well, you are actually the only person that can do that procedure.’ It’s a lot of knowing your boundaries where you are. Yeah, we have power but the doctors are ultimately the ones diagnosing and treating these patients. We’re just following through with their orders.” (Steve, 29, ICU)

The participants discussed how hierarchy plays an important role in their teamwork. Particularly in the OR, the hierarchy was even stronger than in other contexts. Jessica described the hierarchy among team members in the OR as follows:

“In the OR, it is pretty intense. Because in the OR, [...] we provide a service to the surgeon. So everybody caters to the surgeon. The surgeon is like the king, [nurse] anesthetists are like the peasants, and they blame everything on us. Seriously, there is definitely a level of hierarchy in the OR – like the surgeon, anesthesiologist, CRNA, OR nurse, surgical tech [technician], anesthesia tech. There is definitely a level of hierarchy.” (Jessica, 28, Nurse Anesthetist)

Andrew also explained how the hierarchical power structures contribute to miscommunication.

“One of the things that seems to lead to miscommunication in hierarchical [settings] is the more hierarchy there is, the more [indirect communication there is] they call it speech mitigation. In a deferential way, [a nurse might] ask, ‘Is everything ok?’ When really you mean, ‘It looks like there is a lot of bleeding going on in the [patient]. Did you cut something that you weren’t supposed to? What’s going on?’ But, you might ask it in an indirect way. The more hierarchy there is, the more mitigated someone’s speech is going to be.” (Andrew, 44, Anesthesiologist)

Despite the best efforts of healthcare institutions (including mandatory classes for communication), hierarchical speech persists within hospitals [31, 82], which participants discussed in great detail. For instance, they talked about how levels of hierarchy impact their day-to-day activities. When people from different levels of the hierarchy work together, individuals from lower levels of the hierarchy tend to avoid speaking up when they see something being done incorrectly, or individuals with higher levels of hierarchy do not take lower level people's concerns seriously which is consistent with studies from the literature [60]. For example, studies show that physicians perceive teamwork differently than nurses, and they have a higher level of satisfaction with team settings than nurses [55, 78].

Danielle gave an example of her own experience with hierarchical culture when she informed a physician about a patient's condition and the physician did not believe her or take her concerns seriously.

"A nurse feels like something is important or something is wrong with a patient and communicates that to the physician, but maybe the physician doesn't feel you [are correct] or they don't want to accept the fact that the patient is getting sicker." (Danielle, 35, Critical Care)

All seven participants either discussed assigning robots tasks that may stress power dynamics or expected robots could challenge the existing dynamics. In this way, robots communicate between nurses and clinicians as a neutral third party, and remove the *negative social aspects of hierarchical culture*. For example, Lauren, Andrew, and Steve spoke of the complicated social dynamics involved in the essential process of using a checklist before a procedure in the OR. Often in these situations, nurses with lower rank are responsible for ensuring that the team (including higher ranked clinicians) adheres to protocol. However, this reversal of power dynamics increases tension when the lower ranking clinician reveals errors in the higher ranking clinician's process, which Lauren discussed when describing her experience of pointing out errors to physicians.

"They [a hospital] expect nurses to watch them [physicians] do it [a procedure], but it is just a really hard dynamic to be told by the nursing staff that, 'Hey, you just broke sterile procedure and you need to start over.' " (Lauren, 38, Critical Care)

Allowing higher ranking teammates to skip checklist steps is not only an interpersonal problem but also a patient safety risk that can be addressed by removing social considerations from the interaction altogether. Robots assuming the job of checklist supervisor would alleviate nurses of the obligation to confront and correct higher ranking clinicians. As neutral agents, robots stipulating adherence to protocol implies no insubordination, nor does it challenge the social power dynamics of the hospital hierarchy.

"[The robot is] not going to move onto the next step until it's done, whereas if it's a nurse, they're like, 'Come on, let's just get on with it.' And they skip steps whereas this [the robot] isn't going to skip steps. It won't allow you to move on to the next step until [the checklist is] done. So, yeah, something like that would be an interesting assessment of [...] flattening the hierarchy." (Andrew, 44, Anesthesiologist)

The participants also mentioned that using robots would objectify this process. For example, in some cases, when nurses point out the necessity of sanitation to a provider, that provider sometimes takes it personally and feels uncomfortable about being called out. With robots, nurses do not need to worry about whether the provider would take this rebuke personally. Also, the providers can focus on the sanitization procedure without interference from nurses.

"There are a lot of times when the nurses are [...] at [the patient's] bedside. We are the ones who are presenting the information to the doctors [and] what needs to be done. The doctors make a decision based on what we tell them. But sometimes they don't listen to what we have to say, [which] is the problem. Or they cut us off or don't give us [the] time we need to tell them. 'Hey you need to check this patient out, you need to check this lab work, you need to look at this vital sign'. [...] If there were ways for them to get the information from a third party that's not the nurse [...] or just tell them 'Hey check out this vital sign or check out this lab result. It seems odd to me [or] the patient looks blue, or looks yellow', to give them the information that they may not want to hear [...] from the nurses, or that the nurses might be too afraid to tell them." (Sarah, 28, ICU)

**4.1.2 Challenging asymmetric power dynamics with administrators in a hospital.** Over half of the nurse participants (4/6) also expressed their frustration with how hospitals, as an institution, disregard their concerns. Although nurses best understand "bed-side" stories, the main interests of hospital administrators appear more concerned with money. Lauren explained how her interests conflict with administrators' interests as follows:

"I know what they [hospital administrators] are looking at. They are looking at their bottom dollar. I look at my challenges at the bedside. I am gonna do really amazing patient care. Talk to me more about what I can do for my patients, but increasing your numbers? Even though it helps patients, it's not tangible to a bedside nurse." (Lauren, 38, Critical Care)

As administrators had different priorities from nurses, nurse participants feel their efforts are devalued. Danielle, who holds both nursing and teaching faculty positions, described how she tried to improve a charting process so that nurses can more efficiently and accurately generate charts.

"I helped develop a charting system for this [process], hoping that it was going to be a huge success, but it was not. And so now another group is revisiting on how to improve that and we have had multiple people say, 'You know, it would be better if I had something handheld.' But, all of these things sound really great but then it comes down to expense and practicality." (Danielle, 35, Critical Care)

The charting system that Danielle helped develop was a success in educational settings. However, when they attempted to deploy the system in a real hospital, institutions decided that the time of nurses was better spent on their current jobs rather than learning how to use this new system, so Danielle's efforts only wasted her time and resources.

Occurrences such as Danielle's cause participants to feel insignificant to the institution. In addition to leveling the clinical hierarchy as discussed in Section 4.1.1, participants also envisioned that a neutral, third-party robot could generate objective data that they can present to their institutions' administrators to substantiate their concerns. For instance, Andrew discussed how such a robot could administer checklists to prove that nurses completed their tasks even if physicians do not follow the checklist protocol.

"Having the ability to sort of override aspects of the protocol would be important for the physician to say, 'That's not relevant in this situation for this reason, so we're not doing that.' And then, be able to move on. But, [...] at least now there is a reason that has been documented of why that step wasn't done. So that might be an interesting way [to maintain accountability]." (Andrew, 44, Anesthesiologist)

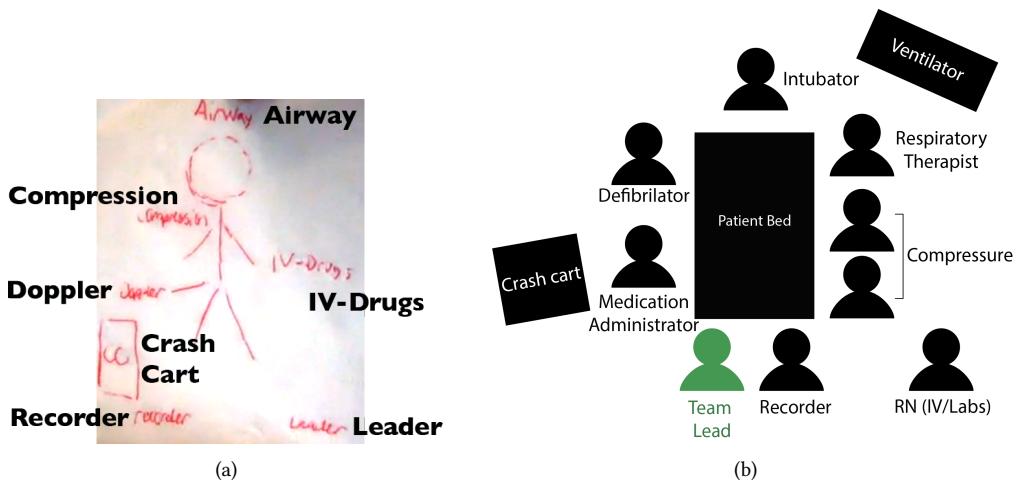


Fig. 3. (a) Jessica's (Nurse Anesthetist with 5 years of experience) drawing of a team's configuration around a patient during resuscitation. Some of the roles that team members must assume include the following: *Airways* stabilize the patient's breathing and ventilation; *Compressors* perform chest compressions (CPR); *IV-Drugs* administer IV and medication; *Doppler* utilizes ultrasound to monitor blood flow; *Recorder* documents all tasks performed during the code; *Leader* dictates tasks to the team. (b) shows a clearer version of (a), image used with permission from [26].

Such data would show which aspects of standard protocols were skipped and why. This information reflects the perspectives of nurses and provides crucial evidence for administrators to consider when making institution-wide changes.

#### 4.2 Robotic Crash Carts for Coding Situations

All seven participants indicated that they mostly work individually but work as a team in safety critical situations. This finding aligns with previous studies [5, 84]. One of the most predominant team activities in hospital settings takes place during coding situations, where an interprofessional team of clinicians work to resuscitate a patient. Resuscitation, also known as codes, "are emergency situations that involve the treatment of a patient who is experiencing a cessation of breathing or heart activity" [41, 59]. During resuscitation, clinical teams follow standardized algorithms from the American Heart Association, such as the Adult Cardiac Life Support algorithms (ACLS) [59] and the Pediatric Advanced Life Support (PALS) [41] algorithms [26]. ACLS and PALS are commonly used in "code blue" situations which are safety-critical, time-sensitive situations. A code requires team members to assume numerous roles, including Team Leader, Recorder, IV provider, and Head Nurse (See Fig. 3(b)). These roles determine the actions each provider should perform, and may change throughout the code depending on the providers' prior experience. While PALS and ACLS algorithms provide reference guides for code situations, referring to and ensuring that the team follows the algorithm is primarily the responsibility of the team leader. Therefore, successful execution of this highly stressful and dynamic teaming scenario requires fluent team coordination. As Sarah explained:

“One person is doing compressions, one person is doing meds, one person is looking at the clock, one person is documenting everything. And so it’s just really making sure everyone knows their roles, and can do them effectively.” (Sarah, 28, ICU)

In code situations, a crash cart is essential as it contains medicine and equipment for resuscitation. According to all participants, a crash cart is always located in a designated location in a hallway, and nurses bring them to a patient’s room as soon as a code occurs. While discussing the potential use of RoboTSS, participants explained how a standard crash cart can become a robotic cart with RoboTSS 1) to generate choreography, 2) to manage supplies in the cart, 3) to support decision-making processes, and 4) to generate patient charts. Participants envision the robotic crash cart as a central system that can orient the human team throughout code situations.

**4.2.1 Choreography Generation.** In prior CSCW work, Pine [63] explained how nurses in labor and delivery units choreograph multiple streams of work as they move from one task to another [7]. In our study, participants envisioned employing choreography for interprofessional team coordination within a code (or an OR), which aligns with findings in healthcare literature [34]. Four out of seven participants implicitly and explicitly envision employing RoboTSS as a choreography generation system.

During a code, spatial positioning (choreography) of team members is an extremely important and an often overlooked factor in team coordination (See Fig. 3a for an illustration drawn by Jessica). Choreography (also known as spatial reconfiguration [62]) in healthcare is the process of coordinating among a team through space, time, energy, and rhythm [72]. Lauren explained the concept of choreography as below:

“So one of the important things in simulation that is helpful is to – we call it choreography – so if certain people are standing in a certain place, it goes smoother if people know where they need to be in order for the flow to be happening best. And of course it is different for every place or environment, but in general [it is] around the patient’s bed – where different people stand can help facilitate easier movement and fluidity and communication. So I think that is also a helpful component – when you’re looking at a group – identifying where somebody that is managing should stand versus where somebody that is doing this should stand and where equipment should come in, [and] who places it.” (Lauren, 38, Critical Care)

Jessica described how she envisions the robot would interact with the team, as follows:

“The robot could say, ‘Ok, we need this many people in the room, you stay in here, you stay in there, you stay in there.’ You know? There’s some type of way to figure out what’s the most efficient configuration. The robot could direct people in that way.” (Jessica, 28, Nurse Anesthetist)

In addition to physically moving people as Jessica envisioned, we also inferred that the robotic crash cart could choreograph and manage team members during resuscitation.

Steve explained that choreography would also influence other nurses to better allocate their efforts even when in other patient’s rooms. He described how a number of problems regarding teamwork originated from nursing shortages, as nurses become susceptible to being overworked, working long hours, and ultimately burning out. He stated that he would prefer to continue taking care of his primary patients if he is not needed for the code.

"We don't have that many [...] Like I said, we have ten nurses, three techs, that's it. There's three rooms. So there's an endless possibility of, are we maximizing the amount of people that we have in a room? Or minimizing the minimal amount? That's basically what we would need of people in a room to take care of this patient so that everything else on the unit can get done. If there only needs to be ten people in a room, why are there 14, why are there 15 people? It [the robot] can maybe delegate, say, 'We don't need you at this time,' and it will allow them to leave." (Steve, 29, ICU)

In this way, a robotic crash cart could also enhance the workflow of other nurses outside the room. In addition to improving workflow, Lauren discussed how choreography can improve sterility in the OR. She envisioned using *choreography generation* as a way to reduce infection rates during invasive procedures and to improve coordination among providers to ensure that they stay within the sterile field.

"I think in terms of identifying where these breakdowns [in sterile field] are happening, [a robot] would be great. [...] [In current training practices,] a patient would have two people here, two people there, watching each other to make sure there was no break – to allow the pathogen to spread. But, in that situation that would be great for somebody – a robot to be watching the person and go through these steps and saying what it is that they need to do." (Lauren, 38, Critical Care)

**4.2.2 Supply Management.** Four out of seven participants expected their robotic crash carts can manage medication and equipment. Sarah explained the types of supplies typically stocked in a crash cart:

"And in that cart there is all of the, what we call rescue medication. So it has drawers full of medications, drawers pulled up, like saline, supplies too, intravenous tubes if we need to start IVs. And a bunch of other things that we would need in that scenario to try and bring that person back to life, in essence." (Sarah, 28, ICU)

A crash cart is an important supply management system which should be ready for a code at any time. However, as a code can sometimes take more than an hour, nurses often forget to restock medication and equipment in the carts after these hectic situations. Although healthcare professionals are fully proficient to run codes, missing supplies cause serious delay for these time sensitive code situations. As Rebecca said:

"Even as an older nurse, sometimes you go in there [the crash cart], and something's missing. That's bad. It should never be missing, but it is." (Rebecca, 28, Pediatrics)

Thus, a participant expected a robotic crash cart to notify them whenever there are missing supplies so they will be ready for emergency situations at any time. Since code situations can occur periodically in hospitals, a robotic crash cart's ability to self-maintain supplies is helpful for nurses. Even during code situations, when missing supplies are detected, a robotic crash cart can ask other nearby staff to bring supplies to them. Steve explained such a potential scenario:

"If we need something from the back room for an emergency situation, the computer would know that they [a particular staff member] are the closest person to that back room. It would ring to their phone, or ring to them like, 'Emergency, bring this to such and such room.' That would actually be really nice because a lot of times you end up running up and down the hallway for this. Then you come back, 'Oh, now we need this.'

I've got to run back down the hallway and come back. So [...] in terms of your project, I think that would be cool." (Steve, 29, ICU)

Also, participants envisioned a robotic cart would automatically move to a room with a code situation to decrease preparation time for the resuscitation process. Additionally, a robotic cart is expected to open a drawer through voice command and dispense materials, as Rebecca described:

"For a crash cart where you can be like, 'This concentration of Epinephrine,' and it just opens the drawer, and opens the latch or something, or being able to utilize things like that would be easier." (Rebecca, 28, Pediatrics)

Of the various team members in code situations, participants envision a robotic crash cart would stay near the person administering medication or the one shocking the patient, which is also related to choreography that we discussed above.

**4.2.3 Decision Support.** Five out of seven participants would like RoboTSS to support team decision making processes in code situations. Participants discussed procedure verification as an important role in facilitating situational awareness and transparency between the robot and its team members. Participants discussed how important verification is to ensure that the robot crash cart correctly instructs teams as they go through steps in PALS and ACLS algorithms, as they can change based on a patient's medical history as well as their constantly evolving condition.

"Verification is [...] taking advantage of the robot's ability not to miss a step [...]. That's kind of when you have decision support or something verifying that all the steps get done and there's a provider doing those steps." (Andrew, 44, Anesthesiologist)

This decision support can make teamwork "foolproof" (Rebecca, 28, Pediatrics) in this stressful and safety critical situations. Participants expected a robotic crash cart to be aware of a patient's condition, suggest appropriate dosages of medication, and track administered medication dosages. As a way to help a crash cart understand the patient's condition, participants' indicated interest in incorporating sensors on the crash cart (See Fig. 4). Sensors on the crash cart provide the patient's vital signs so that the robot can understand the progression of the code and provide status updates of where the team is in the code, how long they have until the next step of the resuscitation algorithm, and what drugs are needed next. Jessica illustrated how a robotic crash cart can utilize sensors and communicate with team members:

"If [the robot] senses where [you are] in the code [...] it could tell you, 'One minute and you can give EPI [Epinephrine],' or '30 seconds and you can give EPI', or 'It's time to check your H [possible causes of the code in the ACLS algorithm e.g., hypovolemia, hypoxia/hypoxemia, hydrogen ion excess, etc.] and Ts [possible causes of the code in the ACLS algorithm: tamponade, toxins, tension pneumothorax, etc.].' If they know it's a delay of some sort, it could sense what the cardiac monitor is saying, like if the cardiac monitor is saying the patient is in VFib [Ventricular fibrillation], the robot could sense what the monitor is telling them. Or if the robot could be the one telling everyone what the rhythm is saying – it could actually tell people what to do and be like, 'Ok, you have 30 seconds left on your chest compressions, the next compressor needs to be ready,' or 'One minute until you give this', '30 seconds until you give this', 'You gave this however long ago.' " (Jessica, 28, Nurse Anesthetist)

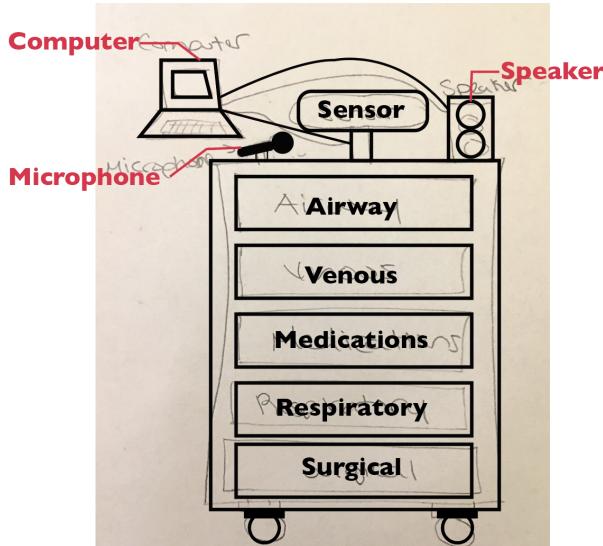


Fig. 4. The robot crash cart that we collaboratively designed with participants for resuscitation procedures. It includes equipment for airway support, venous access, and respiration, as well as medications and surgical equipment. A sensor on top of the robotic crash cart can be used to perceive team members, a speaker and microphone can be used for the robot to communicate with the team, and the computer can be used to run RoboTSS.

One of the most important decisions resuscitation teams make in code situations is administering medication. Sarah explained that a decision support function could help distribute work among team members and prevent situations such as the following:

"Sometimes if I'm supposed to be doing the medications, I'm drawing up the medications or administering the medication. But if the person that I'm working with doesn't know that I'm doing it, they may have grabbed the same medication and they're drawing up the same medication. And so we're doing the same thing at the same time." (Sarah, 28, ICU)

In pediatrics, dosing is more complex, and mistakes can cause more severe harms. As Rebecca stated:

"In peds [pediatrics], everything is weight-based. In a code situation, for an adult, [it is] easy. All the numbers are the same. In a code situation for a child, we have to do math. We have to make sure that we are providing the right amount of dosage for this child because if we do not, we could kill them. They're much more fragile to certain medications than adults are. So we use a length-based tape measure [to] measure how tall the kid is, and it gives us an estimate of if this kid is this tall, how much they should weigh. Because in a code situation, we don't always get a chance to weigh the patient if they're someone new coming in. So we'll use that length-based tape in order to say, 'Okay. This is the weight of the patient.' " (Rebecca, 28, Pediatrics)

For this reason, the pediatrics ICU where Rebecca works already utilizes sensors to monitor the vital signs of their patients. This enables healthcare professionals to be more aware of the patient's

condition during the code situation. In addition to this existing technology, Rebecca envisioned a robotic crash cart to calculate proper dosages for pediatric patients.

“If we could log that weight into a computerized system, and it pops up all of our doses, when we should give what, those are just other additional elements that could be added to something like a smart cart, at least in the peds [pediatrics] world. We have all those things on our crash cart, but they’re in paper form and sometimes hard to flip through. We have a binder that is based on weight. So we do the tape measure, we find out how much their height is to match whatever weight is the average weight for that height, which doesn’t always work if it’s an overweight kid.” (Rebecca, 28, Pediatrics)

One of the most salient team challenges in this context: variability in proficiency levels across team members. When a code is announced in the hospital, providers rush to the patient’s room. This results in an inconsistent team composition, including team members who don’t often work together, which can be challenging because they have to learn how to collaborate together on-the-fly. Furthermore, depending on the institution, nurses may rotate between units in the hospital, so some may not have recent experience with codes. As Jessica put it, “*When I was on ortho (orthopedics), I never had a code, and when I was in the ICU, I had maybe five or six codes in one week.*” Furthermore, as each hospital has its own ways of dealing with code situations [27, 28], travel nurses must quickly adopt to new procedures.

Because codes are safety-critical, high stress situations, human errors inevitably occur. Thus, a majority of participants discussed the potential to use RoboTSS to help improve team collaboration in coding situations and to support and empower providers that are less experienced.

“Sometimes you have people, younger nurses who don’t know or haven’t experienced a code very often, until they get in that situation, and they may freeze or not remember anything. So that would be helpful in those situations, to have a smart system that would walk you through step by step and knowing what needs to be done next and how it should be done.” (Sarah, 28, ICU)

Rebecca compared a robotic crash cart to an Automated External Defibrillator (AED), which enables people with no medical experience to manage sudden cardiac arrest. The medical device analyzes the heart’s rhythm and delivers an electrical shock or defibrillation.

“So I feel like as far as robotics goes, if there was some type of technological device that could walk a group of people through a code situation, I think it’d be helpful because a lot of things that we do is down to the minute. If it’s been two minutes, then we need to switch out our compressions. If it’s been three minutes, then we can give another dose of this drug. In that sense, as far as something that guides the situation much like how an AED does for somebody who has no medical experience, that [the robot] will guide when it’s time to do certain things.” (Rebecca, 28, Pediatrics)

**4.2.4 Charting.** Participants cited communication breakdowns within the team as another problem that occurs during codes. It is the responsibility of the Recorder to document the team’s activities during a coding situation. Therefore, it is their responsibility to actively listen to their teammates to record an accurate manifest of what the team is doing, the time they start a step, the dosage of medications being administered, what steps of an resuscitation algorithm are skipped, and the time they finish a step. Not to mention, all of these activities occur within minutes of each other. Studies have shown that recorders resort to documentation on paper towels [28].

In order to mitigate the communication and documentation challenges associated with coding situations, participants envisioned ways to reduce their workload by offloading these responsibilities to robots. All seven participants discussed charting and documentation issues in our interviews and expect help from a robot.

Because robots are skilled at performing tedious, repetitive tasks, participants indicated that they could be used to walk the team through a code in real-time, similar to the work of Gonzales et al. [29]. Additionally, participants were further interested in integrating robots into the hospital's electronic healthcare record (EHR) system so that the robot could update a patient's chart after a procedure. Participants stated that this can prevent nurse burnout as well as enable all members of the clinical team to focus on the technical aspects of the code instead of documenting it. Nurses' difficulties working on documentation along with other tasks were similarly addressed in ethnographic observation of nurses in the labor and delivery unit [63].

"When you're charting through a code situation, you're manually writing it, which means you could be missing a lot of things going on. There's tons of people in there. People are screaming out things. [...] So being able to essentially have a printout of that mixed in with when meds were given, yeah, it'd be much easier if the computer could compile all that information together." (Rebecca, 28, Pediatrics)

"I always thought that it would be better to chart visually or electronically than actually transcribing what already happened, just like a charting robot [...] aware of what took place and then the chart is generated sort of live, [in] real-time, rather than by providers after the fact." (Andrew, 44, Anesthesiologist)

Also, participants discussed how it would be useful for a robot to automatically identify roles of team members as it walks them through an resuscitation algorithm in order to improve chart reporting. This could provide fine grained documentation of what actions team members performed along with their role and how their roles changed over time.

"If the robot could detect everybody's roles and what's going on and run people through the [coding] algorithm and then print out a sheet of when everything was given what all happened when, that would be great." (Jessica, 28, Nurse Anesthetist)

According to our participants, roles are typically assigned in an ad-hoc manner by the team leader and in some cases, the nurse that is assigned to the patient as they have the most update-to-date information about the patient's medical history.

"The head doctor should be the one that's assigning these roles and delegating the task. Sometimes it's the charge nurse of the unit. And the charge nurse typically doesn't have patients. They are just the manager that circulates and helps out with everything else. So sometimes the charge nurse will do it [assign roles], or other times it [role assignment] will be the nurse that is assigned to the patient. Because typically we like the nurse who was assigned to the patient not to be involved in any of the hands on stuff. So because they typically know more of the background, more of the patient's story, it's easier for them to relay that information if they're not working on other tasks." (Sarah, 28, ICU)

#### 4.3 Concerns about new robotic technologies

Although participants were excited to envision robots as a way to empower themselves, they also had some concerns about this new robotic technologies. Nearly all participants (6/7) voiced their

concerns regarding 1) how a robot could incorporate context dependency in teamwork; 2) emerging roles of robots as new social actors; and 3) privacy issues.

**4.3.1 Importance of context dependency in teamwork.** More than half of the participants (4/7) stated that in order for robots to work effectively with human teams, they need to understand the situational context of team activities (e.g., the patient's medical history, current needs of the team).

For example, participants reported that their resuscitation algorithms are highly situational, and they worried whether robots have the flexibility to adjust to the team's situational context. Although Sarah thought a crash cart robot that goes through each step of a code would help nurses, due to technological limitations, RoboTTS will have trouble adjusting to unpredictable situations to provide appropriate steps. She stated that the main structure of algorithms for code situations follow the same structure, which is called "ABC": 1) open Airway, 2) check patients are Breathing and 3) check Circulation of blood flow. However, she reported that each step of codes is unique almost every time.

"Every code is going to be different in some way depending on, 'Why did the patient code? What is their diagnosis? What caused the code?' So I think that it would just be hard to be able to design an algorithm [for a robot], or a system that would be able to differentiate what situation and what steps, or what directions to give in what situation."

(Sarah, 28, ICU)

She compared the variation in resuscitation algorithm execution among different patients to how cold symptoms vary from person to person:

"It's just like with any disease or illness, it can manifest in different people in very different ways. So even though we both may have a cold, I may be very congested and have a temperature, whereas you might just have a runny nose and a cough or something. Different illnesses manifest themselves differently in different people. So it's just, it's hard to have one set [resuscitation] algorithm that applies to every person." (Sarah, 28, ICU)

Three other participants stated that the resuscitation process varies not only depending on patients, but also depending on hospitals, departments/units, and even the leader of each code. Danielle explained the contingency of code situations as follows:

"And the problem is it [the resuscitation process] varies from hospital to hospital, it varies from unit to unit within your own hospital, it varies on who's on that day. It's funny because we all are trained the same way. Ideally, we're all doing the same thing but every situation is a little bit different so it's really hard to keep replicating the same thing and get really good at it because sometimes you find someone in the bathroom who needs to be coded. Sometimes they're in bed." (Danielle, 35, Critical Care)

Participants also worried whether robots might become one more addition to bureaucratic procedures, which are usually "protocolizations." From the nurses' perspectives, protocols are often developed from administrators' perspectives often without taking nurse workflow into account, thus adding more work and hindering how they deliver care to patients.

**4.3.2 Concerns regarding robots as new social actors.** About half of participants (3/7) discussed how robots would bring new challenges to teamwork as additional actors. For example, Lauren was excited about having a robot as a neutral party to go through a checklist with physicians to support nurses; however, she also stated that it would be "creepy" to be watched by robots or to be notified by robots for their sterility-relevant mistakes. She reported to us that:

"In that situation, that would be great for somebody [...] a robot to be watching the person and go through these steps and saying what it is that they need to do. But, it is still kind of creepy, honestly to me, I am trying to think [about] what they would be like." (Lauren, 38, Critical Care)

Also, Danielle assumed that a third party robot might only make their communication with physicians more complicated.

"For example, sometimes I feel like if something goes on with a patient, you're supposed to go tell your charge nurse and then the charge nurse is supposed to tell the doctor. And I think that I just want to talk to the doctor. I want to be transparent and have direct communication because the more people you add in, it's like the game of telephone. The message gets misconstrued so my only fear for having more people communicating is confusion." (Danielle, 35, Critical Care)

In her previous experience communicating with other healthcare professionals, she found a mediator between two people only decreases "transparency" and wanted to make sure a robot would consider the transparency issue.

*4.3.3 Privacy issues.* Two participants (Rebecca and Lauren) explicitly discussed the privacy concerns robots may introduce to hospitals. For example, Rebecca expressed apprehension about who would have access to the data showing her performance in her pediatric ICU. During the interview, she explained how the parents of pediatric patients sometimes lash out against healthcare providers in grief.

"If you've ever met a parent that has their child in the hospital, they are looking for reasons for things not to be their fault. We're not saying that they are at fault, but they are always going to be looking for reasons why the kid got sick or got worse or, 'You guys caused this.' There's a lot of blame that happens, and that just has to do with grieving and dealing with a high-stress situation. That's the only reason why I advocate for not having cameras in actual rooms in [coding or OR] situations." (Rebecca, 28, Pediatrics)

In Rebecca's unit, parents are not allowed to record healthcare professionals working. If they violate this policy, they cannot bring their cellphones to the unit anymore. If something goes wrong within a code situation with a baby, "it may never be enough for a parent or a family member who's watching." She also explained how the medical community feels about cameras as follows:

"Nobody wants a bunch of cameras watching them while they're doing their job, especially in a job where people like to sue you and don't understand how much human error has to be, sometimes, well-received in the medical community because we're human. We do make mistakes. I don't see hospitals agreeing to it. It would be a huge liability. But also as staff, it doesn't make you feel, I guess, safe at work." (Rebecca, 28, Pediatrics)

Lauren's comments, described previously, echo this concept of "creepiness" of being watched at work all the time. Thus, Rebecca and Lauren suggested that a robot with recording functions might be more appropriate for educational settings, such as simulation and training centers.

## 5 DISCUSSION

We presented how participants envisioned using RoboTSS to empower them to challenge hierarchical culture and improve team collaboration. This is a holistic approach to nurse empowerment which does not only focus on speaking up behavior, but also overall job satisfaction which is

Table 2. Design Implications to Empower Nurses. These implications

demonstrate the design concept, the method that is used to empower nurses (challenge authority, improve team settings or both), the team settings in which the design component is used for (operating room (OR) or resuscitation code), the user's perspective of why the design component is important, and an example which captures the desired robot behavior.

Design Concept	How to Empower Nurses	Team Setting	User Perspective	Example
<b>Robotic Crash Cart</b>	Improving Team Collaboration	Codes	Team members have different levels of experience performing codes.	Robots can walk team member through codes so that team members with less experience in codes do not have to rely on reference guides.
<b>Choreography Generation</b>	Improving Team Collaboration	OR and Codes	Team spatial configurations vary based on the institution; yet, it greatly impacts how teams position themselves around patients as well as whether teams break sterile field. Thus, an effective and automatic spatial configuration strategy is needed.	Robots can generate spatial configurations of teams to promote strategic spatial coordination configurations.
<b>Error Identification</b>	Challenging Authority	OR and Codes	Breakdowns in teamwork cause 70% of all preventable deaths and disability in healthcare. Providers would like a way of identifying when team members commit errors, such as breaking the sterile field.	Robots can use their mobility and sensors to move around complex team configuration, identify when team members commit errors, and inform them in a timely manner.
<b>Checklist Verification</b>	Challenging Authority	OR and Codes	Team members with low power dynamics are often afraid of speaking up when they identify mistakes.	Robots can be used as an intervention to communicate standard protocols to the team in order to empower team members with low power dynamics.
<b>Role Identification and Assignment</b>	Improving Team Collaboration	OR and Codes	Enables robots to identify what actions are being performed so that it can assist with coordination, communication, and documentation support.	Robots should provide a means of identifying team members' roles in order to understand what they are responsible for at any given time of an algorithm.
<b>Chart Generation</b>	Improving Team Collaboration	Codes	Alleviate pressure on the recorder to document codes, to reduce cognitive load.	Robots can autonomously identify team actions during a code and automatically update electronic health records.

consistent with Richard et al.'s work [68]. We encapsulate how our participants envisioned technology to support nurse empowerment in a set of design implications, which we discuss below (See Table 2). These design implications present opportunities for robots to tackle interesting and exciting problems. Furthermore, they consider the team settings, the method used to empower nurses, the vision for empowerment, as well as an example of how robots can advocate for nurse empowerment.

## 5.1 Design Implications

**5.1.1 Robot Crash Cart.** Participants envisioned novel ways to use RoboTSS in time-sensitive and safety-critical teaming situations, like codes, to reduce cognitive load and improve team collaboration. One of the most unique design ideas was the Robotic Crash Cart, which had several features. First, it can autonomously navigate to a patient's room to be available for the clinicians when they arrive. This helps clinicians avoid engaging in non-value-added tasks, by taking time away from treating patients to locate a crash cart.

Second, when the team arrives, the robot goes through the resuscitation algorithm (medical protocol) with the team in real-time. This is particularly helpful to give clinicians immediate situational awareness when entering the room, as well as for helping less experienced clinicians know which steps to follow. In contrast, experienced nurses wanted to manually control how the

robot provides this help, to support flexibility depending on each patient's health condition and medical history.

Third, it can automatically sense where team members are during a code, and provide equipment at the right time. For example, it would automatically open the relevant drawer, and show which supplies they need to pick up. This enables clinicians to quickly locate the supplies they need.

Finally, the robotic crash cart can support automatically resupplying itself. After codes are completed, clinicians do not often have time (or remember) to restock crash cart supplies, which adversely affects future codes. By supporting this practice automatically, the crash cart can help to reduce clinical cognitive load, as well as improve patient safety.

**5.1.2 Choreography.** Participants generated a unique way of employing RoboTSS for choreography generation, which helps team members spatially coordinate as they work together at a patient's bedside. Since physical movement is an important part of team collaboration, a series of CSCW research investigates spatial coordination as a design theme for cooperative work in clinical settings [3, 63, 66]. Pine defined choreography as "the embodied work of balancing and maintaining multiple simultaneous streams of work and bringing them together into a single coherent stream of actions" [63]. In clinical literature, Johnson et al. [34] discussed how choreography increase team efficiency in resuscitation situations as team members can allocated to best perform their work.

In our work, participants envisioned choreography to address how robots can physically allocate multiple people with different roles and distribute labor of the team members considering patients' medical history and specialities of team members. For example, when a code is initiated, the robot can support efficient choreography of clinicians by considering room size, specialties of clinicians on the floor, and their years of experience. The robot can also consider how the clinicians in the room should move around considering medical protocol and a patient's medical history.

A potential approach to integrate automatic choreography generation with existing technology in the healthcare space is for the robot to present the generated choreography on an existing shared display [12, 26, 27, 62]. Using color-coded position pads on the ground which aligns with the shared mental model, team members can easily interpret where they should be positioned at any given time. After the robot presents a map showing the choreography, it can also physically move around to accurately allocate team members. As the robot keeps only clinicians who are essential for their teamwork, other clinicians can return to their patients and efficiently allocate their time. In the OR, the robot can also help team members to position themselves within sterile sections of the room and enhance patient safety.

**5.1.3 Checklist Verification and Error Identification.** Participants envisioned using RoboTSS as an autonomous social intervention mechanism to support administering standard protocols and real-time error identification in teams. This novel design concept uses robots as a neutral third party for communicating information that has caused problems stemming from team hierarchy (e.g., speaking up). For example, instead of nurses administering checklists, robots can autonomously navigate to the leader of the team (e.g., a physician) and administer the checklist as a neutral actor. This prevents high ranking team members from bypassing standard protocols, which can prevent patient safety risks. Additionally, the autonomous real-time error identification design concept can support safety lapses in teams as they work together. This gives teams the autonomy to focus on technical aspects of the code instead of monitoring each other to ensure patient safety.

**5.1.4 Role Management and Chart Generation.** Participants identified role management as a mechanism to support and empower nurses, because it is a challenge that arises when interprofessional teams come together. Role management is a design concept that can be useful for educational training, resuscitation, and surgery, as role assignment determines the actions of team members.

Particularly in dynamic, safety-critical settings such as resuscitation, team members' roles change over time, which leads to challenges in situational awareness and common ground [26]. Thus, participants envisioned RoboTSS to assist with decision support through role management.

Robots are well-suited to this problem due to their embodiment, mobility, and active perception capabilities. For instance, robots can automatically position themselves around the patient's bedside, working side-by-side with clinical teams to identify and adapt to team members' roles and notice how these roles change over time. Additionally, robots can assist with assigning roles to team members as groups expand, which is particularly useful for coding situations when providers of different hierarchical levels rush to the patient's room and need to begin working quickly.

A robot's mobility and role management capabilities could also support documentation and accountability challenges in clinical teams. For example, using its role assignment design mechanism, robots can provide fine-grained documentation of the team's actions, administered medications, and the timestamps for these events. Furthermore, this design concept can be integrated with the robotic crash cart to enable it to walk the team through a code, manage team roles, and document the team's progress in real-time. This can also relieve a code's Recorder from documentation so that they can focus on other aspects of the code (such as treatment).

## 5.2 How The Robot Team Support System (RoboTSS) Can Empower Nurses

Through a collaborative design process, participants expressed how they would design the Robot Group Interaction Module in RoboTSS to support and empower them in teams. In its current state, RoboTSS takes images as input and outputs group identifications within images (See Fig. 1). After conducting interviews, we found that participants wanted to empower nurses by enabling robots to collaboratively work with teams by providing decision support within the team's workflow. Thus, RoboTSS can preserve the output group identifications, and additionally can support role management, error identification, and choreography generation.

Role management is a design concept that can generate a semantic role label for team members. For example, the physician would have a label "physician", a nurse would have a label "nurse", etc. This provides a high-level representation of the role composition in teams for RoboTSS. Additionally, error identification can generate a verbal alert to the team when it identifies a mistake. For example, if the robot observes a team member breaking sterile field, it can inform the team that by saying "The physician broke sterile field. Please re-sterilize." Finally, choreography generation can provide a verbal indication to team members of their position assignment. Using a position map around the patient, RoboTSS can verbally indicate where each team member should stand as well as when they need to move to a new position. By addressing the aforementioned problems, robots can gain a high-level understanding of team collaboration – that is, what are the goals of the team? What are each individual team member's responsibility? How does the team work together? And, what are the roles and responsibilities of the robot?

## 5.3 Challenges with Placing Robots in Safety Critical Settings

Even the most well-designed technology can be disruptive to workflow when it is introduced to a new setting. In safety-critical settings, particular care must be taken to avoid distracting or interrupting healthcare providers, as doing so could cause a PME and cost somebody their life. Therefore, the robot must promote significant benefits to healthcare providers, patients, family members, and other stakeholders [69]. However, there exist a number of challenges with introducing robots to safety-critical settings that must be considered in order to maximize the safety, utility, and likelihood of adoption of the robot [37, 69]. In this section, we discuss the technical and social challenges with placing robots in hospital settings, as well as potential solutions to these challenges.

**5.3.1 Technical Challenges.** Safety-critical spaces are often fast-paced and dynamic, with people and equipment constantly shifting. These conditions, coupled with physical constraints such as narrow halls, crowded rooms, and chaotic environments, can impede a robot's ability to perform its tasks safely and efficiently. The design implications raise many technical challenges such as sensor placement and mobility, computer vision challenges such as occlusion, and enabling robots to accomplish their goal in noisy environments. While the exact technical solutions to these problems are outside of the scope of this paper, there are a number of approaches that may be utilized in these spaces to enable a robot to accomplish its goals safely.

One challenge is understanding the commands and intentions of human teammates when the environment is loud and noisy. Typically, robots can use microphone arrays to understand human speech through natural language processing techniques. However, these methods often struggle to interpret speech in loud, noisy environments. One potential design solution is to equip team members with wearable microphones to provide the robot with clearer data that can be interpreted by existing natural language processing techniques. However, further research is needed to explore how wearable microphones will integrate into existing clinical workflows [73].

On the other hand, robots can infer the needs of team members based on their actions rather than through explicit commands. However, perceiving and recognizing the activities of healthcare professionals is a challenge in these hectic environments. These tumultuous spaces can exacerbate common computer vision challenges such as occlusion, inconsistent lighting, and limited visibility. One approach to circumventing these problems is by equipping team members with wearable sensors [24, 42]. This approach enables robots to recognize the activities of the wearer without relying on visual cameras or requiring them to be in the robot's line of sight.

Additionally, co-located teams frequently communicate using nonverbal cues and often bypass standard protocols based on a patient's continuously changing health condition. This presents many design challenges as the robot will need an understanding of the patient's condition as well as the verbal and nonverbal means of human communication. Enabling robots to understand verbal and nonverbal communication is an active field of research and with numerous approaches that can be used within this space to address such challenges [80].

Prior work on introducing robots to hospital settings have investigated training professionals to control robots from a distance (e.g., teleoperated robots for surgery [62]). However, this creates perception challenges with the robots sensors [8, 12], lack of situational awareness [8], difficulty building shared mental models [8, 12, 62], and maintaining common ground with the team [19, 35]. In studies that address these problems, robots are already developed and placed on the market for a specific use-case. Therefore, our work offers exciting research opportunities as we make no assumptions about the robot's capabilities or morphology, factors that have been shown to impact the team's collaborative workflow.

**5.3.2 Social Challenges.** Our work reveals some of the tasks that healthcare providers feel would be of greatest benefit to teams, which in turn will improve the likelihood that they will accept and utilize robots in these spaces. Furthermore, numerous robots have been successfully integrated into various clinical settings [1, 23, 32, 46, 54, 58] which motivates the potential for robots to be designed for team settings as well. Our work raises many opportunities to design robots that can work effectively in team settings while addressing social challenges such as reluctance to adopt the robot in team workflow, disruption of the existing workflow, and the possibility of unexpected consequences of robots in these spaces.

During interviews, participants indicated hesitation in adopting new technology. They were primarily concerned that the low technical literacy of healthcare providers would lead to clinical ineffectiveness of the robot. One solution to this problem is to leverage existing technology in these

spaces that providers already use and are familiar with. For instance, the robot can communicate with the team via the shared display (discussed in Section 5.1.2) for tasks such as choreography generation and role assignment. Thus, providers can benefit from new robotic technology without excessive training or inconvenience.

Potential resistance to robotic technology can also come from team members higher in the clinical hierarchy that may be challenged by robots. This challenge can be addressed with the proper design of robot feedback to higher ranked team members, similar to the work of Jung et al. [36]. Another way of addressing this problem is to design the robot to challenge the team as a whole in addition to higher ranking team members.

Additionally, placing new technology in these environments can disrupt the existing workflow of teams. This challenge becomes particularly problematic for decision-making design aspects such as role identification and task assignment, as robots need to execute these tasks accurately without distracting or disrupting team members during critical situations. For instance, team member roles change throughout the time that they treat patients, but robots need to automatically and autonomously adapt and understand when this transition occurs. One solution is to use artificial intelligence and machine learning models to automatically infer roles and assign tasks. To exercise transparency with the team, the robot can exhibit its understood knowledge on the shared display, so the team can both employ this information and correct it if necessary.

Finally, extensive realistic tests will help unveil the unexpected consequences of robots in these spaces. For instance, physicians may require more extensive training to become accustomed to a robot conducting role assignment, particularly among those who have more experience. Additionally, clinical teams are trained to monitor each other's behavior in order to minimize patient safety risks. Robot assignment could cause the roles to become more rigid, with physicians focusing only on their given role without tacitly monitoring each other or helping with other tasks. Researchers and stakeholders must perform thorough tests in realistic environments (e.g., clinical simulations) to critically explore how to integrate robots to existing workflows with minimal interference. Our work opens the door to further examination of the impact of robots in these spaces.

#### 5.4 Limitations and Future Work

While our study introduces design concepts to support and empower nurses, there are some limitations to note before integrating robots into healthcare settings. First, while our participants work throughout the US, they represent perspectives and cultures specific to the US. Nurses and clinicians in other countries may have different ideas regarding how a robot can help empower them, or to what degree they would need empowerment. For instance, nurses in Japan may need more help bridging the hierarchical gap due to cultural values associated with seniority, gender, and modesty [61].

Additionally, this paper focuses on the perspectives of nurses, who constitute only one group of healthcare providers. We chose to focus on empowering nurses as this has the potential to significantly improve patient safety. However, we did not consider how robots would impact other team members both higher and lower in the clinical hierarchy. In the future, it would be useful and interesting to consider the perspectives of other healthcare providers in order to thoroughly understand how robots can best suit the needs of everyone on the care team. This understanding is important as robots would impact the workflow of each person on the team, each of whom also influence patient outcomes.

Finally, while we present multiple approaches to empower nurses in this paper, all of our participants specialized in a specific area (e.g., anesthesiology, ICU). As a result, these perspectives

are not necessarily reflective of the experiences and needs of all nurses. Thus, there are likely more approaches in addition to the ones we presented that would also empower nurses.

In the future, we plan to continue our development of RoboTSS through iterative design and testing of our system in real-world settings. We plan to build a prototype of the robotic crash cart and test it with nurses and both educational and real-world settings to determine its effectiveness in empowering nurses. One challenge that may occur while testing our system is that clinical teams can potentially bypass our robot as it administers standard protocols. This is a problem that we plan to investigate as well as robot behaviors that promote user adoption in clinical settings.

As shown in the healthcare literature, nurse empowerment is an important issue for patient care and safety [30, 67, 68]. In this paper, we explored how nurses envision designing technology to support and empower them, which we used to glean design implications for robots in healthcare. We hope this study shed lights on investigating teamwork from nurses' perspectives and promotes further exploration for nurse empowerment in the CSCW community.

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