Effects of Experience and Workplace Culture in Human-Robot Team Interaction in Robotic Surgery: A Case Study

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Abstract

Robots are being used in the operating room to aid in surgery, prompting changes to workflow and adaptive behavior by the users. This case study presents a methodology for examining human-robot team interaction in a complex environment, along with the results of its application in a study of the effects of experience and workplace culture, for human-robot team interaction in the operating room. The analysis of verbal and non-verbal events in robotic surgery in two different surgical teams (one in the US and one in France) revealed differences in workflow, timeline, roles, and communication patterns as a function of experience and workplace culture. Longer preparation times and more verbal exchanges related to uncertainty in use of the robotic equipment were found for the French team, who also happened to be less experienced. This study offers an effective method for studying human-robot team interaction and has implications for the future design and training of teamwork with robotic systems in other complex work environments.

Keywords: Human-robot interaction; robotic surgery; verbal communication; workflow; workplace culture

1. Introduction

In recent years, reports of a high number of deaths and patient injuries due to medical error have been published [1-5]. Research uncovered alarmingly high numbers in the surgical field alone, many of which were preventable [6-7]. Rapid introduction of complex technology and unfamiliarity with new technology were cited as causing confusion and human-machine interaction challenges [8]. This phenomenon is readily observable with the increasingly common use of surgical robotic systems in the operating room (OR). Even though they provide increased precision in surgical manipulation and ergonomic benefits to the surgeon over traditional laparoscopic surgery [9-10], the robotic systems introduce a layer of complexity to the traditional workflow in the OR. That is, in addition to the continual management of equipment and the status of the patient during a traditional surgical procedure, the surgical team must also coordinate the preparation of the robot and associated specialized robotic instruments. Difficulties in dealing with new technology often manifest as poor teamwork and communication within the OR, leading to blurred lines of responsibility, delays in treatment, misdiagnosis, and harm to patients [11-14].

Evaluation of Human-Robot Interaction

Human-robot interaction (HRI) is a relatively new field of research. Little work has been done to measure and understand how people interact with robots. For this reason, human-computer interaction (HCI) studies can provide a rich base for research in HRI. Indeed, HCI techniques are typically used for the analysis of human-robot systems. For example, ethnographic studies have been used to study the nature of social interaction and organization in air traffic control and were shown to be an important process in system design [15]. The use of 'The Wizard of Oz' techniques, where interactivity normally controlled by computer technology is simulated manually by the researcher, has been utilized by Weis et al. [16] to evaluate user's interaction with a humanoid robot in a collaborative task. One of the most common methods in HCI is the participatory design technique. It consists of involving target users in the design process. This aims to build systems that better fit the users' needs. This method has been used by Harris et al. [17] to design a web controlled mobile robot.

The use of HCI techniques for HRI has been found to be limited [18]. These limitations can be linked to the fact that robots are not typical computer technologies, per se [19]. Compared to computers, robots are considered active components of the system that operate in a dynamic environment [20]. They have a physical and social presence in the humans' personal space that set them apart from other interactive artifacts [18]. These characteristics suggest changes in the way humans interact with these new technologies. For that purpose many researchers suggest that the HCI evaluation methods should be applied to HRI with care [16, 18, 21].

Cultural Effects on HRI

Three classes of robots have been suggested: industrial robots, professional service robots that operate in work organizations and public settings, and personal service robots [22]. These three kinds of robots have different capabilities, different user groups, and different contexts of use [22]. In other words, the human-robot interaction varies depending on the cultural setting. "Culture" can be defined based on nationality, languages, socioeconomic status, religion, ethnicity, or more generally, "sets of beliefs, norms, expectations, and traditions which are common to all members of the same population subgroup, but differ among members of different population subgroups” [23, p. 321].

Culture found in a workplace setting falls under the much studied umbrella of organizational culture. According to Schein, organizational culture encompasses “a pattern of basic assumptions, invented, discovered or developed by a given group, as it learns to cope with its problems of external adaptation and internal integration that has worked well enough to be considered valid and, therefore is to be taught to new members as the correct way to perceive, think, and feel in relation to those problems” [24, p. 111]. There are three levels of organizational culture: observable artifacts, values, and basic underlying assumptions, and one can begin to understand a particular organizational culture through the examination of one or more of these levels [24]. Another model describes organizational culture along four dimensions, including a group’s mission, adaptability, involvement, and consistency and can be either internally or externally focused [25]. Organizational culture can also vary as a function of national or regional differences. In an influential study of organizational culture, Hofstede provides a compelling case for organizational differences between national and regional culture groups influencing the behavior found among different worldwide offices of the same company [26]. Characteristics such as power hierarchy, acceptance of risk and uncertainty, individualism vs. collectivism, and traditional masculine vs. feminine values, underlie these organizational differences [26].

Thus, the organizational changes caused by the introduction of robots poses a variety of design and adaptation issues, and are specific to the operating room workplace culture [27]. Studying the integration of the robots in the OR workplace culture and their impact on team communication can provide insight into the nature of human-robot interactions. The goal of this research was to examine *human-robot team interaction* in a complex environment, such as the surgical OR. A second objective of this research was to present a methodology for investigating human-robot team interaction based on communication analysis. In this paper, the methodology is applied to the examination of the effects of workplace culture and experience differences on HRI in the surgical OR, to demonstrate its utility.

Communication in Robotic Surgery

Previous research has shown that the introduction of robotics into the operating theatre alters the traditional surgical team structure and communication patterns [28]. For example, the surgeon performs the robot-assisted procedure while seated at a console away from the patient and the operating table, and as a result, is physically separated from the rest of the team. This setup prohibits face-to-face communication during the operative part of the procedure. Thus, coordination of procedural tasks performed by the assistant, such as changing instruments or irrigating, becomes more complex. One study suggested that team members adapt to the changes brought by the robotic surgical system by communicating more frequently than in a similar, minimally invasive procedure, and this effect is even more pronounced with novice teams [29]. Previous ethnographic research in robotic surgery suggests a shift in the social dynamic of the OR team in which the robot substitutes work tasks traditionally performed by the surgical assistant, altering the social reliance between the surgeon and the rest of the team [30]. Given the changes in team structure and team dynamics introduced by the robot, it follows that the established method of information dissemination may also be altered. Cao and Taylor compared traditional minimally invasive surgery with robotic minimally invasive surgery for cholecystectomy procedures and found a large difference in the amount and type of information communicated in the two surgical teams [31]. For example, tasks such as instrument changes required significantly more physical steps and verbalization to complete in the robotic case [31]. Additionally, the increased amount of verbalization between team members in the robotic case yielded greater chances for miscommunication and error.

A controlled study of open, scripted, and automated communication styles in robotic surgery found that simulated surgeon-nurse teams performed faster in the scripted and automated conditions, but the automated conditions had the highest error rates due to unfamiliarity with the new technology [32]. This suggests that pointed, procedure-related communication has a positive effect on performance in an environment where a robot is introduced into the workflow.

Increased verbalization and team coordination in robotic surgery is expected to be more pronounced when the team members are even further separated physically, as is possible with the use of robotics for telesurgery. The concept of telesurgery is gaining ground among forward thinkers in the field, in which a surgeon may perform a procedure on a patient located remotely through the use of robotic and telecommunication technology. Telesurgery introduces an additional challenge of team coordination between the control and the operative sites when these sites are physically separated by large distances. In addition to the necessary coordination related to preparing the robot and specialized instruments, maintaining patient status, and ensuring a smooth flow of the procedure, the remote teams must also coordinate their activities, often with a time lag due to transmission bandwidth limitation [33]. Delays in feedback have been shown to adversely affect the performance and coordination of remote manipulation tasks and communication [34]. Research has suggested that more effective training and evaluation methods, along with a focus on teamwork and communication, may mitigate some of the risks of patient harm in robotic surgery [35-37].

Moreover, cultural differences between the remote teams can further complicate the coordination efforts. Professional, organizational, and ethnic or regional cultures often combine to shape human behavioral patterns and beliefs. Differences in cultural norms can result in different views on safety, procedures, use of technology, and interpersonal relationships within the work environment [38]. Moray has studied cultural ergonomics related to technology use, and cites anthropometric issues, stereotypes related to a culture's response to stimuli, and language/iconic differences as the primary causes for cultural difficulties in the use of technology [39]. Ethnic and language cultural differences add a layer to expectations of behavior and working standards in the medical field. In the OR, there are certain standard views about team hierarchy, decision-making power, and levels of trust and respect between medical personnel. Organizational factors as basic as shift scheduling, and those affecting task outcomes such as job priorities, may also affect coordination between disparate cultural groups. In surgery, ignoring such professional, organizational, or ethnic cultural factors may negatively impact OR dynamics [40].

Established teams with team members who have worked together over time develop interpersonal relationships that facilitate trust and communication in the pursuit of shared goals [41]. Unfamiliar team members, perhaps new to the surgical team, or working on a remote team during telesurgery, will have less of a chance to build rapport and trust with others, yet they need to rely on communication and personal interaction in order to complete the task at hand within the given timeframe. This may negatively affect team performance, and as a result, outcomes of the care to the patient. As cultural norms dictate the behavior of individuals and teams in social settings, it is important to understand these differences to be able to facilitate the cross-cultural team communication for telesurgery.

This paper reports the results and methodology used to examine real, uncontrolled, robotic surgery cases for the effects of workplace culture and experience in HRI. The use cases were surgical teams in two different ORs across two different countries – France and the US.

2. Methodology

Communication analysis, as a general methodology to study teamwork effectiveness and workflow coordination, has been used in various contexts such as aviation and medicine. However, as the environment in each of these contexts is characterized by its own set of constraints, the methodology must necessarily be modified to adapt to the specific environment being studied.

In general, real-time verbal utterances by team members are recorded along with observable events, either using hand-written notes or videotapes. These verbal and non-verbal events are then analyzed for content and/or pattern, based on the research questions. A coding scheme can be generated according to the themes that emerge, allowing for subsequent detailed analysis. Typically, verbal data can be processed and categorized as single-statements in which each verbal utterance is considered a separate communication entry, or contextual summaries with content, participants, and timing of events. In the medical environment, verbal and non-verbal data have been collected in real-time during surgeries, transcribed, and subsequently categorized into themes (e.g., equipment, planning, and non-task related) [29]. Another approach is to group communication data into types of communication failure caused by flaws in content, audience, or purpose [12]. In aviation, single-statement verbal events have been recorded, transcribed, and then analyzed for patterns such as questions/directives followed by responses/one-bit acknowledgements [42]. Transcribed verbal events have also been analyzed to look for themes related to the usage of first person plural (we, us, and ours) or verbal events related to a successful outcome or sense of achievement [43].

Even though these aviation studies are normally in simulated environments, we used the same approach in acquiring the data and looked for similar patterns of communication as indicators of human-robot team interaction.

In this research, a hybrid approach was used in order to assess verbal data based on both communication content (topic) and pattern. Because the goal was not to specifically look for poor communication or performance indicators, but instead to characterize and understand the behavior of teams in the presence of a robot, we chose this hybrid style of analysis, as it provides several different perspectives for looking at communication. Content analysis can be tailored to look for specific topics of verbal exchanges in surgery, or can be developed over time based on the themes that emerge in preliminary observations. On the other hand, pattern analysis provides a more generalized approach to measuring characteristics of team interaction and performance. It allows for comparison across surgical domains (robotic, laparoscopic, and open surgery) and can serve as a contrast to aviation. Studying only topics of conversation may not reveal cultural or experience differences, and studying only patterns of communication may not reveal the specific workflow points which engage a team to a higher degree.

Research Setting

A field study was conducted in the hospital OR to examine the communication patterns of surgical teams while they performed a surgical procedure using a robotic system. Only gynecologic procedures were observed in this study, allowing us to compare team communication of different teams independent of the surgical procedure. However, given the complex nature of surgery, and the constraints of scheduling and space within the OR, data collection for this observational study was purely opportunistic. In other words, we did not alter the physical environment or the course of events within the OR during observation. Two different surgical teams were observed during the spring of 2011; one at a teaching hospital in Boston, US, while the other was at a teaching hospital in Nantes, France. The surgical team in the US contained a mix of novice members and experienced members of robotic surgery. In contrast, the French team members were all new to robotic surgery (having performed less than 5 cases).

Fig. 1 The da Vinci surgical system, showing (from left to right) the patient cart, console, and tower

Both hospitals used the da Vinci robotic surgery system from Intuitive Surgical, Inc. There are three components in the da Vinci system (Figure 1): an ergonomic surgeon’s console, a patient cart with four robotic arms, and a vision system (referred to as the tower, consisting of speaker and monitors, placed near the operating table).

Data Collection

The research utilized a classic approach to analyze behavior and team interaction, consisting of observations of live surgery, and semi-structured interviews with the surgical team outside of the OR.

US Data Collection

Two regularly scheduled gynecology robotic surgery cases were observed in the US OR. During observation, hand-written notes were taken throughout the procedure. The notes consisted of general descriptions of the physical environment, the team composition, and progress of the operation with time-stamped events such as intubation, anesthesia administration, incision, robotic docking and undocking, closure, extubation, transfer of patient out of room, etc. In addition, the researcher recorded, as much as possible, the verbalized communication events that occurred in the OR.

France Data Collection

A parallel approach was used in the robotic OR in France. Hand-written notes were taken during observation of two regularly scheduled gynecology surgical procedures. In addition, two digital video cameras, as well as a directional microphone, were used to record all surgical events and verbal communication between the surgical team members. Figure 2 depicts the placement of the video cameras within the robotic operating space. It was possible to create a more detailed timeline of observable surgical events (such as intubation robotic docking, etc.) from subsequent transcription of the video and audio recordings.

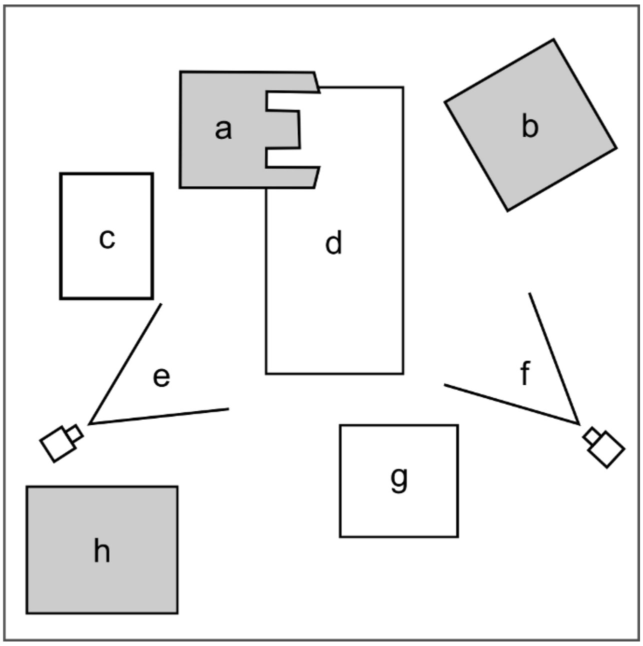

Fig. 2 Placement of digital video cameras shown in physical layout of operating room (a) Robotic patient cart (b) Robotic tower (c) Sterile instruments table (d) Operating table (e) Camera (f) Camera (g) Anesthesiology equipment (h) Robotic console

Data Analysis

Data were analyzed by first examining the hand-written notes and available video recordings of the surgeries. A high-level workflow analysis was conducted to characterize the different phases of robotic surgery; common surgical events found in all four cases were used to create a typical/canonical surgical workflow diagram. These events included tasks such as preparing the patient, preparing the equipment, and use of the robot during surgery. These events are also readily identifiable when directly observing or viewing the videos of a surgery. Next, a timeline analysis was performed to map the observed surgical events to each of the robotic surgical phases, and to calculate performance time for all of the phases in each of the four robotic cases.

Verbal Exchange Taxonomy
Equipment
E1 - Instrument change or request, clean camera
E2 - Equipment adjustment - monitor, table, lights, camera
E3 = Equipment not working / not set up
E4 - Uncertainty in equipment use / teaching use
E5 - Equipment preparation
Procedure
P1 - Task related action irrigation/cutting/suturing etc
P2 - Manipulation or removal of organs/tissue
P3 - Discuss/clarify strategy/plans/procedure/technique
P4 - Localization of organs/anatomy/where to work
P5 - Medication/anesthesia related
P6 - Status related - request patient status or info from chart
Other
WF - Non-verbal/verbal workflow related
O - Unrelated conversation, discuss other cases etc.

Table 1 Topic of verbal exchange taxonomy applied to US and French robotic surgical data

Recorded verbal exchanges between the French surgical team members were transcribed and translated from French to English. All verbal data (transcribed and hand-written) were then coded according to a communication content taxonomy (Table 1) adapted from [29] and also based on observed communication in this field study. The taxonomy defines three different verbal exchange topics: equipment-related, procedure-related, and all other topics.

Because the robotic surgeries in France were recorded on video, a more detailed analysis on the verbal data was performed on the French data only. This analysis used a secondary coding scheme, adapted from previous work on team performance and communication in the aviation industry [42]. The purpose was to analyze communication patterns of the team in order to further understand how experience level or workplace culture may factor into the team's use of the robot. Single statement verbal data were coded according to six different categories: a) uncertainty statements or questions, b) action statements requiring team member to perform a task, c) one-bit acknowledgement statements following (a) or (b), d) responses, more than one-bit of info following (a) or (b), e) planning statements, f) factual statements.

Once the data were coded and organized into a tabular format, patterns of team interaction during various phases of the robotic surgery were extracted by coding each single-statement verbalization according to one of the six pattern codes listed above.

Finally, semi-structured interviews with several of the surgical team members were conducted in order to obtain more information as to their training background, hospital process, opinions of teamwork, and to provide insight into the strategies and difficulties encountered by novice users of the robotic system.

3. Results

Two US and two French gynecologic robotic surgery cases were observed and analyzed, totaling 14.5 hours of observation data. Both US cases were robot-assisted hysterectomies. The first US case lasted 220 minutes from the time the patient was brought into the room until the time the patient left the room. The second US case lasted 210 minutes from the time the patient was brought into the room until the time the patient left the room.

Both cases had a similar makeup of team members: an attending robotic surgeon, physician’s assistant, scrub nurse, and circulating nurse, all of whom were experienced at robotic surgery. They also all had an assistant surgeon and a medical student who were less experienced with robotic surgery. Both cases had an anesthesiologist and a representative from Intuitive Surgical, the manufacturer of the da Vinci system. The first French surgery lasted 260 minutes from the time the patient was wheeled into the operating room, and the second observed surgery lasted 250 minutes from the time the patient was brought into the room. The French team had a similar composition for both cases; there was an attending surgeon, assistant surgeon, three nurses, and an anesthesiologist who were all new to robotic surgery. A representative from Intuitive Surgical was present at both cases. The first observed French procedure was to remove the right ovary and the second procedure was removal of the para-aortic lymph nodes. Tables 2 and 3 show excerpts of the transcribed and processed verbal data collected during the observations.

Docking Excerpt from US Team	
Circ. Nurse:	CN driving robot to table, ask guidance from PA
PA:	Yell to stop when almost at patient legs
Circ. Nurse:	Asks Surgeon if need pedal adjustment at console
PA:	Directing placement of patient cart
Rep:	Directing arm placement
Surgeon:	Discusses robotic strategy with surgeon trainee
Surgeon:	Directs camera positioning
Surgeon:	Asks scrub nurse to adjust a tool

Table 2 Excerpt from summarized verbal data showing communication during robot docking activities in a US surgical team

Port Planning Excerpt from French Team	
Surgeon 1:	This is where port 1 will go, because here <pointing to another spot> we will place port 2.
Rep:	Yes, it's ok.
Surgeon 1:	Should they be separated by at least 5-6 cm?
Rep:	Yes, remember it will change when we insufflate.
Surgeon 1:	We will put one here and here, not along the same line?
Rep:	Yes, exactly.
Surgeon 1:	We will put one here laterally, and then place another one here?
Rep:	Yes.
Surgeon 1:	Should it be like this <indicates on body>, because if I put it there, it will be along the same line.
Rep:	Yes.
Surgeon 1:	<pointing> There?
Rep:	Yes, there is not so bad.
Surgeon 1:	Now the ports are shifted so they are not along the same line.

Table 3 Excerpt from summarized verbal data showing communication during robot port planning activities in a French surgical team

Workflow Analysis

A robotic surgery procedure can be divided into five phases (Table 4) that are largely centered on the preparation and use of the robot. Each of the phases is marked by identifiable start and end points and contains one or more tasks. Figure 3 shows the result of the workflow analysis in which each phase is broken down into smaller tasks. While the workflow shows a typical order of tasks, derived from the overall observational data, there were slight variations in task order between the US and French teams.

Definitions of robotic surgery phases

Phase	*Definition*
Preparation	Begins after anesthesia is administered and ends just before the first skin incision. Includes preparation of robotic equipment, other surgical equipment, and patient.
Port placement	Begins with the first skin incision and ends when all of the trocars have been installed and the team is ready to dock the robot.
Docking	Begins when a team member first begins to move the robot to the operating table. Ends when the camera or last instrument is properly installed on the robotic arm and attached to a trocar in the patient.
Console	The surgeon works a the console to complete the technical part of the surgery. The surgeon is assisted by a nurse with instrument changing, camera cleaning, and irrigation/suction. Begins when the surgeon first sits at the console and ends when the surgeon announces he or she is finished and leaves the console.
Undocking	Begins when the first instrument or camera is unattached from its trocar, and ends when the robot has been moved away from the operating table.

Table 4 Definitions of the phases of robotic surgery, developed based on observational data of US and France procedures

In the preparation phase, both nurses and surgeons performed activities divided into five tasks such as preparing the robot and positioning the patient on the operating table. During the port placement phase, the surgeon, aided by an assistant, installed the trocars into the patient's abdomen and insufflated the abdominal cavity to create a work volume.

The docking phase was divided into three steps: (1) moving the patient cart from the corner of the room to the operating table, (2) positioning the robotic arms and locking them into the trocars in the patient, and (3) inserting instruments and the camera into the robotic arms.

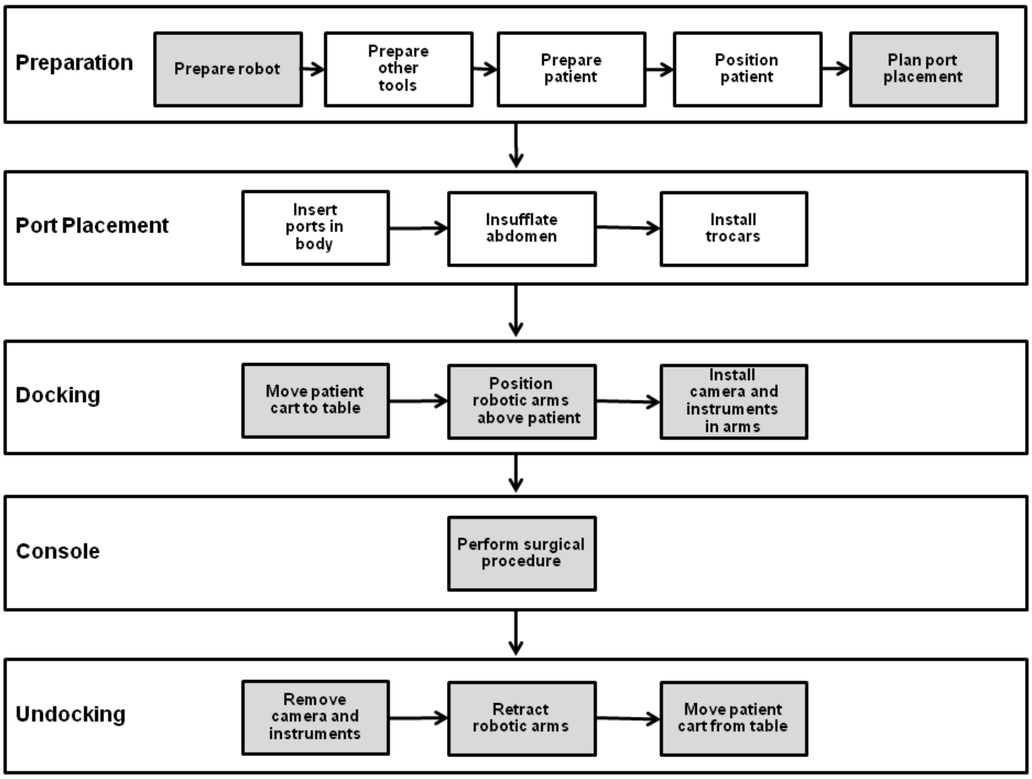

Fig. 3 Workflow diagram depicting each of the robotic surgery phases for this analysis. Each phase is shown along with the steps performed during that phase, listed in a typical working order. Boxes highlighted in gray are robotic specific tasks

After adjusting placement of the robotic arms to avoid both external collisions as well as internal tool collisions, the surgeon moved to the robotic console, stationed in the corner of the OR (Figure 2), and began the operative phase of the procedure at the console. In general, the surgeon worked independently, requesting instrument changes or irrigation/suctioning to be performed from the assistant or scrub nurse as needed. An image of the robot in the French OR is shown in Figure 4. In general, the surgeon worked independently, requesting instrument changes or irrigation/suctioning to be performed from the assistant or scrub nurse as needed.

At the completion of the robotic portion of the surgery, the robotic arms were withdrawn and the robot was moved into the corner of the OR. The closure phase was not included in this analysis because it occurred after the robotic portion was complete and was variable from one case to another due to factors not related to HRI (e.g., patient condition, type of procedure, or scheduling of the next procedure).

Fig. 4 Robot in French operating room during surgical procedure, console phase

Timeline Analysis

Figure 5 shows the results of the timeline analysis for the five phases of robotic surgery for all four cases (two US cases and two French cases). The results show that the French team had longer phase times for preparation, port placement, and docking, whereas the US team had longer console and undocking phase times. For example, the US preparation times were 42 minutes and 32 minutes for the two observed cases. The preparation phase times for the French team were 75 minutes and 76 minutes for each of the two French surgeries.

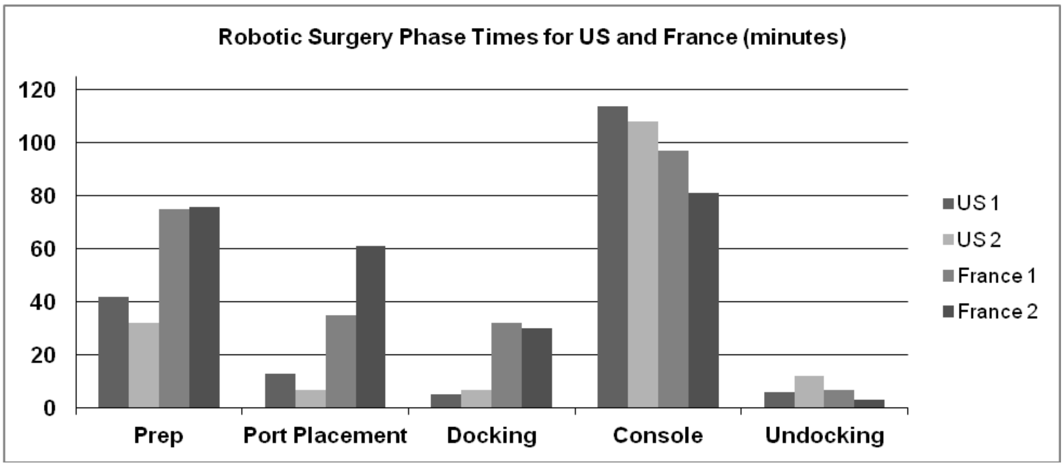

Fig. 5 Phase times in minutes for each of the five robotic surgery phases, shown across observed US and French procedures

Differences in Roles

In the US, there were at least five team members working in the OR during a robotic procedure: the surgeon, a second surgeon who may be experienced in non-robotic surgery but who was new to robotic surgery (referred to as surgeon trainee), a physician's assistant (responsible for assisting the surgeon with preparation and planning tasks, and providing surgical assistance at the operative site through an "assistant port" in the patient), and two nurses (one scrubbed in and one circulating), and a medical student. The dominant topics in the US OR were 36% equipment-related and 53% procedure-related. Topic percentage was computed by dividing the number of recorded verbalizations for each category in the content taxonomy by the total number of verbalizations.

Figure 6 depicts each of the team members found in the US robotic OR shown physically distributed around the robotic operating space. Each team member's dominant topic of verbal exchange with the surgeon is shown, based on the verbal exchange taxonomy analysis. These values were computed by counting the number of verbal exchanges between two team members for each of the verbal exchange categories and dividing that tally by the total verbal exchanges for the pair.

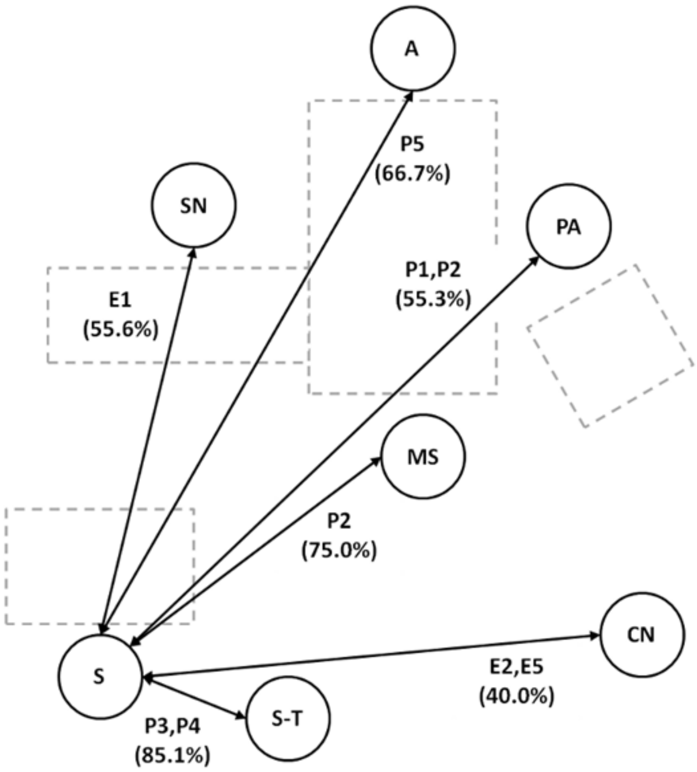

Fig. 6 Allocation of the most frequent topic and percentage of verbal exchange with surgeon in US team based on verbal exchange codes (from Table 1). (A) Anesthesiologist, (SN) Scrub Nurse, (PA) Physician's Assistant, (MS) Medical Student, (S-T) Surgeon Trainee, (S) Surgeon, (CN) Circulating Nurse

The topics of discussion varied depending on the roles of the team members involved each exchange. Out of all of the verbal exchanges between surgeon and surgeon trainee, 85.1% of them related to strategy, technique, and working site localization. The surgeon's verbal exchanges with the nurses involved equipment preparation and use (55.6% and 40.0% for the scrub nurse and the circulating nurse, respectively).

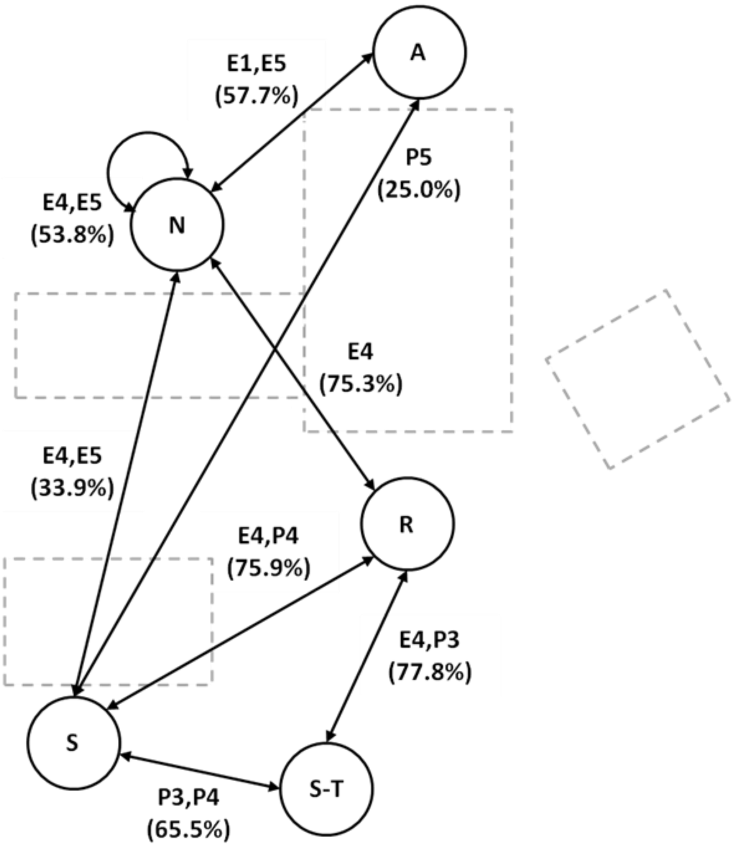

Fig. 7 Allocation of the most frequent topic and percentage of verbal exchange in French team for Port Planning and Docking phases, based on verbal exchange codes (from Table 1). (A) Anesthesiologist (N) Nurse, (S-T) Surgeon Trainee, (S) Surgeon, (R) da Vinci Surgical Representative

Figure 7 depicts each of the French team members physically distributed around the robotic operating space. There were two surgeons, both new to robotic surgery (one surgeon had completed several robotic surgery cases while the other surgeon had completed none), and two nurses being trained together in the roles of scrub nurse and circulating nurse for robotic surgery. Because the nurses alternated the roles of circulating and scrub nurse between each case, assisting each other in all duties so as to learn the required tasks, they were merged into a single role of "nurse" for this analysis. A third nurse was present in the surgeries and also assisted the other nurses with surgical duties. There was also a representative from Intuitive Surgical present, as well as an anesthesiologist.

The French surgeon and surgeon trainee primarily discussed strategy, technique, and working site localization (65.5%), and the interaction with the nurses centered on preparing and learning how to use/prepare the robotic equipment (33.9%). The nurses primarily discussed usage and preparation of the equipment (53.8%). The representative from Intuitive Surgical was involved in verbal exchanges related to both equipment use and procedural technique for port placement (75.9%).

Communication Analysis of Select Phases

Table 5 shows a comparison of verbal exchanges between the US and French teams for all phases of robotic surgery except undocking, which varies based on other underlying factors such as whether there is another procedure scheduled. All verbal events were categorized according to the taxonomy independent of role or who was talking to whom. Percentages of verbal events in each content category were calculated based on the tallies of each category divided by the total verbal events in the surgery.

The average value was taken between the two observed cases. In the phases leading up to use of the console, the US team had a total of 36% equipment related verbal exchanges and 53.5% procedure related exchanges. The French team's verbal exchanges were 56.5% equipment related and 39.1% related to procedure. In the category of uncertainty in use of equipment, the French team had 25.4% exchanges as compared to 4.5% in the US. Conversely, the US team had 13.5% verbal exchanges related to manipulating organs and tissues vs. the French team, who had only 0.9% similar exchanges.

Prep, Port Placement, Docking, Console Phases Verbal Exchange Topics		
Description of Code	US %	France %
Equipment Related		
E1: Instrument change or request	10.0	7.7
E2: Adjust equipment	11.0	9.5
E3: Not working/not set up	3.0	2.5
E4: Uncertainty in use/teaching use	4.5	25.4
E5: Equipment Preparation	7.5	11.4
Procedure Related		
P1: Task related (irrigation, sutures)	7.5	4.4
P2: Manuipulation of organs/tissue	13.5	0.9
P3: Strategy/clarify plans/procedure/technique	17.5	19.3
P4: Localization of organs or workspace	8.0	13.2
P5: Anesthesia or medication	5.0	0.3
P6: Patient status/underlying patient condition	2.0	1.0
Other: Other cases, other conversation	10.5	4.5

Table 5 Comparison of preparation and docking phase topics between US and French teams

Communication Pattern Analysis

Table 6 shows the results of the communication pattern analysis for the French team. The percent usage of each type of pattern (listed in left hand column of the table) was calculated by tallying the number of verbalizations coded for each pattern type within each phase and dividing by the total number of verbalizations for that phase.

Prep, Port Placement, Docking, Console Phases Pattern Analysis	Prep %		Port Placement %		Docking %		Console %		
Description of Code	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Total %
Uncertainty statements or questions	35.3	22.5	26.7	21.7	22.9	28.1	21.8	24.4	25.3
Action statements or requests	7.5	5.5	13.3	16.1	23.2	22.9	28.9	8.6	15.2
One-bit acks to uncertainty/action	11.4	5.5	3.6	8.6	7.1	4.8	6.7	8.0	7.4
Responses to uncertainty/action	29.7	20.3	21.0	19.0	28.6	23.3	18.8	18.9	22.4
Planning statements	9.8	39.6	22.6	21.1	12.8	17.6	17.2	35.5	22.1
Observable fact statements	2.9	1.6	12.8	8.9	4.2	4.3	6.7	2.3	5.1
Other	3.3	6.6	0.0	4.5	1.2	1.0	0.0	2.7	2.4

Table 6 Pattern analysis comparison of single statement communication data for the two observed French team robotic surgeries

4. Discussion

Workflow Analysis

The workflow analysis facilitated development of a high-level understanding of the required tasks for robotic surgery. Five robotic phases (Table 4) were defined in order to describe the typical progression of robotic surgery, as indicated by readily identifiable events in the environment. Within each phase were one or more tasks; overall, the workflow presented in Figure 3 shows the large number of tasks that directly involve the robot, thus necessitating HRI.

Analyzing the workflow of robotic surgery also showed the similarities and differences in tasks between the US and French teams. Each of the teams followed slightly different workflows, which may be shaped by both experience level and difference in hospital setting.

Surgical teams work to achieve goals related to safety, timeliness, sterility, resources, roles, and situation [44]. However, differences can exist in the order or emphasis of these goals based on the workplace culture found in an OR. While the workflow diagram shows a typical order of tasks, derived from the overall observational data, there were slight variations in task order between the US and French teams. For example, the US team completed most of the robot preparation prior to the patient entering the room, whereas during the French team cases, the robot was prepared concurrent to the port planning by the surgeons. The difference in task order may be influenced by patient throughput and time priorities at the hospital. Similarly, there were recorded instances in the US data where the team discussed the next case or a later case, yet similar observations were not made in France, further suggesting differences in priority based on organizational and work cultures at the hospitals. Task order differences could also be a result of experience level with the robot, since the novice French team had not yet optimized their preparation activities in robotic surgery.

Timeline Analysis

An analysis of the time needed to complete each phase of the surgery provided an indication of the performance of the US and French teams. The initial analysis (Figure 4) shows that the French team took longer in the phases leading up to use of the robot, but the US team spent more time executing at the console. While console time represents the longest phase, it is procedure dependent, and may not provide a good indication of human-robot performance when compared across different cases. Preparation, port placement, and docking times, however, are independent of the surgical procedure, and the workflow analysis showed that all of these phases required multiple steps. It takes more time and careful planning to ensure proper setup of the equipment and installation of the ports and tools. While some of the time difference between the US and French preparation may be attributed to the experience levels of the teams, during interviews the French team stressed an emphasis on preparation. Taking more or less time during preparation of the robotic environment may be a result of the policies and attitudes that exist within the particular hospital (workplace culture differences), or even as a result of differences in medical training (professional culture differences). At the same time, the longer times of the French team may also be indicative of interaction challenges when using the robot as a new technology.

Differences in Roles

The results also shed light on the interpersonal structure from which roles emerge in the OR. As shown in Figures 6 and 7, the team composition was different in France than in the US in both size and roles. For example, the US team utilized a physician’s assistant to oversee port placement, docking, and to assist with surgical tasks. In France, such a position did not exist, but the same duties were performed by the nurses and surgeons together. In France, the surgeon was more involved in each step of preparation; the US surgeon took on more of an overseer and approver role, delegating many tasks to the rest of the team. The roles found in each of the operating teams also suggest that different workplace cultures exist between the French US hospitals. Previous research has shown that blurred lines of responsibility and assumptions about provider skills and knowledge may contribute to delays in patient care and adverse events [7]. For future telesurgical environments, it is important to consider how duties will be divided between the remote teams and that each team member is provided with a clear definition of expectations to support his or her role.

The results also show that the French and US teams share similar topics of discussion; the surgeon and surgeon trainee discuss strategy, technique, and working site localization, and communication with nurses is largely centered on equipment. Even for an experienced team such as the US, there are emergent themes where the team members must discuss and clarify how to interact with the robot.

Communication Analysis

Communication analyses suggest differences in style and experience level. As indicated by Table 5, the US team spent a larger percentage of communication discussing the procedure. However, the French team's exchanges suggest uncertainty in use of the equipment that may be indicative of a novice team. While the US team was discussing equipment adjustment in order to optimize the robotic setup, the French team was discussing the use and function of the equipment. These differences may also be indicative of a cultural difference, where in the US management of the case is different than in French surgery. At the same time, both teams still had to devote a large percentage of communication to discuss equipment. This supports the idea that the introduction of a robot to the OR necessitates continued discussion related to the new robotic equipment, even for an experienced team such as in the US.

During the procedure, the US surgeons directed verbalization towards manipulating organs and tissues while working in the body. In contrast, the novice French team spent little time in this category, as they were more focused on locating where to work and understanding usage of the equipment. As teams devote a larger percentage of communication to uncertainty in equipment use and uncertainty in procedural steps, there is potentially a higher chance for communication breakdowns and miscommunication, which may jeopardize patient safety. Therefore, the results of this analysis shed light on possible causal factors that could lead to patient harm.

The verbal exchange topics of the US team were also more widely distributed throughout all the topics of exchange, also suggesting a difference in experience level. It may also be indicative of a cultural or hospital organizational difference, where in the US management of the case is different than in French surgery.

Communication Pattern Analysis

The pattern analysis of the French data suggests several things related to this novice team. Overall, there were more uncertainty/question statements than action/command statements. This suggests that the inexperience of the team necessitated more clarification related to the robotic surgery activities. There were also more detailed responses than one-bit responses (i.e., “yes” or “okay”). This result suggests both a lack of experience (which in turn requires more information feedback), but also could indicate team culture. Throughout the entire preparation phase, the surgical team members in France were constantly communicating, clarifying next steps or cross-checking with each other. While at first glance this could be a result of a novice team who is uncertain of their actions, this style of communication did not change from the first observed case to the second, despite the gain in experience. Therefore, it could also indicate workplace cultural values that emphasize open communication and information sharing.

Finally, the number of planning statements increased from case 1 to case 2. This result suggests that the novice team was learning and gaining confidence, allowing them to discuss plans and strategy, as opposed to focusing more on equipment issues.

In certain phases of robotic surgery, there were lower percentages of verbal responses (e.g., docking, port placement, and console). This is not necessarily indicative of poor team communication. Analysis of the video logs revealed that in these phases, many responses were issued non-verbally. Examples of these occurred when the surgeon asked for a tool and the nurse handed the surgeon the tool immediately, or when the surgeons discussed port placement and indicated with their hands or instruments instead of providing verbal confirmations.

The difference in response type between port placement and docking also suggests something about the team's interaction with the robot. The higher percentage of action statements/commands during the docking phase is indicative of how the surgeon and rep must issue commands on how to set up the robot at the operating table. For docking, non-verbal responses (in the form of moving the robot) were sufficient to close the loop on positioning directions offered by the team, helping to explain the lower percentage of response statements. However for port planning, the team closed the loop with verbal communication, as indicated by a higher percentage of response statements. The surgeon's willingness to talk aloud not only solidified his understanding of the process, but allowed other team members to experience the same understanding and learning.

Summary of Findings

It is difficult to define HRI, especially in a complex and dynamic environment such as the OR. In this case study, we examined workflow, time, roles, and communication in an effort to understand the interaction found in the robotic surgical setting.

Beginning with high-level observations that formed a picture of the overall process and workflow, teams in two different countries were observed to share the same end goal of delivering surgical care to a patient. By defining each of the phases of robotic surgery, similarities and differences emerged in the paths followed by the teams. For example, the teams followed slightly different workflows, and the roles of the clinicians working in each country differed along with varying communication styles. These differences may be shaped by experience levels in use of the robotic system, as well as organizational and cultural influences.

Subsequent levels of analysis identified areas that suggest a high degree of interaction based on workflow, time, and communication results between the two observed teams. By analyzing the verbal exchanges for communication content, frequent topics of discussion about equipment and use of the robot were observed, suggesting that the adoption of such a new technology may be challenging, even for a more experienced team. These results also suggested the impact of experience level and workplace factors on team behavior robotic surgery. In addition, conducting a dual communication analysis across both the topic of exchange as well as the pattern of communication further facilitated the understanding of human-robot team interaction by revealing indicators of communication style and learning of a novice team over time.

If cultural ergonomic considerations are commonly applied to the design of medical devices, then team interaction and training methods need to be studied as well in order to facilitate the development of successful telemedicine applications. A goal of this study was to understand human-robot team interaction in robotic surgery. The results revealed that differences between work sites and teams may benefit from a common set of training and communication protocols in order for remote teams to collaborate effectively and synchronize the workflow. Use of a surgical robot requires many changes to planning and use of equipment as compared to minimally invasive surgery. Roles, tasks, and workflow need to be well-defined using a common language agreed upon and understood by all members of the local and remote teams. This preliminary research provides an important first step to understanding HRIs in complex work environments such as surgery and in understanding the effects of culture and experience between different teams.

While this case study examined surgical teams that happened to be in different countries, therefore implying the existence of regional cultural differences, the method and findings are most importantly generalized to human-robot teams working as a single unit, or comparing human-robot team interaction between different units, offices, or geographic locations.

Limitations and future work

This research was a preliminary analysis of human-robot team interaction in surgery. While many conclusions can be drawn, the data set was small. Data collection in a dynamic environment such as surgery generally proves to be challenging; uncertainty in the environment can cause cancelled surgeries and delays, making it a time-consuming field study. Capturing all concurrent tasks through video and audio analysis must be carefully planned. The additional step of translating and understanding the context of a foreign operating team adds an additional layer to data analysis. The original two US surgeries were not videotaped; therefore it was not possible to complete a direct comparison of single statement data with the French team.

A direct comparison of team performance between a robotic-assisted surgery and non-robot-assisted surgery [31] was not conducted using the proposed methodology. Future studies may employ this approach to examine its applicability in HCI research.

5. Conclusion

The shift from traditional minimally invasive techniques to robotic surgery is a large step. In the former, surgeons are separated from the patient by simple hand-held surgical tools. Conversely, in the latter a complex computer driven electro-mechanical machine is inserted between the surgeon and the patient. Any new technology introduced into an established system will face obstacles in terms of re-training, adoption, and adjustments to procedure. The surgical domain is not different in dealing with new technology; changes to established medical protocols and workflows in a high stress environment such as surgery may have a direct effect on the safety of the patient and outcome of procedures. The results presented in this paper demonstrate an effective methodology that can be applied to the study of human-robot team interaction in a dynamic work environment. In this particular instance, we were also able to draw conclusions about the effects of experience level and cultural differences on human-robot team interaction with robotic technology. Understanding these factors will not only allow for improvement of the technology and advancement of safety to the patient, but will provide a setting in which to implement future telesurgical systems in order to deliver surgical care between remote locations.

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References

[1] Kohn L, Corrigan J, Donaldson M (2000) To err is human: Building a safer health system. Natl Academy Press, Washington, D.C.

[2] Commission to the European Parliament and the Council (2008) Communication on patient safety, including the prevention and control of healthcare-associated infections COM 836 Final, Brussels

[3] Eurobarameter (2006) Medical Errors. Special Eurobarameter 241

[4] Baker GR, Norton PG et al (2004) The Canadian Adverse Events Study: the incidence of adverse events among hospital patients in Canada. Canadian Med Association J 170(11):1678-1686

[5] Wilson RM, Runciman WB, Gibberd RW, Harrison BT, Newby L, Hamilton JD (1995) The quality in Australian health care study. Med J Aust 163: 458-71

[6] Gawande AA, Thomas EJ, Zinner MJ, Brennan TA (1999) The incidence and nature of surgical adverse events in Colorado and Utah in 1992. Surg 126(1):66-75

[7] Landrigan CP, Parry GJ, Bones CB, Hackbarth AD, Goldmann DA, Sharek PJ (2010) Temporal trends in rates of patient harm resulting from medical care. N Engl J Med 363:2124-2134

[8] Cook R, Woods D (1996) Adapting to new technology in the operating room. Human Factors 38(4):593-613

[9] Ballantyne, GH (2002) Robotic surgery, telerobotic surgery, telepresence, and telementoring. Surgl Endosc 16(10):1389-1402

[10] Lee E, Rafiq A, Merrell R, Ackerman R, Dennerlein J (2005) Ergonomics and human factors in endoscopic surgery: A comparison of manual vs telerobotic simulation systems. Surgl Endosc 19(8):1064-1070

[11] Christian CK, Gustafson ML, Roth EM, Sheridan TB, Gandhi TK, Dwyer K et al (2006) A prospective study of patient safety in the operating room. Surg 139(2):159-173

[12] Lingard L, Espin S, Whyte S, Regehr G, Baker G, Reznick R et al (2004) Communication failures in the operating room: An observational classification of recurrent types and effects. Qual.Saf.Health.Care 13(5):330-334

[13] Mills P, Neily J, Dunn E (2008) Teamwork and Communication in Surgical Teams: Implications for Patient Safety. J Am Coll Surg 206(1):107-112

[14] Williams RG, Silverman R, Schwind C, Fortune JB, Sutyak J, Horvath KD et al (2007) Surgeon information transfer and communication: Factors affecting quality and efficiency of inpatient care. Ann Surg 245(2):159-169

[15] Hughes J, King K, Rodden T, Andersen H (1995) The role of ethnography in interactive systems design. ACM Interact 2(2):56-65

[16] Weiss A, Bernhaupt R, Schwaiger D, Altmaninger M, Buchner R, Tscheligi M (2009) User experience evaluation with a Wizard of Oz approach: Technical and methodological considerations. In: Proc Intl Conf on Humanoid Robots, pp 303-308

[17] Harris E, Lamonica A, Weinberg JB (2004). Interfacing the Public and Technology: A Web Controlled Mobile Robot. Accessible Hands on Artificial Intelligence and Robotics Education: Working Papers of the 2004 AAAI Spring Symposium Series, AAAI Press, Menlo Park, CA, pp 106-110

[18] Young JE, Sung J, Voida A, Sharlin E, Igarashi T, Christensen HI, Grinter RE (2011) Evaluating Human-Robot Interaction: Focusing on the Holistic Interaction Experience. Int J Social Robotics 3(1):53-67

[19] Friedman B, Kahn P, Hagman J (2003) Hardware Companions? What online AIBO discussion forums reveal about the human-robotic relationship. In: Proc of SIGCHI Conf on Human Factors in Computing Systems, ACM, New York

[20] Burke JL, Murphy RR, Coovert MD, Riddle DL (2004) Moonlight in Miami: A field study of human–robot interaction in the context of an urban search and rescue disaster response training exercise. Human Comput Interact 19:85-116

[21] Fernaeus Y, Ljungblad S, Jacobsson M et al (2009) Where third wave HCI meets HRI: report from a workshop on user-centered design of robots. In: Adjun Proc of ACM/IEEE Int Conf on Human-Robot Interact. ACM, New York, pp 293–294

[22] Thrun S (2004) Towards a framework of human-robot interaction. Human Comput Interact 19:9-24

[23] Jentsch F, Hoeft RM, Fiore SM, Bowers CA (2004) A Frenchman, a German, and an Englishman…: The impact of cultural heterogeneity on teams. In: Kaplan M (ed), Cultural Ergonomics, Advances in Human Performance and Cognitive Engineering Research, 4:317-340

[24] Schein EH (1990) Organizational Culture. American Psychologist 45:109-119

[25] Denison DR, Mishra AK (1995) Toward a Theory of Organizational Culture and Effectiveness. Organizational Science 6(2):204-223

[26] Hofstede G (2001) Culture's Consequences: Comparing Values, Behaviors, Institutions, and Organizations Across Nations, 2nd edn. Sage, Thousand Oaks

[27] Mutlu B, Forlizzi J (2008) Robots in organizations: the role of workflow, social, and environmental factors in human-robot interaction. In: Proc ACM/IEEE Int Conf on Human Robot Interact, Amsterdam, NL

[28] Healey A, Benn J (2009) Teamwork enables remote surgical control and a new model for a surgical system emerges. J Cogn Technol. Work 11(4):255-265

[29] Nyssen A, Blavier A (2010) Integrating collective work aspects in the design process: An analysis case study of the robotic surgery using communication as a sign of fundamental change. In: Palanque P, Vanderdonckt J, Winckler M.(eds), Hum Error, Saf Systems Dev. Springer, Berlin, pp 18-27

[30] Wasen K (2010) Replacement of Highly Educated Surgical Assistants by Robot Technology in Working Life:Paradigm Shift in the Service Sector. Int J Social Robotics 2(4):431-438

[31] Cao C, Taylor H (2004) Effects of New Technology on the Operating Room Team. In: Khalid HM, Helander MG, Yeo AW (eds) Working with Comp Systems, pp 309–312

[32] Webster JL, Cao CGL (2006) Lowering communication barriers in operating room technology. Human Factors 48:747-758

[33] Marescaux J, Leroy J, Gagner M, Rubino F, Mutter D, Vix M et al (2001) Transatlantic robot-assisted telesurgery. Nature 413(6854):379-380

[34] Ottensmeyer MP, Hu J, Thompson, JM, Ren J, Sheridan TB (2000) Investigations into performance of minimally invasive telesurgery with feedback time delays. J Presence: Teleoper. Virtual Environ 9(4):369-382

[35] Helmreich RL, Merritt AC, Wilhelm JA (1999) The evolution of crew resource management training in commercial aviation. Int J Aviation Psychol 9(1):19-32

[36] Guerlain S, Turrentine FE, Bauer DT, Calland JF, Adams R (2008) Crew resource management training for surgeons: Feasibility and impact. Cogn Technol Work 10(4):255-264

[37] Gaba DM, Howard SK, Fish KJ, Smith, BE, Sowb YA (2001) Simulation-based training in anesthesia crisis resource management (ACRM): A decade of experience. Simul & Gaming 32(2):175-193

[38] Helmreich RL, Wilhelm JA, Klinect JR, Merritt AC (2001) Culture, error, and crew resource management. In: Salas E, Bowers CA, Edens E (eds) Improving Teamwork in Organizations, Applications of Resource Management Training. Lawrence Erlbaum, New Jersey

[39] Moray N (2004) Culture, context, and performance. In Kaplan M (ed) Cultural ergonomics. Elsevier, Amsterdam, pp 31-59

[40] Helmreich R, Merritt AC. (2001) Culture at work in aviation and medicine: National, organizational and professional influences. Ashgate, Burlington

[41] Meyerson D, Weick KE, Kramer RM (1996) Swift trust and temporary groups. In Kramer RM, Tyler TR (eds) Trust in organizations. Sage, Thousand Oaks, pp 166-195

[42] Bowers, CA, Jentsch F, Salas E, Braun CC (1998) Analyzing communication sequences for team training needs assessment. Human Factors 40:672-679

[43] Sexton JB, Helmreich RL (1999) Analyzing cockpit communication: The links between language, performance, error, and workload. In Proc of the Tenth Int Symp on Aviat Psychology, Columbus, OH

[44] Lingard L, Reznick R, Espin S, Regehr G, DeVito I (2002) Team communications in the operating room: Talk patterns, sites of tension, and implications for novices. Academic Medicine 77(3):232-237

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