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Barriers to Efficiency in Robotic Surgery: The Resident Effect

Monica Jain[a], **Brian T. Fry**[b], **Luke W. Hess**[c], **Jennifer T. Anger**[a], **Bruce L. Gewertz**[a], and **Ken Catchpole**[a,d]

Monica Jain: monica.jain@cshs.org; Brian T. Fry: brian.fry@umich.edu; Luke W. Hess: luke.hess.sd@gmail.com; Jennifer T. Anger: jennifer.anger@cshs.org; Bruce L. Gewertz: bruce.gewertz@cshs.org; Ken Catchpole: catchpol@musc.edu

[a]Cedars Sinai Medical Center: 8700 Beverly Blvd, Los Angeles, CA 90048, USA

[b]University of Michigan Medical School: 1301 Catherine St, Ann Arbor, MI 48109, USA

[c]Pennsylvania State University: University Park, State College, PA 16801, USA

[d]Medical University of South Carolina, 167 Ashley Avenue, Charleston, SC 29425, USA

Abstract

Background—Robotic surgery offers advantages over conventional operative approaches, but may also be associated with higher costs and additional risks. Analyzing surgical flow disruptions (FDs), defined as "deviations from the natural progression of an operation," can help target training techniques and identify opportunities for improvement.

Materials and methods—Thirty-two Robotic Surgery operations were observed over a six-week period at one 900-bed surgical center. FDs were recorded in detail and classified into one of 11 different categories. Procedure type, robot model, and resident involvement were also recorded. Linear regression analyses were used to evaluate the effects of these parameters on FDs and operative duration.

Results—Twenty-one prostatectomies, 8 sacrocolpopexies, and 3 nephrectomies were observed. The mean number of FDs was 48.2 (95% CI 38.6–54.8 FDs), and mean operative duration was 163 minutes (95% CI 148–179 minutes). Each FD added 2.4 minutes (p=0.025) to a case's total operative duration. The number and rate of FDs were significantly affected by resident involvement (p=0.008 and p=0.006, respectively). Resident cases demonstrated mostly Training,

Corresponding author: Ken Catchpole, PhD. Medical University of South Carolina, Department of Anesthesia and Perioperative Medicine, 167 Ashley Avenue, Suite 301, MSC 912, Charleston, SC 29425, USA. 1-843-792-4955. catchpol@musc.edu.

Author contributions: K.C. and J.A. designed the study. K.C. developed the methodology and observation methods used, which were adapted by B.F, L.H., and M.J. B.F. and L.H. performed the primary data collection and initial data analysis. M.J. provided conceptual, clinical, technical, and analytical assistance throughout all aspects of the study. K.C. performed the final statistical analysis and modeling. K.C. and M.J. prepared and edited the manuscript. B.F, and J.A. and B.G. edited the manuscript. The study was overseen clinically and conceptually by B.G. at every stage.

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Equipment, and Robot Switch FDs, whereas non-resident cases demonstrated mostly Equipment, Instrument Changes, and External Factors FDs.

Conclusions—Though the FDs encountered in resident training are more frequent, they may not significantly increase operative duration. Other FDs, such as Equipment or External Factors, may be more impactful. Limiting these specific FDs should be the focus of performance improvement efforts.

Keywords

human factors; error; safety; teamwork

Introduction

As the healthcare system becomes increasingly more complex, the opportunities for errors in patient care also accumulate [1]. Current evidence suggests that organizational complexity, reliance on high-technology equipment, and the lack of systematic communication are the foremost factors that affect the rates of unintentional patient harm in the United States [1,2]. The operating room, a unique healthcare environment at the intersection of all of the above factors, is exceptionally prone to errors in care and patient harm, with 47.7–50.3% of all in-hospital adverse events occurring in the operating room [3].

The introduction of Robotic Surgery has changed the delivery of surgical care in the last decade [4]. By providing improved articulation, added magnification, and three-dimensional imagery, Robotic Surgery has provided surgical tools that, in some fields, have replaced traditional open and laparoscopic techniques. Although this increased sophistication may offer some advantages over conventional operative approaches, it is a significantly more complex system associated with higher costs, additional risks, and new challenges [5]. In addition to requiring the development of new psychomotor and hand-eye coordination skills, these activities also require distinct approaches to communication, teamwork, and the overall surgical process. Despite the use of highly trained, experienced operating room personnel, errors are multifactorial in origin, related to both the machines themselves and the machine-human interface [4,6]. Although not all errors lead to adverse events, observational studies have demonstrated that the accumulation of 'minor' events predisposes to 'major' events that have the potential for serious patient harm. This is potentially due to the fact that minor events decrease the team's capacity to deal with unexpected major events [6–8]. Understanding the distinct processes related to Robotic Surgery enables the development of training and standard practices that can increase patient safety, improve efficiency, and reduce costs [6].

Human Factors is the study of the relationship between people and systems. It can provide insights into the optimization of tasks, technology, environment, training, teamwork, and organization to provide safe and efficient care [9–11]. New technologies require new competencies related to technical skills, knowledge, teamwork, communication, training, and problem resolution. While simulation and training programs aim to reduce some of these challenges, they frequently do not capture the more complex aspects of care such as teamwork and communication, equipment reliability, or surgeon decision-making. Previous

studies in Cardiac, Orthopedic, Vascular, Trauma, and General Laparoscopic Surgery have successfully used direct observation to understand and address these often ‘hidden’ everyday challenges that reduce efficiency and safety [9–19].

Surgical Flow Disruptions (FDs) are defined as “deviations from the natural progression of an operation,” and can diagnose system weaknesses in teamwork, equipment, distractions, training, and resource availability [11]. Examples of FDs include when the attending surgeon, resident, or operating room staff cannot hear each other and have to repeat communications; the staff fails to retrieve a suture, instrument, or piece of equipment in a timely manner; or the attending surgeon stops operating to provide instruction to residents or staff. FDs have been empirically associated with surgical errors, adverse events, and inefficiency [6,11,20,21]. Understanding the etiology of FDs in Robotic Surgery will help to target training techniques and identify opportunities for improvement.

In this study, by observing Robotic Surgery cases, we sought to explore the deviations from the optimal progression of robotic operations. We investigated the effects of FDs, resident involvement, and other contextual parameters on operative duration, and explored the number and types of FDs with and without residents. Our first hypothesis was that the total number of FDs in Robotic Surgery cases would be affected by the presence of residents and the phase of the operation. Here, we leveraged the unique environment of our academic medical center with a mix of teaching and private (non-teaching) faculty. Our second hypothesis was that surgeon console time would be affected by procedure type, resident involvement, and the number of FDs. Overall, we aimed to identify barriers to efficiency and safety that could be overcome in order to deliver higher quality, more cost effective care.

Materials and Methods

We performed a prospective observational study of Robotic Surgery operations at one 900-bed tertiary care medical center, at which approximately 500 Robotic Surgery operations are conducted per year (50% Urology, 25% Gynecology, 15% Cardiac Surgery, and 10% General Surgery). An opportunity sample of Robotic Surgery operations was observed over a six-week period This protocol was approved by the Institutional Review Board (IRB) within the hospital at which this study was performed (Pro00028833). A waiver of informed consent was granted by the IRB provided that patient identifiers, patient demographic information, surgical outcomes, and operating room physician and staff identifiers were not collected.

The methodology for systematically categorizing and measuring surgical FDs used in this study has been previously developed and validated by Human Factors experts [11,21]. Specifically, an experienced Human Factors researcher trained two medical student researchers in the theory of Human Factors and in the observation of FDs. The researchers were also trained to understand the basic steps for each type of operation to be observed, and were familiarized with the surgical subspecialties, the operating room environment, and the operation of the robot by an expert Robotic Surgeon. The surgical teams were informed that researchers would be observing the cases in order to understand surgical processes, and were instructed not to interact with the researchers in order to reduce bias. Additionally, intra-

observer bias was minimized through the use of a standard data collection and classification method, practice, cross-observer comparisons, mutual and expert support, and ongoing feedback and discussion during training. The first ten Robotic Surgery cases observed were used to train the researchers and were eliminated from the final data analysis. Interclass correlation was calculated to ensure inter-rater reliability.

Robotic Surgery operations performed on the Da Vinci S and Si model robots were directly observed from the time the patient entered the operating room to the time the patient left the operating room. The researchers recorded each occurrence that appeared to disrupt the natural progression of the operation, as defined in prior studies [6,11,20], and made notes on each of these FDs. Additionally, the operative duration was divided into four phases: Phase 1: Pre-robot - patient entry into the operating room to abdominal insufflation; Phase 2: Robot docking - abdominal insufflation to surgeon on robot console; Phase 3: Surgeon console time - duration of main operation, including the entire time that the surgeon is on the robot console; and Phase 4: Robot undocking and closure - surgeon off console, robot undocking, closure of incisions, anesthesia end, and patient exit from the operating room. The times at which and the phase of the operation in which the FDs occurred were also recorded. The FDs were then classified into one of 11 different categories (Table 1). Surgeon console time, resident involvement, robot model, and procedure type were also recorded.

For all cases, the attending surgeons were experienced in Robotic Surgery, having performed >250 Robotic Surgery operations each prior to the start of this study [11], and were proficient in the types of operations observed in this study [11]. The residents involved had undergone institution-specific, standardized Robotic Surgery training prior to involvement in the operations. Although not specifically measured in this analysis, residents at our institution typically perform more Robotic Surgery cases and spend more time on the robot console with each additional year of residency training. Finally, the scrub technicians and the circulators had been trained in Robotic Surgery, and were very familiar with all of the surgeons and other team members in all cases observed.

Power calculations were based on a prior observational study of FDs in Robotic Surgery performed at our institution [11]. In this study, training cases demonstrated a mean FD rate of 10.5 FDs/hour, and non-training cases demonstrated a mean FD rate of 8.5 FDs/hour. Observation of at least 6 cases with residents present and 6 cases without residents present provided 80% power at α=0.05.

We analyzed operative duration, FDs, and FD rates (number of FDs/operative duration) separately. Student's T-tests were used to compare the type of operation, and a linear regression model was used to evaluate the overall effects..

Results

(i) Overall Results

Twenty-one prostatectomies, 8 sacrocolpopexies, and 3 nephrectomies were observed, with a total of 146 hours and 52 minutes of observation time. The Da Vinci S model robot was used in 14 cases, and the Da Vinci Si model robot was used in 18 cases. Nineteen cases involved

residents, and 13 cases did not. Interclass correlation between the two observers was 0.894. A total of 1542 FDs were recorded. Average operative duration was 275 minutes (95% CI 257–293 minutes), and mean surgeon console time was 163 minutes (95% CI 148–179 minutes). The mean total number of FDs per case was 48.2 (95% CI 38.6–54.8 FDs), and the mean FD rate was 10.4 FDs/hour (95% CI 8.55–12.31 FDs/hour). The most frequently observed FDs were Training, Equipment, and Instrument Changes.

(ii) Effects of Procedure Type and Phase of Operation

The mean durations for the procedures were: 283 minutes for prostatectomies (95% CI 258–307 minutes); 275 minutes for sacrocolpopexies (95% CI 250–301 minutes); and 221 minutes for nephrectomies (95% CI 197–245 minutes). The mean total number of FDs was 45.3 for prostatectomies (95% CI 32.4–58.2 FDs), 61.9 for sacrocolpopexies (95% CI 49.2–74.6 FDs), and 31.7 for nephrectomies (95% CI 0–64.3 FDs). The mean FD rate was 9.5 FDs/hour for prostatectomies (95% CI 7.2–11.9 FDs/hour), 13.4 FDs/hour for sacrocolpopexies (95% CI 11.3–15.4 FDs/hour), and 8.9 FDs/hour for nephrectomies (95% CI 0–18.5 FDs/hour). Figure 1 displays a further breakdown of this data across the four operative phases.

Figure 2 displays the distribution of FD types across the four operative phases, illustrating the changes in the task demands in each stage of the operation. Phase 1 is dominated by Coordination FDs, reflecting the challenges of ensuring that all of the instruments, supplies, and personnel are appropriately prepared for the operation. Phase 2 consists mostly of Equipment FDs, which demonstrates the challenges of robot docking. Phase 3 is mostly composed of Equipment and Training FDs, which likely relates to the demands of performing the main operation. This pattern of FDs is similar in Phase 4 as well. Of all of the operative phases, Phase 3 was the longest in duration, contained the most FDs, and had the highest FD rate.

In Figure 3, the FD types are broken down by the procedure type. Equipment, Coordination, and External Factors FD types also varied by procedure type, reflecting the varying demand of different procedure types. Training FDs also vary across procedures, though this in part reflects a sampling issue (residents were involved in all sacrocolpopexies, but no nephrectomies).

(iii) Effect of Resident Involvement

The mean total number of FDs was 60.8 with resident involvement (95% CI 47.8–73.8 FDs) and 29.8 without resident involvement (95% CI 22.1–37.4 FDs) ($p=0.0012$). The mean FD rate was 12.7 FDs/hour with resident involvement (95% CI 10.4–15.2 FDs/hour) and 7.0 FDs/hour without resident involvement (95% CI 4.4–9.3 FDs/hour). The mean operative duration was 285 minutes with resident involvement (95% CI 263–306 minutes), and 260 minutes without resident involvement (95% CI 229–291 minutes).

Given that residents were present in all sacrocolpopexies and were not present in any nephrectomies, our analysis of operative phase duration and FD types related to resident involvement focused on prostatectomies alone. Phase 2 was significantly longer with a resident present ($t=2.1$, $df=18$, $p=0.026$). Resident involvement did not significantly affect

the duration of any other operative phases. In cases with resident involvement, Phase 3 had significantly more FDs (t=2.9, df = 11, p=0.008) and a significantly greater FD rate (t=2.9, df = 12, p=0.006). Within Phase 3, cases in which residents were present had significantly more Communication (t=1.8, df = 16, p=0.0455), Training (t=8.25, df = 10.2, p<0.0001) and Robot Switch (t=6.1, df= 10.1, p<0.0001) FDs, but had significantly fewer Instrument Changes (t=−1.9, df=13.9, p=0.037), and Environment (t=−1.8, df= 19.7, p=0.0425) FDs than cases in which residents were not present. These differences can be seen in Figure 4. No other effects were found on phase duration, total number of FDs, or FD rates that were attributable to residents.

(iv) Surgeon Console Time and Resident Involvement

To understand the effect of resident involvement on FDs and operative duration specifically during the main portion of the operation (Phase 3), we evaluated the durations of time that attending surgeons and residents were on the robot console during prostatectomy and sacrocolpopexy teaching cases. On average, attending surgeons spent 107 minutes (95% CI 88–125 minutes) on the robot console, which was approximately twice as much time as residents (Mean 59 minutes, 95% CI 48–69 minutes). This amounted to residents spending an average of 36% of Phase 3 duration on the console (95% CI 30–43%).

Both residents and attending surgeons encountered a similar number of FDs during Phase 3, with attending surgeons experiencing 22.3 FDs during Phase 3 (95% CI 13.3–31.2 FDs), and residents experiencing 20.3 FDs during Phase 3 (95% CI 16.4–24.1 FDs). However, due to the shorter duration of resident console time, FD rates were approximately doubled for residents (Mean 21.7 FDs/hour, 95% CI 17.7–25.7 FDs/hour) as compared to attending surgeons (Mean 11.4 FDs/hour, 95% CI 8.6–14.2 FDs/hour). The mean number of Robot Switch FDs per operation was 6.9 (Range 2–18 FDs, 95% CI 5.1–8.7 FDs). Aside from Robot Switch FDs, the difference in the total number of FDs arose almost entirely from Training FDs, with attending surgeons experiencing 3.1 Training FDs/hour (95% CI 2.1–4.0 FDs/hour) and residents experiencing 14.7 Training FDs/hour (95% CI 11.8–17.7 FDs/hour).

(v) Model of Overall Effects of FDs on Operative Duration

Finally, we sought to explore the overall effect of FDs and training on surgical efficiency. We modeled the effects of resident involvement, and FDs on total operative duration and Phase 3 duration for prostatectomy cases in linear regressions.

For total operative duration (r^2=0.28), each FD added 2.4 minutes (t=2.5, p=0.025), with no significant effect due to resident involvement. Phase 3 duration (r^2=0.25) was significantly affected by Phase 3 FDs, each of which added 2.0 minutes (t=2.4, p=0.028). A trend towards decreased Phase 3 duration with resident involvement was observed, however this did not approach statistical significance (t=−1.9, p=0.071).

Discussion

This study quantifies the effect of resident involvement on the process of Robotic Surgery operations, as measured by FDs, and subsequently quantifies their effect on operative

duration. Exploring FDs, FD rates, and operative duration in this manner aids in understanding barriers to safe and efficient surgical care in Robotic Surgery. Additionally, these results constitute an important step in understanding how to train robotic surgeons. The finding that the majority of FDs in cases with resident involvement were Training FDs is likely not surprising. Cases with resident involvement also contained more Communication FDs, possibly due to the increased numbers of operating room personnel. However, the presence of residents did not significantly increase operative duration; in fact, the regression analysis demonstrated that there was a trend towards decreased operative duration with resident involvement. This, combined with the finding that FDs themselves were significantly associated with increased operative duration, is an indication that not all FD types have the same effect on the flow of the operation. Residents may facilitate the progression of operations by offering assistance, despite pauses to offer instruction. Additional studies classifying the clinical impact of each type of FD and improving the multi-variable statistical models could predict where to target quality improvement or training initiatives.

This is a partial replication of our previous observational studies of Robotic Surgery [11]. In this study, we specifically focused on the role of resident involvement in the flow of Robotic Surgery operations. Only cases in which residents had undergone institution-specific, standardized Robotic Surgery training were evaluated, as opposed to our prior study in which both residents and fellows with varying levels of Robotic Surgery training were included. The differences in the results between our current study and our prior study, which found that training cases were associated with a significantly increased operative duration, could signify the importance of standardized training for Robotic Surgery at the resident level. Additionally, although there have been some attempts to structure the learning processes required to convert residents into expert robotic surgeons, there are still many opportunities to improve these processes, both within and outside of the operating room.

The main operative procedure (Phase 3) contained a significantly higher number and rate of FDs across all procedure types. Additionally, similar to previous studies, we also found that Equipment, Coordination, and External Factors are frequent causes of FDs, and also contributed to surgical delays across all procedure types [6,11]. Demands changed across the various operative phases. Sacrocolpopexies experienced significantly more FDs in the Robot docking (Phase 2) and the Robot undocking and closure (Phase 4) phases, and nephrectomies experienced significantly fewer FDs in the Pre-robot (Phase 1) phase. Although the small sample size may have created bias, these data lend credence to the idea that surgeons and operating room staff may be more familiar with docking and undocking procedures in nephrectomies and prostatectomies rather than sacrocolpopexies, or that differences in anesthesia and patient positioning between the procedure types affects the flow of these operations. Moreover, sacrocolpopexies often included additional non-robotic procedures, such as sling placement for stress incontinence, which could possibly account for increased operative duration and increased equipment and staffing needs.

These data are useful for guiding interventions to improve the efficiency of Robotic Surgery, and can act as a baseline for the evaluation of future interventions. A range of solutions that have been deployed in similar studies might be employed to address the FDs found in our

study. For example, teamwork training or pre-operative briefings can reduce Coordination FDs, and improved equipment design or the regular use of appropriate instrument maintenance, such as warming the camera to avoid camera fogging, can help reduce Equipment FDs. Checklists, are often overused as a 'go-to' solution, but with careful development, they may be particularly useful for technology management [22]. Since Robotic Surgery changes not only the surgical skills required for an operation, but also the communication, teamwork, operative process, operating room staff skill requirements, instrument and supply management, and even the necessary room size, successful solutions will need to be reconfigured specifically for Robotic Surgery. For example, one of our consistent observations is that changing the robotic instruments requires improved coordination and communication with the resident, scrub technician, and circulator, as the surgeon is sitting at the robot console and not standing directly at the operating room table. If adequate coordination and communication do not exist, FDs and operative delays increase. Future analyses will include sub-classifications of the most frequent FD types in order to target specific interventions in Robotic Surgery.

The direct observation of FDs is becoming an increasingly useful methodology for understanding the everyday challenges associated with delivering care in a range of operations and other acute environments. However, this approach suffers from a number of limitations as well. Firstly, we were reliant on the skill of the observers, and while considerable efforts were taken to ensure inter-rater reliability, the observations were nonetheless prone to some bias. Neither of the two observers were experienced surgeons or Human Factors experts, and hence, they may have failed to recognize certain surgical deviations that experts may have detected. Nevertheless, we have found this method generally effective, and even if some of the more technical details may have been missed, we have found that clinically-naïve observers are actually more sensitive to significant process deviations.

In the current study, the opportunity sample created imbalances in the data, especially with the low number of nephrectomies observed and the nesting of some training cases within specific procedure types (i.e. no nephrectomies involved residents, while all sacrocolpopexies involved residents). Although the sample size is large in comparison to similar observational studies [23,24], and we believe that we controlled for procedure type as much as possible in our analysis and statistics, our conclusions were nevertheless limited. Follow-up studies will seek a more structured selection of cases in order to decrease this bias.

Though the general consensus in observational studies of surgery is that the observers have little effect, it nevertheless remains a concern. The overall numbers and rates of FDs may, in reality, be higher than observed in this study, even though the surgical teams were asked not to interact with the observers, and the observers themselves were largely unobtrusive. Still, as compared to retrospective studies, which are prone to hindsight bias and can only detect rare adverse events, the benefit of such prospective, observational studies in allowing the study of intra-operative near misses, team performance, and other more frequent, but subtle, intra-operative events is realized. In this study, we did not collect outcomes data, thus we could not compare the effect of FDs or operative duration to patient outcomes.

Although this study was performed at a single institution, a number of other studies at various institutions have demonstrated similar types of FDs, regardless of the type of surgery observed [9–19]. Such observational studies allow for a systematic, quantitative, and replicable assessment of the surgical process and environment. The numbers and rates of FDs at our institution can be used as benchmarks for the delivery of Robotic Surgery, both within the institution and as a comparison to other institutions. Finally, the data from this study should be used to guide the development of interventions to improve efficiency in Robotic Surgery, which can then be disseminated to other institutions.

Conclusions

Through the observation of 32 Robotic Surgery cases, we were able to model the effects of resident involvement and procedure type on the surgical process and operative duration. Our data demonstrate that FDs significantly increased operative duration. Additionally, we found that cases with resident involvement featured a considerable number of FDs, but were not significantly longer. Exploring and minimizing Equipment, Coordination, and External Factor FDs may yield a more efficient operative process for Robotic Surgery cases. Our data also present opportunities to improve teaching within and outside of the operating room for both residents and operating room staff.

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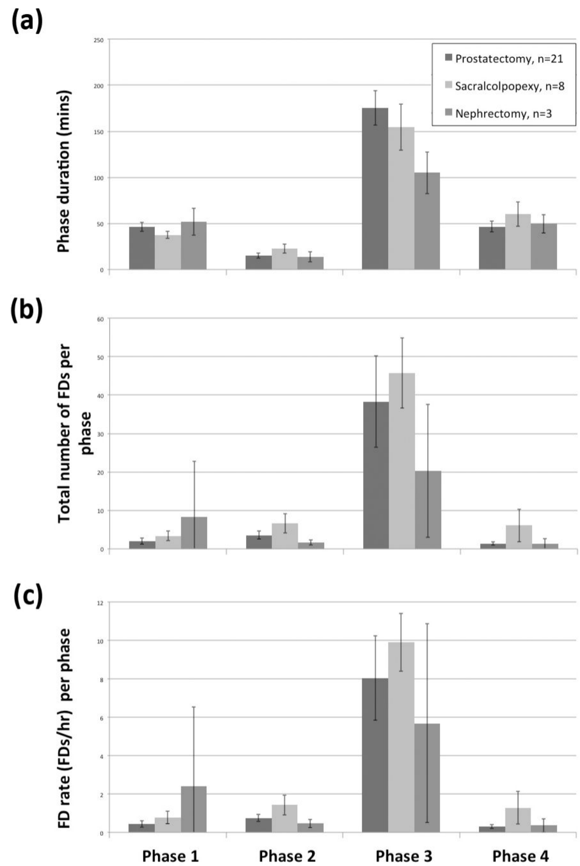

Figure 1. Duration, Flow Disruptions, and Flow Disruption rates by operative phase and procedure type

a) Average duration (minutes) of each phase. b) Average number of flow disruptions. c) Flow disruption rates. Error bars show 95% Confidence intervals. (Phase 1 - Pre-robot, Phase 2 - Robot docking, Phase 3 - Surgeon console time, Phase 4 - Robot undocking and closure).

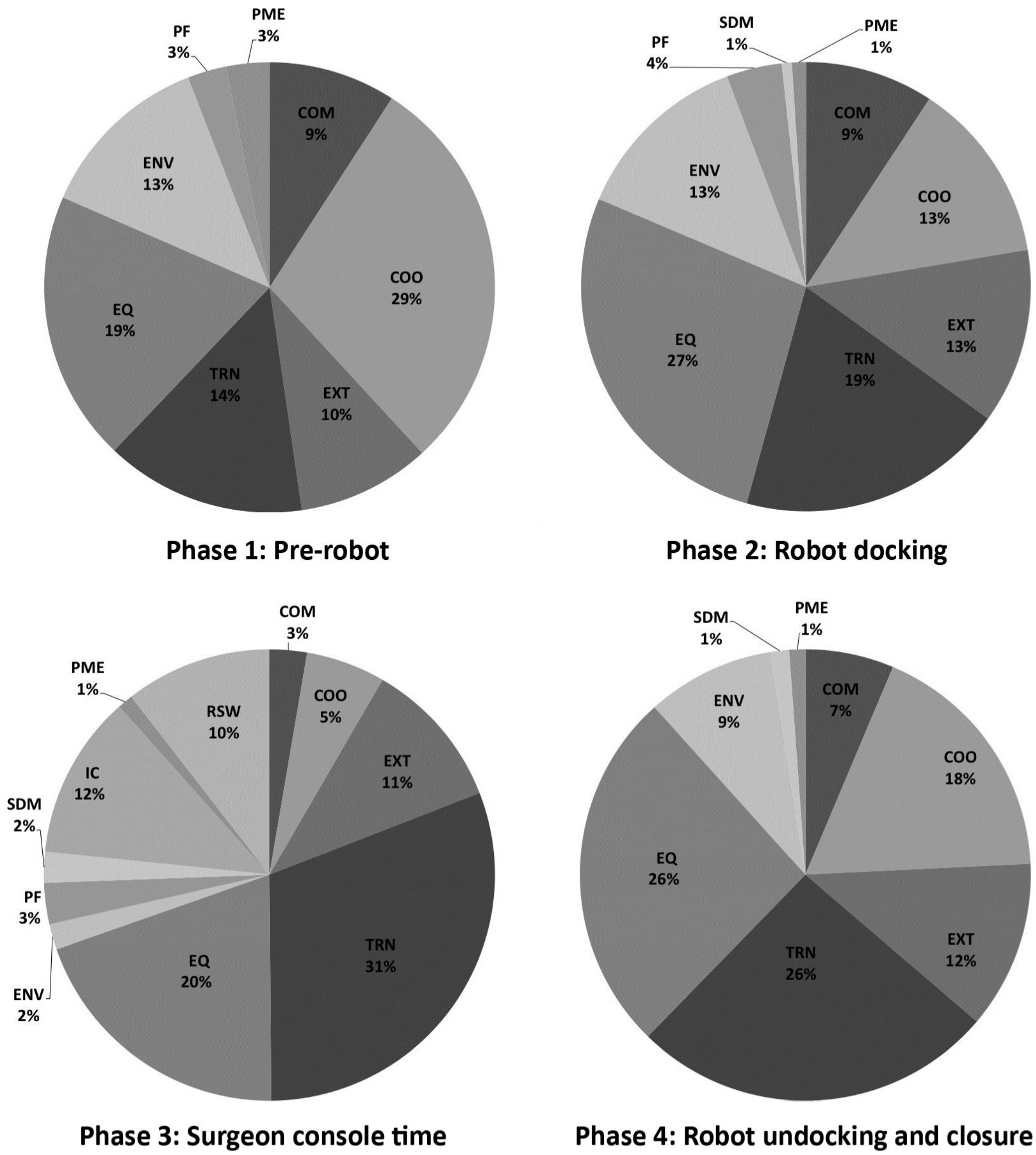

Figure 2. Flow Disruption types by operative phase

The relative distribution of FD types across the four phases of the operation. FD type abbreviations: COM=Communication; COO=Coordination; EXT=External Factors; TRN=Training; EQ=Equipment; ENV=Environment; PF=Patient Factors; SDM=Surgeon Decision Making; IC=Instrument Changes; PSM=Psychomotor Error; RSW=Robot Switch.

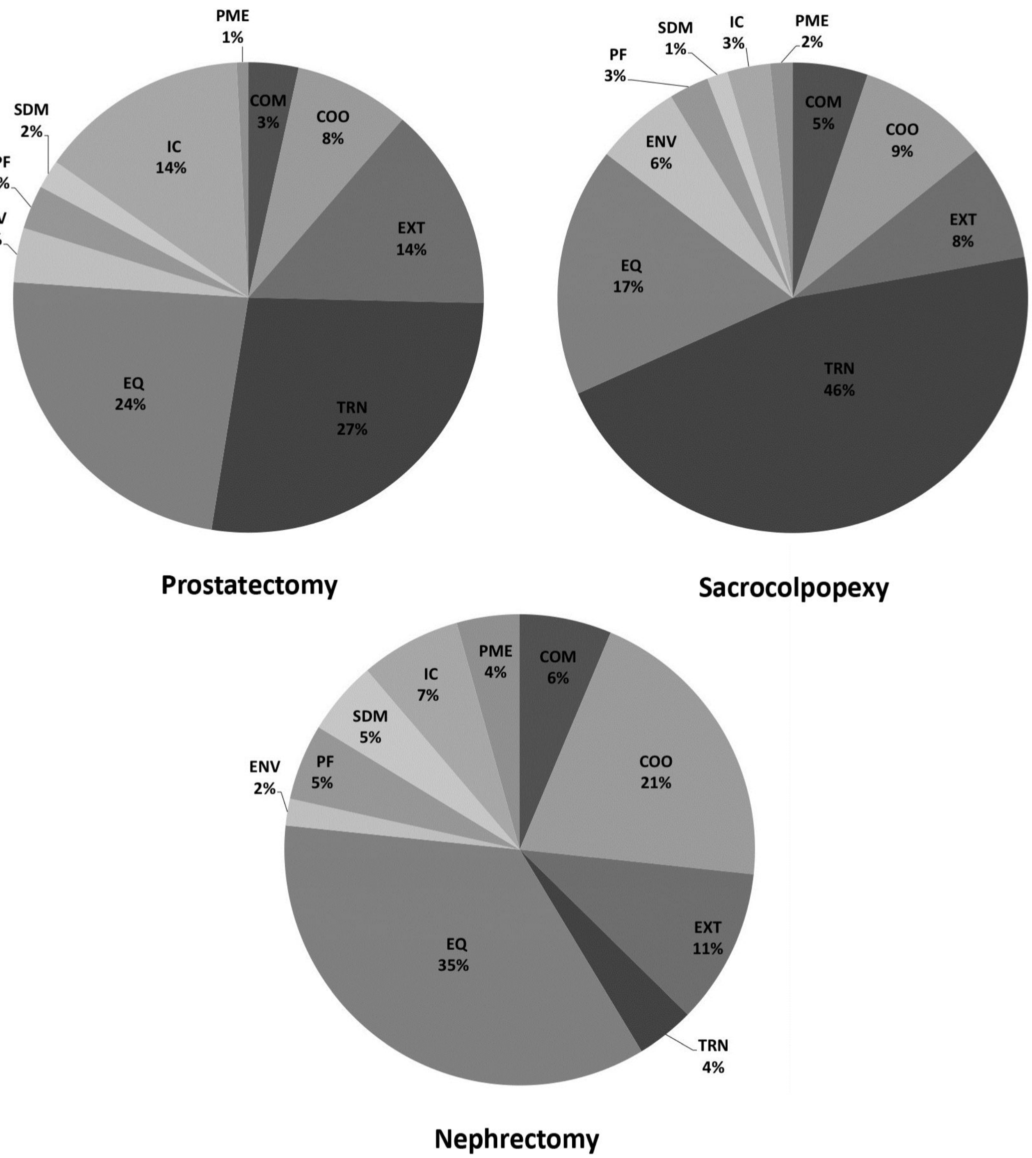

Figure 3. Flow disruption types by procedure type

The relative distribution of FD types across the surgical types. FD type abbreviations: COM=communication; COO=coordination; EXT=external factors; TRN=training; EQ=equipment; ENV=environment; PF=patient factors; SDM=surgeon decision making; IC=instrument changes; PSM=psychomotor error; RSW=robot switch.

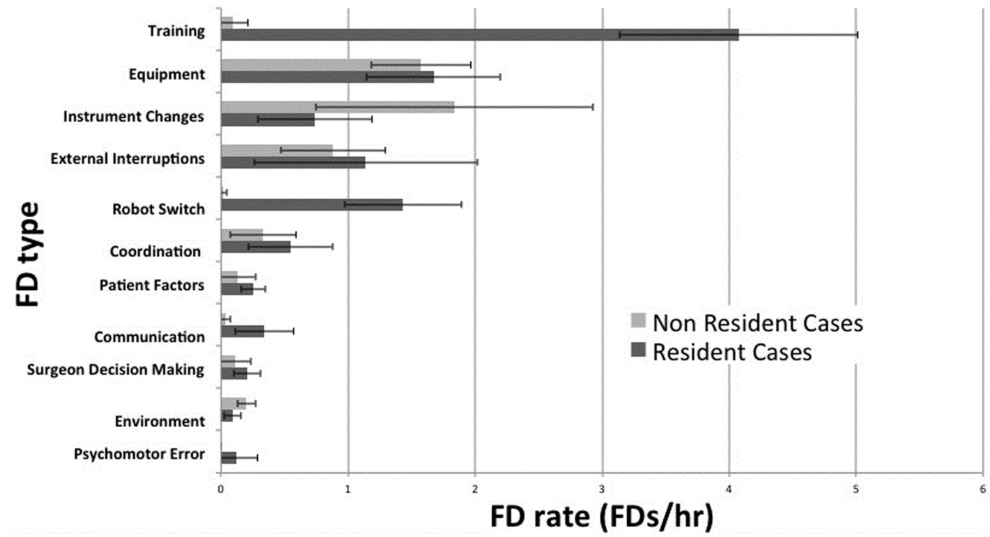

Figure 4. Flow Disruption Rates by type, with and without resident involvement during the prostatectomy surgical intervention phase

A focused evaluation of surgeon console time of 21 prostatectomy cases demonstrating the frequency of the different types of flow disruptions in training and non-training cases. Error bars represent 95% confidence intervals.

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Table 1

Flow Disruption types and definitions.

Categories	Definitions
Communication (COM)	Any miscommunication that impacts surgery progress
Coordination (COO)	Any lapse in teamwork to prepare for/conduct surgery that affects surgery flow
External Factors (EXT)	Any interruption that is not relevant to the current case or surgery
Training (TRN)	Any instruction by the attending surgeon to fellows, residents, or medical students
Equipment (EQ)	Any equipment issue that affects surgery progress
Environment (ENV)	Any room conditions that impact surgery progress
Patient Factors (PF)	Any patient characteristic that impedes efficient surgery progress
Surgeon Decision Making (SDM)	Any surgeon pause to determine next surgical step
Instrument Changes (IC)	Any changes in robotic instruments during surgery
Psychomotor Error (PME)	Any human error by attending or resident
Robot Switch (RSW)	Any switch in controls on the console