Sensing (Co)operations: Articulation and Compensation in the Robotic Operating Room

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Drawing on ethnographic fieldwork in two different teaching hospitals that deployed the da Vinci surgical robot, this paper traces how the introduction of robotics reconfigures the sensory environment of surgery and how surgeons and their teams recalibrate their work in response. We explore the entangled and mutually supportive nature of sensing within and between individual actors and the broader world of people and things (with emphasis on vision and touch) and illustrate how such inter-sensory dependencies are challenged and sometimes extended under the conditions of robotic surgery. We illustrate how sensory (re)articulations and compensations allow the surgeon and surgical teams to adapt to a more-than-human sensorium and conclude by advocating new forms of sensory-aware design capable of enhancing and supporting embodied sensory conditions both individually and across teams.

CCS Concepts: • **Human-centered computing → Computer supported cooperative work; Empirical studies in collaborative and social computing;** *Collaborative and social computing theory, concepts and paradigms;*

AUTHOR KEYWORDS

Sensing; teleoperation; distributed teamwork; robotic surgery; collaboration

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1 INTRODUCTION

For over 15 years, surgical robots such as the da Vinci by Intuitive Surgical, Inc. have been utilized for minimally invasive surgery across a growing number of surgical specialties [72]. Robotic technologies such as the da Vinci developed in part from Defense Advanced Research Projects Agency (DARPA) projects, which sought to remove the surgeon's body from the battlefield by deploying a remote-controlled robot in her place [23]. The da Vinci entered the commercial marketplace in the early 2000s, building on and sometimes replacing

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earlier laparoscopic (keyhole) techniques in which surgeons operate by manipulating long sticks passed through small incisions in the patient's body. Robotic surgery technique is considered by some to be a "great equalizer" between surgeons who have mastered the highly skilled laparoscopic technique and those who perform open technique [56]. During laparoscopic practice the surgeon is "half in the information world and half in the real world" [67:129] as the surgeon's body is partially distanced from the operative site. The da Vinci's new ensemble of computational and robotic technologies increases this distance by completely removing the surgeon from the bedside. In these contemporary robotic surgeries, surgeons and assistants sit at consoles often placed in the far corner of the operating room (OR). From their location, they access the patient not with their hands but remotely, by peering into eye pieces that render the surgical site in magnified and three-dimensional form while manipulating the arms of the patient-side robot via joysticks. In such a configuration, surgeons are simultaneously immersed in and distanced from the surgical field [57] and must rely on vision as their primary sensory modality. This represents one step further into the "information world" of surgery, as surgeons (and wider teams) come to depend more on visual signal and less on sensory flows tied to tactile, aural, and embodied experience.

These experiences of sensory loss and displacement have been accompanied however by novel acts of sensory compensation and (re)articulation, at both the individual and team level, as the essentially collaborative nature of surgical work accommodates and responds to changes in the sensory environment. *Sensory compensations* allow for the continuation of embodied and collaborative work (such as surgery) when conditions of the sensorium, or the entire sensory condition as a whole [51], are in flux or imbalance. This work is performed by and across both individuals and wider surgical teams and setups. As certain sensory modalities are vacated or reduced, others are intensified and reworked – or as Ralph Waldo Emerson's classic essay *Compensation* reads, "To empty here, you must condense there" [22:97]. At the same time, new processes of *sensory articulation* emerge – defined by Latour [40] as a focused and deepening sensorial awareness or knowledge that opens the individual to the complexities of the world – as robotic surgeons and their teams learn to see and navigate the patient body anew through (re)engineered forms of human-robot sight. Both of these techniques surface within and are impacted by existing social relationships within the operating room, changing both relations among the team and the organization of work.

Drawing on observations and interviews occurring over a 14-month period of ethnographic fieldwork in operating rooms and related work in Computer Supported Cooperative Work (CSCW), sensory anthropology, media studies, and Science and Technology Studies (STS), we explore the complex ways both surgeons and surgical teams have responded to restore and reinvent the collaborative nature of surgical work under the shifting sensory landscape of robotic surgery. We open by describing the ways in which existing forms of surgical care have absorbed and adapted to robotic technologies that supplant and/or extend human sensing. We then examine how surgeons re-articulate notions of sensing as mediated through robotic machines – and compensate for lost or missing sensory modalities (primarily touch), and seek new more-than-human senses that restore their connection to the patient body. We then demonstrate the reconfiguration of surgical teams in ways that enable them to share pertinent sensory information that would otherwise go unheard, untouched, or un-sensed; here we pay special attention to how these new sensory relations and correspondences operate as a form of consensus that must either fit within existing social hierarchies of the team or motivate a reorganization of social relations. Finally we conclude with broader findings surrounding human sensing and recommendations for the design and deployment of robotic tools that acknowledge, encompass, and attend to the complex, collaborative, and embodied practices that comprise sensory enactments in robotic teams.

2 GATHERING THE SENSES

In 1971, the embodied navigational skills of Hipour, a Pacific Island seafarer, were documented by anthropologist David Lewis [41] as the two crossed over 500 miles of ocean without the use of the available sailing technologies of the day. During their week at sea, Hipour's use of tacit and embodied knowledges and sensory cues, emanating from the apparently track-less ocean, informed his understanding of place and direction, ultimately guiding their journey towards a distant island. Lewis explained Hipour's wayfaring techniques: how he positioned his body in relation to the stars and navigated with outstretched arm and hand as a visual tool; how he listened for different species of birds through the fog, using their cries to help judge distance from the various islands they inhabited; how his body felt the crests, patterns, and currents of the waves to gauge proximity to near and distant lands. Hipour the navigator had no notion of the imaginary lines of latitude and longitude and paid no heed to the imaginary boundaries that had been erected by imperial powers generations before; nor could he make out the written marks of language. Yet using his embodied and entangled senses of self, place, and environment – the feel of the waves, the alignment of the stars, the calls of the birds – he drew a rich sensory map and navigated across it. In the words of contemporary Fijian writer and anthropologist Epeli Hau'ofa, a seafarer like Hipour embodied the nature of the sea by *becoming the ocean* [29].

This relation between sensing, embodiment, and worldly knowledge has been a long-standing concern of twentieth-century anthropology. Working against presumptions of the universalism and self-evidence of the senses (roughly, that sensory experience is in principle everywhere the same and 'speaks for itself'), foundational work by Claude Levi-Strauss [42], Marcel Mauss [43] and Walter Ong [54] has mapped the relationship between sensory experience and the organization of culture, showing how uniquely-situated and historical sensory practices are embedded in wider cultural forms and 'ways of seeing' – and conversely, how different cultural formations afford different kinds and possibilities of sensory experience. Levi-Strauss (1969) for example argued that early acts of scientific and cultural production were intimately entwined with sensory perceptions and that the ordering of the senses was both unique and variable across different civilizations [74]. Mauss (1973) studied the physicality of embodied movements across the globe, finding that kinesthetic "techniques of the body" (as well as other forms of sensing) are learned behaviors uniquely developed across culture, time, and place [43]. Ong (1982) argued that the sensorium (understood as an "operational complex" comprised of the entire sensory apparatus) functioned as a useful method for distinguishing and deciphering cultures and could be understood in terms of distinct "sensorial ratios" that were reorganized as needed to prevent "abundant and overwhelming" sensual experiences [54].

Even as classic anthropologists sought to reimagine sensing and embodied knowledge within the flux of social and cultural life, other approaches to sensing remained grounded in more foundational philosophical systems that had been in place since the ancient texts of Plato and Aristotle compartmentalized and ranked sensing into the five unique modalities of vision, hearing, touch, taste, and smell [37]. In response, more recent work in sensory anthropology has sought to reimagine sensing outside of these limitations, pushing against what Rodaway [66] has described as a reductive "hyper-realization" of sensing that separates, simplifies, and ranks sensory experience into discrete sensory modalities. In a similar vein, Classen [18], along with discourses of sensory psychology, envision the human sensorium to include many more than the "big five" senses listed above, extending sensing to include over 30 distinct sensory modalities that range from proprioception – the sense of one's body in space – to the sensing of temperatures, of pressure on one's body, of the uncanny, and of being looked at. In addition, theories of 'amodal sensing' have been developed by sensory psychologists to include sensory information that is not specific to a particular modality but is foundational to all, such as rhythm, duration, intensity, and synchrony [7]. This has led scholars like Sarah Pink and David Howe [58] to theorize an interconnected sensorium in which the senses appear as entangled and emergent complexes, rather than as unique "receptors" that move along separate channels of perception. Ingold, drawing on the work of Gibson, has built on the same body of work to emphasize an active and practically embedded conception of sensing that is deeply connected to a body that is "…continually on the move, actively exploring the environment in the practical pursuit of its life in the world." [31:261]. Other scholars have extended the emphasis on embodiment to focus on the undervalued modality of hands and handwork within the sensory hierarchy of contemporary work practices. Prentice's [60] study of surgeons and surgical work with both simulated (computational) and physical patient bodies, for example, decenters the role vision plays in the formation of surgical knowledge, finding that knowledge of patient anatomy resides tacitly within the surgeon's hand, bodily actions, and maneuvers. Sennett [70] and Crawford [20] have each emphasized the value of hands, touch, and tactility in the anchoring of contemporary work practices and the wider forms of meaning and human value these support and give rise to.

In a similar way, recent work in STS has explored the essential relationship of sensing to knowledge, including in complex, distributed, and technologically-mediated environments. Vertesi's [73] study of the visual information practices of the Mars Rover and its associated human teams found that coordinating visual meanings across distributed people and things (including between planets) was influenced both by the social politics of the engineering team at work, their consensus-building techniques, and their learned ability to communicate with one another, including via the mechanism of embodying the rover itself. In separate studies of soil scientists [26] and oceanographic research vessels [27], Goodwin emphasized the learned and collaborative nature of sensory experience, showing how seemingly 'raw' sensory inputs are apprehended and internalized through tools and disciplinary conventions – whether the mechanism of the Munsell color chart, or the intricacies of field-specific knowledge and technique that give vastly different views of the same "space." In Latour's [40] study of perfumists (or "noses"), bodies that are learning to be affected by the world (through identifying certain smells in finer and finer detail) are becoming *articulated* bodies that must come to terms with the world's deepening complexities as they appear through finer and finer sensibilities. This gives rise to an increasingly cultivated and fine-grained set of sensory distinctions that explode rather than collapse the sensory experience of the world (for the appropriately skilled and trained practitioner); or as Latour argues, "the more you learn…, the more difference exists" [40: 213]. Sensing, like data [10, 24] is never raw.

But if sensing is learned, collaborative, and embodied, it is also – as work in STS and media studies has long held – *mediated.* Understanding mediated forms of sensing through bodily interactions with tools and media – whether scalpels or images on the screen – has been central to the work of media theorists since McLuhan classically (re)defined media as "extensions of man" [47] capable of igniting a "recalibration" of the human sensorium. More contemporary media theory argues that media extend the senses by reaching outward from the body while also turning inwards, connecting to human propensities such as the desire and ability to reach, grasp, or use tools [44]. This makes sensing itself a kind of emergent relationship or collaboration between self (or selves) and world, and one that leaves neither side untouched. For this reason, as Mark Cote has argued, there is "…no *a priori* or *natural* configuration of the human sensorium in the way that McLuhan suggested, rather, sensory perception has only ever (and always) calibrated in relation to the material world" [19:1].

Such insights have begun to bump up against recent efforts in robotics and allied fields, which increasingly seek to understand and design for the shifting sensory environments that accompany the development of new computational tools in workplace and other environments. Emerging work from engineering and related communities has explored aspects of technologically-mediated sensing, often approaching the senses as separate and distinct modalities to be augmented or supported with new computational devices [21, 4]. As applied to surgical settings, efforts at sensory enhancement and new tool development have often followed from and contributed to a kind of double compartmentalization: first, the isolation and frequent prioritization of one sense over another; and second, the isolation and privileging of one sensory vantage point over others (in the case of surgery considered here, typically that of the surgeon) [52, 53, 3].

Such efforts run against the essentially collaborative nature of team- or group-centered activities – and many of the core findings of CSCW and allied fields. A large body of work in this area has begun to consider and design around the lack of specific sensory modalities when interacting across distance [11, 50, 48, 69, 55]. Other work [35, 16] has explored the experiences of loss and recalibration associated with sensory change in collaborative work environments (such as ecological research and fine art furniture production) and its effects on senses of professional identity and vocation [35] and the process and attributions of creativity within teams [15]. Still other threads, including design-oriented inquiries, have begun to explore "hybrid" forms of human/machine sensing [14,49].

Within the surgical context considered here, Mentis et al have studied the sophisticated ways that surgical actors learn to "see" their patients through mediated images in minimally invasive surgery [46]; and the negotiations through which shared visual and sensory meanings are constructed within wider surgical teams [45]. Koschman et al [39] have discussed surgical sensing as *procedure work* or work that requires all parties (and at all points) to coordinate shared understandings of what is occurring. An important series of papers by Randell et al [61, 62, 63, 64] has explored the *communicative* nature of surgical work, showing how robotic surgeons come to rely more heavily on communications from their team in order to achieve situational awareness of patient status, supporting (and indeed necessitating) more collaborative models of decision making. These findings are echoed by other recent studies of the robotic OR [3, 17, 2], which find that robotic operating teams must learn new methods of communication that are "…verbal, systematic and safe," and that surgeons learn to rely more on verbal exchanges with the team to mitigate the loss of haptic access to the body and visual access to the team [6]. Tiferes [72] and Catchpole [16] point towards the importance of body gesture and non-verbal communication within and across robotic teams, calling attention to variations of interaction and the idea that such interactions rely on explicit team training.

Read together, this work suggests an important split between how sensing in collaborative and technologically-mediated work environments like robotic surgery has been conceptualized and approached: on the one hand, in a compartmentalized, single-sense way, often centered on the experiences of a central user/knower (here, the surgeon); on the other, in a more distributed or collaborative way that takes account of wider shifts in the (multi)sensory environment as experienced, navigated, and worked through by teams as a whole. Our work falls for the most part in this second category and builds on many of the findings and core recognitions above. First, it reveals how understandings of the material and sensual qualities of the world (here, the surgical environment) stem from the body and interdependent and interconnected sensory modalities within it. Second, it shows that sensing is not limited to the self but is shared and entangled across complex worlds of people and things; put differently, that sensing is a collaborative accomplishment. Last, it suggests that technological devices have a profound capacity to reorder the sensorium in both its individually experienced and collectively shared forms, leading to new and often partial (re)articulations of the world and the forms of collective practice (here, surgery) built around it.

In the sections below, we discuss findings stemming from the robotic OR as they relate to notions of sensing with and through machines. We chart new collaborative forms and challenges that have grown up in the shifting sensory environments of robotic surgery (including in the crucial relation between vision and touch). And we describe the crucial work of compensation and (re)articulation by which shifts and losses in the collaborative sensory environment are absorbed, remediated, and made whole.

3 RESEARCH SETTING, DATA COLLECTION, AND ANALYSIS

Over a period of 14 months, the research team carried out ethnographic fieldwork at two teaching and research hospitals in the United States. We shadowed abdominal surgeries with two surgeons in a large medical center (H1) and gynecologic surgeries with one surgeon in a medium-sized community hospital (H2). In total, we observed 31 surgeries (16 robotic, 15 nonrobotic) and wrote detailed ethnographic fieldnotes for each. Twelve of these (7 robotic, 5 open) were videotaped by placing four cameras within the OR. During observations, we stayed with the nurses, entering the operating room as preparation for surgery started and leaving after the room had been cleaned at the end of the surgery. We conducted semi-structured interviews organized around different roles of the surgical team, benefits and challenges of working with the robot, and reported changes to the sensorial environment experienced through surgical action. Interviews took place with 6 surgeons, 3 residents, 1 intern, 1 student, 4 first assistants, 7 scrub techs, 6 circulators, 1 charge nurse involved in scheduling and distribution of resources, a human factors expert at the FDA who was involved in granting approval for the Da Vinci Surgical System, as well as 2 representatives of the robot's manufacturer *Intuitive Surgical, Inc.* Fifteen of these were hour-long formal interviews conducted via teleconferencing tools or via the telephone. Due to the specific working conditions and preferences of some participants, we conducted 18 interviews in the field, interspersing questions with the participants' work routine and recording them on video and/or in the fieldnotes. Nurses were often reluctant to schedule a formal interview outside their working hours but engaged with our questions while they prepared the room, waited for the patient to arrive, or during quieter moments of the procedure. All interviews were transcribed and then coded following grounded theory principles [25]; key terms or phrases related to sensing and the sensorium emerged as prominent themes in our preliminary ('open') coding and were then used to guide subsequent observations and interviews.

We selected the surgical specialties (abdominal and gynecologic) due to their relatively mature and stable use of the Da Vinci Surgical System, which was approved for these domains by the US Food and Drug Administration (FDA) more than a decade ago. This enabled us to focus our inquiry on surgical practices that have achieved some measure of standardization and ordinary (as opposed to experimental) practice – though as we quickly discovered, no two surgeries (as no two bodies) are ever truly alike. Following the insights of Strauss [71] and Becker [9], that social activities (from healthcare to art) are organized and upheld within "social worlds" that extend well beyond 'star performers' and local sites of practice, our conception of surgery extends not just to the immediate team engaged in the mechanical act of surgery but the larger network and worlds in which surgical sensing, care, and meaning unfolds. Both acts of teaching (or apprenticeship) and wider industrial networks are crucial elements in those worlds; our analysis therefore includes the shifting role of sensing in the surgical training of residents and the engineering and support teams responsible for maintaining the da Vinci robots.

3.1 The Surgical Team

The surgical teams studied here are highly-specialized units in which each team member has a specific role and skill. The surgeon leads the team and carries out major parts of the surgery. She takes full responsibility over the wellbeing of the patient before, during, and after the procedure. Two types of nurses support the surgeon: The *scrub tech* is responsible for passing instruments and works inside the sterile field, while the *circulator* fetches tools from the nonsterile area, counting all instruments and sponges throughout the surgery to make sure nothing is left inside the patient. The circulator also documents the surgical procedure by entering data into the computer's record system. Further, there is the anesthetist who narcotizes the patient and monitors vital life functions throughout the surgery. In robotic surgeries (or other more difficult surgeries) there is also a first assistant (often a Registered Nurse First Assistant, RNFA), who assists the surgeon by standing at the patient's side. In teaching hospitals, like the ones we did our research in, there are also surgeons-to-be at several stages of training: residents, interns (first-year into their residency), and students. A typical surgical team thus consists of at least five members. In teaching hospitals, this number grows to 8-10 people. Complicated surgeries are often staffed with several nurses as well, so more than one scrub tech and circulator may be present at times to ensure smooth handovers when nurses are leaving for their scheduled breaks.

The spatial arrangements of robotic surgery are similarly complex. The da Vinci Xi Surgical System consists of three parts spread throughout the operating theatre (see fig. 1-4). The patient cart (fig. 1), about the size of a large refrigerator, is docked at the operating table with the thin ends of its four extendable arms inserted into the patient through small incisions. The surgeons control movement of the robot arms through the consoles (fig. 2), which are usually placed against one of the walls of the operating room and allow the surgeons to view the three-dimensional video stream from inside the patient, captured by the endoscope. The endoscopic camera feed is also made available to the rest of the team through several screens (fig. 3). One of them is mounted on top of the vision cart, which also contains the robot's computing equipment and a microphone system.

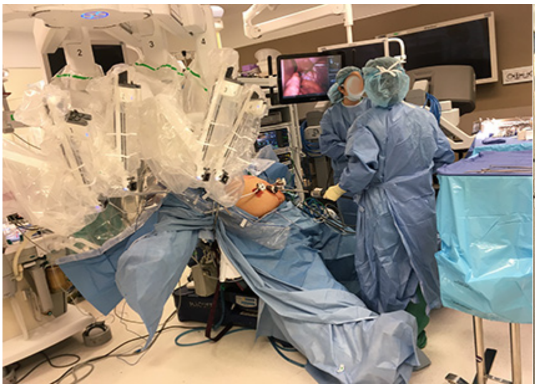
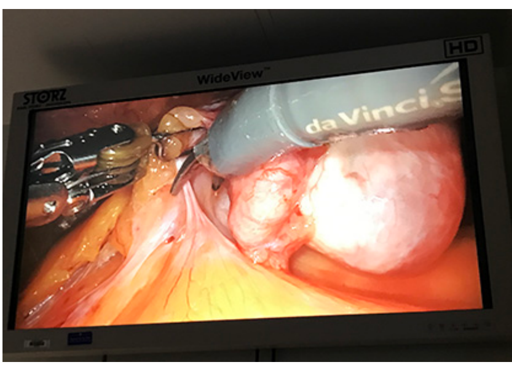


Fig. 1. Patient cart at the bedside, Fig. 2. Surgeon and Resident at console



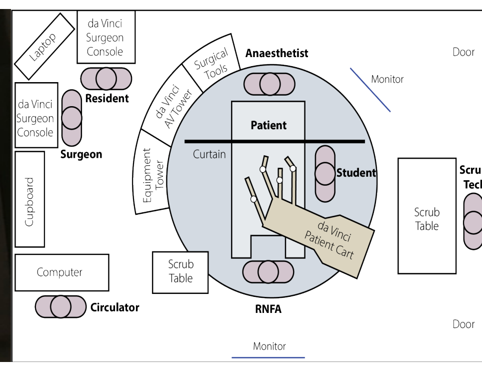


Fig. 3. Camera feed from endoscope broadcast to screens in the room, Fig. 4 Typical layout of a robotic operating room

4 INSIDE THE ROBOTIC OR

The doors to the OR swing open and closed as people in surgical scrubs quickly come and go, carefully navigating around equipment and coworkers. Opposite the doors, several machines are powered off but stay within arm's reach of the team in case they are needed for the day's procedures. The machines share the space with trays of surgical tools placed in neat rows on stainless steel tables, and on the wall above these hangs a whiteboard scrawled with handwritten notes listing patient names, procedures, surgical start times, and other information. Other equipment - empty plastic bowls, oxygen tanks, lights attached to arms, hoses, a cart holding both clipboards and loose sheets of paper, an overflowing garbage can, wall cabinets with glass doors, and a stool on wheels near the computer desk where the circulating nurse enters information – fill the perimeter of the room. The space resembles an artist's studio or maybe a mechanic's shop, rich with a variety of tools, written pieces of information, and people busy at work. In the middle of this lies the patient, hidden from sight and partially surrounded by an inner circle of machines, some attached to her body, that will keep her alive, asleep, and desensitized during the upcoming procedure. Their cables hang onto the floor and coil into neat, well-disciplined loops in bright yellows, whites, and grays. The anesthetist sits near the patient's head and watches a monitor stacked in a tower of machines, while two nurses stand at her side watching a monitor hung at eye level. Opposite the nurses and above the patient hovers the massive surgical robot with its four arms reaching into the patient's abdomen. The abdomen is extended, having been inflated with CO_2 gas to create an open space to allow the robotic tools to operate. Occasionally it speaks to the team in a cool, female voice. Its arms make a whirring sound while its plastic-bag-like material crinkles. The room is noisy and mechanical in other ways, too - air circulation units that supply the room with air chilled to 52 degrees Fahrenheit hum loudly overhead, insufflation machines make a vacuuming sound, machines monitoring patient vitals emit rhythmic tones that change to signify wellness or emergency, a wall telephone rings with frequency and is answered by the circulating nurse with a curt, "OR 74!" Over this the surgeon is playing a series of YouTube selections that include quick-tempo pop music or smooth classic rock of the 1970s, interspersed with commercials for car insurance, or web browsers, or fantasy T.V. shows. At times the team members move their bodies to the beat, sometimes singing along, and the robot, too, seems to be moving its arms to the rhythm, dancing. The lighting in the room switches back and forth between bright, dim, or even dark, as the robot changes according to the visual needs of the surgeon. Procedures waver between intensely busy and dramatically boring. During these quiet moments, the team, often on their feet for 10 hours a day, stand and stare at the screens (fig. 5) that hang in the dark - away from, yet into, the patient's body with new forms of intimacy, focusing on the incredibly clear visuals of organs, tissues, vessels, and soft organic parts in reds, oranges, and yellows that present a stark contrast to the reflective steel tools and coarse, black thread used for stitching. Other times, when not in the sterile field immediately surrounding the patient, they look at the screens of their smartphones - texting family or scrolling through Facebook, waiting to be called to action.

Fig. 5 Nurse views procedure on screen while resident observes through da Vinci console (right). Patient cart (left) is attached to patient.

The surgeon himself is sitting at a machine placed across the room with his head down, eyes focused into the machine's fixed stereoscopic viewer. His back is turned away from his team. In each hand, he grasps and manipulates, with his thumb and first two fingers, two extremely nimble rotational controllers that act as joysticks guiding the robotic arms. At the tip of each of these robotic arms is a “wristed” end, capable of rotating 360 degrees. These robotic wrists might hold a scalpel, scissors, a Bovie cauterizer, a needle driver, a stapler, a fiber optic camera and light, or several other attachments. With shoeless feet, the surgeon operates the robotic clutch that allows him to switch between arms. He can also hand control off to the resident sitting at her own console nearby, so that she, too, can operate the robot. Thanks to the robot’s camera, they both see the patient’s interior through their 3D video feed while the rest of the team follows along by watching any of the four large television monitors hanging at eye level around the room.

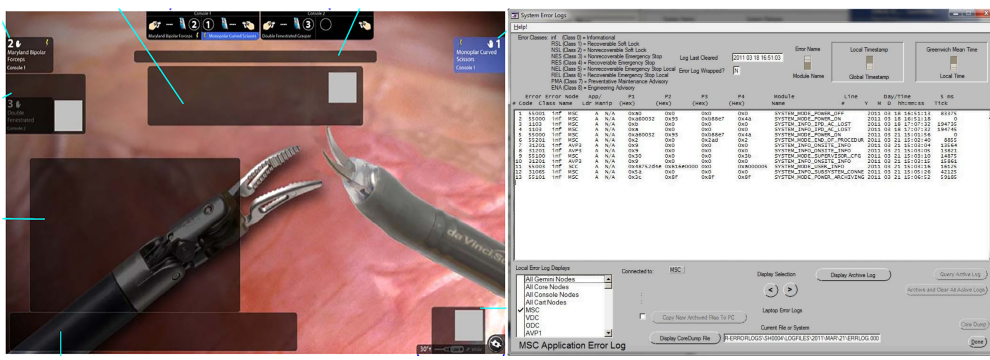


Fig. 6 Surgeon’s view from console, Fig. 7. Diagnostics view from Intuitive Surgical, Inc., *OnSite*.

4.1 Surgical Sight

Within the robotic operating room, procedures begin with the team establishing collective lines of sight. “Seeing” in the robotic OR is accomplished by connecting all eyes (including technological ones) to the patient body in various ways, as the team collaboratively achieves, then works to maintain, the complex connections between people and things that allow surgical work to move forward. Throughout procedures, “eyes,” including mechanical or computational ones, are routinely guided by the team on where to look, and at times, this new form of robotic sight malfunctions or disorients. The signal cannot seem to connect, is obstructed, misunderstood, or must travel through social hierarchies that place limits around who can see or interpret the scene at hand. At the end, this line of sight is dismantled as each eye returns to its own solitary “body” and unique vantage point.

4.1.1 Establishing Surgical Sight A nurse technician begins the process of establishing surgical sight within the OR as she presses the power button on the bulky da Vinci patient cart, then turns to look at one of the monitors. She waits for the usual color bars to appear, but surprisingly, the screen stays black and empty. She troubleshoots by pressing buttons and wiggling cords, tracing video cables from component to component. The circulating nurse passes by the tech nurse and says, “*the primary signal should be SD1.*” The circulator turns the patient cart off and back on again, an age-old trick in AV troubleshooting, but to no avail. Acknowledging that she is out of maneuvers, she quickly picks up the phone and asks for the “AV guy” to be sent to OR 84. Later, once the video signal sent from the da Vinci to the monitor is working properly, the circulating nurse, dwarfed by the patient cart, steers it across the room towards the operating table. She relies on the gestures of her co-workers and, says one tech nurse, *“everybody else’s eyes”* to direct her safe approach, ensuring the patient and the boom light above the operating table are not hit by the robot's dangling arms. Once parked, she applies the cart's brake, then touches a green avatar of a male figure in supine position that has appeared on the cart's touch screen. She touches the avatar's right abdominal side, telling the da Vinci where its placement is in relation to the upcoming procedure. In response, the cart shines a green X onto the patient. The robot slowly scans the patient's body until the scrub nurse intervenes and centers the light beam over the surgical site. Satisfied with its location, she presses another button. This triggers the robot to begin wiggling its arms in micro-movements as it calibrates to the patient, identifying the best arm arrangement for reducing collisions. The robot flashes red, orange, then blue lights as it warns the team by serenely yet firmly announcing, "*Do not move the operating table while the da Vinci is docked.*" It then prompts the team to continue their work setting up visuals by reminding them that "*it is time to insert the endoscope.*" Its voice is calm and feminine. Once the endoscope is placed, the entire team, robot included, will each have their own lines of sight configured.

The Resident Nurse First Assistant (RNFA) prepares to insert the da Vinci's endoscope into the anesthetized patient. As he powers on the scope and slips it into a port, or an opening cut into the patient, the monitors around the room change their image from the static color bars to video that reveals the scope as it tunnels deeper and deeper into the patient. Images of bright pink and yellow tissue appear on the screen, illuminated by the scope's small but powerful light. The team turns to watch. When the tool reaches the surgical location, the RNFA stops pushing and "hands up" to the da Vinci by clicking his end of the scope into a robotic arm. When ready, the surgeon will control the camera from the console across the room. The robot acknowledges receiving the tool by blinking a light on the patient cart in blues and greens. A nurse passing by collects and loops extra video cable and rests the bundle on the sleeping patient's thighs to reduce the risk of the patient's legs becoming entangled.

Once the delicate, sociotechnical lines of sight have been established for the team, it is time for the RNFA to insert additional tools into additional ports to see the interior of the patient and his work area. He accepts a long rod from the tech nurse and inserts it into the patient about an inch, then gazes upward at his nearest video monitor. Pausing a moment, he waits for the surgeon, who is partially obscured by a rack of equipment and not aware of what is happening with the patient. *"You gotta follow me,"* the RNFA says loudly, calling for the surgeon's attention to the work at hand. In response, the surgeon leans his torso into the headrest, then maneuvers two small joysticks with both hands in order to control the scope at the patient, providing visuals of inside the patient to the RNFA, who cannot see without the da Vinci camera guiding his work. The monitors reveal that the surgeon is turning the scope inside the patient, rotating until it catches sight of RNFA's tool. The RNFA now has eyes on what is happening in the patient and can see his work. He shifts his focus from the screen to the patient and back again as he continues to carefully insert the tool, then connects it to a da Vinci arm. Later, from their seats at the consoles, the surgeon and resident explore the patient body as they operate. The endoscope provides them both with an immersive, high-resolution, three-dimensional and magnified view of the surgical site, and the robot layers these visuals with additional information about the status of the da Vinci[1] (fig. 6).

[1] Along with increased magnification and 3D immersive vision, the surgical field has new forms of information ready and available to surgeons. By focusing their vision on other areas within the viewfinder, in many instances partially-opaque black boxes with textual

This new robotic sight allows for more detailed and precise surgical activities that in turn give way to more complex surgical procedures. However, this vantage point is vastly different from viewing the body with human eyes at the patient side, and, as a result, surgeons must learn to re-articulate visions of the patient body at new scale. Adjusting to new anatomical landscapes can be accompanied by struggle and disorientations on the part of the surgeon. Surgeons using the robot must learn to find their way through the body at a new scale – as if tunneling through or 'scuba diving' in the patient – and speak of 'getting lost' or 'getting turned around' while learning new navigations. They must use their eyes alone, without the learned guidance of their hands, which have memorized the feel of different tissue types. One surgeon reported, *"It's a skill you have to develop, it takes time...when you learn, it's not good for the patient. You learn by your mistakes. You get into other things. You get into the bladder, you get into the rectum, get into whatever...it's the same type of mistakes you'd make in the learning curve for open surgeries. I've done between 7,000-8,000 hysterectomies, open. I could do one with my eyes closed, just by the feel...the early robotic days were hard. When you can feel tissue, you can get a sense of what's where, just from the feel."*

The same surgeon who spoke of "getting lost" in the patient is teaching the resident anatomy. The resident is exploring the patient with the robot, pushing tissue aside with one of its arms, hunting for an ovary that is no larger than an almond. The team watches as she moves a metal tool, gently digging around. *"I don't see it,"* she says to the surgeon. He responds sharply that she should pay attention to the ureter, tissue that is most easily damaged by the robot. Assisting her on where to look, he maneuvers a digital green arrow to appear on both of their screens and uses it to point to the ovary, guiding her eyes. Then, teaching the observing students also in the OR, he asks if they can recognize a different anatomical landmark revealed on the monitors. No one replies to his inquiry. *"If you don't know that, figure it out,"* he says almost sternly. Suddenly, shifting his attention back to the intern's robotic movements, he calls out to her, *"Stop! Stop! See the vessel?"* It takes shockingly little time for a nicked blood vessel to fill the cavity with blood, obstructing the endoscope's camera and halting the procedure.

Further on in the day, the surgical team interprets scenes from the monitor and grows concerned. They are watching the surgeon move a robotic tool in what they feel is dangerous proximity to the patient's bladder. Without hesitation they call out their warnings.
RNFA: *Careful Doc, you're getting close to the bladder.*
Scrub Nurse, loudly: *"Woah, woah, woah!"*
The surgeon dismisses their concerns tersely and continues on with the procedure. It is difficult for an untrained eye to determine if he has changed his course or not. In interview, the surgeon explains his management of moments such as these, when his team becomes a kind of backseat driver and questions his movements. *"I remember an instance where there was someone on the team who wanted to replace my judgment with his. There was a little bit of a confrontation that I didn't want to have and deal with in the OR. I dealt with it later. There is a hierarchy, and his say wasn't going to be the final say. Now, looking back, I'm not sure; he might've been right."*

As we have seen, the robot brings new ensembles of human-machine sight to the OR that can be both extraordinary and disorienting, as well as new forms of collaborative sight as every eye

information, they can find data about the machine's general status, information regarding the endoscope's angle and magnification, or critical announcements regarding aspects of the device itself.

on the team becomes essential to the surgeon and the work at hand. At times achieving consensus through multiple viewpoints comes naturally, while at others, the team disagrees and difference must be resolved through hierarchical relationships that draw on authoritative systems that privilege the surgeon. In addition, robotic surgeons must also come to terms with re-learning patient anatomy as the da Vinci's powerful and unique lines of robotic sight drastically change the scale and scope of the surgeon's orientation and relation to the patient, leading them to re-learn or re-articulate past ways of seeing. Likewise they must train student eyes to distinguish between similar tissue and organ types, creating new visual vernaculars that replace traditional styles of teaching anatomy.

4.1.2 Losing Sight Mid-procedure, the surgeon communicates to his team that there is a problem with the scope. *"The right.. the right is totally blurry,"* he says. Yet around the room, the image on monitors appears crisp and clear. The surgeon realizes there's a discrepancy between the image on the monitor the image he sees. He presses a button at his console and sends his video signal to the team's monitors. The image changes to one that is blurry and difficult to see. The RNFA attempts to troubleshoot. He withdraws and wipes the scope in the chance that blood or other tissue has coated the lens. Once clean he reinserts, and for a moment the image is clear again. The surgery continues for about a minute but visuals quickly deteriorate again. The surgery pauses while the scope is removed, wiped, and reinserted a second time. A moment later the surgeon says, *"I can't do it, I can't see. The whole thing is fogging down."* The team discusses options, including making changes to the insufflation, while the robot sits idle. They decide to remove the scope and warm it for a moment. The surgeon offers a suggestion that the port location is the cause. Suddenly he calls out to the circulator, *"Can you change that music?"* He sounds irritated. Once the scope has been warmed, it is reinserted. It fogs again. The surgeon, now standing, walks from the console to the RNFA. Standing just outside of the sterile space, he points to the suction machine. *"Turn that down, it's too noisy."* The RNFA complies, then turns his attention to the insufflation machine. He holds a tube in one hand and says to the surgeon, *"I'll detach this for you and see if it helps."* After removing and reattaching the tube, the RNFA detects a kink in the tube and diagnoses it as the cause of the scope's blurring. With the problem identified and treated accordingly, the visuals return and stay crisp, and the surgeon completes the procedure without additional interruptions. The surgeon does not comment again on the overt sounds occurring within the room.

The RNFA stationed and scrubbed at the bedside routinely proves himself to be an important liaison for the displaced surgeon. The role of the RNFA has evolved in some hospitals specifically to assist with robotic procedures, so that a dedicated staff member maintains responsibility - not only for management of the robot - but for relaying to the surgeon forms of sensory information that she would otherwise have lost. The RNFA explains, "*I'm just keeping one eye on the robot, one on the screen, listening to what's going on with anesthesia...I kind of just listen to what's going on. If I hear things, the pitch of the monitors change, I'll just ask anesthesia if everything's okay. If there's a problem that arises, if the arms [of the robot] are hitting...I maintain that there is no injury to the patient...the surgeons are more focused in on what's happening in the visual field."*

This sensory sharing and new relationship between the RNFA and surgeon is especially pronounced when surgeons, who are 'swimming' in the patient, focused and operating via the vantage point of the scope, cannot look away without risk to the patient. Looking away from the surgical scene inside the viewfinder during a bleed can result in lost visuals or other disorientations that make relocating the trouble area difficult. They must hold and maintain visual focus during certain moments of the procedure and learn the safest moment to break their surgical gaze. For surgeons, knowing when to look away is a cultivated skill. They relate operating the da Vinci to driving a car and dropping their line of sight to curbing the vehicle. *"You stop what you're doing, and you find a safe time to stop. It's like being on the highway, and you need to pull over - you don't stop in the middle, but you pull over to the side, in a safe way."* If they can't break the line of sight, they must rely on the RNFA to keep eyes on other aspects of the patient and procedure as it unfolds at bedside. Intuitive Surgical explains, "*...the surgeon is not standing there, and so they do rely on the people who are at a patient's side to be their, you know, their eyes and their ears and their hands, as needed. The surgeon's view is dedicated to the surgical field. We believe that is the most important part for them to see.* Yet, the surgeon cannot intuit when a scope will blur or a broken blood vessel will turn the surgical field red with blood. As we saw above, the team must react quickly to troubleshoot and resolve the surgeon's blind spots.

The vignettes above detail the enhanced forms of sight granted to the surgeon through the da Vinci while simultaneously revealing its fragmented and partial nature. They illustrate an omnidirectional and fragile line of sight that deepens the surgeon's dependence on the team at the patient-side as they reconfigure to 'be his eyes' in the larger surgical environment, or troubleshoot and repair breakdowns in machinery that might render the surgeon 'blind' to the surgical site. Lastly, the robotic surgeon's bifurcated and mediated line of sight requires him to adapt his process to new surgical routines that mediate where his eyes can gaze and when they can look away.

4.1.3 Extended Sight While the surgeon is immersed in the patient, the RNFA is scrubbed, and the team watches on the monitors, Intuitive Surgical, designers of the da Vinci, have their own set of "eyes" on the procedure. When hospitals have subscribed to *Onsite*, the company's live tech support, all system events (such as the surgeon's foot on the pedal, the handoff of controls to the resident, or a tiny tremor in a loosening arm joint) are transmitted as lines of code back to Intuitive's centralized support team located in Sunnyvale, California (fig.7). From there, engineers can monitor and coordinate machine maintenance or initiate remote configuration changes or enable/disable features [33] in any of its nearly 5,000 [34] machines running around the world. Connecting to individual machines also grants the company the capacity to compile and store massive amounts of surgical data collected by the robot as the system uploads logs to Intuitive Surgical servers when idle – potentially storing data from the just over 1 million robotic procedures performed in 2018 alone [33]. This helps support ORs in troubleshooting machines. The RNFA explains his understanding of this, saying, *"If there's a problem with one of the arms, like a little glitch, that sends a code. They have thousands of codes. That code registers right there, and they can say, 'Well, at 8:59:06, we picked up a code of such-and-such and two minutes later, it did this thing. What was going on at your end?' It might have been that Dr. T, who's doing the surgery, said, 'You know, I felt like it was a little jerk in the arm.' Then, they notify their field tech support system. Within 24 hours, tech support is in there, checking everything out to make sure that there's no problems with the robot. Little things, too, like when we call for support, 'why is the monitor not working?' 'Because you didn't turn it on.' 'My camera isn't working.' 'No, doctor, you forgot to turn the light on.' Those things happen. Yeah, they watch everything we're doing...they can see exactly what's happening."* Collecting data in this way points towards new infrastructures of sight and oversight into the surgeon's work, opening the once-closed surgical team to new actors with their own unique responsibilities and objectives.

In earlier open procedures, the surgical site was viewable by the surgeon and the team at bedside. The robot opens the OR to new lines of sight altogether, as what parties can "see" of the surgery expands to include Intuitive Surgical as well as, in some instances, other students or colleagues within the local hospital community. In the robotic OR, anyone who enters the room is given access to viewing the surgery in real-time, and such observations rarely fall within the control of the surgeon. These decisions to broadcast procedures or purchase extended support are made by hospital administrators who seek to extend teaching moments or grant authority to Intuitive Surgical to connect to robotic procedures.

The scenarios described above explore the changing nature of surgical sight at both the intrapersonal and interpersonal level. The extended lines of sight observed in the robotic OR point towards an expanding social world of surgical actors and hints at possible futures that may shift or alter forms of authority away from the immediate surgical team.
In the sections that follow, we shift our focus away from surgical sight by exploring the ways in which the da Vinci robot alters the handwork of surgeons and surgical teams and existing forms of surgical touch.

4.2 Surgical Touch

The da Vinci robot operates with four arms instead of two and boasts articulated wrist movement superior to the human body. Its small tool size allows for intricate and miniscule motions. Marketing materials and video content produced by Intuitive Surgical often illustrate the nimble performance of these robotic tools by showing the robot quickly and proficiently peeling – then stitching back together – the skin of a grape. The arms reduce the surgeon's reliance on his team, simplifying certain elements of the work while providing the surgeon with more control. At the same time, the use of the da Vinci removes both tactile and tacit knowledge from the surgeon and alters traditions of apprenticeship that place surgeon-bodies in direct contact with student-bodies who learn surgical work not through language or observation, but through a transfer of embodied knowledge, by learning "the feel" of patients, tools, and craft. In addition, other elemental components of touch are also removed from surgical practice when human hands are subtracted from surgical care, changing important social ties that connect surgeon to student, team, and patient, while also impacting the surgeon's identity, which has for generations been linked to the conception of "good hands."

The nurse helps the patient climb onto the operating table and holds her hand until the anesthesia takes effect, quietly chatting and answering questions until she is suddenly asleep. Her eyes are taped closed, and the surgeon and resident approach, the latter holding a scalpel in his right hand. The surgeon places his own hand atop the resident's and together they gently glide the tool through the patient's tough abdominal muscles, completing a careful and precise short stroke. The surgeon continues guiding the student's hand in his own, while talking him through the motions quietly, collaboratively making three additional incisions. This conveys to the student not only the surgical location, but the appropriate pressure, strength, and balance needed to cut through the tough abdominal wall without damaging other tissue or organs below. Hand-on-hand, tacit knowledge is in this way transferred from surgeon to student, making the body itself a grounding and embodiment of surgical knowledge [74].

4.2.1 Losing Touch Later, during the robotic portion of the procedure, the surgeon is again teaching the student. This time they are apart from one another; each are at their own separate consoles. The surgeon maneuvers the hand controllers that steer the robotic arm, which holds the vessel sealer (aka 'the alligator'), an electrosurgical instrument that replaces the scalpel seen earlier. The screen shows the alligator as it opens and closes around the patient's tissue, dissecting and sealing blood vessels as it cuts and burns its way through the body. Wisps of smoke and steam rise inside the abdomen and a smell of burning tissue fills the room. The robot sounds a loud tone with every cycle of the alligator's open-close, alerting all that dissection is occurring. In this instance however the surgeon is not dissecting as much as he is strategically marking tissue with burn marks, drawing a map that the student will soon follow on her own. When he has finished creating a dotted line along the dissection path, the surgeon presses his foot on the clutch of the da Vinci and passes control of the robot to the resident. The resident, now operating the alligator on her own, begins to slowly connect the dots with the vessel sealer, dissecting along the surgeon's mapped line. With his voice amplified by the da Vinci's microphone, the surgeon calls for her to work more efficiently, shouting, "*Take a bigger bite! Take a bigger bite*!" In response the resident grabs more tissue with the alligator, presses down on the foot pedal, pinches her thumb and two fingers together, and burns her way along the path. Before each bite the resident pauses, waiting until she hears the surgeon verbalize his approval, often with a simple "okay." More tones, more smoke, more tissue dissected. This repeats for several minutes until the resident passes control back to the surgeon, who sets up the next task.

By creating a visual map within the patient, the robotic surgeon trains the student's eyes rather than her body, displacing tacit knowledges that may have developed across generations of surgeons who learned to feel *where* to cut. Robotic students never learn the "feel" of the two different tissue types and rely instead on the surgeon's ability to craft and communicate what types of visual information are important to notice. Learning to see becomes paramount for surgeons-in-training. Trained and experienced hands know by feel how much 'give' a certain material has before it tears and seamlessly incorporate that knowing into their practice. Robotic surgeons need to gauge, then communicate, when the tear will happen through observation alone. Says one surgeon, "*To teach with the robot, you get visual clues…and you rely on the visual clues. How much smoke is coming out when you get the scissors that close? Or, how much of stretchy tissue is happening before it starts tearing? It's very hard. I watch a lot of videos and tell my fellows, this is how it looks, this is how it looks. And trying to point it out during surgery as well…you're losing one sense and you need to compensate.*"

After having witnessed surgeons move to fully robotic procedures, such compensations are described by Intuitive Surgical. Surgeons, they explain, "*… swear they can feel the tissue through the system…yet what they're doing is replacing tactile cues with visual cues….One of the surgeons told me you can always tell when a suture is pulled to the right tautness because it starts to exude liquid out of the suture itself. They have all these visual cues, color changes, all sorts of things that they use, and surgeons who have been practicing for a while will absolutely tell you, and I put in quotes, 'they can feel the tissue.'*"

Not all surgeons we interviewed discussed compensations stemming from the loss of touch in nearly as seamless a way however. Some gave accounts more centered on feelings of loss or absence. "*The robot frustrates me*," reported one surgeon. "*I like to be able to touch things and touch patients, and when I'm operating, I like to use my hands - and I don't get that experience* *when I'm operating robotically. It really feels like a video game, because you can't feel anything. I mean you can see everything perfectly, but you can't feel anything. When I operate, I don't just operate with my eyes – you can also hear tissue when it's getting cut. I've been like, 'did you HEAR that?' you know, when there's something strange – so I think it involves every sense you have. You know it's the hearing of it, it's the touching of it – and it lets me know how easy a plane is going to be dissected if I just touch it, and it peels away like butter, or if it doesn't move at all. There's a lot to be gained that I feel I need as a surgeon. I like to touch tissue. It's something I struggle with, with the da Vinci.*" In addition, losing touch is more than haptic or tactile sensing. Surgeons operating without touch hint at also losing elements of proprioception, or the sense of where their bodies are in space. "*The nature of the robot is that the surgeon does not know where his arms are,*" said one surgeon (?). This sentiment may point towards the way that touch might be grounding[2], or how surgeons feel their own body in relation to the surgical act. Without hands, they become disembodied.

Robotic surgeons who miss the grounding nature of touch often approach the surgical site after the major work is completed, closely observing the patient and their work with human hands and unadorned eyes. After scrubbing in, the surgeon walks to the patient and pulls the overhead light close to the operative site. He reaches two fingers into the incision and stretches it wide, then gently tugs on the stitched tissue, pulling it outward from the body. He lowers his torso and takes a close examination, feeling the tissue as he rolls it in both hands and looks. When satisfied, he gently stuffs the tissue back with fingers deeply inserted into the incision. By approaching the patient in this way, with hands and eyes unmediated, he confirms to himself through an embodied, sensate experience that the procedure has gone as desired. He signals to the team to wrap it up and they begin closing.

In other cases, the loss of hands is connected to a loss of surgical skill. Explains one surgeon, *"There is a component to surgery where you prefer to actually use your hands to handle tissue, and that is why many of us gravitated to the field. Great surgeons are born with hands, like a professional athlete. With the robot, you don't get tactile feedback from the tissues in your hands, and especially if you have fine hands, good hands, that feel, that component is missing."* The notion of "good hands," whether trained or innately begotten, does not necessarily translate to "good robotic hands." Says the RNFA, *"With some robotic surgeons it looks like they are playing the accordion. It's just flailing arms and legs. You look over and .... can tell that there's a struggle. They would probably be better off, I don't know, doing the case laparoscopically. I think they've been at it long enough to know that, I think, they've reached their peak as far as being able to do things robotically. They're not going to get better. That's just the level that they're going to function at. I keep a close eye on those few that I know of. When I see their name pop up on a schedule, I just kind of look to make sure proper back up support is available.*" This points to the new reality that good robotic surgeons must have good robotic hands, or good robotic technique. And despite the assurances from Intuitive Surgical, Inc. that the da Vinci is the "great democratizer" [33] of all surgeons, improving the skills of those who are not operating at the same level as their peers, the statements from the surgical staff above hint that not all surgeons can master the da Vinci - or orient towards its unique computational system.

[2] Grounding in communication theory, as posited by Herbert Clark and Susan Brennan [17], points towards forms of discourse that provide "mutual knowledge, mutual beliefs, and mutual assumptions." Here we emphasize grounding in an embodied sense, roughly the anchoring of bodily experience in space and in relation to other objects (as in the resistance between tissue and hand). This, too, however, can be shared, as discussed further below.

Other surgeons hinted that along with losing a sense of touch, a sense of identity was also lost – and replaced by the robot.
Interviewer: "*Would you miss surgery if automation was the future?*"
Surgeon: "*Do I miss it? Yeah*".
Interviewer: "*You miss the craft*?"
Surgeon: "*Yeah, I'm a cutter. I don't want the machine doing it. I like doing it, I am the machine. I am the machine.*"

For others, surgical touch is entangled with activities related to a "human" touch, often witnessed in the moments occurring just after a surgical procedure is completed. Immediately after operating, the surgeon strips off his gloves and mask and heads to the telephone. Glancing at the phone number written on the leg of his scrubs he dials the patient's family and speaks into the mouthpiece in a quiet, soothing voice. For this surgeon, despite the technical importance and purpose of surgery, making this call is the human touch often mentioned by him as the "*most important*" aspect of surgical care; and one that developed slowly over years of practice and his own experience as surgeon, patient, and family member on the receiving end of such phone calls.

Other innate forms of human touch were witnessed as the surgeon grasped the hand of his student during teaching moments, transferring tacit knowledge difficult to transmit through language alone. In addition to sharing information about force, motion, and pressure, such instances may also communicate more affective states and senses of connection, alerting each party to the emotive state of the other [36]. This dual nature of touch, where the things we touch touch us back in return, brings our bodies closer to the world of people and things and in this instance, other types of sensory knowledges that help shape and direct our interactions and collaborations with others [59].

As the above sections have shown, "good" surgical hands evoke more than the mechanisms used for manipulating tissue. Surgical hands are explorative hands, helping operative teams to navigate through and draw sensory information from the uniqueness of each surgical encounter. The complex practices of the hand are also entangled with the surgeon's identity as both "cutters" and practitioners of an affective "human touch," that deepens surgical practice with moments of care. Without the surgeon's hand (or body) at the patient and with no new student hand to train, the slow, accumulated forms of tacit knowledge that have long guided surgical work and shaped surgical hands may recede – even as new configurations of human-robot touch and technologically mediated experiences (as when robotic surgeons claim that they can "feel" the patient through the robot) begin to emerge.

5 DISCUSSION

Like Hipour's oceanic navigation, forms of surgery that existed before the da Vinci robot were guided by the surgeon's ability to apply a wide-ranging sensory apparatus to the navigation and repair of patient bodies [38]. The surgeon was able to feel and identify the source of a sudden bleed with a gloved finger, to know in a tactile way that her sutures were appropriately tied based on the tug of the surgical thread, and to interpret the sounds of scalpel meeting diseased or scarred tissue in ways that informed and guided her technique. Her body held technique and tacit knowledge passed from surgeon to surgeon over the long history of surgery, itself acting as a kind of archive of surgical knowledge. The da Vinci robot alters this tradition of surgical work by replacing an embodied and rich sensory practice with one that relies on new, sometimes 'thinner,' combinations of human/machine sight. Disembodied robotic surgeons no longer feel, smell, or hear their patient during procedures, and can no longer fully utilize the surgical knowledge held in their own bodies. Despite this, surgical work continues: in part due to the (re)articulations and compensations of the surgical team as they endeavor to support the desensitized surgeon; and in part due to the adjustments of the surgeon herself as her own sensorial practice shifts and accommodates to the "information world" of the robotic OR.

Through observing robotic procedures in the OR, several interrelated takeaways surrounding sensing in individuals, collectives, and with robotic collaborators surface and open new lines of discussion surrounding complex sensory phenomenon. These observations point towards the senses as interconnected, in flux, and distributed within and across a world of people and things. They also shed light on the remarkable capacity of individuals and teams to form new embodied and mediated engagements with the world, described here as sensory (re)articulations and compensations. Taken as a whole, these findings offer CSCW and related communities new insight into the design and deployment of robots, calling on designers to consider how such technologies might support and enrich the complex sensorial apparatus of correspondent users and the entire collaborative team.

5.1 Sensing is shared and entangled across sensory modalities.

Findings from within the robotic OR run counter to notions of sensing that have taken hold of Western imaginations since Platonic times. They align more closely with sensory anthropologists who argue the senses cannot be isolated from each other, finding they are entangled, interconnected, and function in unison. Surgery, we learned, as a deeply embodied process, "*... involves all the senses at once.*" The sound tissue makes when cut, the tactile feedback received through the hand and instrument, the smell of blood or diseased tissue all combine with the visual to enliven the surgeon's entire sensorial experience in ways that strengthen knowledge and engagements with surgery's unique "world of materials" [32]. Likewise surgical sensing is not limited to the "big five" senses so often thought of in Western culture. Whether there are five, ten, or even more sensory modalities at play in the OR, an adjustment to one impacts or alters another. The robotic surgeon who was suddenly "blinded," for example, quickly experienced the soundscape as unbearable. Only when sight returned did the audio levels cease to be an issue for him. That losing sight might impact the aural capacities of the surgeon in such a way reinforces the notion that the senses are interrelated in complex and unpredictable ways.

5.2 Sensing is shared and entangled across people and things.

As anthropologists from Levi-Strauss onward have argued and as we observed in the OR, human sensing develops in accordance with existing social, material, and cultural milieus. Sensing in the operating room is achieved in accordance with its own discipline-based proficiencies, team hierarchies, and contextual responsibilities. Throughout our observations, the team routinely negotiated and shared sensory information with one another in an effort to build a larger, co-constructed shared "sensorium" made possible not by one body (and their unique vantage points and knowledges) but by multiple bodies -- and not by bodies alone, but by bodies and machines, working together and constituting a "surgical sensorium."

Robotic teams have access to new lines of sight through video monitors that reveal surgical procedures previously hidden, opening the team to new potentials for shared sensing. Socially, surgical teams operate as hierarchies, however, that are structured in ways that privilege the surgeon's ability to determine and decide *which* sensory information is crucial to the task at hand. When the surgeon's proximity to a patient's bladder alarmed the team, the surgeon promptly dismissed their concern. Such occurrences illustrate the occasionally tense relationships that can exist between collaborative sensing and establishing consensus, and existing social orders or hierarchies within teams. At the same time, these lines of sight diverge, as video channels deliver the surgeon one vantage point and the team another. This difference created tensions when the team needed consensus to effectively troubleshoot. These scenarios point to the challenges faced by collaborative teams when reaching for consensus at the junctures of complex technologies and existing social contingencies. Sensing as a team, whether as "procedure work" or negotiated social act, does not come effortlessly, and rigid social orders can run against new technological affordances that might otherwise lead towards new forms of collaborative sensing.

Sensing with people and machines may empower sight even as it makes it fragile and subject to breakdowns (as seen when the da Vinci endoscope failed, when AV equipment could not connect, or when a nicked vessel covered the camera lens with blood) that must be managed by the team during critical and unforeseen circumstances. In this way, distributed sensing under the sociotechnical conditions of the OR are bound by material constraints that render it only as powerful as the loose cable, weakened blood vessel, or bent tubes that endeavor to connect the sensual to the technological.

The da Vinci, as a technological object rooted and connected to various social worlds [8], brings new (often unseen) actors into the OR in ways that extend the social world, bringing unique cultures – in this instance cultures of high technology, as well as stakeholder interests – into existing spaces, potentially shifting the nature of surgical practice to include not just the slow formations of surgical ritual [36] but the ever changing nature of technological updates and upgrades. These new social worlds must co-exist and be managed by the surgical team.

5.3 Sensory compensation and (re)articulation under robotic conditions.

In many ways, surgeons have always recalibrated their senses in relation to the tools and materials at hand, adjusting methods and practice as needed as they progressed from inarticulate student to fully articulate surgeon. As new tools and technologies such as the da Vinci enter the operating room, seasoned surgeons face a (re)articulation under new sensory conditions that in this instance dislocate the surgeon's body – seen here most powerfully as eyes adjust to technological visualizations and hands leave the patient to manipulate joysticks. The surgeons we observed learned to sense the patient body anew, through robotic means. These (re)articulated robotic surgeons, much like Latour's "noses," however, are *partially* articulated surgeons, operating without full sensory range and subsequent sensory knowledges so crucial to earlier forms of surgical work. Recall Latour's students wafting odors, vial after vial, eyes closed, learning to put an abstract name to the abstract aroma that represented a simulated scent. Such contrived experiences are far removed from the sensual characteristics and usual sensory complexities one typically experiences in the world of things, and they fail to take into account the interconnected nature of sensing put forth above. As robotic procedures are adopted by an increasing number of specialties, these earlier sensory articulations begin to fade, potentially becoming lost epistemologies and forgotten surgical technique [65]. Accordingly, such loss presents wider implications for surgical training in general, as surgical interns working with (re)articulated surgeons in the robotic OR will spend more time glancing at screens and less time interacting with and manipulating tissue[3] [7]. Students will "learn how it looks" to be engaged with patient bodies rather than how it feels to navigate, hold, cut, and suture patient tissues.

At the same time, the robotic surgeons we observed can be seen to compensate for changes to the sensorium by developing new sensory awareness that seeks to replace or fill in for missing sense modalities. Recall surgeons above who learn to "see" sutures pulled to proper tautness, or swear they can "feel" through the visual connectivity of the da Vinci alone. Compensation in this regard is discussed by engineers of Intuitive Surgical as a new form of *visual-haptic* sensing, defined as the cross-modal phenomenon where haptic memories are "mapped" against congruent visual representations [30]. In this instance, touch is reimagined as an activity of the eye rather than the hand, though long-term implications that surround how visual-haptics will evolve in new surgical residents is unclear, as there will be no touch for them to remember.

On the team level, sensory compensations also take the form of reconfigurations of work that aim to re-sensitize the surgeon and uphold team sensing. Nurses adjust their role to share sensory cues and feedback regarding information at the bedside and relay information from surgeon to team, often to the extent that new positions are created to support the disrupted sensory conditions of the team.

5.4 Designing robotic technologies for collaborative and embodied work

The da Vinci robot disturbs entangled and established forms of sensing by isolating and privileging some sensory modalities while reducing others, privileging the surgeon's sensing above that of the team as a whole, and displacing forms of tacit and embodied knowledge tied to the senses that have guided surgery for generations. Our observations within the robotic OR problematize current notions of sensing as bifurcated and ranked, and call for sensorial-aware design practices that take into account the rich and interconnected ways in which we sense the world, both as individuals and collectively.

This suggests some rough starting points (though few precise directives) for design. On an individual level, sensory-aware design artifacts might purposively speak to and engage with the full range of interdependent sensory modalities rather than with just one or two distinct sensory modalities that are mediated and enframed [28]. In the case of surgical robotics, current and ongoing efforts to add additional sensory affordances – such as haptics to a handheld controller – would not address the interwoven nature of sensing put forth above, nor would it mitigate the full loss of touch as experienced by surgeons. For a robotic technology to honor complex forms of touch, for example, it might recognize and support the multiple occurrences we have observed in the OR – from the manipulation of materials to exploring and operating with the less tangible spaces of memory, emotion, and embodied forms of tacit knowledge. Such a technology might also imagine the ways it can engage with and support the full range of human sensing.

[3] A third-year Physician's Assistant says that she will not be attending more robotic cases, because there wouldn't be any hands-on work for her. All she does is stand and watch the screen. "I mean, you can change the arms and stuff, but that's about it," she reports.

Additionally, within team environments, sensory-aware robotic technologies engaged in collaborative forms of work should be held accountable not only to primary users (in this instance, surgeons) but to all users. This idea runs counter to overarching narratives that place the surgeon and robot at the epicenter of surgical care, often elevated from the hidden yet crucial support work of the larger operating room team[4]. Such design would support and enhance multiple instances of work across teams. For example, nurses who are burdened to blindly steer the patient cart safely across the OR are also users of the da Vinci, which, in their hands, rapidly transforms from a powerful piece of costly robotic technology into a bulky and potentially dangerous device, heavy and blind to its external environment. To this end, sensory-aware technologies might recognize moments or modes of interaction that occur outside of the immediate (i.e. when tool hits flesh) surgical site.

6 CONCLUSIONS

Observations from the robotic OR provide important insight into the complex nature of surgical work as it engages with and adapts to new robotic tools and techniques. Our study explored the ways surgeons and their teams reconfigure their work to strengthen forms of cooperation and care, in part through techniques of compensation that replace or make up for missing sensory modalities (both individually and across the team), and in part by re-articulating knowledge of the patient body through the introduction of new sensory vantage points. At the same time, we have sought to apply an anthropological lens towards sensing to the robotic OR and have called on designers to take into account the interconnected, social, and multiple senses we employ while engaging in collaborative and embodied forms of work.

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[4] See for instance recent advertising for *Verb*, a robotic surgical tool under development by Google and Johnson & Johnson advertising that they are "all about making the surgeon better" as they develop a robot meant to come "between the surgeon and the patient" to the exclusion of the team, at https://www.verbsurgical.com/about/

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