The Choreography of Care: An Ethnographic Study of Human-Robot Collaboration in Makoplasty Surgeries

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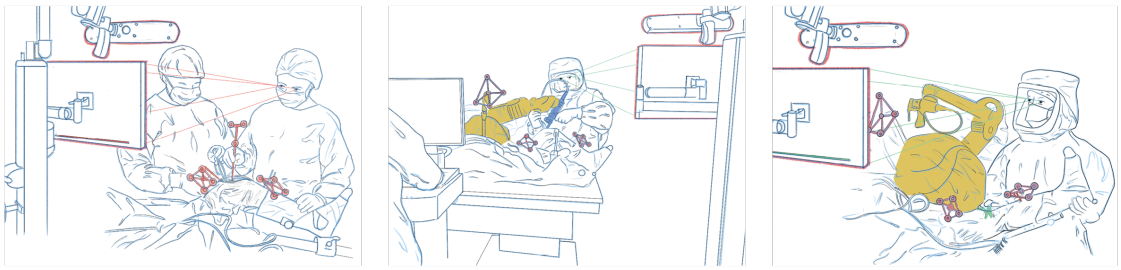
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a. Before the operation, the surgeon and Mako Product Specialist (MPS) review the Mako software containing the 3D anatomy of the patient's joint to plan and determine the surgical approach.

b. The MPS and the scrub nurse start preparing the robot for entering the sterile field by putting a protective drape over the robotic arm.

c. The scrub nurse manipulates the now sterile robotic arm through several pre-determined motions (as indicated by the Mako software) to register the robotic arm for cutting.



d. The surgeon uses a probe on the patient's bone to match the patient's anatomy in the room with the virtual 3D model in the Mako software. This is to "teach" the robot exactly where the patient is within the operating theatre.

e. A saw (for knee) or reamer (for hip) is attached to the robotic arm, and the surgeon removes the amount of bone that was planned in step 1. The surgeon looks at the screen to accurately determine, in real-time, what they are cutting away.

f. A trial implant is inserted and the surgeon manipulates the patient's leg to determine if the optimal implant positioning has been achieved. Again, the surgeon looks at the screen to accurately determine, in real-time, if the desired outcomes of their surgical approach has been achieved.

Figure 1: Makoplasty workflow: team interaction points with the Mako (a–f; illustrations by authors).

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Abstract

Human-Robot Collaboration (HRC) in surgery is rarely a straightforward interaction between one human and one robot. In joint replacement surgeries performed with the Mako robot (Makoplasty), the robotic arm enhances surgical precision while also affecting how collaboration unfolds in the operating theater. Utilizing over

80 hours of hospital-based fieldwork, including observations of 15 Makoplasty surgeries and 10 interviews, we examine how the Mako robot shapes surgical HRC. We demonstrate how surgical teams coordinate via tacit cues, negotiated boundaries, and adaptive role shifts across phases of operation. Through vignettes, we highlight the pivotal role of supporting actors, such as nurses and robotic specialists, in maintaining flow and reveal how responsibility is distributed temporally among actors depending on task demands. We argue that surgical HRC is best understood as a multi-actor choreography rather than a surgeon-robot dyad, offering design implications for co-located surgical HRC systems that support distributed collaboration.

CCS Concepts

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

Keywords

Human-Robot Collaboration; Teamwork; Robotic-Assisted Surgery; Ethnography; Mako Robotic System

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1 Introduction

> "Lights flare bright on the sterile floor, a robot waits, cast in the score. Not fixed in place, nor free to command, a symbiotic bond set to the same stand. Gloved hands in rhythm, a team aware, time to begin the choreography of care" (First Author).

Human-Robot Collaboration (HRC) refers to the ways humans and robots work together on shared tasks, most often imagined as a dyad between a single operator and a machine [29, 62]. In surgical practice, for example, robotic systems such as Stryker's Mako Robotic Arm are introduced to support the surgeon's hand, offering greater accuracy in bone resection (bone cuts) [43, 47, 55]. Yet, collaboration in the operating theater is rarely so straightforward; it brings together many hands, tools, and rhythms simultaneously. Despite HRC's growing attention in Human-Computer Interaction (HCI) [26, 52, 65, 66], much of the literature remains tied to controlled studies [62] or teleoperated systems [29], overlooking co-located teamwork in real-world environments [36, 62].

To understand this complexity, consider the following moment from our fieldwork, which captures the messy reality of the operating theater:

> ***Vignette: Setting the Scene***
> *The team crowds the patient; two surgeons and a robotic arm aligned in purpose. From behind the console, the eyes of the Robotic Specialist peek through the gap. Heads bow so the scout nurse can slide the headphones over exposed ears. "Ready? Haptics on?" A nod and eyes lock to the screen. The saw on the robotic arm begins to sing, a high whine against the bone. Then, silence. The blade stops. "Too many vibrations," the specialist calls out. The assistant moves instantly, twisting like a limbo dancer to evade the robot's line of sight while gripping the leg to damp the tremor. Eyes return to the monitor. Finger on the trigger. The choreography continues.*

This scene illustrates that Makoplasty, joint replacement surgery performed with the Mako, is far from a solitary interaction between a user and a tool. Instead, it is a crowded, sensory-rich negotiation where the robot serves as both a physical partner and a spatial constraint. The surgeon's hands are on the robot, but their attention is on the screen; the Mako Product Specialist (MPS) manages the software that permits the physical action; and the scrub nurse navigates the physical space the robot occupies. Studying HRC in such real-world environments reveals complexities and interdependencies that are often hidden in laboratory contexts. Therefore, this paper asks how collaboration is *actually* performed when humans and robots share space in the operating theater.

Existing HCI literature predominantly characterizes surgical robotics through the da Vinci robotic system, framing coordination as a challenge of bridging the distance between a console-bound surgeon and the patient-side team [14, 41]. While this work highlights the explicit communication required to sustain the "robotic operating theater," it overlooks the distinct dynamics of co-located collaboration. Our study addresses this gap by examining the Mako system, which closely situates the surgeon, scrub nurse, robot, and robotic specialist together within the operating theater. This proximity resolves teleoperation's communication barriers but introduces new socio-technical tensions over competition for space and the maintenance of a collective rhythm. Through an ethnographic account of "Makoplasty," we demonstrate how the robot's role as a semi-autonomous physical constraint shifts the collaborative focus from a distanced interaction to a multi-actor negotiation of labor and space.

While the clinical benefits of Makoplasty for patient outcomes are well-documented [6, 11, 42, 47], less is known about how the system reshapes teamwork, responsibility, and role negotiation in practice. In this paper, we approach the Mako not simply as a surgical technology to be optimized, but as a site for investigating the broader dynamics of multi-actor HRC in high-stakes, co-located environments. Our study asks:

Research Question: How is Makoplasty teamwork enacted as an ensemble form of Human-Robot Collaboration in a co-located operating theater?

To address this question, we conducted an eight-month-long ethnographic study of Makoplasty surgeries at the St Vincent's Private Hospital in Brisbane, Australia. Our fieldwork included in-surgical theater observations of 15 live procedures and 10 informal interviews with surgical staff during breaks, totaling over 80 hours on site. Based on our analysis, we organize our contributions into empirical, conceptual, and design insights:

- **Empirical Contribution:** We provide an in-depth ethnographic account of Makoplasty, distinguishing co-located HRC from the widely studied teleoperated (da Vinci) model.

We detail how the surgical workflow relies not just on the surgeon-robot dyad, but on a "co-located ensemble" that critically includes the Mako Product Specialist (robotic specialist) and nursing staff.
- **Conceptual Contribution:** We articulate a framework of *delegated responsibility* and *spatial negotiation*. We show how the surgeon offloads technical monitoring to the MPS to maintain clinical focus, and how the team physically contorts to accommodate the robot's sensory requirements, redefining the "choreography of care" as a multi-actor challenge.
- **Design Contribution:** We offer guidelines for shifting from user-centric to *ensemble-centric* design. We advocate for systems that support the full collaborative ecosystem; enhancing mutual visibility, supporting non-surgeon roles, and reducing the spatial friction inherent in crowded, high-tech operating theaters.

2 Related Work

Human-Robot Collaboration (HRC) research has moved beyond early dyadic models toward richer accounts of teamwork. To situate our study, we first review how HCI and CSCW traditions on coordination and articulation inform this shift. We then turn to the operating theater as a paradigmatic site for co-located HRC, tracing how ethnographic and human factors studies have examined robotic surgery in both teleoperated (e.g., da Vinci) and co-located (e.g., Mako) contexts. Finally, we contrast how a robotic co-located system presents unique challenges compared to non-robotic co-located systems in the operating theater.

Makoplasty serves as a paradigmatic site for theorizing ensemble HRC because it forces the digital plan and the physical hand to coexist in a single, crowded field. Unlike teleoperated systems that separate planning from action across distance, the Mako system fuses them in a shared space. This setting holds broader significance for HCI as intelligent machines increasingly leave the cage to work shoulder-to-shoulder with human teams. In these emerging contexts, collaboration will rarely be generic; it will rely on ensembles where human actors contribute distinct skills and specialized expertise. Investigating these dynamics within the high-stakes, constrained environment of the operating theater offers a critical vantage point for understanding how such heterogeneous teams navigate friction, rhythm, and responsibility in real-world practice. This organization allows us to connect foundational insights on teamwork with current challenges of surgical HRC, before highlighting how the Mako system reconfigures the choreography of care.

2.1 From Dyads to Teams

HCI has a long tradition of studying how people coordinate work, and these insights form a foundation for understanding HRC. Teamwork has long been a central focus of HCI. Early models, such as the time-space matrix proposed by Ellis et al. [18], classified collaborative work along dimensions of spatial proximity and temporal synchronicity. While influential, these frameworks abstracted the nuanced, lived realities of cooperative activity. In response, ethnomethodological and workplace studies introduced more grounded perspectives, emphasizing collaboration as a situated, embodied, and interactionally emergent practice. Suchman's foundational critique of planning paradigms [58] underscored that human action arises not from predefined scripts but through situated responses to local contingencies. Building on this shift, Schmidt [50] introduced the concept of articulation work to describe the often-overlooked mechanisms by which coordination is achieved in practice.

A similar shift is now visible in HRC research. Early HRC studies typically addressed straightforward, task-oriented interactions between a single human and a single robot. Recent work, however, reconceptualizes HRC as a distributed, collective, and socially embedded accomplishment [2, 8, 28, 60, 64]. This perspective gains increasing relevance as robots acquire more capabilities [3], becoming not only tools but team participants. Johansen et al. [29] trace this trend across diverse domains, including telesurgery [14, 17, 41], planetary exploration [61], and emergency response [59]. In these contexts, robots actively reshape human practices around trust, situational awareness, and coordination, becoming collaborative agents rather than mere tools.

Across this literature, three analytical moves are evident. First, some examine how robotic systems disrupt or reconfigure established team practices [14, 41]. Second, others draw on established theories of human teamwork to inform the design of robotic systems [30]. Third, a growing body of work adopts socio-material perspectives that view the social and the material as inseparably intertwined, to understand how collaboration emerges and evolves when robots become integral to team dynamics [60]. Collectively, these studies argue that HRC requires distinct rhythms, cues, and forms of alignment that diverge from both automation paradigms and traditional models of human-human interaction. For example, Jung et al. [30] introduced backchanneling in urban search-and-rescue contexts, demonstrating how subtle cues facilitate cohesion within human-robot-human triads. Similarly, Tollinger et al. [61] examined collaboration among scientists operating Mars rovers, revealing how shared visual interfaces support collective planning among spatially dispersed team members. Taken together, these studies signal a shift from linear models of command and control to more relational, emergent forms of coordination. To understand and design for HRC, HCI researchers must move beyond dyads to relational, team-based conceptualizations [52]. This pivot opens the door to ensemble-based understandings of HRC, where coordination is distributed across actors, tools, and environments. Yet much of this work remains situated in controlled settings or mediated by distance. What has been less examined is how ensemble HRC is enacted in co-located, high-stakes domains, where human and robotic actors must work side by side. In this context, we use the term 'enacted' to draw on Suchman's distinction between prescribed plans and situated actions [58]. We focus specifically on the contrast between the system's design, which predominantly targets the dyadic relationship between the surgeon and the robot, and its actual performance in practice, where this interaction emerges as just one strand of a broader, team-based choreography. The following section explores how these conceptual shifts unfold in the operating theater, a paradigmatic site for examining ensemble HRC under conditions of urgency, constraint, and interdependence.

2.2 HRC Teams in the Operating theater

Robotic surgery offers a critical site for studying co-located HRC because the operating theater concentrates the very conditions that make human-robot teamwork most demanding: high stakes, temporal pressure, and strict spatial constraints. Prior HCI research has focused on teleoperated systems, such as the da Vinci robot [4, 5, 35], where the surgeon is physically separated from the rest of the team. This separation illuminates how robotic mediation redistributes coordination, communication, and trust. Pelikan et al. [41], for instance, demonstrate how tele-surgical teams navigate the physical, cognitive, and affective distances introduced by console-based operations. Their work builds on Hirschauer's [21] ethnography of surgery, which conceptualizes the surgeon-body as a coordinated collective in which gesture, rhythm, and proximity replace explicit communication. In robotic contexts, this choreography of care becomes more complex. Cheatle et al. [14] and Randell et al. [45] demonstrate how surgical rhythm must be preserved even as robotic systems redistribute labor and attention, while Catchpole et al. [12, 13] emphasize the unrecognized work that sustains safe handovers and shared awareness. Collectively, these accounts demonstrate that robots not only automate surgical tasks but also reconfigure the distribution of work, attention, and responsibility.

Yet these insights are shaped by teleoperated configurations. Whereas da Vinci ethnographies foregrounded collaboration at a distance, Mako exposes how co-located human and robotic actors negotiate proximity, rhythm, and shared responsibility. Unlike da Vinci, Mako requires close spatial alignment within the sterile field between the robot, surgeon, assistant, and the scrub nurse. Existing studies of Mako, however, remain mainly technical or ergonomic, examining factors such as learning curves [19, 33, 34], cognitive load [1], or posture [53]. While valuable, these existing studies concentrate on the surgeon's adaptation and overlook the broader collaborative ecosystem. The mandatory presence of an MPS introduces a dual responsibility structure, placing a technical expert (responsible for the technological side of the procedure) within the theater as an active participant in the surgical flow. Scrub nurses also engage directly with the robot, assisting with tool changes, setup, and draping (see Fig. 1b-c). These roles are not peripheral but integral to timing, rhythm, and safety, yet they remain underexplored in existing research.

2.3 Robotic and Non-Robotic Co-Located Systems in the Operating theater

To understand the dynamics of co-located HRC, it is valuable to examine how other co-located technologies, specifically intra-operative imaging systems, have already reshaped the operating theater. Research in CSCW and HCI has shown that introducing these systems does more than provide visual data; it fundamentally reorganizes surgical teamwork by creating new focal points for shared attention and coordination. Mentis et al. demonstrate that in minimally invasive surgery, the team must engage in significant articulation work to bridge the gap between the digital image and the physical patient [37, 39]. These shared displays become central to the team's synchrony, requiring actors to align their gaze, speech, and physical movements around a shared screen. However, existing



Figure 2: The implant planning can be both displayed before and during the Makoplasty surgeries to inform surgical decision-making.

literature primarily examines these dynamics through *passive* imaging systems; tools that inform but do not act. The Mako system presents a profound shift from this baseline; as a semi-autonomous robotic arm, it possesses agency that directly constrains and informs the team's physical actions. It fuses the physical work of the robotic arm with a digital interface that enables both pre-operative planning and real-time intra-operative flexibility to cater to individual patient's implant size needs, as seen in Fig. 2.

Such integration of digital planning and physical action relies heavily on how information is displayed and consumed. Research on Multiple Device Environments (MDEs) suggests that co-located groups benefit from richly communicative environments that promote awareness through mutual gaze and shared artifacts [37]. Rooksby et al. extend this by describing the "second screen" phenomenon, showing how users actively interweave attention between personal devices (like a phone) and a primary shared display (like a TV) in an embodied, coordinated manner [48]. We observe a parallel dynamic in Makoplasty. The MPS operates a personal computer, a "second screen" visible only to them, while synchronizing their actions with a primary monitor visible to the entire team.

However, unlike the systems described by Mentis [37], where displays might offer varying information or require surgeons to step away to view a secondary screen, the Mako's screens are functional duplicates, as seen in Fig. 3. The MPS manages its interface to ensure the shared display provides an optimal view for the surgeon, such as rotating the 3D model to match the patient's real-time position. In this sense, the MPS's manipulation of the software constitutes "work that enables other work" [49], a form of infrastructural labor that allows the surgeon to read the display without breaking the rhythm of the procedure. Finally, where Mentis et al. argue that surgical training involves "learning to see the body" through a mediated screen [38], we argue that co-located robotic surgery adds a new requirement. The team must not only learn to see the anatomy but must fundamentally understand how to let "the robot see"; interpreting its field of vision and keeping clear of it while being able to read the information it provides on its display.



Figure 3: First author in a mock operating theater. Left-hand side, shows the display that surgeons and staff gaze at (as in this case, during bone cuts) and on the right-hand side, the display of the MPS which mirrors the other display where the "work that enables other work" is being done.

3 Method

3.1 Approach

To investigate how Makoplasty teamwork is enacted as an ensemble form of HRC in a co-located operating theater, we adopted an ethnographic approach [16, 44, 56]. Ethnography offers a unique window into surgical practice, enabling us to capture the lived realities of teamwork as they unfold in the operating theater. For instance, as co-located observers of the operation, we witnessed how a scrub nurse organized tools spatially based on the order in which they were to be handed to the surgeon, or how the MPS anticipated a surgeon's preferred implant view before being asked, and how team members subtly repositioned themselves to negotiate scarce space around the sterile field. These moments, often treated as routine by practitioners, reveal how collaboration is enacted in ways that formal protocols or post-hoc interviews might not capture. By immersing ourselves in the operating theater, we could attend to both the expected and the unexpected and capture the differences between how work is imagined or designed and how it is actually performed [9, 12, 20].

Within HCI, there has been ongoing debate over whether ethnography should be regarded as a *method* in the strict methodological sense or as a broader orientation to inquiry. Randall et al. [44] argue that ethnography follows no fixed rules of application; instead, it is a highly contextualized approach shaped by the researchers conducting it and the setting in which it unfolds. We align with this perspective. Consequently, we frame our study as *ethnographically informed* fieldwork. This approach is particularly suited to the high-stakes environment of the operating theater, where access is constrained and each patient's anatomy requires tailored approaches carried out by an alternating set of actors. In other words, *no two surgeries are exactly alike*. We did not attempt to reduce this variability through standardization; instead, we treated it as a resource for analysis, prioritizing depth and richness of observation over breadth to generate situated insights into how surgical collaboration unfolds in practice.

To further support our inquiry, we complemented our ethnographic approach with Socio-Technical Grounded Theory (STGT) [22]. While Pelikan et al. [41] analyzed surgical observations using classical grounded theory, we found STGT more appropriate for our aims. Its inductive, iterative process is designed explicitly for contexts in which social and technical systems are tightly coupled, such that examining one without the other would offer only a partial account [22]. We selected STGT not only because it foregrounds this socio-technical coupling, but also because it enables us to capture emergent shifts in role negotiation and responsibility that arise in tightly interwoven environments, such as the operating theater. In contrast to traditional ethnomethodological or observational approaches, STGT provides a more systematic and robust method for generating insights from these dynamics, while maintaining flexibility in the scope of analysis.

3.2 Setting and participants

The fieldwork was conducted between December 2024 and July 2025 at a private, teaching hospital in Brisbane, Australia that performs a high volume of Makoplasty surgeries. Across the study period, we observed 15 procedures performed with the Mako robotic system. Before entering the operating theater, we contextualized ourselves by reviewing the existing Mako literature and studying publicly available demonstration videos on online channels such as YouTube. This preparatory step familiarized us with the system's typical workflow and provided a baseline for recognizing deviations, improvisations, and adaptations once in the field. The first two were pilot observations, enabling us to test our data collection approach and familiarize ourselves with the environment before the full study commenced. These pilots were formative: they helped us learn how to move appropriately within the theater space, refine our notetaking structure, and identify early points of collaborative tension around the robot. Table 1 summarizes these cases, including the type of surgery and duration: seven Total Knee Arthroplasty (TKA) cases, six Total Hip Arthroplasty (THA) cases, and two Partial Knee Arthroplasty (PKA) cases. This distribution reflects the typical case mix for Mako-assisted surgeries at the hospital.

Each operation involved a broader surgical team comprising:

- The **lead surgeon**
- The **assisting surgeon** (often newer to the Mako and occasionally operating it under the supervision of the lead surgeon),
- One or more **scrub nurses** responsible for preparing and handling instruments,
- One **Mako Product Specialist** (technical specialist), and
- **Circulating nurses** managing supplies and documentation (when scrub nurses were new to the Mako, circulating nurses often guided them verbally).
- * **The anesthetist** was excluded from analysis, as they are mostly passive throughout the procedure and do not interact directly with the Mako, although their positioning occasionally influenced Mako camera placement.

It is important to note that the Mako Product Specialist (MPS) is a full-time employee of the manufacturer of the robotic system. While industry representatives are common in orthopedic theaters, the MPS role is distinct in its scope and intent. Unlike traditional

Table 1: Overview of observed procedures with the Mako robotic system

Number	Type of Makoplasty	Duration
Pilot 1	Right TKA	95 minutes
Pilot 2	Left PKA	60 minutes
3	Left TKA	93 minutes
4	Right THA	99 minutes
5	Right THA	110 minutes
6	Left TKA	115 minutes
7	Left TKA	110 minutes
8	Right TKA	85 minutes
9	Right PKA	75 minutes
10	Right TKA	130 minutes
11	Right TKA	75 minutes
12	Left THA	120 minutes
13	Right THA	140 minutes
14	Right THA	110 minutes
15	Left THA	128 minutes

implant representatives who often advise on inventory to influence component selection, the MPS has no commercial remit regarding the implants used during the procedure. Instead, their role is strictly operational, focusing on the technical setup and smooth functioning of the robotic system to support the surgical team.

While the operating theaters at this hospital had slightly varying layouts, the positioning of the Mako system was broadly consistent across rooms. In THA (Fig. 4), the surgeon and robot were positioned on opposite sides of the patient.

In contrast, in TKA procedures, the surgeon and Mako are placed on the same side of the patient. For both TKA and THA, the configuration was mirrored depending on the patient's operative side (Fig. 5), ensuring optimal ergonomics and access to the surgical site.

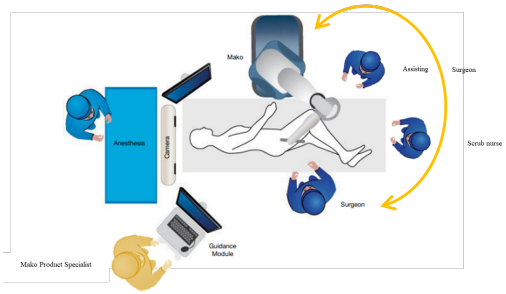


Figure 4: Operating theater layout example of a Mako-assisted right hip replacement, adapted from: Stryker Inc. [Public Domain], via Mako THA Application User Guide, Stryker. (Note: The labels 'Mako Product Specialist', 'Scrub nurse', 'Assisting', 'Surgeon' were overlaid on the original image from the doc).

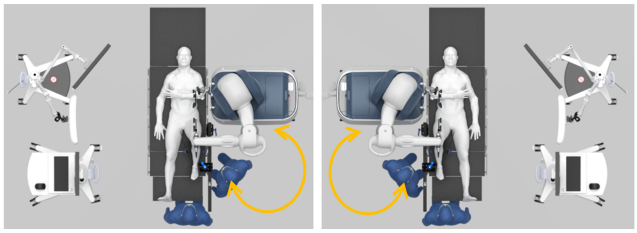


Figure 5: Surgeon and Mako on opposite sides of the operating theater [Public Domain], via Stryker Inc. (Mako TKA Application User Guide, Stryker). In contrast, for TKA procedures, the surgeon and Mako are placed alongside each other on the same side of the patient. For both TKA and THA, the configuration was mirrored depending on the patient's operative side (Fig. 5), ensuring optimal ergonomics and access to the surgical site.

3.3 Data collection

Conducting observations in the operating theater required careful navigation of a densely populated, high-stakes environment. The sterile field around the patient was strictly off limits to non-sterile staff, and maintaining awareness of this boundary was essential to avoid contamination. This virtual boundary meant learning where to stand, how to move in step with the surgical flow, and when to engage without causing disruption.

Under our ethics agreement with the hospital (`HREC_24-07_ABUR`), no video or audio recording was permitted in the operating theater. Written informed consent was obtained from patients before observation. Being physically present in the surgical space presented distinct challenges: theater layouts were crowded with people, equipment, and cables, and movement had to be carefully coordinated with the rhythms of the procedure. We learned to read both explicit and implicit cues from staff to navigate the space, moving only when necessary and positioning ourselves to minimize disruptions to the workflow. Our early pilot sessions were critical in this regard. We entered the field as outsiders to clinical practice, and these initial cases allowed us to gradually build a working understanding of theater norms, etiquette, and timing. In the early stages, we "proceeded with caution in all things," learning progressively how to orient ourselves, when it was appropriate to move, and when to ask clarifying questions. These early experiences were captured in our pilot observations, which also helped refine our data recording structures.

Observations were typically conducted by two researchers (see Fig. 6). To manage the constraint of having only two observers in the theater at a time, we coordinated roles to minimize crowding and reduce the risk of infection. One focused on detailed note-taking of interactions, teamwork, and role negotiation, while the other focused on spatial dynamics, positioning, and the flow of people and equipment around the theater. After each procedure, we compared and discussed our notes, highlighting notable moments, clarifying uncertainties, and identifying emerging patterns. Where appropriate, we were able to ask clarifying questions in the theater, for example, about why a particular action was taken or to confirm the steps of a procedure.



Figure 6: *Left*: two members of the research team (left and middle) and a Mako Product Specialist (right). *Right*: the Mako Robotic Arm covered in a protective drape.

After the surgeries, where possible, we conducted 10 informal interviews with surgical staff comprising three surgeons, four MPSs, and three scrub nurses (Table 2). These conversations were typically held immediately after surgery in the break room, a setting that allowed participants to reflect on the case while it was still fresh in their minds and provided a natural context for debriefing. Unlike the operating theater, where opportunities for dialogue are limited, the break room created an open and relaxed space in which participants could share their perspectives. Following Pelikan et al. [41], we employed informal interviews to capture the personal reflections of surgical staff, complementing our own "outsider's" observational perspective. These interactions were unstructured and conducted without a formal guide. Instead, they served as opportunistic debriefings, allowing us to clarify specific moments from the surgery or discuss broader experiences staff had encountered in other hospitals. For instance, these conversations were crucial for identifying critical workflow disruptions that occur frequently but we only observed once or twice during our specific observation windows. Finally, in these informal interviews, staff would share which moments introduced strain (both of physical and cognitive) and how they experienced it.

We observed various surgical team configurations and noted significant differences in the familiarity of surgical actors (surgeons, MPSs, and nurses) with the Mako. We summarized participants' experience levels in Table 2, distinguishing between high, intermediate, and low familiarity with Makoplasty. These categories are indicative rather than absolute, since even within a single year, surgeons or staff may participate in hundreds of procedures. Interestingly, we observed N_2 and N_3 working with the Mako for the first time, offering a striking contrast with N_1.

The interviews clarified and expanded on our observations, focusing on how different Mako components (e.g., the robotic arm, foot pedal, display screen, probe, and main body) influenced movement in the theater, impacted workflow, and affected ergonomics in tasks we had observed as either alleviating or burdening. We also inquired about teamwork, examining how the Mako influenced coordination between surgical roles. These practitioner perspectives often complemented our "outsider looking in" view, contributing to a more holistic understanding of HRC teamwork in Makoplasty.

Table 2: Informal interviews conducted with surgical staff in the break room. Familiarity: High > 2 years; Intermediate = 1–2 years; Low < 1 year.

Role	Familiarity	Identifier
Surgeon	High	S_1
Surgeon	Low	S_2
Surgeon	Intermediate	S_3
Mako Product Specialist	Intermediate	MPS_1
Mako Product Specialist	High	MPS_2
Mako Product Specialist	High	MPS_3
Mako Product Specialist	Intermediate	MPS_4
Scrub Nurse	High	N_1
Scrub Nurse	Low	N_2
Scrub Nurse	Low	N_3

Observational notes were recorded in a structured spreadsheet organized by surgical phase and by Mako-related tasks (see Fig. 7). We adopted three broad phases (pre-operative, intra-operative, and post-operative), drawing on how surgical staff described the flow of a typical Makoplasty. Pre-operative tasks encompassed preparatory steps such as patient positioning, registration, and planning (Fig. 1a-d); intra-operative procedures involved bone resection and implant placement (Fig. 1e-f); and post-operative tasks included closure steps, such as suturing and cleaning the Mako for the following procedure. This framing enabled us to capture not only the procedural sequence but also to identify when and how HRC became most salient across different stages of surgery.

These notes, together with interview summaries, directly informed the development of ethnographic vignettes. For example, the informal interviews helped add the personalized perspectives of how surgical staff experienced the key moments we outline in the vignettes. By "vignettes" we refer to short, narrative accounts that



Figure 7: A screenshot of the structured spreadsheet used for observational notes, organized by phases (e.g., Phase 1: Pre-Op), division, description, time, and notes.

reconstruct specific scenes in the operating theater, foregrounding the embodied practices, tacit cues, and spatial negotiations through which collaboration was enacted. In the Findings section, we use these vignettes to illustrate how ensemble HRC unfolded in practice.

We acknowledge that our presence may have influenced participant behavior; a phenomenon known as the Hawthorne or observer's effect [22]. However, from a constructivist stance, such influence is not considered a threat to validity. Instead, interactions between observers and participants are seen as part of the process of co-constructing the reality being studied. Over time, staff became more accustomed to our presence and shared more openly, offering context and narrative detail that enriched our understanding. Our position as outsiders to clinical work shaped what we attended to, such as coordination, ergonomics, and role negotiation, rather than clinical outcomes. We view this positionality as a strength, as it enabled a complementary lens on collaboration that may be taken for granted within routine clinical practice; further reflections on the challenges of conducting this kind of in-situ research are presented elsewhere [63]. Consistent with Monahan and Fisher [40], we consider that even when participants adapt their behavior in response to being observed, these performances can reveal profound truths about the social and cultural dimensions of teamwork in Makoplasty surgeries.

3.4 Researchers' Positionality

Before presenting the findings, it is necessary to clarify the research team's positionality. This study emerges from a collaboration between a university research center and an industry partner specializing in the manufacturing of hospital products and equipment, including orthopedic robotics. While the partner organization was instrumental in facilitating access to the surgical site and providing technical context, they held no influence over the data analysis or the interpretation of the findings presented in this work. To ensure a holistic interpretation of the data, the research team combines diverse disciplinary lenses. The primary author has a background in social science, supported by co-authors specializing in design, systems engineering, and medicine. This interdisciplinary approach allowed the team to interrogate findings from clinical, technical, and human-centric perspectives. As part of the research team, which had no clinical background, significant efforts were made to understand how the Mako robot functions in joint replacement surgeries. This included reviewing prior literature, analyzing available videos of the Mako robot in surgery, and conducting a demo session with the industry partner, during which the research team gained hands-on experience with the Mako robot in a simulated environment (as depicted in Fig. 3).

3.5 Data Analysis

Data were analyzed using Socio-Technical Grounded Theory (STGT) [22], an inductive, data-driven approach designed for contexts in which social and technical systems are tightly coupled. We applied STGT's basic stage with an orientation toward documenting the mundane practices of Makoplasty surgeries, rather than focusing solely on exceptional events. Fieldnotes and informal interview summaries were open-coded into coherent segments of text (meaning units) that each captured a single idea, action, or observation. These units were then assigned descriptive codes that captured actions, interactions, spatial arrangements, challenges, and Mako-related tasks. Reflexive memos recorded emerging connections and prompted deeper inquiry.

To analyze our data, we constructed ethnographic vignettes, drawing inspiration from Pelikan et al. [41] and Cheatle et al. [14] and broader methodological discussions on vignettes as an ethnographic subgenre [10]. These vignettes were grounded in field observations and interview notes. Each vignette reconstructed a specific scene in chronological order, capturing spatial relations, tacit cues, embodied practices, and temporal rhythms. What makes these vignettes ethnographic is their close attention to lived detail and context, rather than abstracting observations into thematic summaries. We used vignettes as both analytic and communicative devices, a way to surface dynamics of collaboration that might otherwise remain opaque to those outside the surgical domain. In interpreting these vignettes, we drew on Hirschauer's [21] *conceptualization of the manufacture of surgical bodies* to frame how robotic integration reconfigures aspects of surgical practice compared to non-robotic cases.

Guided by STGT, we compared codes across procedures using constant comparison to identify similarities, differences, and anomalies in how surgical staff interacted with the Mako. Through iterative discussions, we refined categories related to teamwork, tool use, and spatial coordination. By combining vignettes and STGT, our analysis preserved the contextual richness of ethnography while offering a systematic framework for abstraction. While STGT supports eventual theory generation, we present situated findings here aimed at advancing the understanding of surgical HRC as a multi-actor ensemble.

4 Findings

In this section, we present our findings as immersive vignettes that capture moments where Human-Robot Collaboration (HRC) unfolds between surgical team members and the Mako robot. We organize these vignettes chronologically, following the surgical flow from preparation to closure. First, we focus on pre-operative tasks that prepare both the patient and the robot. Second, we examine alternative versions of the cutting phase, contrasting the tactile and ergonomic differences between cutting in TKA/PKA and reaming in THA. Finally, we turn to post-operative tasks that occur once the bone work is complete.

4.1 Pre-operative HRC teamwork in Makoplasty

In addition to traditional pre-operative tasks such as positioning the patient, verifying equipment, and preparing the sterile field, Makoplasty introduces additional steps that integrate the robot into the surgical plan and sterile environment. The Mako must first be informed of the patient-specific plan (Vignette 1A) so it can accurately constrain and guide the surgeon's movements during cutting (Vignette 2A) or reaming (Vignette 2B). It must then be dressed to enter the sterile field (Vignette 1B) and precisely registered to the patient's anatomy within space (Vignette 1C). Based on our fieldnote descriptions, we created three vignettes that set

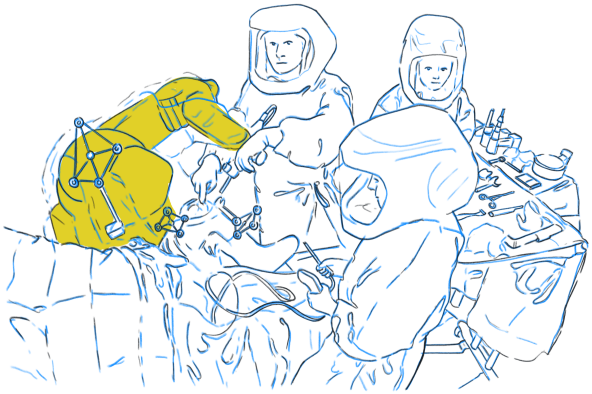


Figure 8: In Makoplasty, the team within the sterile field (typically one robot, two surgeons, and one scrub nurse) works closely together at the intersection of technical, clinical, and sterile boundaries, while overseen by the Mako Product Specialist outside of the sterile field (they are not depicted in this illustration by authors).

the scene and illustrate how HRC is performed in these moments of preparation. These interactions involve not only the surgeon but also the Mako Product Specialist (MPS), the robot, and the scrub nurse, revealing a multi-actor choreography in which technical, clinical, and sterile boundaries intersect (as seen in Fig. 8).

4.1.1 Vignette 1A: Reviewing the Plan.

The surgeon steps into the theater, not yet scrubbed. At the console, the MPS waits with the patient's joint turning on the screen. In the screen, the patient arrives as a geometry, disciplined and still, a person translated into planes, axes, and tolerances. As on the ward, where bracelets are checked and gowns replace clothes, the person is readied to be an object of care. They lean in together. "Any concerns?" "The patient is very muscular," the MPS says, and that is enough. The phrase carries what both already know about how the work will feel. The overlays the surgeon prefers come up. The MPS traces cut lines, pauses at familiar landmarks, and lingers at the edges where decisions tend to slow. The plan shifts by small degrees to maintain the alignment the surgeon favors. No one spells it out. The shorthand is practiced and built across many cases.

They hold the view for a moment longer. Craft and responsibility travel together here. The surgeon remains the final arbiter; yet, the plan is a shared work. A nod. "Let's go with this." The MPS saves the plan. The surgeon turns toward the scrub room. On the monitor, the patient-object holds steady, mapped and waiting, until the work flows from model back into flesh.

Planning is a shared craft in which the digital patient stands in for the person, aligning with Hirschauer's account of the body readied as an object of care [21]. Surgeons described this step as a brief "formal check," which is valuable mainly when the MPS flags expected deviations, such as high bone density. Several surgeons noted that they reserve the right to change later, which places this review as an anticipatory briefing rather than a final lock. MPSs emphasize that repeated pairings make conversations increasingly clinical in tone and content, allowing them to discuss approach rather than mechanics. The main responsibility remains with the surgeon, yet parameter tweaks and anticipatory positioning by the MPS make the plan a jointly produced artifact. Trust operates as an efficient device that enables the ensemble to move seamlessly from plan to field without losing tempo.

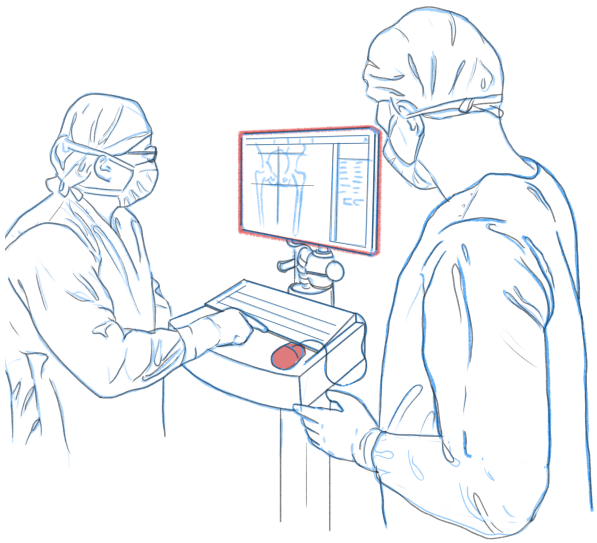


Figure 9: Vignette 1A: Surgeon and MPS review the 3D model of the patient's bone using the Mako software (illustration made by authors).

4.1.2 Vignette 1B: Draping and Arm registration.

The surgeon and assistant return with hands held close, sleeves high, ready to keep the field clean. The triangle forms around the table; the surgeon and assistant at opposite sides of the base, and the scrub nurse at the end, near the patient's feet, passing steel and suture with practiced economy. On the patient, the work has begun. Skin opened. Arrays secured like small flags that will later be read. The body is present, yet ordered, readied as an object of care. The scrub nurse steps out of the triangle with a folded drape lifted like a gown. New to Mako, eyes flick to the MPS. They move together toward the robot. The scrub feeds the drape over the arm, finding the sleeve by feel, not unlike threading an arm through a T-shirt sleeve. From beneath, the MPS takes the same fabric, so sterility holds. Four hands, two sterile and two not, circle the machine. The elbow is covered. Joints and cables disappear.



Figure 10: Vignette 1B: *Left*: MPS and scrub nurse draping. *Right*: scrub nurse registering Mako arm (illustrations made by authors).

The robot is dressed. "Hold it up so it can see you," the MPS says, and steps to the camera. The scrub guides the draped arm into position. On the screen, a sequence appears. Hold. Tilt. Rotate. The scrub follows the instructions, points the arm toward the lens, and waits for the tone. It does not come. A small red mark blinks. The MPS crosses back, adjusts the camera head by a finger's width, returns to the scrub, and checks the image on the screen. Try again. Hold. Tilt. Rotate. The failure chime sounds once more. Minutes turn heavy. Back to the camera. Back to the arm. The instructions are clear and direct, attempting to travel between unsterile and sterile territories, and still, the cues are misaligned. Across the room, the surgeon stands with arms folded, eyes fixed on the robot, their bodies poised at the edge of motion. The choreography pauses. Rhythm thins to a single step repeated. Then it lands. A soft click. Red turns green. The arm is registered. Breath returns to the room. The scrub nurse slides back into the triangle. The MPS lifts its eyes to the screen, satisfied. Robot clothed. Camera aligned. Partner ready. The work can move again.

Draping and registration expose layered boundaries in co-located HRC: sterile and non-sterile, human and machine, seeing and being seen. The scrub and MPS choreograph across these boundaries to preserve sterility while clothing the robot. When registration fails, the ensemble's dependencies become visible. The scrub nurse above reported feeling pressure from the delay and worked to regain rhythm over the next steps. MPSs noted that early misalignment can cast a long cognitive shadow, illustrating how a misstep can reverberate through subsequent steps in the procedure. Such moments make evident the importance of clear prompts, teach-backs, and gentle corrections when experience levels with the robotic system differ within the team. The shift from red to green is both a technical confirmation and a social resynchronization.

4.1.3 *Vignette 1C: Capturing Landmarks.*

The MPS swings the camera back toward the table. Arrays stand tall from the field like small flags, ready to be read. The surgeon glances down, finds the foot pedal the MPS placed earlier by the left heel, and settles their stance. "Ready?" "Yeah." On the screen, the digital joint waits, studded with circles, bubbles to be popped. The surgeon takes the probe. The gaze lifts from bone to monitor. Point to point, the tip meets bone, and the foot presses down to lock the choice. A bright chime answers. Another point, another chime. The mapped body and the present body begin to coincide. From the console, the MPS keeps pace, moving the software along on the surgeon's behalf. Prompts open and close. Frames advance. Nothing breaks the sterile line. The surgeon asks to retake one point. Granted. The bubble returns. Tap, press, chime. The cloud of landmarks fills in, a pattern the robot can learn. A few points emerge for double-checking. Back they go, steady and quick. Tap, press, chime. Green replaces gray. The model settles over the patient like a transparent mold. Surgeon and robot now share the same map. The stage is set for the cuts.

Landmark capture is where co-location becomes fully visible. The surgeon's body acts as the sensing instrument while the MPS advances robotic software from beyond the sterile field. Surgeons reported rapid mastery of the landmarking sequence and, with experience, judiciously skipped landmarking prompts that did not increase confidence, an example of socio-technical tuning for pace without sacrificing accuracy. In ensemble terms, this step establishes the shared reference frame that governs all subsequent actions and rehearses how control, verification, and responsibility will be allocated. Planning becomes a shared artifact shaped by tacit shorthand, the sterile field is extended to the robot through negotiated boundary work, and digital and physical frames are aligned through embodied calibration. Trust functions as an operational resource that enables compressed communication and efficient role coordination. As such, we observe that individual factors play a crucial role, including experience levels with the Mako and the degree of rapport developed through collaboration. In the operating theater, overcoming these different levels of experience with a specific robotic system requires effective communication, especially when bridging sterile and spatial constraints. Effective training programs at a hospital level can also support this.

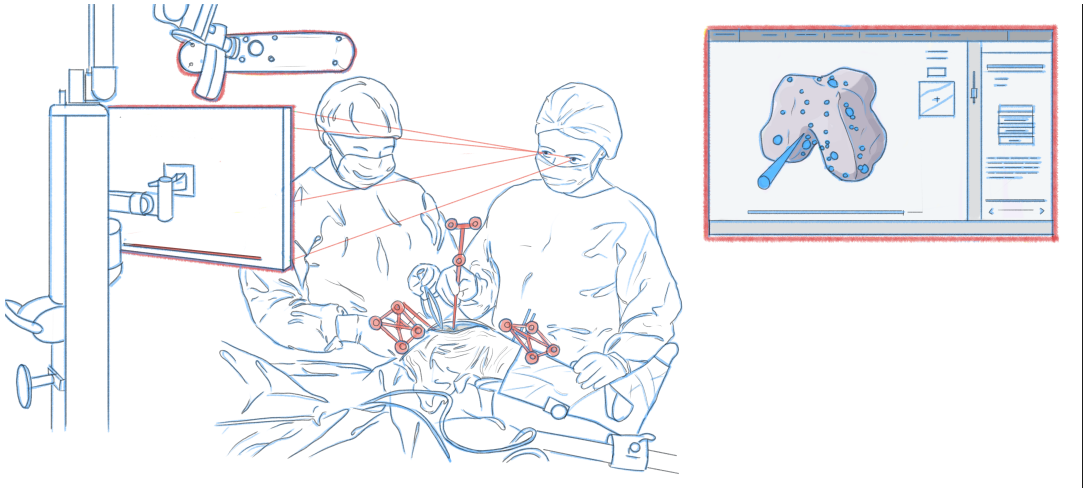


Figure 11: Vignette 1C: Surgeon capturing landmarks using a probe and looking at the monitor (illustration made by authors).

4.2 Intra-operative HRC teamwork in Makoplasty

If the pre-operative phase sets the map, the intra-operative phase puts it in motion. Here, human and robotic actors work in the closest possible coupling: the surgeon's hands on the tool, the Mako's haptics or locks constraining motion, and the MPS monitoring bounds, sequence, and alignment. These are the moments when the choreography of care shifts from preparation to performance, and where precision, ergonomics, and trust are most tightly interwoven. In this section, we present two vignettes from the cutting stage: one from a TKA procedure (Vignette 2A) and one from a THA procedure (Vignette 2B). While both involve aligning the physical cut with the digital plan, they differ in terms of tooling, visibility, and bodily demand. By contrasting them, we show how HRC teamwork adapts to the physical affordances and constraints of each surgical context, revealing the flexibility of ensemble coordination across varied tasks.

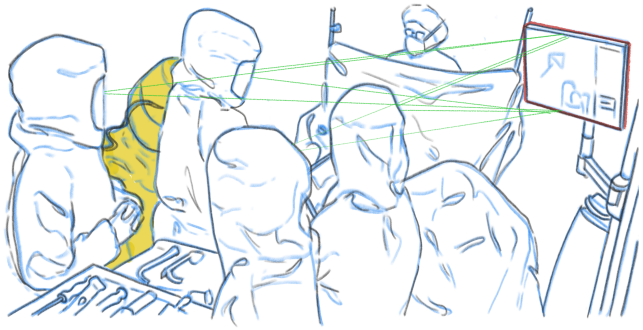


Figure 12: As the team prepares for the cuts, eyes turn to the shared display; aligning both human and robotic intent towards a shared goal (illustration by authors).

4.2.1 *Vignette 2A: TKA cutting.*

It is a matter of placing everyone where they can see and be seen. Navigating the many people, machines, and cables populating the operating theater. The Mako arm, draped and ready, comes within arm's reach of the surgeon. The assistant shifts back to clear the line between surgeon and robot, a path left open for sight and signal. The scrub nurse settles to one side. Headphones are lifted over the surgeon's cap. A slight bend at the neck. Ready.

Steel meets mapped bones. Within the haptic bounds, the blade begins to sing, skimming along the surfaces positioned in planning, removing what the model and the body agree must go. Chips rise, fine as dust, and the tool vibrates with the density they expected. The leg shivers against the cut. The assistant steps in, steadying the limb so that the tremor subsides. The monitor holds its picture of the joint, the cursor tracing along the colored planes, while the surgeon works by feel and sight together. Their glances cross, brief and sufficient. The MPS keeps the sequence moving, confirms the angles in view, and watches the limits that protect healthy bone. The surgeon follows the plan through its set of adjustments, making small changes in the wrist to stay true when the body pushes back. Trust underwrites each motion, the kind built from many cases, spoken in few words and short looks through clear shields. The noise falls away. The blade lifts. The outline on the screen matches the outline in the wound. Planned and present settle into each other. The MPS logs the step. The assistant eases their hold. The surgeon nods once. The arm rests, satisfied, its job done.

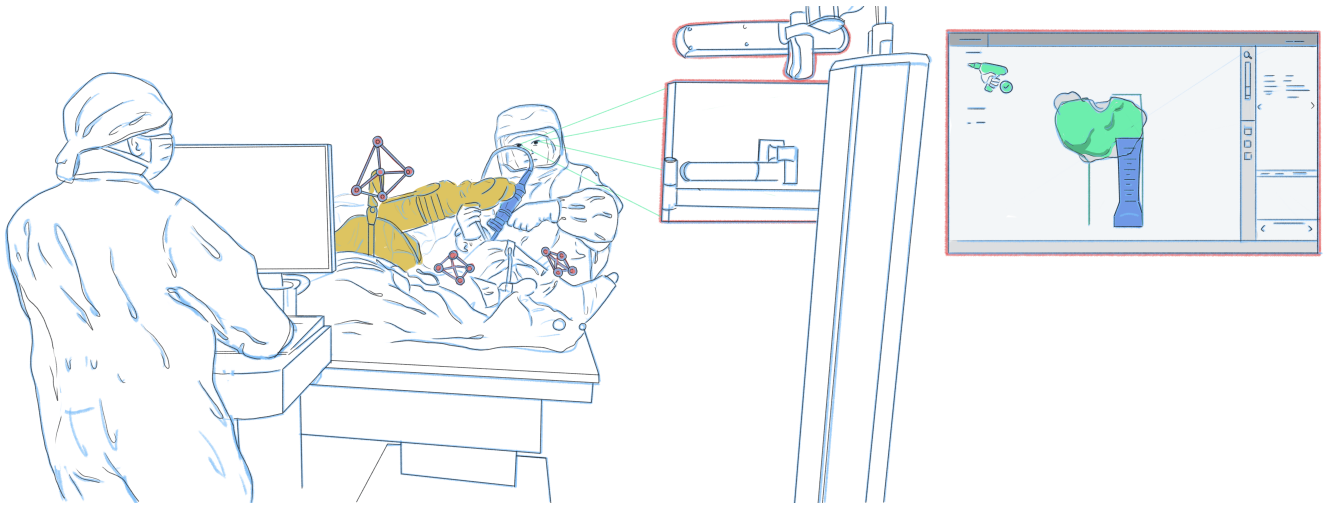


Figure 13: Vignette 2A: Surgeon physically manipulates the Mako arm to perform the cuts as planned (Fig. 1) on the monitor (illustration made by authors).

TKA cutting reveals a multi-actor feedback loop. Haptic limits guard healthy bone, while the surgeon blends tactile and visual cues. Surgeons explain their strong screen focus as an efficiency gain that complements their sense of touch. When arrays are occluded by blood, motion stops by design, and the team orients to the MPS for rapid diagnosis and reset. When vibration threatens precision, the assistant's stabilizing hands close the loop, providing an embodied safeguard that dyadic models overlook. Trust enables swift, almost wordless corrections: the monitor renders the surgeon's actions transparent, allowing others to see when the rhythm falters and anticipate the next move.

4.2.2 *Vignette 2B: THA reaming.*

> *Elsewhere on the list, in a different theater, the same step arrives in a different key. The plan must meet the body again, finding its way through the convoluted operating theater, but here the robotic arm carries a reamer, not a blade. "Is the robot ready to rock and roll?" The MPS nods. "Reamer is a bit dull." A shared glance. They both know what that will mean at a deeper level. "Unlock." The arm frees. The surgeon guides the tool into the wound, sets the angle, and then says, "Lock." The arm holds its line. On the monitor, the hemispherical outline waits, a hollow to be made until model and acetabulum coincide. The reamer blocks the view below the drape, so sight shifts to the screen. Numbers climb. The numbers turn from gray to green as the depth approaches the planned. The hum thickens. The surgeon works with both hands in awkward grips, one on the yoke and one near the elbow of the arm, with shoulders tight. The MPS keeps the sequence alive and watches the bounds. Progress slows against dense bone. "Could you take over for a sec?" The assistant steps in, carries the load, presses through the stall until the surgeon glances up and gives a small yes. The arm eases back. The reamer comes off. The impaction cup goes on. Back into the wound. Hammer lifted. Hammer down. Each strike sends a report across the room. Strike. Check. Strike. Check. "Yeah, I am happy with this." The cup sits true. The arm unlocks and is drawn away. Partner excused. The scene returns to hands, steel, and the mapped body now taking shape in bone.*

THA reaming shares the same structural goal of plan-to-bone alignment yet redistributes effort through different tooling and visibility. A "slightly dull" reamer becomes a forecast of greater force and prolonged time. Surgeons described fatigue points during depth work and the need to hand off to assistants. Several noted that impaction is loud and physically demanding, which shifts more attention to the display. Here, the MPS maintains sequence and bounds while the surgeon and assistant exchange control to manage load. Roles adapt in flight to keep progress and geometry in register.

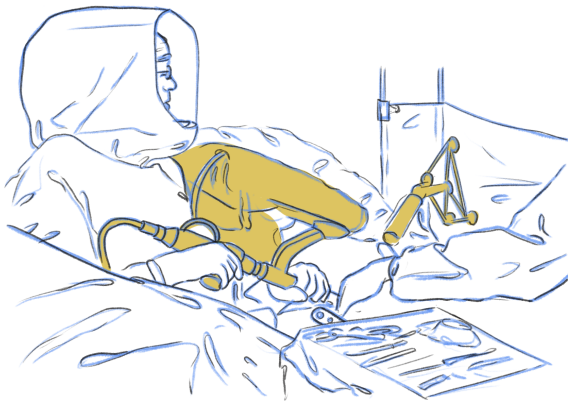


Figure 14: Vignette 2B: Surgeon uses both hands to perform the reaming in THA (illustration made by authors).

Across TKA and THA, intra-operative HRC is a dynamic ensemble. The robot's constraints form one part of a control system that also depends on human sensing, judgment, and physical intervention. Trust, tacit signaling, and quick role adaptation maintain alignment between plan and anatomy under changing physical and temporal pressures.

4.3 Post-operative HRC teamwork in Makoplasty

Once bone work is complete, Makoplasty transitions into a phase where the robot's role shifts from active cutting or reaming to supporting verification, trialing, and final implantation. Here, collaboration is less about shared manipulation of the surgical tool and more about coordinating information, components, and timing across the ensemble. The surgeon, MPS, and scrub nurse adjust their roles to ensure that implants are selected, positioned, and secured in line with both the pre-operative plan and intra-operative realities. Following this, the team dismantles the robotic setup and restores the theater to a ready state for the following case.

In this section, we present two vignettes from the post-operative stage. The first (Vignette 3A) focuses on trialing and implantation, where decision-making flows shift between human and robotic actors. The second (Vignette 3B) examines closure, highlighting the often-invisible infrastructural work required to reset both the robot and the operating theater for future procedures.

4.3.1 *Vignette 3A: Trialing & Implantation.*

The robot rolls back to the edge of the scene. The monitor stays, a bright witness at the shoulder of the table. The MPS turns to the scrub. Implants are theirs to steward. "Do you still want the same size?" "Yes, and bring me a size up as well, please," the surgeon says, eyes still on the field. The MPS slips into the hallway, returns with the implant boxes (sealed packs of components), holds the labels high for a quick check, and passes them across the sterile boundary to the scrub. The scrub peels back the foil seals and opens the sterile trays with a click, laying out the metal trial parts that will be briefly inserted to check fit. Steel changes hands. Trial components seat. The leg is lifted and translated, flexed and extended, rotated and held. The surgeon watches the screen while moving the limb, bringing the patient's body to meet the digital plan rather than the other way around. Lines steady. Offsets settle. For the first time, the MPS awaits additional information from the surgeon on the patient's body, rather than the other way around, bounded by what the camera can see; the surgeon's hands supply the missing measure. MPS asks: "how does it feel? Are you happy with that?"

Trials come out. Finals go in. The MPS calls the next size, fetches, and transfers. The scrub opens and loads. The surgeon sits and checks, eyes flicking to the monitor after each step. Surgical actors dancing around the space, navigating the machines and wires, serving as the surgeon's body, all while the robot stands watching idly.

Here, "boxes," "foil seals," and "trays" refer to sterile-packaged implant components that are opened and staged at the sterile boundary, making material handling and handover rhythm central to keeping the case moving.

Trialing and implantation invert information flow. The surgeon becomes the MPS's sensor, providing tactile and spatial feedback that the camera cannot capture. The MPS manages logistics and software checks while the scrub coordinates tools and components. Decision rights return to surgical authority, yet the robot continues to structure movement, timing, and checks from the periphery. Teams described this moment as a hinge where the ensemble either loops back for refinement or commits forward.

4.3.2 *Vignette 3B: Closure.*

The rhythm softens. Each actor turns to their part. At the table, the surgeons stitch, hands small and steady, the talk light again. A weekend plan. A story half told. Skin meets skin, and the line closes. The scrub nurse moves through the field with practiced calm. Drapes come off and go into bins. Sharps into the right tray. Swabs and towels counted back, voice low and exact. Count correct. Instruments nested and ready for sterilization. The MPS gathers the scattered traces of the robot's role. Foot pedal lifted from the floor. Case saved. Software closed. Camera hood wiped. Arm joints and housings are cleaned, and the cables are coiled and set aside. The screen returns to its home view. The machine rests. Monitors quiet. The arrays are removed. The mapped body on the display fades while the patient on the table becomes a person again. Sheets are drawn up. The room sheds its urgency. One last look around. The triangle fully disperses. The MPS checks the cart and wheels the arm to its mark for the following list. Another theater, another team, another body to translate. The choreography of care resets.

Closure disperses tight coupling into parallel strands of work. The maintenance and reset that follow are infrastructural supports for future HRC. Surgeons complete suturing, scrubs restore sterile order, and the MPS returns the robot to baseline. Teams described this routine as the quiet backbone of reliability that keeps lists on time and the following case ready.

Across all phases of Makoplasty, from planning and draping to cutting, implantation, and closure, HRC emerges as an ensemble performance shaped by spatial proximity, mutual visibility, and role interdependence. The vignettes show how collaboration is enacted through tacit shorthand, boundary work, embodied calibration, adaptive role shifts, and infrastructural maintenance. These practices maintain surgical rhythm, facilitate rapid problem-solving, and ensure alignment between the digital plan and the patient's anatomy under changing conditions. In addressing our research question, we find that HRC in Makoplasty is not a static configuration of surgeon and robot, but a fluid, multi-actor choreography that adapts to the affordances, constraints, and contingencies of the operating theater. The following discussion examines how these findings extend current understandings of co-located surgical HRC and consider their implications for the design of surgical robots and the teams that work with them.

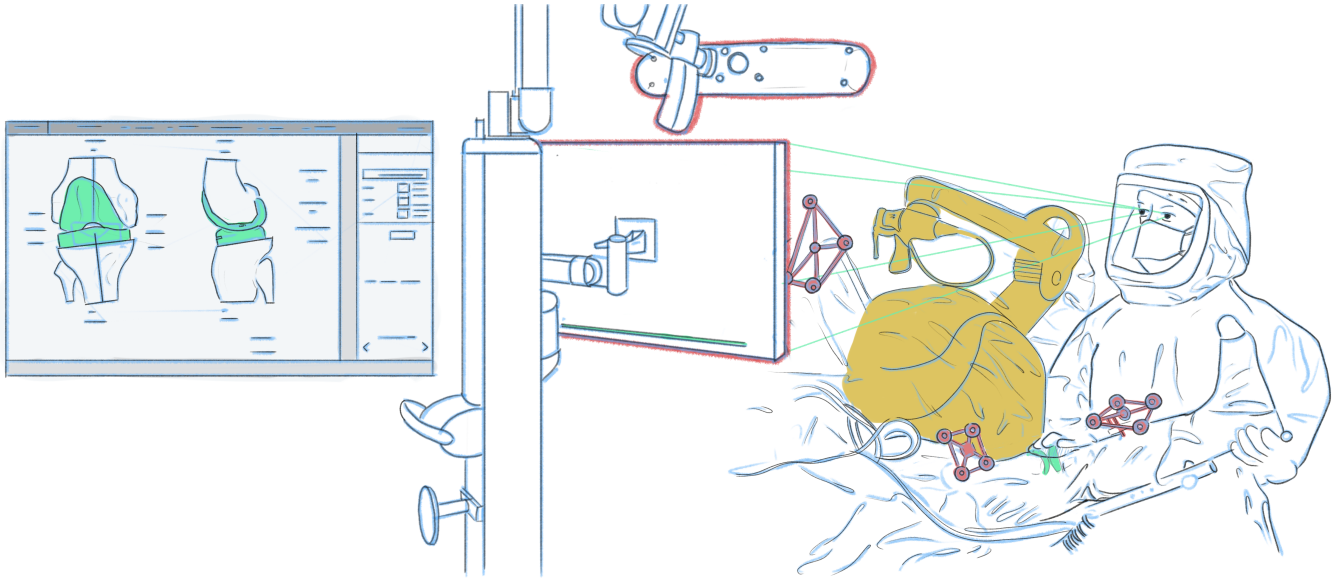


Figure 15: Vignette 3A: Surgeon manipulates the leg to assess how the implant sits within the patient's joint (illustration made by authors).

5 Discussion

Our study addresses the question: *How is Makoplasty teamwork enacted as an ensemble form of Human-Robot Collaboration in a co-located operating theater?* We argue that Makoplasty exemplifies HRC as an ensemble practice, in which collaboration is not only co-located but also bodily negotiated and dynamically redistributed among actors in the theater. In contrast, much of the surgical HRC literature draws on teleoperated systems, such as the da Vinci, where physical separation between the surgeon and team restructures communication channels (e.g., Catchpole et al. [12, 13], Pelikan et al. [41], and Cheatle et al. [14]). Our findings highlight how the proximity between the robot, surgeon, MPS, and scrub nurse produces a distinct choreography of care. This resonates with prior HCI work that calls for moving beyond dyadic models of HRC (Johansen et al. [29] and Jung et al. [30]). Our in-theater observations provide empirical evidence of how such ensemble coordination unfolds in real-time. Collaboration is not driven by rigid task charts but by glances, handovers, and micro-adjustments within shared space. Across phases, experience with the Mako system and rapport built over repeated pairings compress coordination, stabilize tempo, and shape who 'leads' at moments.

5.1 Delegated Responsibility

A central contribution of this study is the documentation of temporally delegated responsibility. In this arrangement, the surgeon retains ultimate accountability for patient outcomes yet temporarily cedes control to the Mako Product Specialist (MPS) during technical or robotic sequences. Rather than displacing surgical authority, responsibility is redistributed and supplemented by **robotic authority,** sustaining surgical flow and ensuring desired outcomes. What we mean by this is that, where appropriate, the surgeon turns to the MPS to draw on their robotic expertise to clarify moments where the choreography falters, including: troubleshooting relating to the hardware of the Mako robotic system (e.g., robotic arm, camera, arrays, and display) or the software, but also to discuss technical approaches. This redistribution, where the surgeon shares "authority" in this sense, illustrates how Makoplasty teamwork operates as an ensemble practice, with responsibility dynamically shared across human and robotic actors to maintain coordination and flow. This highlights how, in successful HRC ensembles across domains, human actors may hold dedicated roles based on their own experiences and expertise to complement different parts of the ensemble.

5.1.1 Phase Gating. Delegation is often aligned with the natural boundaries between surgical phases. At these junctures, responsibility was temporarily reallocated to facilitate a smooth transition into the next stage. For example, during draping, the MPS was delegated responsibility to assist and, when needed, direct the scrub nurse. Although the surgeon was not directly involved, this task ultimately supported their later work in bone resections. By anchoring responsibility to clearly defined tasks, teams reduced ambiguity over roles and made accountability more visible, reinforcing ensemble coordination.

5.1.2 Spatial Reach and Sterility. Responsibility was also shaped by physical reach and sterile boundaries. Non-sterile adjustments, such as repositioning the Mako camera or changing the software view, were delegated to the MPS, who operates these technologies outside the sterile field on behalf of the surgeon. Sterile actions, such as bone registration, remained under the surgeon's direct control. We observed scrub staff and the MPS coordinating closely during draping, with sterile and non-sterile hands moving together around the robotic arm. In these moments, delegation was determined less by expertise and more by who could act without breaking sterility

or disrupting the line of sight, illustrating how spatial constraints contour ensemble collaboration.

5.1.3 Anticipatory Delegation. Repeated pairings fostered a form of experience-conditioned anticipation. MPSs familiar with a surgeon's style preloaded overlays, staged instruments, and queued software steps before explicit requests were made. In one planning check, a surgeon's brief nod was sufficient for the MPS to finalize the plan, a moment that illustrated how responsibility could be delegated based on rapport and tacit shorthand. These anticipatory practices compressed coordination time and stabilized tempo but also relied heavily on trust built over repeated cases, underscoring the importance of ensemble members becoming familiarized with each other's robotic experience levels and workflow preferences.

Taken together, these mechanisms illustrate that delegation is not an ad hoc adjustment, but a structured, yet dynamic practice that sustains surgical rhythm.

5.2 Delegation as Ensemble Work

These observations extend HRC research, which calls for moving beyond dyads [29], by showing that control is not only shared but also conditionally delegated. What makes delegation effective is not the fallback to another actor in the event of an error, but the orchestrated redistribution of responsibility across phase boundaries, spatial logic, and accumulated collaborative experience. This reframing aligns with CSCW notions of articulation work [51, 57] and theories of distributed cognition [24, 25, 27], which emphasize how cognition and control are produced through coordinated activity across people and artifacts rather than located in any single operator. These mechanisms extend current understandings of ensemble HRC by showing that delegation is not simply a safety fallback, but an orchestrated feature of high-functioning surgical teams. This reframing echoes the emphasis on articulation work and distributed cognition in CSCW and HCI, while extending it into the domain of co-located surgical robotics. In our analysis, we observe that the Mako influences this distributed cognition in two critical areas. First, it reconfigures the theater's spatial logic into a fragile computational state. Because the system relies on a rigid registration process, the tracking arrays become critical cognitive artifacts; displacing them necessitates a complete system reset. Consequently, the team engages in a collective "spatial hygiene," managing not only their own movements but the sightlines of others to preserve the robot's visual link. This monitoring is often offloaded to the MPS, whose position outside the sterile field provides the necessary vantage point to protect the system's state while the surgeon focuses on the wound and direct manipulation of the robotic arm. Second, unlike passive imaging systems that merely *display* information [37, 39], the Mako acts as a semi-autonomous partner that physically *enforces* it. During cutting, the robot restricts the surgeon's hand within haptic bounds, effectively offloading the cognitive burden of boundary control from the human operator to the machine. This demonstrates a shift in which robotic agency actively participates in the distributed cognitive loop, correcting and constraining human action in real time. In doing so, we extend articulation work [57] and distributed cognition [24, 25, 27] into surgical HRC, showing how responsibility becomes a resource actively configured in practice rather than a static allocation of roles, and also subject to evolution over time.

5.3 Negotiating roles

Responsibility shifts sit within a broader fabric of role renegotiation that unfolds moment to moment. Because Mako couples a digital plan to physical execution, the ensemble is kept in constant alignment with work: sensing, deciding, and acting are distributed across people and machines, and are reconfigured by what the task, the room, and the tools demand. Our vignettes make visible how this distribution is accomplished in practice. During landmark capture, the surgeon's body performs sensing while the MPS advances software states, ensuring precise coordination across sterile and non-sterile roles. During TKA cutting, the assistant's stabilizing hands matter as much as the surgeon's micro-guidance within haptic bounds, closing a control loop that dyadic models cannot account for. During THA reaming, load management becomes a negotiated exchange between surgeon and assistant, while the MPS maintains sequence and limits. The note that a reamer is "a bit dull" operates as a forecast of effort, shaping how roles are pre-emptively adjusted. In troubleshooting, the MPS directs action from outside the sterile field while the scrub translates those directions into embodied adjustments. During trialing, the information flow reverses, and the surgeon becomes the MPS's sensor, supplying tactile judgments that the camera cannot capture.

5.3.1 Experience and Rapport. Two variables significantly influence the smoothness of these negotiations: experience gradients and rapport. When surgical staff are less familiar with the Mako, a greater portion of the coordination burden shifts to explicit instruction from the MPS and confirmation talk from the scrub and assistant, as seen in the registration vignette. When staff have significant experience, tacit signaling carries a greater portion of the load, enabling a faster tempo and tighter synchrony. Rapport, built across repeated cases, allows small glances and single words to stand in for longer exchanges, which in turn shortens recovery after minor breakdowns. In our observations, this often became visible in subtle anticipations: a scrub nurse already moving toward the drape before being asked, or an MPS queuing a prompt the surgeon had not yet requested. These moments showed how rapport transforms explicit coordination into tacit alignment.

5.3.2 Repercussions of missteps. Teams also described the cognitive shadow of early missteps: the residual disruption to rhythm and shared understanding that persisted after a failed registration or avoidable pause, often dragging into subsequent steps unless someone deliberately re-synchronized the ensemble. Experienced MPSs treated these shadows as part of their work, using short recaps, micro-briefings, or a deliberately slower cadence to restore synchrony. We refer to this practice as tempo repair: deliberately modulating the pace to reset the ensemble's rhythm and restore confidence. These observations reinforce HRC literature that treats the operator as plural [29, 31, 52, 54] and align with ethnomethodological accounts of coordination as sustained by mutual monitoring, local repair, and situated workarounds under time pressure [24, 45, 58]. As with the delegation mechanisms summarized in

Table 3: Mechanisms of delegated responsibility observed in Makoplasty teamwork, with definitions, empirical examples, and design implications.

Delegation mechanism	Definition	Observed in vignette(s)	Design implication
Phase gating	Responsibility shifts at natural boundaries underpinned by surgical expertise and robotic expertise, anchoring accountability and reducing ambiguity	Planning (1A), Registration (1B), Cutting/Reaming (2A/2B)	Interfaces should signal task boundaries explicitly, supporting handovers as orchestrated events rather than ad-hoc decisions
Spatial reach & sterility	Responsibility maps to those who can act without breaking sterility or line-of-sight	Draping/Registration (1B), Landmark capture (1C)	Systems should provide dual views: sterile actors need prompts embedded into tool handovers, while non-sterile actors require extended console views
Experience-conditioned anticipation	With repeated pairings, MPSs pre-stage actions in line with a surgeon's preferences; delegation happens through shorthand cues rather than explicit instructions	Planning (1A), Cutting (2A), Trialing (3A)	Interfaces could embed surgeon preference profiles and adaptive guidance modes (expanded prompts for novices; collapsed shorthand for mature ensembles)

Table 3, these negotiations rely on phase, space, and experience to structure tempo.

5.4 Tempo in HRC

Our findings extend HRC research by foregrounding tempo not merely as a metric of efficiency, but as a collective achievement. This resonates with CSCW scholarship on temporal rhythms in medical work [7, 46], which argues that time in the hospital is not just a chronological measure but an interactive accomplishment maintained through social coordination. We extend this view into the robotic theater, showing that tempo is a property of the ensemble: how quickly roles can be renegotiated, how effectively breakdowns can be repaired, and how smoothly tacit cues can replace explicit talk. While HRC literature often quantifies this as fluency, the synchronization of action between human and machine [23]; our ethnographic data reveals the invisible articulation work required to sustain it. We repeatedly saw surgeons skipping prompts or assistants steadying limbs before being asked, making tempo visible as an emergent property of the ensemble rather than an individual action. In our cases, selective skipping during landmark capture and screen-anchored attention during cuts were not shortcuts but learned calibrations of pace. These behaviors rest on a shared understanding of what the system would accept and how the team would recover if it did not. For HCI, this suggests that supporting ensemble HRC means designing for the rhythms by which multi-actor teams maintain alignment with digital plans under pressure, rather than solely optimizing the robot's speed.

5.5 Design for the ensemble

Designing only for a surgeon-robot dyad risks missing the underlying infrastructure that sustains teamwork. Our findings suggest that systems should be ensemble-ready: able to represent role, state, and handover, and adapt support to differences in experience and rapport. Consistent with prior work [12–14, 32, 41], it is evident that surgical HRC does not merely add a tool compared to non-robotic cases but reconfigures the labor of the entire room. It asks more of the team as a cohesive unit. Therefore, it is critical to design for the periphery as much as the center. Empowering not just surgeons but the entire surgical team with clearer system feedback allows them to anticipate the robot's needs, ultimately reducing friction for the surgeon.

Role-aware yet synchronized interfaces. Surgeons, MPSs, and scrub staff each require interfaces tailored to their tasks yet anchored in a shared state. For surgeons, this could mean glanceable indicators of progress and tolerances, along with prompts for arm alignment and ergonomic grip. For scrub staff, lightweight checklists can translate system prompts into sterile actions, such as which tool to pass next or when a blade or reamer is becoming too dull for smooth cuts. For MPSs, deeper diagnostics remain critical, including live feedback on registration accuracy, array fixation, arm calibration, and optimal camera positioning, enabling quick intervention if the situation changes. These role-specific views must remain synchronized to maintain a coherent picture of the procedure. As shown by Mentis et al. [37–39] in the context of co-located imaging systems, multiple monitors, positioned for both sterile and non-sterile staff, help externalize the surgeon's actions and the system state, establishing common ground across the ensemble. In line with Clark and Brennan's theory of grounding [15], such displays reinforce a shared mental model, enabling anticipation and coordination with minimal verbal exchange.

Guidance that adapts to experience. Designing for the ensemble requires systems that support the varying expertise levels of different team members, akin to the instructional practices observed by Mentis et al. [38]. When actors signal low familiarity, the system could expand micro-prompts and provide teach-back tips (e.g., Hold, Tilt, Rotate), while allowing experienced teams to collapse prompts into compact cues. Recovery playbooks for common breakdowns, such as array occlusion, should pair sterile-safe steps for scrubs with non-sterile steps for MPSs. Surgeon preference profiles could be more embedded in the software display, preloading overlays, sequences, and instruments to help other staff anticipate next steps.

Beyond screens. Ensemble performance also depends on organizational and spatial arrangements. Stable pairings of surgeon, MPS, and scrub foster trust, shorthand, and tempo, enabling actors to anticipate one another's moves. Yet, as Catchpole et al. warn [12], this anticipation is fragile. It is constrained by the physical layout of the theater, including the occlusions of machines, wires, and the complex circulation of human bodies in a crowded space.

Taken together, these implications shift the design lens from the surgeon-robot dyad to the surgical ensemble. What matters is not only the surgeon's interface but also how MPSs, scrubs, and assistants are supported in guiding, translating, and anticipating one another's actions. In high-stakes environments, collaboration endures when the system itself helps the ensemble stay in rhythm. The robot may be constant, but the ensemble is not and nor is the patient. Surgeons, MPSs, scrubs, and assistants each introduce variability through their styles of practice, compounded further by patient differences and hospital contexts. Together, these shifting conditions make Makoplasty teamwork an always-contingent achievement.

6 Limitations and future directions

This account is situated within a single hospital with a specific staffing model, case mix, spatial layout, and adoption history. For example, the teaching hospital we observed at typically has smaller rooms than other hospitals in the country. The spatial layout and room size can significantly affect how surgical staff navigate and operate within such a space. The local ecology shapes the choreography between the Mako and the surgeon, as well as between MPSs, scrubs, and assistants. Longitudinal access enabled depth yet narrowed breadth. The next step is to test transferability across hospitals with different room geometries, visibility constraints, and staffing patterns, and to compare across platforms to separate robot-specific patterns from ensemble invariants. Mixed-methods designs can link ethnographic observation to time-motion data, interaction logs, and brief post-case probes to quantify the effects of experience and rapport on tempo, interruptions, and recoveries. Moreover, formative prototyping of ensemble-ready features, such as role-aware views, adaptive guidance, recovery playbooks, and theater-wide state panels, would enable the evaluation of whether shared situation awareness improves, whether interruptions decline, and whether recovery after minor breakdowns is shortened without compromising safety. Finally, knee replacement surgery is standardized compared to procedures that rely on flexible decision-making. It would be valuable to examine these less structured contexts to understand how humans and robots adapt to surgical requirements that demand greater flexibility from the entire system.

7 Conclusion

This paper reframes surgical Human-Robot Collaboration (HRC) as ensemble work: co-located, bodily negotiated, and dynamically redistributed among the surgeons, Mako Product Specialist (MPS), and scrub nurse. Our vignettes show how collaboration persists through phase gating, spatial reach, and practiced shorthand, with responsibility delegated based on expertise and positioning in the operating theater. Experience with Mako and team rapport emerge as first-order determinants of tempo and recovery: mature ensembles compress coordination and repair slips quickly, while newer configurations rely on explicit instruction and confirmations to keep rhythm. The MPS is not peripheral, but a co-lead at the digital-physical seam, orchestrating registration, sequencing, and degraded-mode recovery. At the same time, assistants and scrubs provide stabilizing and translational functions often overlooked in dyadic accounts. For HRC theory and design, the target is the ensemble. Supporting this finding requires systems that surface role, state, and handover information, adapt guidance to the experience, and remain legible across both sterile and non-sterile positions. Organizational choices, such as stable pairing, team-based rehearsal, brief teach-backs, and room ergonomics, further amplify these capacities. By prioritizing these socio-technical dynamics, HCI research can ensure that future surgical robotic systems support the full complexity of human interdependence. Designing for the ensemble thus makes surgical precision a collective achievement of the entire team (including the robot and its specialist), embodying the challenge of "Creating Tomorrow Together" through a truly shared *choreography of care*.

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References

[1] K Abbruzzese, Z Byrd, R Smith, A Valentino, L Yanoso-Scholl, M Augustus Harrington, and B Parsley. 2020. ASSESSMENT OF SURGEON BIOMETRICS DURING MANUAL AND ROBOTIC-ASSISTED TOTAL HIP ARTHROPLASTY. *Orthopaedic Proceedings* 102-B, SUPP_1 (Feb. 2020), 101–101.

[2] Favour Aderinto, Josh Bhagat Smith, Mark-Robin Giolando, Prakash Baskaran, and Julie A Adams. 2024. Improving human-robot team transparency with eye-tracking based situation awareness assessment. In *Companion of the 2024 ACM/IEEE International Conference on Human-Robot Interaction*. ACM, New York, NY, USA, 177–181.

[3] Karyne C S Ang, Shankar Sankaran, and Dikai Liu. 2025. Advancing sociotechnical systems theory: New principles for human-robot team design and development. *Appl. Ergon.* 129, 104604 (Aug. 2025), 104604.

[4] Ignacio Avellino, Gilles Bailly, Mario Arico, Guillaume Morel, and Geoffroy Canlorbe. 2020. Multimodal and mixed control of robotic endoscopes. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA.

[5] Ignacio Avellino, Gilles Bailly, Geoffroy Canlorbe, Jérémie Belgihti, Guillaume Morel, and Marie-Aude Vitrani. 2019. Impacts of Telemanipulation in Robotic

Assisted Surgery. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19, Paper 583)*. Association for Computing Machinery, New York, NY, USA, 1–15.

[6] R Banchetti, S Dari, Maria Elisabetta Ricciarini, D Lup, F Carpinteri, F Catani, and P Caldora. 2018. Comparison of conventional versus robotic-assisted total hip arthroplasty using the Mako system : An Italian retrospective study. *J Health Soc* (2018).

[7] Jakob E Bardram. 2000. Temporal Coordination –On Time and Coordination of CollaborativeActivities at a Surgical Department. *Computer Supported Cooperative Work* (May 2000).

[8] Shreyas Bhat, Joseph B Lyons, Cong Shi, and X Jessie Yang. 2024. Evaluating the impact of personalized value alignment in human-robot interaction: Insights into trust and team performance outcomes. In *Proceedings of the 2024 ACM/IEEE International Conference on Human-Robot Interaction*. ACM, New York, NY, USA, 32–41.

[9] Ann Blandford, Erik Berndt, Ken Catchpole, Dominic Furniss, Astrid Mayer, Helena Mentis, Aisling Ann O'Kane, Tom Owen, Atish Rajkomar, and Rebecca Randell. 2015. Strategies for conducting situated studies of technology use in hospitals. *Cogn. Technol. Work* 17, 4 (Nov. 2015), 489–502.

[10] Anna Bloom-Christen and Hendrikje Grunow. 2024. What's (in) a vignette? History, functions, and development of an elusive ethnographic sub-genre. *Ethnos* 89, 5 (Oct. 2024), 786–804.

[11] Emily K C Bullock, Michael J Brown, Gavin Clark, James G A Plant, and William G Blakeney. 2022. Robotics in Total Hip Arthroplasty: Current Concepts. *J. Clin. Med. Res.* 11, 22 (Nov. 2022).

[12] Ken Catchpole, Ann Bisantz, M Susan Hallbeck, Matthias Weigl, Rebecca Randell, Merrick Kossack, and Jennifer T Anger. 2019. Human factors in robotic assisted surgery: Lessons from studies 'in the Wild'. *Appl. Ergon.* 78 (July 2019), 270–276.

[13] Ken Catchpole, Tara Cohen, Myrtede Alfred, Sam Lawton, Falisha Kanji, Daniel Shouhed, Lynne Nemeth, and Jennifer Anger. 2024. Human factors integration in robotic surgery. *Hum. Factors* 66, 3 (March 2024), 683–700.

[14] Amy Cheatle, Hannah Pelikan, Malte Jung, and Steven Jackson. 2019. Sensing (Co)operations: Articulation and Compensation in the Robotic Operating Room. *Proc. ACM Hum.-Comput. Interact.* 3, CSCW (Nov. 2019), 1–26.

[15] Herbert H Clark and Susan E Brennan. 2004. Grounding in communication. In *Perspectives on socially shared cognition*, Lauren B Resnick (Ed.). Vol. 429. American Psychological Association, Washington, 127–149.

[16] Andrew Crabtree, Mark Rouncefield, and Peter Tolmie. 2012. *Doing Design Ethnography*. Springer London, London.

[17] Pieter Duysburgh, Shirley A Elprama, and An Jacobs. 2014. Exploring the social-technological gap in telesurgery: collaboration within distributed or teams. In *Proceedings of the 17th ACM conference on Computer supported cooperative work & social computing*. ACM, New York, NY, USA.

[18] Clarence A Ellis, Simon J Gibbs, and Gail Rein. 1991. Groupware: some issues and experiences. *Commun. ACM* 34, 1 (Jan. 1991), 39–58.

[19] Andreas Fontalis, Babar Kayani, Joshua W Thompson, Ricci Plastow, and Fares S Haddad. 2022. Robotic total hip arthroplasty: past, present and future. *Orthop. Trauma* 36, 1 (Feb. 2022), 6–13.

[20] Dominic Furniss, Aisling Ann O'Kane, Rebecca Randell, Svetlena Taneva, Helena Mentis, and Ann Blandford. 2014. *Fieldwork for healthcare: Case studies investigating human factors in computing systems*. Springer International Publishing, Cham.

[21] Stefan Hirschauer. 1991. The manufacture of bodies in surgery. *Soc. Stud. Sci.* 21, 2 (May 1991), 279–319.

[22] Rashina Hoda. 2024. *Qualitative research with Socio-technical grounded theory: A practical guide to qualitative data analysis and theory development in the digital world* (2024 ed.). Springer International Publishing, Cham, Switzerland.

[23] Guy Hoffman. 2019. Evaluating fluency in human–robot collaboration. *IEEE Trans. Hum. Mach. Syst.* 49, 3 (June 2019), 209–218.

[24] James Hollan, Edwin Hutchins, and David Kirsh. 2000. Distributed cognition: toward a new foundation for human-computer interaction research. *ACM Trans. Comput. Hum. Interact.* 7, 2 (June 2000), 174–196.

[25] James D Hollan, Edwin Hutchins, and David J Kirsh. 1999. KDI: A distributed cognition approach to designing digital work materials for collaborative workplaces. *nsf* 98, 9873156 (1999), 73156.

[26] Damian Hostettler, Simon Mayer, Jan Liam Albert, Kay Erik Jenss, and Christian Hildebrand. 2025. Real-time adaptive industrial robots: Improving safety and comfort in human-robot collaboration. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1–16.

[27] Edwin Hutchins. 1995. *Cognition in the wild*. The MIT Press.

[28] Rabeya Jamshad, Arthi Haripriyan, Advika Sonti, Susan Simkins, and Laurel D Riek. 2024. Taking initiative in human-robot action teams: How proactive robot behaviors affect teamwork. In *Companion of the 2024 ACM/IEEE International Conference on Human-Robot Interaction*. ACM, New York, NY, USA.

[29] Stine S Johansen, Claire Brophy, Markus Rittenbruch, and Jared W Donovan. 2024. Characterising CSCW research on human-Robot Collaboration. *Proc. ACM Hum. Comput. Interact.* 8, CSCW1 (April 2024), 1–31.

[30] Malte F Jung, Nikolas Martelaro, and Pamela J Hinds. 2015. Using robots to moderate team conflict: The case of repairing violations. In *Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-Robot Interaction*. ACM, New York, NY, USA.

[31] Malte F Jung, Selma Šabanović, Friederike Eyssel, and Marlena Fraune. 2017. Robots in Groups and Teams. In *Companion of the 2017 ACM Conference on Computer Supported Cooperative Work and Social Computing*. ACM, New York, NY, USA.

[32] Falisha Kanji, Ken Catchpole, Eunice Choi, Myrtede Alfred, Kate Cohen, Daniel Shouhed, Jennifer Anger, and Tara Cohen. 2021. Work-system interventions in robotic-assisted surgery: a systematic review exploring the gap between challenges and solutions. *Surg. Endosc.* 35, 5 (May 2021), 1976–1989.

[33] Babar Kayani, Sujith Konan, Atif Ayuob, Elliot Onochie, Talal Al-Jabri, and Fares S Haddad. 2019. Robotic technology in total knee arthroplasty: a systematic review. *EFORT Open Rev.* 4, 10 (Oct. 2019), 611–617.

[34] B Kayani, S Konan, J R T Pietrzak, S S Huq, J Tahmassebi, and F S Haddad. 2018. The learning curve associated with robotic-arm assisted unicompartmental knee arthroplasty: a prospective cohort study. *Bone Joint J.* 100-B, 8 (Aug. 2018), 1033–1042.

[35] Solène Lambert, Sandrine Voros, Geoffroy Canlorbe, Jocelyne Troccaz, and Ignacio Avellino. 2024. Understanding takeovers and telestration in laparoscopic surgery to inform telementoring system design. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1–17.

[36] R Lunding, Tiare M Feuchtner, and Kaj Grønbæk. 2025. Investigating AR assistance for human-robot collaboration in mould assembly "in the wild". *Human-Robot Interaction* (March 2025), 540–549.

[37] Helena M Mentis. 2017. Collocated use of imaging systems in coordinated surgical practice. *Proc. ACM Hum. Comput. Interact.* 1, CSCW (Dec. 2017), 1–17.

[38] Helena M Mentis, Amine Chellali, and Steven Schwaitzberg. 2014. Learning to see the body: supporting instructional practices in laparoscopic surgical procedures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA.

[39] Helena M Mentis and Alex S Taylor. 2013. Imaging the body: embodied vision in minimally invasive surgery. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA.

[40] Torin Monahan and Jill A Fisher. 2010. Benefits of "observer effects": Lessons from the field. *Qual. Res.* 10, 3 (June 2010), 357–376.

[41] Hannah R M Pelikan, Amy Cheatle, Malte F Jung, and Steven J Jackson. 2018. Operating at a distance - how a teleoperated surgical robot reconfigures teamwork in the operating room. *Proc. ACM Hum. Comput. Interact.* 2, CSCW (Nov. 2018), 1–28.

[42] Piergiuseppe Perazzini, Michele Trevisan, Paolo Sembenini, Francesco Alberton, Mara Laterza, Alberto Marangon, and Bruno Magnan. 2020. The Mako ™ robotic arm-assisted total hip arthroplasty using direct anterior approach: surgical technique, skills and pitfals. *Acta Biomed.* 91, 4-S (May 2020), 21–30.

[43] Rohan Prakash and Yuvraj Agrawal. 2023. Robotic technology in total knee arthroplasty. *Br. J. Hosp. Med.* 84, 6 (June 2023), 1–9.

[44] David Randall, Mark Rouncefield, and Peter Tolmie. 2021. Ethnography, CSCW and ethnomethodology. *Comput. Support. Coop. Work* 30, 2 (April 2021), 189–214.

[45] Rebecca Randell, Stephanie Honey, Jon Hindmarsh, Natasha Alvarado, Joanne Greenhalgh, Alan Pearman, Andrew Long, Alexandra Cope, Arron Gill, Peter Gardner, Alwyn Kotze, David Wilkinson, David Jayne, Julie Croft, and Dawn Dowding. 2017. *A realist process evaluation of robot-assisted surgery: integration into routine practice and impacts on communication, collaboration and decision-making*. NIHR Journals Library, Southampton (UK).

[46] Madhu Reddy and Paul Dourish. 2002. A finger on the pulse: temporal rhythms and information seeking in medical work. In *Proceedings of the 2002 ACM conference on Computer supported cooperative work*. ACM, New York, NY, USA.

[47] Martin Roche. 2021. The MAKO robotic-arm knee arthroplasty system. *Arch. Orthop. Trauma. Surg.* 141, 12 (Dec. 2021), 2043–2047.

[48] John Rooksby, Timothy E Smith, Alistair Morrison, Mattias Rost, and Matthew Chalmers. 2015. Configuring attention in the multiscreen living room. In *ECSCW 2015: Proceedings of the 14th European Conference on Computer Supported Cooperative Work, 19-23 September 2015, Oslo, Norway*. Springer International Publishing, Cham, 243–261.

[49] Steve Sawyer and Andrea Tapia. 2006. Always articulating: Theorizing on mobile and wireless technologies. *Inf. Soc.* 22, 5 (Dec. 2006), 311–323.

[50] Kjeld Schmidt. 2011. *Cooperative work and coordinative practices: Contributions to the conceptual foundations of computer-supported cooperative work (CSCW)* (2011 ed.). Springer, London, England.

[51] Kjeld Schmidt and Liam Bannon. 1992. Taking CSCW seriously: Supporting articulation work. *Comput. Support. Coop. Work* 1, 1-2 (March 1992), 7–40.

[52] Eike Schneiders, Christopher Fourie, Stanley Celestin, Julie Shah, and Malte Jung. 2024. Understanding entrainment in human groups: Optimising human-robot collaboration from lessons learned during human-human collaboration. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1–13.

[53] Laura Y Scholl, Emily L Hampp, Vincent Alipit, Nipun Sodhi, Manoshi Bhowmik-Stoker, Jonathan Dropkin, Antonia F Chen, and Michael A Mont. 2022. Effect of manual versus robotic-assisted total knee arthroplasty on cervical spine static and dynamic postures. *J. Knee Surg.* 35, 9 (July 2022), 1010–1018.

[54] Sarah Sebo, Brett Stoll, Brian Scassellati, and Malte F Jung. 2020. Robots in groups and teams: A literature review. *Proc. ACM Hum. Comput. Interact.* 4, CSCW2 (Oct. 2020), 1–36.

[55] James D Sires, Johnathan D Craik, and Christopher J Wilson. 2021. Accuracy of Bone Resection in MAKO Total Knee Robotic-Assisted Surgery. *J. Knee Surg.* 34, 7 (June 2021), 745–748.

[56] J P Spradley. 2016. The ethnographic interview. (2016).

[57] Anselm Strauss. 1985. Work and the division of labor. *Sociol. Q.* 26, 1 (March 1985), 1–19.

[58] Lucy A Suchman. 1987. *Learning in doing: Social, cognitive and computational perspectives: Plans and situated actions: The problem of human-machine communication* (2 ed.). Cambridge University Press, Cambridge, England.

[59] Mason Swofford, John Peruzzi, Nathan Tsoi, Sydney Thompson, Roberto Martín-Martín, Silvio Savarese, and Marynel Vázquez. 2020. Improving social awareness through DANTE: Deep Affinity Network for clustering conversational interactants. *Proc. ACM Hum. Comput. Interact.* 4, CSCW1 (May 2020), 1–23.

[60] Angelique Taylor, Tauhid Tanjim, Michael J Sack, Maia Hirsch, Kexin Cheng, Kevin Ching, Jonathan St. George, T Roumen, Malte F Jung, and Hee Rin Lee. 2025. Rapidly built medical crash cart! Lessons learned and impacts on high-stakes team collaboration in the Emergency Room. *Human-Robot Interaction* (Feb. 2025), 501–510.

[61] Irene Tollinger, Michael McCurdy, Alonso H Vera, and Preston Tollinger. 2004. Collaborative knowledge management supporting mars mission scientists. In *Proceedings of the 2004 ACM conference on Computer supported cooperative work*. ACM, New York, NY, USA.

[62] Jasper Vermeulen, Glenda Caldwell, Müge Teixeira, Alan Burden, and Matthias Guertler. 2024. To safety and beyond! A scoping review of human factors enriching the design of human-Robot Collaboration. *IxD&A* 61, 61 (June 2024), 42–65.

[63] Jasper T Vermeulen, Stine S Johansen, Alan G Burden, and James L Dwyer. 2025. Removing the drapes: Reflexive insights on research into real-world surgical human-robot collaboration. In *Proceedings of the 37th Australian Conference on Human-Computer Interaction*. ACM, New York, NY, USA, 868–875.

[64] Aakash Yadav and Ranjana Mehta. 2024. Beyond dyadic interactions: Assessing trust networks in multi-human-robot teams. In *Companion of the 2024 ACM/IEEE International Conference on Human-Robot Interaction*. ACM, New York, NY, USA, 1153–1157.

[65] Xiliu Yang, Nelusa Pathmanathan, Sarah Zabel, Felix Amtsberg, Siegmar Otto, Kuno Kurzhals, Michael Sedlmair, and Achim Menges. 2025. Exploring the use of augmented reality for multi-human-robot collaboration with industry users in timber construction. In *Proceedings of the Extended Abstracts of the CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1–8.

[66] Yan Zhang, Tharaka Sachintha Ratnayake, Cherie Sew, Jarrod Knibbe, Jorge Goncalves, and Wafa Johal. 2025. Can you pass that tool?: Implications of Indirect Speech in Physical Human-Robot Collaboration. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1–18.