Warm Solutions: Centering Nurse Contributions in Medical Making

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Making medical devices in healthcare settings engages practitioners in organizational innovation. Nurses improvise physical workarounds at the bedside in response to patient needs. Yet nurse-led problem-solving is rarely centralized in an emerging innovation ecosystem through medical making. We interviewed medical makers in six healthcare makerspaces to understand factors for nurse inclusion in the medical making ecosystem. Findings from 16 multi-stakeholder interviews with 6 facilitators and 10 nurses in the USA, reveal insights into nurse-led problem-solving with and without the use of physical prototyping (making) in formal innovation spaces with maker technologies. We report how a nurse's capacity for making is practice-driven to address in-patient discomfort, repair their own practice, and update standardized workflows. Most nurses iterate on low-tech solutions facing barriers to formal collaboration when they attempt to scale up. Their technical capabilities extend from innovation-centered resources (e.g., lab spaces, technologies), often with complete reliance on facilitators who have limited authority in the medical system. We contribute to themes around practice-based innovation, participation in technology design, and articulation work for collaborative innovation. From nurse makers' experiences, we discuss how nurse participation can be supported in healthcare technology design.

CCS Concepts: • **Human-centered computing → Human computer interaction (HCI)**.

Additional Key Words and Phrases: healthcare; pandemic ; making; medical; clinical innovation; maker culture

ACM Reference Format:
Udaya Lakshmi and Rosa I. Arriaga. 2022. Warm Solutions: Centering Nurse Contributions in Medical Making. *Proc. ACM Hum.-Comput. Interact.* 6, CSCW2, Article 351 (November 2022), 25 pages. https://doi.org/10.1145/3555771

1 INTRODUCTION

Nurse contributions, and nursing work itself, have a complicated past as gendered work in medical practice. Despite a higher presence of nurses in the healthcare workforce in the USA [47], nurse absence is conspicuous in present-day point of care innovation in healthcare settings [2, 8, 37] though nursing journals suggest nurses collaborate within their community of practice [5, 30, 53]. Seldom invited to participate in wider technology initiatives, nurses may devise their own workarounds at the bedside [21] based on their practice-based insights. We set out to understand challenges to participate in existing pathways in the market, practice, or unexplored collaborations.

Technologies to support practice-based insights expand the scope for organizational innovation [4]. A similar trend in hospital makerspaces enables healthcare practitioners to make physical prototypes with consumer fabrication technologies supported by digital infrastructures (e.g., design repositories and skillshare exchanges) [21, 34, 37]. Making in healthcare settings to drive innovation, relies on the collaborative expertise of multiple stakeholders. These sites are located in traditional

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2573-0142/2022/11-ART351
https://doi.org/10.1145/3555771

hospitals with the goal of prototyping medical devices to improve care practices [26, 33, 34]. Nurse-led contributions in this emerging ecosystem of medical makers offers an opportunity to explore CSCW and HCI themes at emerging sites of innovation primarily in informal collaborative spaces [27, 35]. Nurse problem-solving informs three themes: the design of shared infrastructures [3, 13, 32, 34], the role of values of care [54, 57] in participation [17, 59], and design as everyday creativity [28] among nurses. In this paper, we highlight nurse experiences as a stakeholder group central to public health conversations at the onset of the COVID-19 pandemic in 2020.

The COVID-19 pandemic made public health, a personal concern. Healthcare settings became inaccessible to family caregivers transferring the responsibilities to care for those in long term in-patient settings to nursing staff overnight. Media attention on nursing efforts during crisis, like COVID-19, re-enforced stereotypes of frontline workers' resilience with notable examples of nurses who made their own masks and other devices [62]. While adaptation may seem inevitable during a crisis, unlike other frontline workers (e.g., emergency technicians, firefighters) nurses were responsible for the continued care needs of patients. Such proximity, even before the crisis, influenced the adaptive mindset of some nurses to craft protective devices [33] while being *there*, and available in every way that matters, to care for patients in the isolation ward and beyond.

Nurse resourcefulness is not an overnight phenomenon [19, 53]. In fact, ingenuity at the bedside is integral to routine nursing work, at least per literature in the USA, as evident from improvised hospital equipment dating back to World War II [15]. A prominent example of nurse-led innovation during wartime can be seen in Florence Nightingale's organization of patients by severity of condition in another war, the Crimean War (1853-1856), which became the model for the modern day intensive care unit [58]. With the rise in consumer grade technologies, how do nurses participate in formal spaces for innovation alongside other healthcare practitioners? We foreground nurses in our study to highlight the unique perspectives of a group prone to solve problems in everyday practice. We recruited 16 such individuals for interviews, four of which occurred during the first 6 months of the pandemic, to take stock of nurse roles in innovation. Across the USA, we collected perspectives from stakeholders –6 facilitators and 8 nurses including educators in hospital makerspaces. The 10 nurse participants reflect a corresponding representation of women (90%) and White/Caucasian (80%) among Registered Nurses (RNs) in the USA according to the *National Nursing Workforce Survey*, 2017 [47]. Two nurses who do not use these spaces provide non-user perspectives. From their experiences, we identify a broader understanding of nurse roles in technology design when they lead the problem-solving process.

We start with a historical review of existing literature on nurse innovation [15, 21] and standardized nursing as a profession in the USA [18, 38]. We are guided by Young and Gomez-Marquez's prior work [21], a historical survey of nurses in the USA as innovators and marginalization over time, to foreground nurse-led approaches in maker spaces. In our study, nurses reflect on problem-solving to describe their activities yet they may not identify it as innovation, making, or prototyping. We argue for recognizing nurse experiences with the material practices as activities inherent to making in response to opportunities they encounter when solving problems in their daily practice. Their experiences further highlight the need for support in carrying out a specific kind of cooperative work for large-scale collaboration: articulation work [44]. Embedded in complex cooperative arrangements, missing articulation work around nurse ideas or insights can impede efforts to either contribute to incremental innovation or realize innovative products within the medical hierarchy.

We contribute findings around three areas in this study. First, we describe how nurses iterate on low-tech solutions to alleviate patient discomfort, correct workflow gaps, and repair equipment to perform nursing work. Second, we analyze how nurses need for institutional support emerges from their position in the medical hierarchy. With low visibility into process-level impact for patient safety and medical liability, they prioritize a solution's validity for a specific patient over

general reliability of use. The latter situation is the rule unless they have adequate leadership or facilitator support. Third, nurse capabilities to act on their insights, as hands-on technology users, extends from innovation-centered resources (e.g., lab spaces, technologies) on-premises often requiring technical experts and research skills for articulation work [44, 48]. Other barriers to formal collaboration including time, technical risks, and skepticism in current hierarchical systems. We discuss how nurse capacity for action with technology must be re-configured to expand their participation in innovation with careful consideration of the trade-offs to support nurses efforts and centralize patient needs in healthcare organizations.

2 RELATED WORK

Nurse problem-solving activities precede the recent advances in consumer grade fabrication, craft, and other maker technologies. In this section, we argue for an understanding of nurses' role in present-day medical making collaborations for healthcare innovation based on a historical background of nurse inventions from practice-based experiences.

2.1 Organizational Innovation and Nurse Roles in Technology Design

Opportunities for innovation in healthcare organizations is tied to technology adoption. Such transformation over time requires de-centering existing ways of knowing and doing work [41]. Within organizations, process-based technologies may be introduced by management (e.g., electronic health records), yet practice-based innovation where employees improvise to "make sense of and act coherently in the world" [41] help understand evolving uses of technology [9]. As healthcare employees, clinicians are motivated to innovate in their healthcare practice for personal, professional, or social reasons [2, 6, 8, 20, 34]. When realized as products, practice-based insights transform communities of practice [39] and the market [24] after individuals overcome organizational challenges. Arvindsson et al. describe challenges at three stages: concealing early ideas till investments are justified, sequencing to mobilize internal support, and anchoring ideas to structures for future transformations [4]. Underlying all three stages are structural hierarchies affecting employee participation in innovation. For example, physicians, often lead innovators [56], may benefit from their position in the medical organization supported by manufacturing regulations, institutional liability, and end-user safety to access resources for patient-centered treatment innovations [8, 26, 34]. Other healthcare workers, such as nurses, though similarly compelled to act at the patient's bedside to maximize person-centered well-being may face different challenges in presenting insights to uphold prevention, adherence, and holistic care in their practice [16]. From two medical innovation projects, Mork et al. outline how the collaborative process highlights power imbalances and enables negotiations between different communities of practice [39]. Few studies examine formal, organizational sites of innovation to understand how employees collaborate and overcome these challenges in addition to the limited integration of nurse insights technology design described in the next two subsections.

2.1.1 Limited Healthcare Technologies for Nursing Work. Nurses play an active and intimate role as primary caregivers for in-patient elderly care, hospice, and pediatric care. Because nursing work exceeds standardized process [12], a nurse's insights into opportunities for design are keenly oriented to emerging healthcare practices. Recognizing these insights has the potential to create upstream-downstream shifts, to borrow a metaphor from public health [60], on technology design. For example, a centrally designed technology may automate nursing work for standardized IV procedures across departments over local priorities of nurses in hospice care. The downstream effect displaces nurse agency to provide high quality care personalized to the human that is invisible to designers [48]. The upstream effect of hidden nurse insights, viewed as common sense care

practices, leads to technology workarounds or abandoning workflows over time. Bowker and Star frame these effects in classifying nursing work leading to complex trade-offs between surveillance and agency among nurses [12]. Overall, designing technology for healthcare needs requires an evolving understanding of nursing work to ensure wider impact on first the organization and subsequently the healthcare practices. We explore this dual effect from a case study of technology designs initiated by nurses firmly grounded in their practical insights and needs.

2.1.2 Challenges in Designing Healthcare Technologies with Nurses. Previous technology design studies incorporate nurse perspectives [1, 31] but are primarily driven by the researchers' priorities and methods. In designing novel technologies, such as using body sensors to identify training in emergency scenarios [22], nurse insights are limited to evaluating the technical design. Other studies indicate that technologies designed with a narrow focus on tasks may improve usability of universally designed devices or medical supplies [1, 14, 31, 61]. However, this burdens nurses with the task of adapting designs for emergent or unforeseen needs in their work. For example, Wu's usability study of tablet inputs and large-screen displays explains how critical care nurses are more likely to write down actions and patient vitals to record it for their reference when the technology is no longer accessible on such shared technologies [61].

Participatory and co-design approaches can delineate the effects of hierarchies at work in shared use by decentralizing the physician view as the default clinician perspective [1, 31, 52, 61]. Yet even in participatory and co-design settings, Ostergaard et al. describe nurses were reticent to contribute to the design process because they struggled to perceive their insights as critical to the technology outcome [42]. In a sense, the act of participation helped them become more aware of their ability to inform design. Tang and Chen describe a similar phenomenon in their study where they observed collaborative reflection across stakeholders when determining technology readiness for EHR system deployment in a small clinic. In their study, the hospital staff iteratively learn from each other through collaborative reflection to solve problems beyond individual reflections leading to better adoption of the system. While these methods can lessen the downstream effect especially in technologies automating nursing processes to ensure reliable standards, it is unknown how nurses cope with dynamic needs encountered in nursing work. Along these themes of discovery from participation and driving technology design, we shift our lens to nursing practice itself at emerging sites of technology use and creation: hospital makerspaces.

2.2 Medical Making as Innovation and Historical Nurse Contributions

Makerspaces and fabrication technology labs have recently emerged as sites of innovation [7, 35]. Studies reveal social, economic, and cultural factors impact technology's role in such sites [35, 45]. Hui and Gerber describe how makers in general-purpose makerspaces develop entrepreneurial careers and skills [27], while others point to an understanding of sociotechnical infrastructure shaped by maker culture [7]. The trend in hospital makerspaces [43] involves academic STEM collaborations in the USA and key healthcare entrepreneurial actors (e.g., Maker Health and Maker Nurse [63]). However, innovation activity in hospital makerspaces, which results in novel products, is notable as it carries additional risks; this requires wider collaboration to offset risks of medical making at least in the USA [34]. Medical makers rely on existing infrastructure currently used by hobbyists (e.g., Thingiverse, Github), resources for consumer grade fabrication (e.g., 3D Printing), or other maker technologies [34, 55]. Studying the ecosystem of medical makers offers an opportunity to understand the design of spaces, systems, and structures for wider participation in design processes. While recent studies on medical making describe limited prototyping in clinical care [26], extensive collaborative networks [33, 34], and safety-oriented practices [26, 33, 34], no studies to our knowledge examine nurse contributions to formal innovation.

The term nurse making is synonymous with nurse innovation over the last decade. Historically, nurses shared their improvisations in USA magazines till the 1960s [21]. Around the time *The American Journal of Nursing* stopped featuring nurse-led improvisations, a larger shift to professionalize nursing work was underway [21]. For instance, the Nurse Training Act in 1964 formalized and streamlined training protocol for nurses in the USA with an emphasis on evidence-based practice [38]. By the 1990s, nursing literature points to epistemological concerns around what counts as evidence while *"the profession began to formalize and align itself more closely with science"* [18]. Though some nurse researchers and educators may have received the training required for scientific publication, it is unknown how this fundamental shift from practice- to research-driven nursing practice affected nurse perceptions of innovation within traditional medical practice. Nurses who usually undertake patient education for preventive health and more integrated solutions in organizational innovation spaces [21, 33].

Problem-solving for care engages two types of reasoning: clinical and practical. Clinical reasoning, rooted in medical specializations, is guided by additional information around social relationships and concerns to inform decision making; typically focused on alleviating disease symptoms [10]. Practical reasoning is primarily driven by daily goals of caring for patients and ongoing developments in their environments. While nurses use clinical reasoning in administering standardized clinical procedures, they may apply practical reasoning at times directly in conflict with clinical reasoning [21]. From nursing literature, we know nurses express a moral responsibility to create workarounds in standardized procedures [10, 11]. Physicians are known to work around systems in their daily workflows (e.g., EHR systems ([51] yet may not be subjected to routine surveillance at the task level. Nurses at the frontline tend to be more constrained partly due to the procedural demands of their clinical work within the healthcare organization. Asurakoddy et al. describe nurse innovation behavior among public health professionals in how "doctors demonstrated the skills of gathering knowledge, whereas nurses exhibited the skills of new idea generation which was more important in innovating behavior process" [5]. Practice-based innovation can accommodate multiple perspectives for patient-centered care as seen in cases where clinicians have improvised equipment long before the presence of maker technologies [2, 15, 21, 23]. Due to their recurring and prolonged responsibility for patients, nurses are constantly driven to innovate at point-of-care because they face visceral demands to care for patients with unanticipated and critical conditions. Gomez-Marquez and Young describe nursing work to improvise as bedside "stealth-making" with a focus on materialized artifacts. Most nurses tinker with existing devices, create workarounds, or adapt parts of their environment. Nurses' expertise in problem-solving, critical thinking, and prototyping becomes apparent in experiments with hands-on fabrication technologies and craft [21, 63] or other innovation activity [30, 53]. In this study, we foreground nurse roles in formal maker spaces for collaborative medical innovation as emerging medical makers [34].

3 METHODS

Nurse participants in our study represent a subset of professionals in active nursing positions in the USA Within the scope of this study, we recruited 16 participants between October 2019 and September 2020 to understand nurse contributions in maker technology initiatives in healthcare institutions. We shortlisted five existing healthcare facilities (e.g., , hospitals, health sciences institutes) from public media mentions and the first author's existing network of medical makers. In addition, we reached out to nursing professionals in our personal and academic networks to survey wider perceptions of makerspaces and making within the nursing community. We began by approaching nurse participants who self-identified as makers or innovators. Two participants explicitly stated that they did not make physical prototypes. We include their perspectives in this study as non-users of maker technologies.

Table 1. Participants identified by maker affiliation with description of educational background, role in problem-solving, making, or innovation, and details of space with participant demographics data where (*) indicates a person of color.

ID	Profession	Specialty	Role	Environment	Identity	Experience
E1	Nurse Practitioner (PhD)	Neonatal, Maternal care	Educator	Health University Makerspace	Female	5+
E2	Nurse Practitioner (MS)	Critical Care, Surgical	Educator	Private Hospital, Makerspace	Female	5+
E3	Nurse (BS)	Critical Care	Educator	Hospital Makerspace	Female	10+
E4	Nurse Practitioner (MS)	Prenatal Care, Midwifery	Educator	Hospital Makerspace	Female	20+
E5	Nurse Practitioner (PhD)	Gerontology	Educator, *Non-user*	Hospital Makerspace	Female	30+
N1	Nurse (PhD, Masters)	Endocrinology	Entrepreneur	University Maker Program	Female	5+
N2	Nurse	Midwifery	Entrepreneur	Hospital Maker Program	Male*	25+
N3	Nurse	Prenatal Care	Prototyping	Hospital Makerspace	Female*	5+
N4	Nurse	Cardiac, Midwifery	Prototyping	Hospital Makerspace	Female	35+
N5	Nurse Practitioner	Pediatric care	*Non-user*	Hospital Innovation Lab	Female	45+
F1	Lab Manager	Education Sciences	Facilitator	Health University Makerspace	Male	5+
F2	Project Manager	Management, Education	Facilitator	Hospital Innovation Program	Female	10+
F3	Researcher	Graphic Arts, Engineering	Facilitator	Hospital Innovation Lab	Male	5+
F4	Branch Manager	Library Sciences	Facilitator	Health University Makerspace	Female*	5+
F5	Nurse Practitioner	Education, Leadership	Facilitator	Hospital Makerspace	Female	3+
F6	Design Engineer (PhD)	Arts, Design	Facilitator	Hospital Makerspace	Female	2+

3.1 Participants

Our goal is to understand the extent of nurse integration into medical making activities. Organizers or administrators in makerspaces offer a unique perspective in their role as support staff [33]. We reached out to nurse innovators or collaborators based on initial recruitment and interviews with these facilitators (F1–F6) who oversee collaborations. All six facilitators are trained in allied skills to facilitate maker efforts. These facilitators often perform administrative duties combine skills required in making along with formal research, engineering, and design expertise. We reached out to facilitators in six healthcare institutions to leverage their visibility across maker projects. We highlight three unique participants; a trained nurse who is a facilitator and two nurse-entrepreneurs (N1, N2). Both decided to develop their ideas from prototypes into products outside their original institutional environments.

3.1.1 Recruitment Criteria: We recruited 10 nurses associated with five of these spaces in the USA described in Table 1. During interviews, we found two did not use maker technologies despite their awareness of such spaces on their hospital premises. We retain their perspectives as they were considered problem-solvers by others in the study. They offer insights into their experience of non-use to inform the limitations of technological adoption in practical contexts [9]. All others were actively involved in fabrication spaces located or related to institutions sharing four characteristics: (1) collaborated or directly prototyped solutions for training or point-of-care use, (2) applied craft or digital fabrication technologies (e.g., laser-cutting, 3D printing, electronics), (3) worked as or with nurses on at least one prototype, and (4) were subject to the USA's institutional or other manufacturing and regulatory frameworks.

3.1.2 Advanced Nursing and Educators: Nurses achieve seniority as they advance in their professional practice by shifting into specialized, managerial, and educational roles. In our study, based on facilitator insights, we identified two groups of nurse stakeholders: educators and bedside nurses. At least half our participants operate in teaching hospitals contributing to a higher number of nurse makers who are educators in our study. However, the nursing profession requires nurses to undergo recurring certifications to update process-related and specialization-specific knowledge with implications for senior nurses. This is somewhat represented in how all 10 of our participants had part-time or full-time experience as nurse educators. Table 1 has details of 10 certified nursing

professionals who are all registered nurses. Some have advanced degrees and others specialized training in critical care, pediatric care, and other areas.

3.2 Data Collection

With institutional review board approval, all participants provided informed consent. We recruited participants through snowball sampling methods starting with our personal networks. We emailed 6 administrators of institutional maker spaces for semi-structured interviews. These participants referred us to 10 other participants within their institutional and other maker networks. We interviewed 2 non-users: N5 moved to a rural area from an urban area similar to N6 where they each had access to maker technology. We offered flexibility in research methods —a survey, emails, and interviews to suit our participants' availability, though we rely mainly on interview data in this paper. We recorded all 16 interviews conducted over 30–60 minute phone calls. All interviews were conducted by the author between October 2019 and September 2020.

Our goal required identifying an ecosystem of nurse collaborators –educators, managers, and facilitators –to understand factors influencing participation in technology design through medical making. We study perspectives of nurses who have access to technical capabilities on-premises. We referred to their activities in these spaces as problem-solving in our recruitment email and interviews. We intentionally chose a less value-laden term than innovation, prototyping, or making to counter any underlying notions of novelty, engineering, or hacking that nurses might have based on a close reading of prior literature on nurse innovation. Before recruitment, the first author undertook a literature review of nurse perspectives in blogs, articles, and formal nursing academic journals briefly summarized in the related work. The review led to a set of research questions grounded in historical nursing innovation explored in this study. Nurse contributions have been minimized in the past [21] in part as gendered work performed largely by women [48]. Some nursing work at the bedside (e.g., patient notes) is known to be routinely overlooked by internal classification systems in hospital settings [12]. Such routine erasure of nursing work is likely to influence how nurses view their contributions. Keeping this in mind, we first asked for their definition of problem-solving, and then probed for instances of physical prototypes (i.e. making) to understand the role of materials and technology use. We report findings from participants' challenges in problem-solving, description of physical prototyping experiences, and their perception of both maker technology as well technology's role in innovation for nursing as a profession.

We collected non-user perspectives to explore their perception of technology needs and maker technologies in nurse-led problem-solving. We added one COVID-19 related question enquiring about the state of medical supplies and its effect on their daily work as a maker. We report these additional responses from (F6, E3, E4, N3) due to their availability for interviews in September 2020. We also received email responses in July 2020 from (N5, N2, F4, F1) when we reached out to all the participants interviewed in the study. The first author interacted with all the facilitators prior to this study for academic work.

3.3 Data Analysis

Interview audio data transcripts were generated with Otter.ai. Two researchers independently developed bottom up codes from a subset of interviews for initial themes around *motivations, barriers, process, materials*, and *innovation*. In bi-weekly discussions, as we conducted more interviews, we iterated upon these themes to synthesize axial codes around three categories. First, different stakeholder *motivations* for solving problems they faced in their workflows, typically in enhancing nurse training or direct patient care. Second, their prototyping experiences with descriptions of physical infrastructure (e.g., space, materials, equipment) to highlight *barriers, process, materials*. Third, when describing the current status of their ideas, they conveyed self-perceptions as makers

and reflections on wider *innovation* activities. Each of these categories were refined further based on iterative coding of interviews as described in:

- **Contexts for Problem-solving**: Situations described by nurse collaborators when they observed peers' actions to intervene by solving problems with physical solutions. They identified specific materials, technologies, and resources in healthcare settings.
- **Perceptions around Innovation**: Concepts mentioned by participants when relating their experiences of problem-solving within their routine work that guided decisions to persist or desist when faced with challenges. We focus on perceptions of the nursing profession, their individual role, and the use of maker technologies within the scope of this study.
- **Skills, Resources, and Capabilities**: Mentions of makerspace resources (i.e. materials, training, policy, and other forms of support) as reflected by participants when they identified gaps in skills to help them realize ideas. This includes challenges in existing technologies and overall infrastructure for healthcare innovation.

In the next section, we map key findings in each category to describe relevant categories across problem-solving contexts at the bedside, conceptual beliefs about their innovation, and prototyping capabilities with maker technologies to highlight factors influencing nurse-led solutions.

4 FINDINGS

A nurse (N5) must *"figure out how to problem solve"* in her daily work. Nurse problem-solving closely maps to the process of design starting with the problem identification stage confirming findings from other medical makers [26, 34, 46]. A more relatable term than innovation, problem-solving helped nurse participants reflect on experiences of contributing to prototyping, innovation, or making regardless of formal outcomes. We organize findings from three stakeholders: facilitators, nurse educators, and nurses. Each stakeholder is linked to maker initiatives in their primary healthcare institution though their problem-solving activity may occur elsewhere. We organize thematic findings around practice-based contexts, perceptions, and capabilities across three sections.

The first section confirms how nurse insights originate at patient bedsides. It may at times lead to changes in the larger environment or nursing practice. The second section delves into new insights around nurses' underlying notions about innovation, collaboration, and support required to pursue prototyping solutions. The final section combines the influences of contexts and concepts to outline the gaps in socio-technical capabilities such as resources (e.g., materials) to realize initial insights into innovation.

4.1 Caring at Bedsides Requires Innovation

"Because nurses are amazing inventors, when we don't have the exact tool that we need, we will make it available. With our close interaction, at the bedside, we know exactly what we need." (E3)

A nurse's insight grows at points of interaction with patients in her role as an educator, manager, or specialist. E3 describes her reasons to introduce nurses that she trains to making through an exercise re-thinking IV holders in the hospital makerspace to create a foundation and expectation among nurses to adapt at the bedside.

Nurse challenges in performing routine work often require adapting their environments [29, 53]. We found participants were compelled to prototype in two contexts at the bedside. One context expands on practice-wide impact when nurse leadership is involved in problem-solving to build prototypes from patient-centered insights. They may improve training with tools for specialized nursing practices or devices to improve standardized workflows. The other confirms a wider perception of MacGyver nurses [21] at the frontline of patient care –they respond to patient

discomfort and care needs. Notably, these two descriptions of physical prototyping at the bedside can overlook a more pervasive trend of repair activity among nurses who adapt technology to meet their own practical needs. For example, a nurse may create shorthand codes for in-person patient notes [61] that need not be recorded yet help organize her workflow.

4.1.1 Bridging Workflow Gaps. Nurse solutions can expose overlooked gaps or outliers in patient care not yet included in standardized workflows. N1, a nurse who holds an advanced nursing degree, speaks of her prototype developed during her doctoral research.

> *"It's not really much of a help to solve the problem if it's not being implemented on a wide scale [...] If I designed something like this [redacted], it would be a device that is hands off. It would work in the flow of a hospital birth." (N1)*

A Doctorate in Nursing Practice (DNP) involves a practice-based intervention in nursing based on observations in practical workflows. N1's observations of an unregulated process workaround among midwives in postpartum care included the use of a basin to monitor the rate of blood loss in pregnant women to forecast possible time of intervention. By attaching a digital meter, her thesis research project developed the insight into a possible medical device. N4's effort to achieve a scale of deployment in the hospital was guided by her insight into standardized workflows. Alongside other nurse educators in our study, such beliefs that scale justifies effort highlights how nurses need to be equipped two-fold, first to identify a robust solution from practical insights and second to articulate its impact in line with institutional priorities. F4 explains how a nurse maker in her lab space could reserve resource time and materials for her prototype on managing pressure wounds because it aligns with nursing departmental goals.

> *"The lead nurse on [redacted] said she's made this one of her personal goals [...]. Improving pressure wounds [management] is one of the strategic goals for the medical center and the nursing department." (F4)*

The dual capacity of articulating insights and visibility of priorities is vested in nursing researchers. Nurses with advanced degree (E1—E3, N1) had the educational training and time to argue their case for institutional resources to create, adapt, and advocate solutions. Additionally, F6, F5, E3, N1, and N3 mentioned how they had more time and flexibility when making prototypes in their academic stints as researchers. Educators have a similar capacity to advocate for resources because in E4's experience, the department is likely to *"trust that you're presenting them with evidence based practice."* Apart from educators in our study, all participants had part-time teaching responsibilities at the same or local nursing colleges. In these roles, according to facilitator F6, they seem to gain insight into procedures to innovate on their specialized practice as nurse leaders. Educators with such visibility into standard operational procedures are able to scope their problem space to independently adapt prototypes to be integrated into the practice, as F6 describes:

> *"The hardest part of innovation is finding the right problem. It's less about the solution and more about understanding the problem, because you can create a solution that, down the line, creates other problems." (F6)*

Artifacts to ensure consistent nursing performance (E1—E4) are no doubt welcome in a litigious healthcare environment. Educators who collaborated with facilitators (F1, F4, F6) recreated patient skin (E1, E2) and fashioned midwifery tools (E1, E4), wound detection (E3), patient education models (E1) as training tools for process-based learning. With repeated hands-on practice, a nurse retains procedures better to avoid clinical mistakes especially when unusual patient symptoms occur at the bedside. For example, E2 models unusual sutures with her learning tool made of silicone to create lifelike fake skin draped over a mannequin for *"nurses' capabilities to apply that process"* in neonatal care complications they might someday see it in the real world.

> *"If the patient is sick, the nurse is still the one taking care of that patient, so I think they become innovative more because of desperation than time in the in-patient setting." (F2)*

Nurses may encounter problems in both out-patient and in-patient contexts depending on their role. We found that the latter created a more visceral response in nurses across specializations. In the quote above, facilitator F2 muses, along with F4 and F6, how desperation sometimes propels action among in-patient nurses. At other times, nurses witness individual patient's discomfort to intervene with short- and long-term solutions.

Short-term prototypes seem to coincide with device failure in meeting specific patient needs. F2, F4, F6, and nurses (N1—N4) mentioned patient cases where a device caused pain, inconvenience, or risk over time. F3 at a pediatric care center explained how most medical devices designed for adults need to be adapted for children's needs. For instance, a ventricular assist or an artificial heart may be available for adults though developing a pediatric version is considered an innovation worthy of National Institute of Health (NIH) funding and incentives. This may lead to, and often does, intellectual property concerns around medical devices. The purpose of facilitation then is to *"leverage the interest in creating a solution"* according to F3 who, like every facilitator in this study, works with internal departments and external partners such as local startups, engineering schools, and a network of makers in surgical 3D printing.

Similarly, others (F4, F6, N1, and N3) pointed to devices unsuited to women patients' needs. F4 describes an instance where two nurses noticed a female external catheter, a standardized design made by a non-medical person, did not adapt well to an obese woman. It caused her pain and increased risk of infection from prolonged use. The two nurses iterated on a solution made of vulcanized rubber with patient feedback to develop an attachment. In the context of another project, N3 explains how iterating on her low-tech maternity gown design with F6 solves a recurring problem in prenatal care when new mothers' struggle to sleep when strapped to a baby,

> *"It was really unsafe, even though we tell them you need to really put the baby back [on your skin...]. There's many devices actually available out there to do skin-on-skin, but not a hospital gown." (N3)*

Nurses in our study prototype solutions to prevent recurrence of problems for future patients. All nurse participants in our study approached facilitators to brainstorm approaches once they had a solution in mind though facilitators (F2, F4—F6) shared instances where they helped refine the problem space as well. Unlike patient bedside interventions (N1—N4), nurse educators E1–E3 drew from repeated patient observations to create training tools. These tools improved wider process knowledge in nursing practice. E1 mused that all her tools are from in-patient insights to explain why sometimes *"it's acuity of the patient"* referring to medical acuity, or severity of illness symptoms, that prompt her to improve training procedures for greater retention of unique cases. Other educators explained how a nurse's perceptual acuity to patient conditions in situ can equip nurses with enough insight to act on the ethical imperative to intervene.

4.1.2 Repairing to Perform Routine Tasks.

> *"Nurses alleviate problems by using tape to create a better catheter bag [. . .] It's just that it's not documented the same." (E3)*

Nurses balance conflicting priorities to care for patients, caregivers, and clinical processes. Echoing E3's remark above, participants (F4—F6, N2, N4, N5) mentioned instances where problem-solving alleviates temporary conditions in nurses' work. They were unlikely to openly discuss bedside ingenuity based on perceived censure among nurses for their deviations from standards. Participants reflected on how others in their department adapted devices, process flows, and created temporary environments in crisis situations (N3, E3, E4) motivated by an immediate need to cope

with their responsibilities. Such improvisations help them to perform their nursing tasks in ways that may circumvent standardized practices.

Not all problem-solving is sanctioned. Nurses deviate from manufacturer instructions for use at times raising ethical concerns [11]. In our study, we found this is because the device design seemed to functionally fail in supporting nurse work at the bedside. Sometimes, they worked around procedures based on their values for speed, efficiency, or patient engagement. N5 explains how nurses in her unit worked around using a barcode scanner designed for safer prescription entries. The tags placed on the patient's arm interfered with nurses' efforts to maintain eye-contact to establish trust in the short time available with patients during the discharge process leading to questionable deviation from procedures.

> *"On each piece of medication that have the same kind of barcode on it, everything has to match up and be scanned. [re: the scanner] It's a safety thing to keep people from making errors, but that's one of the things we nurses learn to work around. They'll print real bar codes, tape it down on a desk, so they can handle it. [...] They have like a little cheat sheet with the extra barcodes already loaded on there, but it'd be very easy to click on the wrong one." (N5)*

In relating this example, N5 did not condone risking patient safety. However, she reflected that often technologies were designed without nurse inputs or insights and how this introduces complications in nurse workflows. At other times, breakdowns occur due to unpredictable in-patient conditions. Participants (F3, E2, N2, N4, N5) explain not all breakdowns could be foreseen while anticipating them can lead to a process where ideas emerge from nurse specific concerns. For example, E2 described a nurse's initiative to create a baby apron with pockets to carry seven or eight babies in case of a fire going on to explain that *"sometimes nurses create things just with what they have in the closet."*

When nurse-led problem-solving occurs under the radar, they seem to engage in repair work to adapt devices to their specific needs in the form of customization. F6 describes how nurses *"were putting these scrunchies on their feet, so that they wouldn't trip over"* standard issue personal protective equipment (PPE) during the early days of the COVID-19 pandemic. PPE worldwide is sized for male bodies, unsuited to a 90% female workforce [47] kept mostly on its feet. Though minor, oversight in universal design of essential medical supplies prompt nurses to adapt or create workarounds to perform tasks specific to nursing work at the bedside.

4.2 Becoming Innovative is a Challenge

> *"I thought I was going to invent something, I was going to build it, and I was going to help a lot of people. But there's a lot of due diligence that comes with starting a business. I didn't know any of that information from the beginning." (N2)*

A nurse's perception of what counts as innovation is influenced by concepts around scale and, reflexively, of herself as an innovator. N2 shares how his perceptions underwent a change when he decided to set up a product-based business in a region with fewer medical manufacturers. When he developed his prototype at the bedside, he had institutional support yet failed to attract formal collaborators within the medical community as an individual nurse entrepreneur. While nurse resilience could fuel an adaptation mindset, scaling up from prototypes to innovation demands nurses to overcome more practical and systemic barriers to explore innovation pathways in medical communities or the wider market. Each pathway entrenches a notion of resilience in nurses learning to use technologies, document processes, and the myth of a lone inventor.

4.2.1 Reticence to Collaborate.

"Nurses as professionals are going to be more likely to trust another nurse and may open up in different ways than with somebody who they're not familiar with." (F5)

Even before nurses attempt prototyping, they seem to operate from a position undermined by historical erasures in nursing work [12]. F5, the only nurse-facilitator in our study reflects on how a *"trust thing"* pervades nursing practice as her observation of reticence in a community. However, medical making requires collaboration as it occurs at the intersection of legal, regulatory, and medical institutional policies. Most participants (all except N3, F1, and F3) alluded to reasons for skepticism about working with in institutional systems. Some mentioned instances of overlooked contributions (e.g., F4 on doctors taking credit, N1 on institutional ownership claims) and others referred to historical inventions or forgotten nurse contributions (F2, F4-F6, N1, N4). Of relevance to this insight is nursing's shift towards a research-driven science from a practice-driven technical profession in 1950s [15]. E2 shares her insights as a nurse educator on how a turn towards evidence-based practice may have required nurses to describe and collect evidence to support their prototypes at the bedside. Without adequate direction, it is likely their early ideas exclude nurses because they were not recorded in formal literature:

"In about the 1950s and 60s, [nursing] started practicing more evidence based practice, which kind of pushed some of the inventions that nurses were making out because out of the literature, because they weren't researched." (E2)

On the other hand, internal erasures exist in nursing work [12]. As discussed earlier, some nurses are wary about sharing their risky workarounds to perform routine tasks. A parallel concept at work is evident in how nurses speak about their ingenuity as *"what I have to do to do my job."* F2 who developed programs in her hospital for grassroot collaborations mentions an attitude of dismissal among nurses who she actively recruited for her innovation program's projects at a private hospital. A facilitator or a leader, according to participants (F2-F6, E2, N3) observes creative opportunities from nurse insights. Nurses tend to self-censor or opt out, especially senior nurses with more experience and training were risk-averse in technology experiments. Yet all facilitators and some participants (N2, N4, N5) indicated that senior nurses improvised at the bedside too. As N4, with 35+ years of nursing practice, asserts, *"nurses are very rule following people"* but need *"some ego because you need to nurse"* at the bedside to contain the chaos of caring for patients. In this context, N4 highlights the conflict between social expectations and individual risk in experiments required for problem-solving. Nurses who solve problems take action based on insights in their work environments. Often these actions and insights are seen as an extension of nursing work; a part of their organic routine. They rarely see their activity as an opportunity for innovation.

4.2.2 Risky Unregulated Technologies. The risks of experimentation with medical making are more unclear for nurses. Physicians at least know the risks of liability even if they offload device quality for safe use to facilitators. Nurses prefer to adjust and adapt medical supplies compared to regulated medical devices. For example, IV holders as medical supplies are not regulated and therefore not standardized. F1, F2, E4, N2, and N4 each mentioned workarounds or fully implemented solutions they made (F6, E2) in their departments. F6 explains how the right infrastructure helps assure participation in a healthcare makerspace,

"The space matters, and who's involved matters, simply because in the USA, medical manufacturing laws seem to mandate some things, but not some other things." (F6)

When regulatory gaps exist, physicians perceive risks differently from nurses in this process. F4 points out how regulatory gaps in medical making stop nurses far more than doctors who act from a position of power to *"surge ahead anyway."* F6 offers the same opinion by drawing a line between bedside problem-solving and innovation as separate modes with the remark that

nurses are *"not necessarily always tinkering."* In her experience, and others' (F5, N1, N4, N5), nurses innovate when they plan to implement solutions at scale, which invariably requires justifying the use of institutional resources at least for prototyping in healthcare settings. Then, they develop their prototypes to explore one of two pathways for formal research or companies.

4.2.3 Articulation for Scale. Innovation, like research and entrepreneurship, requires additional effort to gather resources. In formal spaces of innovation, nurses turned to their collaborators to articulate their ideas and advocate for adequate resources. In this study, facilitators, often also project managers (all except F3), were crucial to translate scope of work and connect nurses with experts. Administrative foresight can ensure funding and material support within the institution. Facilitators in our study wrote grants with all nurse participants (except N1 and N2). Others applied to programs outside the hospital (N1, N2, N4) for mentorship, expertise, and explored market-driven pathways. F1, F4–F6 explained how they communicate and direct nurses to learn about institutional policies around intellectual transfer, innovation safety, and expectations of support for makers overall. F4 provides a glimpse into how the university expects part of the profits when a prototype becomes a product when the inventor directly takes it to market.

> *"Anything that is made here or is created using any of [F4's university] resources, services or anything like that, belongs to [them...If] you will pay for marketing and I believe manufacturing, they say looks as though it's going to be big and make money, [redacted] does not own it, but they do get 40% of the profits." (F4)*

Branching out of institutions requires nurses to engage in formal networks like startup consortia, academic conferences, and communities like maker faires. The access to these sociotechnical networks prepares individual innovators to understand how to negotiate and pivot their solutions for market needs. Participants (F3–F5, N1–N3) expressed concerns establishing mentoring or coaching relationships for nurses outside their immediate nursing community in the hospital. N1 and N2 who became entrepreneurs cited challenges in scaling up their products. N2 noted his region's lack of investment in medical devices leading him to write an NIH grant for his patent-pending device. N1 highlights her choice of a startup to raise money as a signal that *"something is worthwhile"* in her prototype. She identifies a range of specialized experts and material resources, but looking back on challenges over two years, the need for formal support remains unmet.

> *"I was looking for funding, but really mentoring, training. I'm having a hard time finding it [...] I've connected with people who connected me with people. I've been learning a fair amount. But, it's informal." (N1)*

4.2.4 Scientific Boundaries. In formal medical research, evidence and the systems to generate scientific data are bounded by specific standards for what counts as research. While this rigor is necessary for medical research, problem-solving of the kind nurses seem to undertake may not be easy to translate into formal methods. Healthcare professionals have accessed emerging technologies through *"innovation labs"* in public and private hospitals long before the maker movement. We found traces of innovation-centered language across participants associating scientific notions of measuring quantitative effects to justify qualitative improvements in care. Facilitators (F2, F3, F5, F6) think such strict notions of innovation could deter nurse participation in experimentation. They adopt a more casual approach in their makerspace pop-ups and lab sessions to imbibe wider maker communities' values of openness. However, F1 and F4 describe how their academic makerspace only attracts nursing students when educators bring them in. Unless they make one-off prototypes (E2 and N4), institutional sets the tone for nurse participation. F3 captures how his lab in a pediatric care center attracts institutional support because it carries connotations of a scientific research center with resources similar to a makerspace.

"Maker is [a term] barely utilized in hospitals. More often the terms innovation lab, or printing lab… because 'lab' has the connotation of a higher science approach. " (F3)

Not all nurses want support because they are less amenable to creating solutions at scale. N4 and N5, both older nurses, weighed in on judicious use of 3D printing material when a device needs to be created instead. They would rather transfer responsibility to a different community of biomedical engineers. Younger nurses (N1-N3, F5) seemed more interested in collaboration to actively participate in the research pathway based on their role in practice or explore the market pathway with wider partnerships.

4.2.5 Individual Resilience and Relationships. Unlike other medical makers, nurses operate at the intersection of gender, racial, and socioeconomic pressures either directly or indirectly on behalf of vulnerable patients. Though we did not frame explicit questions to probe these sociological influences, it is possible nurses in our study faced biases on one or more fronts in their situations as persons of color performed gendered work [47, 48]. From their experiences, F2 and F4 as well as nurses (N1, N2, and N3) attribute external reasons for stalled projects including but not limited to stopped funding, inadequate mentorship, or formal collaboration to see their prototypes through the required institution- or market-defined process. N1, N2, N5, F4, and F5 expected to balance personal goals with a demanding job towards a greater goal to benefit nursing practice. F5 describes her extraordinary transition from a nurse practitioner who spearheaded two years of projects with a grant she wrote, then worked with hospital management to advocate for a makerspace, and continued to fundamentally create her position with others to build a culture of innovation.

"We would prototype, and at the point of care, we started trying it, whether that was with cardboard, or scissors, or glue, all the way up to 3D modeling. We built this culture, people were engaged. They're excited about their work, they had the 'we can' attitude." (F5)

F5's success required personal time spent at conferences, online communities, and management meetings with the external mentors in a health-focused maker community outside her institution; without a guarantee of personal rewards. Despite facilitators' view of culture and other apparent challenges discussed in this section, we noted a consistent reference to personal grit among nurses. The myth of the individual inventor or heroic designer [49] was evident especially among facilitators with design training (F4–F6) and entrepreneurs (N1, N2). From N5, the most experienced nurse in our study, and other senior nurse educators, nursing work requires resourcefulness, dedication, and constant learning on a routine basis by *"sharing tricks of the trade."* As innovators, regardless of the pathways, extending their capabilities seems to re-enforce this narrative of resilience to materialize their insights as lone crusaders first though every participant in this study had collaborators. When asked, participants rated nurse willingness (F4, F6, N2, N4), persistence (F1, F3, N2, F5), and duty to share learning (F2, F4, N1) as the three most influential reasons nurses innovate. In short, a nurse's individual resilience is viewed as a prerequisite though experiences indicate a higher reliance on relationships to participate in medical making.

4.3 Capabilities to Overcome Prototyping Constraints

"I see solutions where doctors try to automate some of the processes in nursing, because they see there's not a lot of reliability. [Doctors] already have a standpoint of liability and safety for the patient and not necessarily a warm solution for the patient." (F6)

A nurse's capabilities are enhanced by technology to perform patient-centered tasks. As F6 observes, doctors prioritize safety, reliability, and liability in their technology-based innovation. Though no one in our study contests the need for caution, most facilitators (except F1) mention how nurses prioritize patient perspectives and lives to create, as F6 eloquently puts it, a *"warm*

solution" for the human being. Physicians, while equally motivated to intervene on behalf and in the service of patient care [25, 34], prototype physical devices from their orientation to advance novel research, specialized practice, and social impact. Nurses differed from other medical makers [34] in how they iterate, when they seek expertise, and in finding formal collaborators.

4.3.1 Low Tech Iteration. When prototyping their ideas for devices, nurses used low tech materials to iterate on form and function. In contrast, most collaborators (F1, F4–F6, E1–E4, N2, N4) noted physicians prototype high tech solutions to manage the pathological condition. Nurses invariably used materials suited to their solution (e.g., wood (E1, F4), cloth (N3), velcro (F4), foam (E4, F4, N1, N4), Play-Doh (F2)). Nurses who made physical artifacts looked for experiential feedback loops with other nurses and facilitators as primary collaborators. N2–N4, E3, E4, and F6 each shared instances adapting IV holders (N2, N4, F6), faceshields (E4), and surgery environments (F1–F4, E3) with better equipment. F4 describes how a team of 4-5 nurses improved a recliner for spinal surgery patients by testing different blocks of foams cut to be *"much more ergonomic"* with patient feedback over four iterations of their initial idea.

Once they developed a low fidelity prototype, nurses could look for ways to adapt it further. Nurse (N1–N4) descriptions highlight their iterations are based on practical use (eg maintenance or re-use). Some added technical features with electronics (N1, N2) and digital fabrication (E1–E3, N2, N4) with technical expertise from facilitators. Educators adapted low fidelity prototypes for workflow integration with facilitators (F3–F6) who mention these project materials are selected by the nurse educators to serve multiple purposes. E1 explains how a cervical dilation tool to train midwives who learn to accurately assess dilation by making a board with cutouts of responsive silicone materials all while ensuring group bonding.

> *"The tool was conceived by me only because I didn't want a wooden or plastic board. I wanted something that mimics what the cervix might feel like at different valuation. Again, and again, I was trying to figure out something that they [students] could do together as team building. But I also wanted to have utility." (E1)*

More importantly, nurses (N2–N4) showed a nuanced perspective of the patients' life to extend their solutions' effectiveness for patients. F4-F6 who oversee collaborative projects, shared nurse insights that placed the person at the center of solutions even with high tech materials. For example, a nurse solution of a 3D printed IV holder took on animal shapes for use in the pediatric ward. At other times, this leads to changing the environment for care delivery. E4 describes working with F6 and nurse leadership to rally resources for a solution to humanize the pediatric ward with portraits of providers to soothe isolated children during the COVID-19 lockdown.

> *"Putting the patient in the center and helping with their fears and frustrations with not being able to have visitors and connecting with nurses. And so that's how it started." (E4)*

A person-centered approach, described in the previous example, could eventually grew into a hospital wide initiative when the nurse received formal support. Few others, like N2, could pivot an existing patent-pending prototype of an IV line organizer to specific constraints faced by ICU nurses who needed to reduce PPE usage if they had the expertise.

4.3.2 Hands-on Expertise. Most facilitators in dedicated hospital makerspaces (except F4) have technical expertise and project management skills. Without such skills, nurses often expect to hand-off technology use to offset the learning curve. Though F1, F3, and F6 also work with engineering students in their local communities, on-premises support widely affected the extent to which nurses developed their prototypes based on insights. As F4 in her academic maker space shares, nurses expect to hand off their ideas to other experts.

"It's not obvious to them [nurses] that they're supposed to be doing the making themselves.[. . .] We're sort of learning this the same time as they are." (F4)

Nurse educators offered a contrasting perspective on how and when they used prototyping to create learning experiences in their curriculum. E1 and E4 speak from a leadership perspective of hands-on learning for key procedures. Even E5 who does not use the makerspace offers an optimistic view of nurses who are expected to absorb learning challenges and efforts within their schedules to *"to construct something that they know in their head that they need for patient care."* E2 explains that nurses may have a solution for problems but maybe wary to invest in creating a device with unapproved equipment.

"Most nurses will work to solve a problem. It just might not always be streamlined to be[come] a device." (E2)

Unlike educators, nurses are typically overseen by nurse managers. Nurses in our study overextended themselves to develop prototypes on their own time. N2 and N3 developed their projects during educational stints with more flexible schedules. Technology iteration is time-consuming, so it is understandable that nurses with little time to spare from rigorous schedules will minimize its use. F1, F3, and F4 shared times they either handled or handed off actual printing time despite expectations of a hands-on maker approach. F1 empathizes with nursing students' low participation in his collaborations with the department,

"The biggest challenge for the nursing students is time and that has absolutely nothing to do with the makers lab space, or how it's done. [...] It's really hard to take on yet another learning process." (F1)

4.3.3 Formal Collaboration. One alternative to time and technical skill is collaboration with others. Nurse solutions seem to lead to collaborations between nurses when makers align proof of contribution to departmental goals. Yet formal collaboration is not easy because of structural barriers within the medical system. Participants mentioned informal collaboration within the nursing community across problem-solving stages. Though nurses overcame their expressed reluctance to formally collaborate by seeking nurse leadership first, N1–N4 all mentioned how mentoring across a wider network helped them make progress. N3 who was granted a short-term award stopped working on her prototype once her nurse manager was indisposed and eventually passed on. N1 looked for informal mentors outside her university finding them in a national association of nurses. F3 and F4 also mentioned their partnerships in local communities with other makers as does F5 who is deeply embedded in both local maker communities and hospital management. N2, the only male nurse in our study, reached out to physicians to formalize the data collection on his prototype without much progress.

"I went to physician-owned facilities; they have the same amount of red tape as corporations. But I'm not giving up. I'm going to continue and hopefully one of these facilities will allow me to do a pilot study." (N2)

Nurses in our study persisted for some or all of their journey with formal support from hospital leadership, grants, and programs. F2 and F5 each spearheaded a short-term innovation program in their hospitals for grassroot ideas. When these structures fall away, nurse insights circulate among individuals (N1, N2) who must find ways to surface their insights. Facilitators are critical to build the trust required to make nurse insights more explicit; to articulate the insight into a prototype. With nurse participation, they create proof of concepts with materials that are best suited for nursing practice. F2 shares her view of why nurse involvement in traditionally defined innovation projects conflicts with nursing prerogatives to care for patients:

"You have to find an efficient design, take the time to make it, do research on it. It takes a very, very long time. For a lot of nurses that just doesn't necessarily hold their interest, like patient care does." (F2)

5 DISCUSSION: TRANSFORMING HEALTHCARE ORGANIZATIONS FROM THE BEDSIDE

We set out to identify nurses' adaptive problem-solving in innovation spaces at the point of care. Our findings confirm that a practitioner's role influences visibility into procedural improvements in quality of care. Unlike other frontline workers, nurse interactions require them to manage these situations for each patient creating ongoing tacit knowledge, a type of organic wisdom from experiential improvisations [41] from observations of the patient's life [1, 16]. Tacit knowledge can be made explicit when realized with formal support as arguments and/or low-fidelity prototypes for temporary or long-term improvements. Based on making as the context, we discuss how we can encourage clinicians' on-ground tacit improvisations alongside top-down managerial action by overcoming challenges in organizations [4, 41]. Especially for medical innovation, in this section, we argue that nurse participation can update care practices and long-term procedural knowledge. We discuss insights from the case study of nurses in medical making as an exploration of episodic future transformation of healthcare organizations. Our insights highlight the need for negotiating alliances between social actors in the healthcare organization [39].

In this section, we discuss how nurses face constraints in present day makerspaces leading to insights into three challenges: concealing solutions, sequencing resources for innovation, and ultimately falling short of anchoring for future transformation [4]. At makerspaces, nurse participation relies on specific allies to craft arguments and create prototypes. We contribute insights for makerspaces [27, 34, 35] on themes of negotiating expertise in medical innovation [4, 39] and understanding wider participation in making [7, 17, 59] as collaborative design [3, 32].

5.1 Allied and Assisted Innovation: Fostering Trust

Healthcare institutions favor consistency and reliability over risk in care practices. While this upholds safety, standardization often prioritizes clinical reasoning over practical reasoning. This stems from the fear of malpractice suits and inadvertently overlooks insights from nurse's bedside practical reasoning. Nurses, as clinicians, are known to bring perspectives of prevention, recurrence, and oversights in design of devices or environments from their practice [1, 14, 31, 61]. Moreover, nursing philosophy [16] places the prerogative on professionals to uphold ethics of care (i.e. holistic well-being) resulting in short- or long-term interventions to alleviate pain and prevent future harm [10]. In our study, all 16 participants revealed how nurse improvements for patient-centered care may manifest either as devices and/or extend to transform healthcare environments. For example, E2 in our study adapted a wider training protocol to practice wound sutures based on observations of nurses in her unit. When nurses engage in stealth-making as recorded elsewhere in literature [21], their tacit knowledge remained within their community of practice due to a lack of historical trust in existing systems. Fostering trust through visible and formal support can alleviate this challenge in employee-based innovation observed as the concealing stage in other studies [4].

The role of nurse leadership and on-premise technical experts suggest a model of *allied innovation* to encourage nurse prototyping and participation. Facilitators in our study unequivocally note that nurses need help recognizing opportunities for innovation. They oversee medical making in institutional makerspaces and innovation labs [33]. Facilitation invariably creates awareness of interdisciplinary legal facets along with engaging design and engineering expertise to develop collaborations across the medical organization required for formal innovation [39] Educators and nurses further indicate formal support from nurse leaders or managers is central to nurse-led activity

at least within the institutional setting to align resources and create visibility. We hypothesize further expanding human infrastructure through community roles, non-profits, and administrative hand-offs can supplement expertise involved in tasks for sequencing resources for innovation [4] that maybe unavailable on site. In the absence of such facilitation, participants like N1 and N2 shared their challenges finding adequate support for technical needs and mentorship outside their primary institutions. To make progress towards organizational innovation, we discuss how formal roles within the nursing community could help navigate such challenges.

5.2 Seeing, Creating, and Telling: Crafting Arguments

In our study, nuances in nurse orientations to problem-solving are visible in the person-centered solutions they create based on perceptual acuity and proximity to specific patients. While their visibility into patient experiences is unparalleled, advocating for material resources understandably requires articulation work [44, 48]. The articulation of labor required for sequencing long-term resources for innovation [4] is complicated by power structures marginalizing nurses based on historical [21] and current organizational hierarchies. We found few nurses were able to generate preliminary evidence, supportive leadership, on-ground technical experts, and proof of ability to scale before nurses begin to prototype solutions. Though these socio-technical challenges are not unique to nurses [4, 27], their experiences show how explicit organizational support is required to encourage the kind of political shift observed in organizations in other medical innovation projects [39]. When nurses get visibility into institutional priorities (e.g., F4's remarks on how a nurse justified time on a project based on the hospital's quarterly goals to reduce pressure wound instances), they could advocate for resources such as time for on-ground problem-solving. Recent studies indicate there is a finite scope for rapid prototyping process in healthcare settings with low tech materials [26] unless we develop shared systems to support collective innovation [36].

At present, participation in innovation through medical making increases the burden of articulation work on nurses and their early collaborators to justify experimentation in institutional settings. While nurse insights arise from proximity and perceptual acuity, fabrication and other technologies serve to expand on-ground nurse capabilities in institutional settings when they have time to experiment through allied roles as educators or learners. Once they create prototypes with low-tech materials, they must develop evidence per internal standards for evidence and accepted forms of nursing research [18]. Here, creating formal roles in nurse innovation (see F5) and opportunities for collaborative reflection [51] may be useful to help craft arguments, write grants, or form research collaborations. These are skills currently concentrated in nurse educators and researchers who perform articulation work; a criterion of inclusion for some nurses deepening the hierarchy between those with advanced degrees and nurses at the bedside. Those with advanced degrees, as seen in our participant group, tend to be employed in urban or private hospitals [47] representing a widening digital divide within the nursing community.

5.3 Labor of Iteration: Prototyping Solutions

Nurses face challenges that occur at the *"point of interaction"* (E4) with the technology typically when they are with patients. Ideas to improve prenatal, maternal, and pediatric care indicate how bedside interventions rarely scale up to become standard medical devices despite practice level implications. Few nurses developed low-fidelity prototypes into products, even with on-ground technical expertise, without receiving additional institutional support. From our study, we understand that nurses iterate more than physician-makers [26] precisely because nurses develop solutions from in-patient observations unlike process- or technology-led solutions focused on specialized treatments. Nurse solutions then may be tacitly formed based on appropriate scale of intervention for temporary yet immediate patient needs or chronic yet overlooked process gaps

[5, 19, 30, 62]. To prototype physical solutions, the additional complexity of materials requires nurses to engage in experimental processes which Baruch et al. describe in the cost of failed prototypes, sunken time in iteration, and technology experimentation as challenges making in hospitals [8]. The three nurse stakeholder groups in our study identified similar conditions affecting technology and materials used in prototyping process. Some mentioned working with materials to guide others in defining the problem space beyond the bedside to their specialization. Alongside the two non-users of maker spaces in our study, our participants expected to invest personal time in their projects till they could hand off technical development to facilitators. This limited the time they spent developing expertise. Depending on their stature within an organization, apart from resources (i.e. mentors, materials, funding) for prototypes, nurses at the bedside had little room in their daily work to do more than make adaptations when technology design fails.

Based on these findings, we contend that nurse experimentation with one-off low-fidelity prototypes cannot be scaled to current notions of technology-led innovation. In fact, making with its promise of customizability and personalization is suited to this need in nursing work for patient care. Even when nurses are unable to streamline resources, they can be encouraged to improvise with adequate training and recognition of their labor. Their contribution is not only creative resilience [28], within private institutions, it is also invisible labor in nursing practice [48]. A narrow focus on novelty, reliability, and advancing clinical efficiency overlooks the hidden labor of nurses who improvise anyway in their routine work.

From our study on making, we offer a psychosocial perspective around innovation from participants who believe nurse resilience will tide them through challenges to sequencing and anchoring their efforts to transform organizational processes [4]. On one hand, *"all nurses are problem-solvers"* and on another *"nurses don't want obstacles"* revealing the tension between individual commitment to innovate and the collective need for formal organizational support. Integrating nurse participants' view of problem-solving requires healthcare organizations to recognize their activities as nursing work centered on patient care. Within the scope of our work, we suggest implications for systems aligned to short- and long-term problem-solving in medical making infrastructure for innovation.

6 IMPLICATIONS AND FUTURE WORK: NURSE INCLUSION IN INNOVATION

Nurses have a limited presence in formal makerspaces recently introduced in healthcare settings. Understanding nurse challenges in such a niche context is inadequate and future research must explore the complexity of organizational features impacting their participation in healthcare innovation. Nurse participation in making [62, 63], and nurses themselves, can however be centered in technology design. One approach is for formal organizational systems to encourage visibility into nurse improvisations and designing infrastructure for ongoing innovation.

6.1 Visibility for Collaborative Reflection

Revisiting how technology is designed and implemented within hospital hierarchies can encourage nurses to collaborate in technology design as observed in other contexts [51]. One method of introducing on-ground alliances for prototyping is to appoint facilitators and leaders across communities of practice or departments. For example, F2 in our study mentioned putting together teams with at least one nurse to diversify the project team regardless of the person initiating the project. Visibility into the process can create intra-professional alliances over time. Otherwise, nurse participation remains enmeshed in other gendered care practices that undermine on-ground insights. Systematic focus through programs, showcases, and formal positions can provide incentives for nurse participation with clear pathways. In addition, creating role models for nurses across intersections of specializations, age, experience, and extent of solutions creates a more inclusive landscape of innovation for nurses. Makers are amenable to sharing ideas through forms, pop-ups,

showcases, and psychologically safe spaces. We recommend creating levels of expertise in nursing within the hospital environment to create upstream visibility in healthcare to impact technology implementation with realistic insights [61]. Medical making is more likely to invite prototyping collaborations with nurses if they receive facilitation, mentorship, and training to formalize their participation. Without material resources including time and space to experiment in their routine work, nurses cannot engage in medical making. To carry out this responsibility, a formal recognition of its value in healthcare practice is necessary either in training or nurse professional roles. Such policy recommendations are beyond the scope of this paper. However, a near-future approach could be to design communication technologies that allow nurses to translate existing workarounds, prototypes, and bedside interventions with remote collaborators instead of the current focus on sharing finished, technology-led prototypes in repositories like the NIH 3D Print Exchange.

6.2 Notions of Scale for Repair

Not all nurse insights can be applicable beyond singular situations or a specific patient's needs. Yet technology-driven innovation in a privatized healthcare system (USA) is skewed towards scale of impact. This notion of scale is aided by remote systems such as design repositories and shared infrastructure for making tuned to artifacts. Instead, we call on technology designers to expand on the potential of maker technologies to support local, small scale artifacts through shared community resources. Exploring features of digital platforms and entrepreneurship can suggest future design to support medical innovation for actual use. Nurse problem-solving in other emerging sites of repair [28], crisis [33], and community-led innovation [20, 40] suggest untapped creativity to be leveraged through large-scale communities distributing parts of the problem [36]. Arguably, material-based expertise is required to resolve a conflict deep in nursing work wherever applicable in their practice. De-linking scale of implementation from problem-solving may encourage nurses to come forward to design healthcare innovation. However small in scale, as acts of repair and reuse [28], nurses' everyday creativity suggests necessary innovation for care. Further, nurse participation in technology design and innovation ensures their perspectives are introduced in a range of future roles (e.g., both long-term telehealth and short-term crisis management) in healthcare settings. Technology may automate or standardize healthcare functions to become more reliable, accountable, and comparable, but moving towards a future with personalized care relies on the resolution of nurse contributions to improving healthcare.

7 ETHICS AND LIMITATIONS

Our goal is to investigate an understudied stakeholder group in technology design and medical making. Though our qualitative study follows methods in other published work on makers [26, 33, 34], we acknowledge such insights reflect the views of the community of nurse makers to the extent of our interpretation as technology designers. Within the scope of our study, we have relied on historical accounts and background literature to offer visibility into our rationale for analysis. The community of nurse makers is small and tightly knit as we discovered during recruitment. We refrained from member checking or validating our interpretations to protect possible exposure of participant identity due to their familiarity with projects and interactions in maker faires or innovation meets. Instead, in line with qualitative methods, we strive to clarify our approach wherever possible and limit interpretations to the specific contexts described by participants. While a situated, in-person ethnographic observation of nurse problem-solving could yield greater insights, we offer insights based on the methods available to us during a pandemic (i.e. the COVID-19 crisis). We acknowledge the insights in this study are reflective of the participants' experiences yet hope to indicate possible avenues for future work around nursing as a professional community of practice.

Moreover, we note that participants divulged details to the primary researcher, who is not a nurse, about these experiences in an academic research study because of a transferred trust when approached through their institutional facilitators. Any details included are carefully selected with written consent from participants. We chose to trade-off specificity of project level details to maintain participants' privacy and an expressed need for confidentiality. Wherever possible, we have disclosed information on the process within ethical boundaries to protect patent-pending or institutionally restricted devices described in this study. To lower the risk of revealing participants who can be traced through public data (i.e. news articles and blog posts), we draw insights into collaborative infrastructure from participant accounts of primary and secondary prototyping experiences in healthcare settings. We include insights from open source collaborations or details approved by the participants to support findings from primary interviews wherever applicable.

Medical making and nursing practice engages with community networks beyond the USA. Maker participation in traditional health care institutions may rely on global maker technologies [32, 50] yet it is subject to regulatory authorities at the national level. Moreover, nurse certifications and training vary across countries. Hence, we focus on the USA to explore the role of sociotechnical infrastructure particularly in medical device regulation, nursing professional training, and on-premise technology resources. We reached nurses through facilitators that we either knew of, or had access to, leading to a selective sample based on their networks. This limits our understanding to hospital settings that include facilitators not other spaces where nurses may collaborate in other ways (e.g., university makerspaces in engineering programs). These are often in private or teaching hospitals owing to a concentration of skill, industry, and other factors in urban areas that differ from rural or suburban nurse experiences in healthcare.

8 CONCLUSION

A nurse is both a beacon for care and a rare voice in healthcare technology design. In this study, we situate nurse perspectives from their experiences making medical equipment to understand their role in safety-focused, institutional medical making to instantiate potential inclusion in organizational transformation. Nurse insights at the bedside can re-orient healthcare infrastructure to deliver patient-centered care through medical making collaborations. However, expanding technical capabilities is unlikely to be adequate to encourage nurse participation in group work at the point of care. Our study with 16 participants represents an ecology of nurse educators, managers, and facilitators to describe how missing infrastructure interacts with historical skepticism and practice-based constraints to create material and social barriers. We contribute an understanding of when nurses persist in making solutions (i.e. in-patient, bedside, workflows) based on their extent of visibility into the practice to iterate with low-tech materials for innovations in practice. We discuss implications for designing human-material infrastructures to enable nurse participation. We argue that a nurse's practice-based expertise at the frontline of healthcare organizations can guide design attention to systems, process, and workflows rather than other techno-centered approaches often aligned to scale, novelty, and automation.

At present, nurse-led problem-solving remains peripheral to innovation activities in formal medical making spaces. Nurse artifacts and systems orient their practices for better delivery of patient care. They perceive human needs in bedside settings to resolve urgent, chronic, and pragmatic challenges in response to their environment and patient discomfort. Hidden in nursing work, a nurse who performs non-standardized tasks as *"innovation from desperation"* (F2) risks stepping outside her professional capacity to deliver care in ways that remain invisible and therefore undervalued as essential work in shaping healthcare.

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Received April 2021; revised November 2021; accepted March 2022