SPECIAL ISSUE: User Centered Design for Exoskeleton & Exosuit Usage

Supporting Surgical Teams: Identifying Needs and Barriers for Exoskeleton Implementation in the Operating Room

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Objective: The objective of this study was to identify potential needs and barriers related to using exoskeletons to decrease musculoskeletal (MS) symptoms for workers in the operating room (OR).

Background: MS symptoms and injuries adversely impact worker health and performance in surgical environments. Half of the surgical team members (e.g., surgeons, nurses, trainees) report MS symptoms during and after surgery. Although the ergonomic risks in surgery are well recognized, little has been done to develop and sustain effective interventions.

Method: Surgical team members (n = 14) participated in focus groups, performed a 10-min simulated surgical task with a commercial upper-body exoskeleton, and then completed a usability questionnaire. Content analysis was conducted to determine relevant themes.

Results: Four themes were identified: (1) characteristics of individuals, (2) perceived benefits, (3) environmental/societal factors, and (4) intervention characteristics. Participants noted that exoskeletons would benefit workers who stand in prolonged, static postures (e.g., holding instruments for visualization) and indicated that they could foresee a long-term decrease in MS symptoms with the intervention. Specifically, raising awareness of exoskeletons for early-career workers and obtaining buy-in from team members may increase future adoption of this technology. Mean participant responses from the System Usability Scale was 81.3 out of 100 (SD = 8.1), which was in the acceptable range of usability.

Conclusion: Adoption factors were identified to implement exoskeletons in the OR, such as the indicated need for exoskeletons and usability. Exoskeletons may be beneficial in the OR, but barriers such as maintenance and safety to adoption will need to be addressed.

Application: Findings from this work identify facilitators and barriers for sustained implementation of exoskeletons by surgical teams.

Keywords: industrial/workplace ergonomics, interventions, qualitative methods, usability testing and evaluation, surgical care and procedural technologies

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INTRODUCTION

Nearly half of registered nurses in the U.S. have taken days away from work due to musculoskeletal (MS) disorders (*Injuries, Illnesses, and Fatalities Case and Demographic Numbers*, 2018; *Nonfatal Occupational Injuries and Illnesses Requiring Days Away From Work*, 2015). Previous studies found that 60% to 90% of the surgeon population experienced pain, discomfort, or fatigue during or after surgery, and that 77% experienced multisite pain particularly in the neck, shoulders, upper back, and lower back (Alleblas et al., 2017; Dalager, Søgaard, Boyle, Jensen, & Mogensen, 2019; Park et al., 2017; Sari, Nieboer, Vierhout, Stegeman, & Kluivers, 2010; Sivak-Callcott et al., 2011). Janki, Mulder, IJzermans, and Tran (2017) showed that 47.5% of surgeons experienced MS symptoms and 37.5% used medication and/or therapy to reduce pain. These experiences of pain and symptoms directly impacted worker health and patient outcomes; almost half of the surveyed surgeons believed their MS symptoms influenced surgical performance and career longevity (Wells, Kjellman, Harper, Forsman, & Hallbeck, 2019).

Similar to surgeons, other members of the surgical team (e.g., surgical nurses, trainees) also experience substantial levels of MS symptoms, but relatively fewer studies and interventions have focused on this population. Sheikhzadeh, Gore, Zuckerman, and Nordin (2009) reported that perioperative nurses and technicians had a high prevalence of both lower back pain (84%) and shoulder pain (74%). Choobineh, Movahed, Tabatabaie, and Kumashiro (2010) found that 86% of the operating room (OR) nurse population in Japan experienced a form of

MS symptom, whereas Kaya et al. (2008) found that 70% of surgical nurses and 60% of resident anesthesiologists experienced upper extremity tremor. Static stress (e.g., prolonged standing, holding equipment) and moving or lifting heavy equipment were reported as primary causes for pain onset among perioperative personnel (Meijsen & Knibbe, 2007).

Changes in organizational culture, interventions that modify the environment or individual worker (e.g., temperature, psychosocial exposure), and changes in mechanical exposures (e.g., adjusting workstations) are commonly proposed ergonomic interventions in many industries; however, evidence of validity, efficacy, sustainability, and effectiveness remains limited (Westgaard & Winkel, 1997, 2011). Furthermore, important barriers for implementation, such as lack of time, resources, communication, and management support, must also be considered for effective workplace solutions (Yazdani & Wells, 2018). Although incorporating ergonomic interventions into the workplace is challenging across industries (Westgaard & Winkel, 1997; Yazdani & Wells, 2018), it is especially difficult in the OR due to the demanding tasks and restrictive work environment that must prioritize patient safety. Additional barriers in the OR include sterility requirements. Physical interventions appropriate in other industries may not be feasible in the OR; for example, wearable interventions must not extend below the elbows (sterility requirement) and must be able to fit underneath a surgical gown.

Most current interventions in the OR focus on the administrative strategies, for example, rest breaks, guidelines, and mandatory workshops for knowledge sharing of different ergonomic training (Dalager, Højmark, Jensen, Søgaard, & Andersen, 2019). In addition to shift rotation, recent work found that intraoperative microbreaks—specifically short, 1.5- to 2-min breaks at 20- to 40-min intervals—significantly reduced shoulder discomfort and improved physical performance (Hallbeck et al., 2017; Park et al., 2017). Microbreaks overcame the barrier of maintaining sterility in the OR with specially designed stretches and received positive worker feedback. However, administrative interventions can be limited by challenges in obtaining management support, worker/management commitment, and worker resistance to changing the environment (Yazdani & Wells, 2018).

Mechanical interventions to date in the OR have been limited to guidelines for optimal operating table height and positioning for monitors and patients (Berquer, Smith, & Davis, 2002; Van Det, Meijerink, Hoff, Totte, & Pierie, 2009; Vereczkei et al., 2004). Mechanical arm rests, body supports, and ergonomic chairs have been proposed, but there have been limited implementation and worker adoption in the OR (Albayrak et al., 2007; Galleano, Carter, Brown, Frank, & Cuschieri, 2006; Noro, Naruse, Lueder, Nao-i, & Kozawa, 2012; Schurr, Buess, Wieth, Saile, & Botsch, 1999). For nurses and surgical assistants, solutions such as better retractor systems, better instrument or standing support, or wheels for heavy equipment have been proposed (Meijsen & Knibbe, 2007). However, many mechanical interventions are fixed and constrain the surgical team members to the point where they can interfere with task performance. Specifically, the noncyclical and constantly changing task requirements of surgery limit the feasibility of rigid mechanical interventions.

Alongside mechanical interventions at the bedside, surgical techniques have also been developed to improve surgeon ergonomics (Dalager, Søgaard, Bech, Mogensen, & Jensen, 2017; Punnett & Wegman, 2004; Reyes, Tang, & Cuschieri, 2006; Yu et al., 2017). Surgical techniques such as robotic-assisted surgery claim to be more ergonomic and address these issues; however, the benefits of robotic techniques likely focus on the surgeon, with ergonomic risk transferring to bedside surgical assistants who now must work around a large robot (Yu et al., 2017). There is a need for the implementation of dynamic, wearable interventions that take advantage of advances in lightweight and passive materials for the entire surgical team.

Recent advances in exoskeleton technology show promise for health care workers. Exoskeletons are external devices that are worn to support physical demands and task performance (de Looze, Bosch, Krause, Stadler, & O'Sullivan, 2016; Kim et al., 2018; Rashedi, Kim, Nussbaum,

& Agnew, 2014). Upper-body passive exoskeletons use nonpowered elements (e.g., levers and springs) to store energy from human movements and release it when required (Lowe, Billotte, & Peterson, 2019). This lightweight (typically 2.5–5 kg) commercial technology supports workers' arms, shoulders, and/or back. Exoskeletons are a novel potential intervention to address ergonomic risks, with reported success in various industries (e.g., Hensel & Keil, 2019; Kim et al., 2018; Smets, 2019). Bosch, van Eck, Knitel, and de Looze (2016) found decreased back muscle activity and lower discomfort while performing simulated assembly tasks and static holding wearing a passive back-support exoskeleton (i.e., Laevo™). In addition, Liu and colleagues (2018) used an arm-support exoskeleton (i.e., Levitate AIRFRAME™) in surgery and found that surgeons reported significantly less fatigue and less arm and shoulder pain while wearing it.

Although exoskeletons can be beneficial for surgeons and pilot implementation on limited cases has been completed, little attention has been paid to the ergonomic risks of other members of the surgical team. Furthermore, the pilot implementation was not sustained or widely implemented across institutions (Liu et al., 2018). There is a need to identify the needs and barriers for sustainable implementation for widespread adoption and to gain insight into stakeholder perceptions on exoskeletons. The purpose of this work was to determine the facilitators and barriers to exoskeleton technology in the OR as an intervention for reducing upper-body MS pain and discomfort for surgical team members.

METHOD

Study Participants

This research was approved by the Institutional Review Board at the university (IRB #1807587226). Informed consent was obtained from each participant. The participant population included members of the intraoperative surgical team at the patient bedside: surgical nurses, residents, and attending surgeons. Surgical nurses are at the bedside with the attending surgeon to ensure that surgical instruments are available and handed to the surgeons (Yu et al., 2016). Residents are trainees who complete the role of the assisting surgeon; they perform segments of the procedure under the guidance of the attending surgeon or assist to the procedure by holding instruments for visualization.

Study Procedures

Multiple strategies were utilized to recruit participants with intraoperative experience from different surgical roles for the focus group study. A convenience sample of surgeon and resident participants was recruited. Surgical nurses were recruited through a hospital-wide showcase event, where a table was set up with the exoskeleton near the OR front desk at a satellite hospital of a larger health system. The exoskeleton display drew the attention of staff passing by. The snowball sampling technique was used to recruit participants for each surgical role. After obtaining at least one interview from each surgical role to ensure diversity in sampling, a stopping criterion was set as when no new themes emerged. The point of data saturation was defined when this criterion was met (Francis et al., 2010; Saunders et al., 2018). Sampling was stratified to ensure diversity of roles; however, we included all interested participants during the 6-month study period. After providing informed consent, participants completed a two-part study in the following order: (1) individual or multiperson interviews, and (2) a simulated laparoscopic skills task while wearing a passive arm-support exoskeleton (Levitate AIRFRAME™; Figure 1a).

Focus groups. All individual and multiperson interviews are referred to as focus groups throughout this paper. Focus groups were completed to gain insight into the stakeholder's perspectives on passive exoskeletons, specifically arm-support devices. A questionnaire including demographics, work experience, and experiences with MS symptoms was completed. Then, a brief overview of exoskeleton technology was given, and clarifications were provided on any questions regarding the exoskeleton. A script (see Supplemental Material which is available with the manuscript on the *HF* web site) was adapted from Kim, Nussbaum, and Gabbard (2016), which included questions regarding technology adoption, supporting worker's tasks/job, and workplace safety and health. All focus

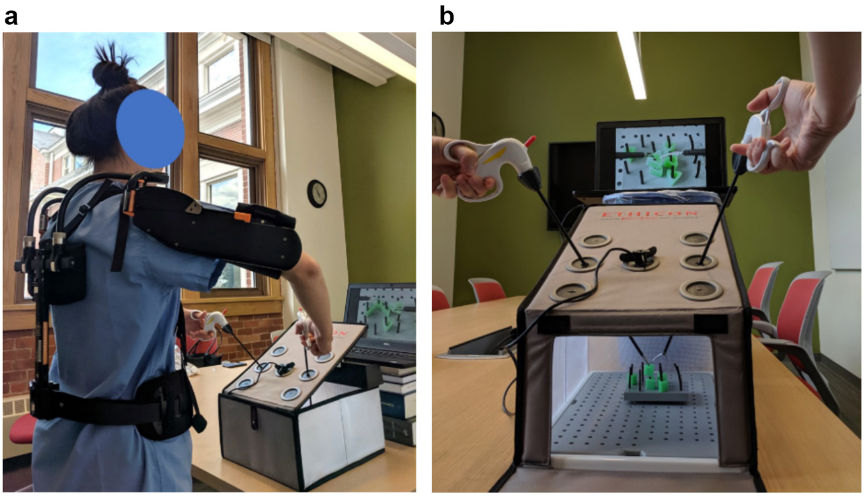

Figure 1. (a) Exoskeleton equipment was worn while performing the FLS task, and (b) inside-the-box view of the FLS task. FLS = Fundamentals of Laparoscopic Surgery.

groups were completed in person by the same moderator.

Seven surgical residents, four surgical nurses, and three attending surgeons participated in this study. The seven residents participated in three groups: one group of three and two groups of two participants. Two surgical nurses participated together, whereas all others and each attending surgeon completed individual interviews. Table 1 summarizes the participant demographics. A surgical nurse was called into an operation and was unable to complete the simulation; however, the participant completed the focus group. Attending surgeons were part of the General Surgery specialty and operated an average of 17 hr per week (average of three cases per day, operating 2 days per week), whereas nurses operated 44 hr per week. Residents were all within General Surgery, and six residents were in their research year (protected from clinical duties). Thus, the resident group reported only operating <5 hr per week. However, all residents had already completed 2 years of their residency in the OR before the study and had described experiencing or hearing about coworkers experiencing MS pain from surgery.

Simulated surgical task. Ten participants completed the Fundamentals of Laparoscopic Surgery (FLS) peg transfer task on the mobile FLS trainer wearing the noted exoskeleton (Figure 1b). Four participants (three residents and one nurse) from the focus groups did not complete the simulation as only one exoskeleton was available at each focus group. Even though some participants were not able to complete the simulated task, all were given an opportunity to try on the exoskeleton. A research team member, who was trained and certified by the exoskeleton manufacturer, was present during every focus group and simulation task. This member helped participants don the exoskeleton immediately before the simulation task. After donning the exoskeleton, the team member adjusted all four points of the exoskeleton and ensured proper fitting for each participant. The time spent to ensure fit (and having only one exoskeleton available) contributed to fewer participants completing the simulation task. In each simulation, participants from all surgical roles (e.g., nurses) completed repetitions of the FLS task for 10 min. For all surgical nurses, this was their first exposure to the task, and thus FLS performance scores were not an outcome metric for this study. The task required the participants to complete and repeat the peg transfer for 10 min. Participants picked up pieces from the pegs and transferred the pieces between the dominant and nondominant hands. This task was validated for surgeon certification in laparoscopic surgical technique (Peters et al., 2004); thus, this task was most relevant to the surgeon role. Although

TABLE 1: Summary of Demographics and Experience of Participants ($M \pm SD$)

	Surgical Residents	Surgical Nurses	Attending Surgeons
n	7	4	3
Age (years)	29 ± 1	40 ± 13	42 ± 5
Experience (years)	3 ± 1	12 ± 3	9 ± 6
Gender (% female)	71	33	33
Operating hours per week	1 ± 1	44 ± 7	17 ± 5

roles of the surgical assistants involve tissue manipulation with graspers, those tasks are primarily static and less dynamic than the surgeon role. We also note that there are other static holding or preparation tasks that nurses perform in an operation that were not represented by this brief simulation. This task was intended to demonstrate the exoskeleton in a task validated for surgical training and provide participants an opportunity to use the exoskeleton. Afterward, the System Usability Scale (SUS) was completed to assess the usability of the exoskeleton (Brooke, 1996). Follow-up questions were asked to elicit impressions of the device.

Data Analysis

All focus group sessions were audio recorded. Recordings were deidentified, and a professional service was used for transcription. The raw transcript data are accessible in a data repository (https://purr.purdue.edu/projects/hf196191). NVivo 12 (QSR International, Melbourne, Victoria, Australia) was used to complete a content analysis through inductive and deductive processes to identify relevant themes from participants' responses (Hsieh & Shannon, 2005; Krippendorff, 1989). Three study team members independently completed the thematic analysis of the first three participants. They then came together to resolve coding discrepancies and identify subthemes. All remaining transcripts were double-coded; a minimum of two independent raters completed every transcript. A team of qualitative methods and clinical subject matter experts were consulted throughout theme development. Data saturation was reached with the 14 participants, as responses by the last focus group were anticipated by the researchers and no new themes emerged (Onwuegbuzie, Dickinson, Leech, & Zoran, 2009; Saunders et al., 2018).

RESULTS

Survey Results

Thirteen participants (93%) reported experiencing MS symptoms within the last year. The one participant who did not report MS symptoms was a surgical resident who spent the entire past year on research (i.e., protected time from clinical duties to dedicate to research). Aching, stiffness, and fatigue at the neck, shoulder, and back were listed as common symptoms. To alleviate their MS symptoms and fatigue outside the OR, participants indicated that they complete stretches inside and outside the OR and exercise (72%). Inside the OR, all participants noted doing small stretches and changing positions to not disturb the surgical instruments. Participants of shorter (less than 160 cm; $n = 2$) and taller (more than 188 cm; $n = 2$) stature noted challenges in managing their MS symptoms due to the height differences among the surgical team. One resident noted, "I'm short so [I] have to use step stools often, and often stacked several high—it become unstable and difficult to use pedals for cautery or shift positions," whereas a taller resident stated, "I am constantly tempted to have horrible posture due to shorter attending [surgeons]." When asked what would help overcome managing MS symptoms, two participants noted a need for interventions that can help maintain posture, whereas others ($n = 4$) highlighted gaining knowledge on ergonomic strains and more personal exercise and strength training.

Content Analysis Themes

Four main themes were identified related to the adoption of exoskeletons in the OR: characteristics of individuals, benefits, environmental/societal factors, and intervention characteristics (see Table 2). These themes

TABLE 2: Themes and Subthemes of Exoskeleton Adoption in the Operating Room Identified From Content Analysis

Theme	Subthemes
1. Characteristics of individuals	a. Awareness of problem/indicated a need for an intervention b. Curiosity c. Champion
2. Perceived benefits	a. Long-term benefits b. Decrease of MS symptoms c. Development of ergonomics training
3. Environmental/societal factors	a. Immediate, observable results b. Familiarity c. Team buy-in d. Safety e. Perception f. Sterilization g. Storage
4. Intervention characteristics	a. Maintenance b. Investment c. Evidence of exoskeleton working d. Usability • Ease of use • Externalities • Weight • Anthropometric fit

Note. MS = musculoskeletal.

were organized considering the Consolidated Framework for Implementation Research (CFIR) by Damschroder et al. (2009). The subtheme of usability was included within intervention characteristics.

Theme 1: Characteristics of individuals. The individuals involved were identified as a key influencer of exoskeleton adoption. This theme encompassed the individuals' attitudes and motivations for change and for the intervention (1a and 1b). The majority of the participants (57%) emphasized that the implementation of exoskeletons would require a champion at an institution to spearhead the efforts (1c), especially for raising awareness to consider career longevity (1a and 2a). Residents in particular mentioned that attending surgeons, especially those who are interested in ergonomics, can serve as champions and help coach them for better ergonomic posture. In addition, individual curiosity (57%) and awareness of MS ergonomics problems (100%) were found as facilitators of intervention adoption in the OR.

All participants were aware of the need for an intervention (1a), and this was grounded on their past experiences. When asked whether they perceived a need for exoskeletons, one participant answered, "I don't think that we know what we're missing potentially. I've done it for eight [or] nine years without it." This sentiment illustrates a barrier to implementation and the lack of awareness of existing ergonomic innovations for everyday workers to prevent MS disorders outside the occupational health and safety communities. Personal connections to the adverse impact of ergonomic injuries were brought up as a strong motivator for practice change, and participants indicated awareness of others who required surgery because of MS disorders. One participant commented, "We are negligent towards our health, all of us are. And I haven't experienced any long-term problem, but I can feel some short-term effects." This sentiment was common, especially among the residents and surgeons. One attending surgeon who is taller also noted,

> there tends to be a significant height difference between me and the surgical trainees with whom I work. And as I result, I'm constantly trying to configure myself in such a way that I allow for them, when they are performing the surgical task, to be in the most comfortable position that they can be in to complete that task, and that routinely makes me have to contort myself in some way to make it so that can happen.

This surgeon was aware of the actions that cause his MS symptoms but recognized that he could not alter his practice for the success of the surgical team.

The awareness of interventions and indicated need for an ergonomic intervention (1a) also encompassed responses regarding previous and current practices to decrease MS symptoms and fatigue. These practices included institutional and personal solutions, such as occupational therapy, yoga, Pilates, and self-medication. All participants heard that others had benefited from these solutions; however, they indicated either never trying these or that these solutions were unsuccessful for them personally.

Theme 2: Perceived benefits. Perceived benefits of the intervention encompassed facilitators for the successful translation of exoskeletons to the workplace. Expected long-term benefits of an exoskeleton (2a) were necessary requirements for implementation and were mentioned by all participants. Specifically, stakeholders expected that exoskeletons would help with issues on workforce retention and prevention of early retirement. One surgical nurse elaborated, "that's true they probably would be more likely to . . . keep on working if they knew that they wouldn't have to be tortured standing there forever." Moreover, the long-term benefits (2a) were linked with an anticipated decrease in MS symptoms (2b). An expected decrease in arm fatigue and pain, less back stiffness and upper shoulder pain, and a decrease in overall strain were noted. Surgical assistants were the user role that was identified to most benefit from exoskeletons (64%). Assistants included residents, medical students, and surgical nurses. Workers in this role, especially first or second assistants, were identified due to their responsibility of maintaining static positions while holding a load to assist the attending surgeon. This responsibility included holding a laparoscopic camera and holding surgical retractors for visualization. One surgeon did not identify a specific worker role, emphasizing that there is no one worker role that can be identified but that it depends on "whoever ends up holding the scope. I think it would be different in each area [and institution]."

Despite coming from different roles, all participants noted the lack of formal ergonomics training at their institution (2c). Current health and safety programs included flyers and annual online wellness modules, but those did not include ergonomics. Further elaborating on the apprenticeship model to learn best practices, workers stated that ergonomics best practices (e.g., keeping elbows near the body, weight shifting, using steps to avoid awkward bending and reaching) were given in an informal way from senior workers or among colleagues:

> I think as individuals, we talk to residents about not hurting themselves. You can see when they're manipulating their bodies in all kinds of crazy ways to accomplish a task, so there's knowledge in that way. But it's not formal training.

Although ergonomic training was lacking, participants indicated that building formal and standardized training around increasing knowledge of MS symptoms and around effective interventions with observable impact may start a dialogue. Many indicated that they believed exoskeletons could serve that role, to increase knowledge on best practices and possible ergonomics interventions.

Theme 3: Environmental/societal factors. External factors, such as environmental and societal, emerged as a theme. Safety and sterility are central tenets in the operating environment, and the impacts of exoskeleton interventions on safety (3d) and sterility (3f) were discussed by 64% and 79% of participants, respectively. Areas of main concern were the exoskeleton arm cuffs (i.e., they must always be above the elbows) and the added bulk to wear underneath the surgical gown. In addition to maintaining the sterile field, sterility (3f) and storage (3g) of the device itself were mentioned. Participants asked hypothetically whether the technology would be better fitted as a personal device or would be interchanged among workers, and if it were to be interchanged, the sterility of the device, where it was stored, and if it could be accessible quickly (i.e., in each individual OR or in a storage room). These were significant concerns that would influence their decision to use it.

Some participants indicated experiencing frustration with other novel tools or equipment implemented in the OR, where breakdowns or troubleshooting often caused unwanted delays. A company representative to address any safety or repair concerns was also stated as a facilitator for implementation, as the hospital technologists would not be responsible for the device; however, this would be an added cost and investment (4b). These logistical factors such as storage (3g), maintenance (4a), and cleaning of the exoskeleton were identified by participants (21%).

Factors of familiarity (3b), perception (3e), buy-in from the team (3c), and immediate observable results (3a) would influence the use of an exoskeleton during every procedure. Although most workers stated that they looked "cool" with the exoskeleton, some mentioned "it looks funny" and that popularity and perception from others may influence their use (3e). Regardless of team perception, conspicuous equipment during patient-facing activities was likely not acceptable in current culture. In parallel to expected long-term benefits (2a), the desire for immediate results (3a) may hinder the implementation because "it's going to be hard to show somebody 20 years down the road, this will save their back." The immediate results of using the exoskeleton (3a) were not categorized within the perceived benefit theme, as workers may not feel an immediate benefit as there is a learning curve in using any technology and workers may experience MS symptoms in other parts of their body (e.g., back or knees instead of shoulders or arms) with their body loads distributed differently.

Theme 4: Intervention characteristics. The theme of intervention characteristics was distilled from responses regarding aspects of the exoskeleton that could either help facilitate or hinder the adoption in the OR. Most workers (71%) reported that investment (4b), specifically monetary, and maintenance (4a) of the equipment would likely influence widespread adoption: "just how long they last versus how long they take to get back up and running. If it's something that your own facility's clinical engineering guy can fix versus the company has to fix" would be a consideration.

Finally, evidence of the exoskeleton working (4d) was categorized separately to represent its public perception (e.g., scientific literature and media). When explaining exoskeleton technology to participants who were unfamiliar with it, examples of passive exoskeleton use in different manufacturing industries (i.e., automotive and aviation) were given, and participants recalled that they have seen press on this technology. This awareness of evidence of exoskeletons working in the different industries shaped participants' impression of the overall technology.

Usability of the exoskeleton (4d) was indicated as having a large influence on adoption (93%). All worker roles noted that whether they used the exoskeleton during surgical procedures would depend on its impact on externalities, such as not hindering other workers, their ability to freely move around the OR, and the preoperative process. Furthermore, the weight and anthropometric fit were specified. Workers, especially those of smaller stature, noted that the technology should not feel heavy or distribute weight poorly, as these aspects will influence using the exoskeleton during every case or only intermittently. An attending surgeon also noted the breathability of the exoskeleton, as surgeons and surgical team members typically feel overheated under a surgical gown. In addition, ease of use, especially in donning the exoskeleton, was noted: "if I can't get that on and get that all fitted within one minute, I don't think I could use it. Cause you just don't have time."

Usability

After completing the simulation tasks, the mean SUS score for the exoskeleton tested was 81.3 out of 100 (*SD* = 8.1) (see Table 3). The system was thus considered usable, falling between the "good" and "excellent" scores and within the acceptable range of usability (Bangor, Kortum, & Miller, 2009). Two attending

TABLE 3: Descriptive Statistics of SUS Scores by User Group

SUS Score	Surgical Residents (n = 4)	Surgical Nurses (n = 3)	Attending Surgeons (n = 3)
$M \pm SD$	83.8 ± 6.0	79.2 ± 7.2	80.0 ± 13.0
Minimum	80.0	72.5	75.0
Maximum	92.5	95.0	87.5

Note. SUS = System Usability Scale.

surgeons provided the lowest SUS score (72.5), which is at the cutoff between "OK" and "good" ranges. Two-thirds of the participants indicated that they agree/strongly agree they would use the system frequently and disagree/strongly disagree that the system was unnecessarily complex. One participant reported a strong agreement that the exoskeleton was very cumbersome to use. Participants provided additional comments, such as the need for a stronger focus on back and neck support, rather than arm support. In addition, an attending surgeon noted that the exoskeleton was not necessary "as elbows were at my side so did not require upper body support."

DISCUSSION

How Themes Inform Exoskeleton Adoption

Our study identified themes for the adoption of exoskeletons in the OR and furthered understanding of facilitators and barriers to stakeholders using this technology. This evidence can be used to build strategies for more widespread implementation for all worker roles in the OR, as well as inform requirements of future exoskeleton design and selection criteria for exoskeletons to be used by surgical team members. For example, regarding concerns of maintenance (Theme 4), it is well known that nursing staff have limited time, especially during OR turnover, so incorporating additional equipment may add to the already high workload. However, exoskeletons can be easily wiped down and arm cuffs easily replaced, thus enabling them to be sterilized en masse. Furthermore, we believe that existing sterility protocols for shared equipment (e.g., lead vests to wear during X-rays) could be adopted to address concerns for the risk of infection and sterility between operations (Theme 3). Adopting the strategies used in other industries, such as assigning an exoskeleton to specific workers or groups of workers and having personnel responsible for only their own fabric components, can also be incorporated into strategies for widespread adoption.

The showcase event used in this study can be a strategy for addressing the identified barrier of familiarity. The event allowed members of the OR team to become aware of the technology, and participants mentioned awareness as a key influence on receptiveness toward the use of the technology. Coordinating this event helped increase communication with OR management and workers about the study. Furthermore, the need for champions (Theme 1), particularly from the attending surgeon and surgical nurse roles, that were enthusiastic of the intervention and dedicated themselves to supporting the exoskeleton to other team members was identified from our focus groups. This resource within the organization is critical to obtain buy-in for new innovations (Wisdom, Chor, Hoagwood, & Horwitz, 2014). For other OR interventions, the traditional process of implementing a new medical device into surgical practice involves an attending surgeon who advocates for the use of a new device and a company representative that is present in the surgical procedures using this device to facilitate smooth adoption. Because ergonomic risk affects the entire bedside surgical team, we found that champions from both surgeons and nurses can better facilitate translation.

Several characteristics of the OR environment may help address noted barriers regarding the logistics of independently donning the exoskeleton. Surgical teams typically have a circulating nurse (who remains nonsterile) who helps put gowns on those who need to be in the sterile field, and this individual could assist in donning an exoskeleton (Theme 4). In addition, it should be noted that although participants needed help here donning the exoskeleton, they were able to independently take off the exoskeleton after the simulation. Having exoskeletons stored in the surgical core, where it is easily accessible to workers, or including it on a specific case cart for specific procedures can also help address logistic barriers (Theme 3).

Worker role and specific operation were key factors identified for successful implementation. Although the attending surgeon was a team member identified as benefiting from this technology (Liu et al., 2018), the exoskeleton may not provide the most value in this role due to the constant movement required to perform an operation. This limitation was further reflected in the usability comments and SUS scores from attending surgeons, who noted that they have been trained to keep their elbows close to their bodies when possible, especially for minimally invasive surgeries. With the exoskeleton, they stated that there was a lack of support and stabilization near the forearms, and this would be more beneficial than support on the upper arms. However, it would be challenging to have forearm support in the OR due to the need for sterility. This remains a challenge for current exoskeletons to make an impact for surgeon workers and should be a critical design requirement for future exoskeletons created for surgical teams. Surgical trainees (e.g., residents or medical students) and nurses may receive the most benefit (Theme 2), because individuals in this role must often maintain static posture, such as when holding instruments (e.g., scopes or retractors). Compared with operative nurses, who take routine breaks, trainees may receive more benefit from this intervention due to the requirement that they remain during the entire surgery. An exoskeleton may thus help address the high perceived physical workload among residents (Yu et al., 2016). Regardless of the OR worker role, the surgical team had similar perceptions of the usability (Theme 4) of the exoskeleton, confirming that this technology can be relevant to the team, despite different tasks and roles. This may be an indication of the need for an intervention due to the entire team experiencing ergonomic risks (Theme 1). In addition, although the overall SUS score was not designed to predict whether users would frequently use exoskeletons, there was a positive response (between neutral and agree) from participants on the SUS item asking whether they would be frequently using this device.

The perception of a need for an intervention and the impact and value of exoskeletons to surgical users likely depend on the number of cases in the surgical day and duration of each procedure (Theme 1). Specifically, there is a trade-off between a reduction in biomechanical load and usability stemming from the time needed for donning/doffing the exoskeleton. The surgical specialty members participating in this study averaged 17 hr per week in an academic hospital, and this likely influenced their comments and usability ratings of the exoskeleton. Other surgical specialties may have longer case durations, and other institutions may have different expectations on operative hours per week; thus, the surgeons' comments here may reflect experiences of other general surgeons at an academic institution and may not reflect other work cultures or surgical specialties. Regarding usability needs for different roles, surgeons interact with patients between cases, where exoskeletons must be removed. This may not be as much of a concern for surgical nurses who do not provide patient/family consultations, but it may explain some of the variation in usability ratings among the various participating roles. Thus, conversations between ergonomists and surgical team members are still needed to develop guidelines that are specific to each institution for use of exoskeletons in the OR.

Parallels to Other Industries

Our thematic findings of exoskeletons for the OR workplace parallel those found in the construction and agriculture workplaces (Kim et al., 2019; Upasani, Franco, Niewolny, & Srinivasan, 2019). The expected benefits of using exoskeletons and usability were identified in all three domains. Particularly, all three studies highlighted an expected reduction in pain and the need for this technology to be integrated into existing work practices. Having familiarity with both MS symptoms and the exoskeleton appears critical to obtaining buy-in to use this as an intervention for all domains. This reflects the CFIR construct of implementation climate (e.g., relative priority), as well as identified barriers for innovations such as a lack of knowledge and training and resistance to change to prevent MS disorders (Yazdani & Wells, 2018). Although parallels existed across these three domains, key differences were identified between health care and the other domains. For the agriculture domain, back and knee exoskeletons were reported to be the most beneficial for workers, whereas the construction and health care domains focused on back- and arm-support exoskeletons (Kim et al., 2019; Liu et al., 2018; Upasani et al., 2019). Differences in organizational structures were also present in earlier studies in different industries. Participants in agriculture were those performing physical work in their own small-to-medium farms. Those in construction were, however, part of small- to large-sized companies with stakeholders from multiple organization levels (e.g., managers and carpenters); this study focused on workers in one single large institution. The resonating themes drawn from implementation science and in the different industries reflect that exoskeletons can be a feasible intervention for many domains.

Limitations

Although any inquiries regarding exoskeletons were initially answered, participants often noted that it was difficult to address its expected impact on surgical workers without trying the exoskeletons first. If the simulation portion of our study was completed prior to the focus group, participants may have answered differently. Moreover, the limited (10-min) time frame over which participants wore the exoskeleton is too brief to mimic the effects of MS symptoms and fatigue experienced in live surgical operations. Although the optimal task would have been to hold an object (e.g., scope) for a prolonged period of time to simulate actual task demands during an operation, we chose the FLS task for its validity in minimally invasive procedures, the time availability of the participants, and for the consistency of task where the positioning reflects upper-arm demands for both attendings and assistants (i.e., surgical residents or nurses) when they manipulate the long-handled laparoscopic tools. Thus, for usability ratings, participants used their operative experience to predict how the intervention would affect actual procedures, and further assessments of tasks performed with and without the exoskeleton in actual work environments are needed to generate biomechanical evidence about the effects of exoskeletons during surgical work. Furthermore, shifts in the exoskeleton were observed (i.e., the arm support moved superiorly during lateral bending), which may have caused nonoptimal force distribution and hence lower usability ratings. Without developing MS symptoms during the simulation, users may not have felt the need for the exoskeleton. Actual use in the workplace will allow for the identification of potential in-task barriers and evidence of effectiveness centered around individual users. However, the simulation was informative to gather participants' perceptions of usability of the technology.

Future work is ongoing to pilot exoskeleton implementation in the OR to gather comparative evidence that this technology is a feasible and effective intervention for reducing surgical team members' MS symptoms. Although briefly discussed in this study, future work can explore synthesizing qualitative data cross-domains to identify domain-agnostic themes regarding exoskeletons in workplaces.

In conclusion, four themes were identified encompassing facilitators of and obstacles to surgical team members using exoskeletons. Specially, this study focused on gaining perspectives from all stakeholders in the OR, especially the surgical team members who are also exposed to ergonomic injury risks yet received less attention than surgeons. Exoskeleton use in simulation suggests acceptable usability for surgical tasks that may translate to the OR. Exoskeletons as an intervention received positive comments, especially from individuals in the nursing role. Thus, exoskeleton technology has the potential in this work environment to improve workforce retention and decrease MS symptoms for all team members. Although adoption of arm-support exoskeletons can be valuable, a key contribution of this initial work is the identification of unique aspects of the surgical environment and barriers and facilitators such as cost and team member buy-in that need to be addressed to help guide future translation of exoskeletons into practice.

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KEY POINTS

- Although musculoskeletal symptoms and ergonomic risks in surgery are well recognized, there are limited effective interventions.
- Four themes of barriers and facilitators for exoskeleton adoption in the operating room were identified: (1) characteristics of individuals, (2) perceived benefits, (3) environmental/societal factors, and (4) intervention characteristics.
- Worker's awareness of the need for an intervention and the exoskeleton usability need to be considered for successful implementation.

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SUPPLEMENTAL MATERIAL

The online supplemental material is available with the manuscript on the *HF* web site.

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