ISSN: 2753-7919
British Journal of Healthcare and Medical Research; Vol. 13 No. 02 (2026) (36-43)
https://doi.org/10.14738/bjhr.1302.20117

Design Principles and Human Factors in Modern Operating Rooms: Impact of Layout, Robotic Integration and Work-Related Stress

Laura Cormio[1]*, Luigi Cormio[2] & Cristian Cannella

1. Department of Industrial Engineering and Mathematical Sciences, Polytechnic University of Marche, Via Brecce Bianche, 12, 60131 Ancona, Italy
2. Urology Unit, "F. Miulli" General Hospital, Strada Prov. 127 Acquaviva, 70021, Acquaviva delle Fonti (Bari), LUM University, Bari-Casamassima, Italy
3. Master Degree in Law, Licensed to practice law

Abstract: The operating room (OR) is a high-risk clinical environment in which spatial configuration, technological integration, and human performance interact to influence surgical safety. The rapid expansion of robotic-assisted surgery (RAS) has significantly transformed traditional OR design requirements, introducing increased equipment density, altered team positioning, and modified communication patterns. Empirical evidence indicates that suboptimal layout, inefficient zoning, and workspace constraints contribute to flow disruptions, cognitive workload, and work-related stress. Robotic systems amplify these vulnerabilities by increasing technological footprint and docking complexity. Flow disruptions, particularly within transitional zones, represent persistent latent conditions affecting workflow continuity. Stress in surgical settings has been associated with impaired communication and performance, suggesting that environmental inefficiencies may indirectly influence safety outcomes. This review synthesizes current evidence on OR spatial configuration, equipment integration, workflow interruptions, and stress in robotic surgery. The findings support a systems-based, human-centered approach to operating room design to optimize efficiency, resilience, and team performance in technologically advanced surgical environments.

Keywords: Operating room design, Robotic-assisted surgery, Surgical workflow, Flow disruptions, Human factors, Work-related stress.

INTRODUCTION

The operating room (OR) is a high-reliability clinical environment in which patient safety depends on the coordinated interaction of multidisciplinary professionals, advanced technology, and spatial organization. Although surgical expertise and procedural technique remain central determinants of outcome, increasing evidence suggests that environmental design plays a decisive role in shaping workflow, communication, workload, and ultimately safety performance [1,2].

Over the last two decades, the rapid expansion of robotic-assisted surgery (RAS) has profoundly transformed the physical and organizational structure of the OR. Unlike conventional open or laparoscopic approaches, robotic systems spatially separate the primary surgeon from the operative field, relocating them to a console while robotic arms operate at the patient's bedside. This reconfiguration modifies team positioning, alters communication dynamics, and reshapes circulation patterns within the room [3,4]. At the same time, robotic platforms substantially increase equipment density. The integration of patient-side carts, vision systems, consoles, cables, and ancillary devices expands the technological footprint of the surgical environment. When implemented in operating rooms originally designed for conventional procedures, these systems may generate congestion, obstruct circulation routes, and require repeated equipment adjustments [5]. Such spatial constraints are not merely logistical inconveniences; they may influence workflow continuity, coordination demands, and cognitive load.

Flow disruptions (FDs), defined as deviations from the natural progression of surgical tasks, have emerged as a robust metric for assessing system inefficiencies and latent safety threats in the OR [1,2]. In robotic procedures, disruptions frequently involve equipment positioning, docking complexity, and coordination around the patient-side cart [6,7]. Importantly, many of these disruptions are directly linked to environmental configuration rather than technical skill alone. In addition, robotic integration introduces psychosocial and ergonomic implications, as surgical stress has been associated with impaired judgment, degraded communication, and reduced motor precision [8-10].

Despite the growing body of literature examining either operating room layout or stress in robotic surgery, these domains are often studied in isolation. A comprehensive understanding of modern OR performance requires an integrated perspective that considers spatial design, workflow disruptions, technological complexity, and human factors as interdependent components of a single socio-technical system. Therefore, this review aims to synthesize current empirical evidence regarding the design of operating rooms in the context of robotic-assisted surgery, with particular emphasis on spatial configuration, equipment layout, flow disruptions, and work-related stress. By integrating architectural and human factors perspectives, this review seeks to clarify how environmental design influences surgical workflow and team resilience in technologically advanced operative environments.

MATERIALS AND METHODS

This study adopted a narrative review methodology [11] to synthesize empirical evidence related to operating room design, with particular focus on spatial configuration, robotic-assisted surgery, workflow disruptions, and work-related stress.

A literature search was conducted in Scopus, Web of Science, and Google Scholar to identify studies addressing the spatial design and structural organization of operating rooms, particularly in the context of robotic-assisted surgery. Keywords included combinations of terms such as “operating room design,” “operating room layout,” “robotic surgery,” “flow disruptions,” “workflow,” “human factors,” and “stress.”

Original empirical studies were considered eligible if they investigated: (1) spatial configuration or zoning of operating rooms; (2) workflow organization in robotic-assisted procedures; (3) flow disruptions or environmental constraints; (4) workload, stress, or communication dynamics in surgical settings. Review articles, editorials, and non-empirical publications were excluded.

A total of 18 studies met the inclusion criteria and were examined and integrated through a narrative.

RESULTS

The analysis of the included studies reveals consistent and converging patterns regarding the impact of operating room (OR) design on workflow organization, disruption generation, and stress exposure in robotic-assisted surgery (RAS). Rather than isolated environmental variables, the evidence indicates that spatial configuration, technological integration, and human performance operate as interdependent components within a socio-technical system [1,2,5].

Spatial Reconfiguration and Redistribution of Roles

Across studies examining robotic-assisted procedures, a recurring transformation is the redistribution of team members within the OR. The relocation of the surgeon to a remote console modifies proximity-based coordination and reshapes communicative hierarchies [3,4]. Physical separation reduces reliance on non-verbal cues and increases dependence on structured verbal exchanges. Observational and behavioral mapping studies demonstrate that robotic integration alters circulation dynamics, particularly for circulating nurses and assistants, who assume expanded navigational responsibilities between sterile fields, supply zones, and transitional areas [12]. This redistribution reflects a shift from a surgeon-centered spatial model to a technology-centered configuration, in which robotic equipment becomes the organizing axis of room geometry. The operating room thus evolves into a distributed workspace, characterized by spatial fragmentation and modified interaction pathways.

Concentration of Disruptions in Circulation Interfaces

Flow disruption taxonomies consistently identify layout-related events as significant contributors to intraoperative inefficiency [1,2]. Within robotic environments, disruptions tend to concentrate in transitional or circulation zones, which connect sterile, support, and workstation spaces [12]. These zones function as high-interaction nodes within the OR network. When robotic arms, consoles, and associated equipment intersect with established movement paths, circulation becomes constrained. The resulting micro-adjustments, such as minor pauses, repositioning maneuvers, or repeated communication exchanges, accumulate across procedural phases [5,6]. Importantly, the reviewed studies indicate that disruption frequency is not solely dependent on overall room size. While smaller operating rooms demonstrate increased workspace constraints, larger rooms with poorly optimized adjacency relationships continue to exhibit layout-driven inefficiencies [5,12]. These findings suggest that relational geometry, namely how frequently used zones are positioned relative to one another, plays a more decisive role than square footage alone.

Robotic Technology as a Complexity Multiplier

Robotic systems substantially increase technological footprint and introduce structured phases of spatial negotiation. Specifically, docking procedures require coordinated alignment of robotic arms, patient positioning, and staff movement within defined clearance envelopes [7]. Empirical workflow analyses identify equipment-related interruptions as a dominant disruption category in robotic procedures [6,13]. These interruptions frequently arise during setup and docking phases, when spatial alignment and equipment positioning are actively negotiated. The introduction of robotic platforms, therefore, amplifies environmental sensitivity. Layout inefficiencies that may be tolerable in conventional surgery become magnified when robotic arms and consoles restrict circulation corridors or reduce workspace flexibility. Robotic integration does not merely add equipment; it introduces temporal peaks of spatial vulnerability during defined procedural stages.

Communication Structure and Cognitive Demand

Console-based surgery modifies communication topology within the OR. Increased reliance on verbal exchanges has been documented in robotic settings, reflecting reduced access to non-verbal coordination cues [3,4]. In environments characterized by equipment density and ambient noise, repeated communication and clarification exchanges may increase attentional demands [13,14]. Communication-related interruptions represent a meaningful component of overall workflow disruption in robotic procedures [6]. The reviewed evidence suggests that these communication adaptations, when combined with spatial congestion, contribute to elevated cognitive workload.

Environmental Stressors and Performance Implications

Stress research in surgical contexts demonstrates that elevated cognitive load and environmental instability may impair decision-making and motor performance [8-10]. In robotic surgery, identified stressors include equipment adjustments, coordination demands during docking, and task complexity [14-17]. Studies examining workload and stress adaptation indicate that experience level and procedural familiarity moderate stress responses [17-19]. Standardized robotic suites and consistent equipment positioning appear to enhance predictability and reduce variability in setup and execution phases. These findings suggest that environmental predictability functions as a stabilizing factor within the robotic surgical system.

Integrated Pathway Linking Architecture and Performance

Across the included literature, a consistent pattern emerges suggesting that operating room design influences surgical performance through a sequential interaction of spatial and cognitive mechanisms. Spatial configuration shapes circulation patterns within the room; circulation constraints increase the likelihood of workflow disruptions; repeated disruptions contribute to elevated cognitive demands; increased cognitive demands may, over time, amplify stress exposure among team members. Therefore, collective evidence seems to support the interpretation that operating room design functions as a structural determinant of workflow resilience and cognitive burden in robotic-assisted surgery.

DISCUSSION

The findings synthesized in this review indicate that operating room (OR) design is not a neutral architectural background but a structural determinant of workflow efficiency, communication dynamics, and stress exposure in robotic-assisted surgery (RAS). When interpreted collectively, the empirical evidence suggests that spatial configuration, equipment density, and zoning logic operate as active variables within the surgical socio-technical system.

One of the most consistent patterns emerging from observational research is the concentration of flow disruptions within transitional zones and areas surrounding the surgical table [12]. Transitional zones are not task-specific areas; rather, they function as circulation interfaces between workstations, sterile zones, and supply areas. Their role as traffic convergence points inherently increases the likelihood of interruptions, cross-traffic conflicts, and cognitive switching demands. The predominance of layout-related disruptions over environmental hazard events [1,2,12] suggests that architectural configuration itself represents a persistent latent condition within the surgical system rather than an incidental constraint.

Robotic systems intensify this structural vulnerability. Equipment-related interruptions constitute a dominant category of disruptions in robotic-assisted procedures [5,6,13], reflecting the substantial technological footprint introduced by robotic platforms. The presence of robotic arms, cables, consoles, and visualization units transforms the OR into a highly equipment-dense environment in which spatial negotiation becomes continuous rather than episodic. Unlike conventional surgery, where spatial organization tends to stabilize once the procedure begins, robotic surgery often requires iterative adjustments during docking and intraoperative phases [6,7,13].

However, room size alone does not resolve these issues. Although smaller rooms demonstrate higher disruption rates [5], larger rooms with poorly optimized adjacency relationships continue to exhibit layout-related inefficiencies [12]. This indicates that relational geometry (i.e., the spatial relationship between high-frequency zones) is more influential than absolute square footage. Effective OR design must therefore prioritize adjacency optimization and circulation logic rather than relying solely on expansion of physical space.

The interaction between environmental configuration and human factors emerges as a central theme. Robotic surgery modifies communication structures by physically separating the surgeon from the operative field [3,4]. Increased reliance on verbal communication, combined with environmental noise and technological complexity, may elevate cognitive load [14,15]. Communication-based interruptions represent a meaningful proportion of observed disruptions [5,6], reinforcing the importance of environmental support for clear and efficient coordination.

Stress findings further highlight the systemic nature of OR design implications. Although stress responses vary by role, experience, and procedural phase, recurrent micro-disruptions, such as equipment repositioning, congestion in transitional areas, or communication repetition, likely contribute to cumulative cognitive burden. Stress in surgical contexts has been associated with impaired decision-making and motor performance [8-10], suggesting that environmental inefficiencies may indirectly influence safety outcomes through psychophysiological pathways. Experience and procedural familiarity appear to moderate these effects, as demonstrated in studies examining workload adaptation and learning curves in robotic surgery [17-19].

From a systems engineering perspective, the OR should be conceptualized as an integrated network of spatial, technological, and human components. Disruptions observed in robotic procedures do not arise solely from technological novelty; rather, they emerge from misalignment between advanced surgical platforms and legacy architectural infrastructure. When robotic systems are introduced into environments designed for traditional surgery, spatial incongruities become visible through increased interruptions, congestion, and workload.

The evidence also underscores the role of standardization and familiarity. Dedicated robotic suites and consistent equipment positioning appear to reduce setup variability and improve turnover efficiency [5,17-19]. This suggests that predictability and environmental consistency may function as stress-buffering mechanisms, particularly during learning curves. Standardized docking pathways, defined equipment parking zones, and minimized cross-traffic may therefore reduce both disruption frequency and cognitive strain.

CONCLUSIONS

The evidence synthesized in this review demonstrates that operating room design functions as a structural determinant of workflow efficiency, team coordination, and work-related stress in robotic-assisted surgery. Spatial configuration, zone adjacencies, equipment density, and docking requirements should not be regarded as secondary architectural features but as integral components of the surgical work system. Rather than isolated inefficiencies, layout-related flow disruptions represent persistent latent conditions embedded within spatial organization. Robotic platforms amplify these vulnerabilities by increasing technological footprint, modifying team positioning, and intensifying communication and coordination demands. The resulting interaction between spatial constraints and human performance underscores the relevance of OR design. Importantly, expanding physical space alone does not ensure improved performance. Optimized relational adjacencies, protected circulation pathways, and standardized equipment positioning are more critical determinants of resilience than square footage. Dedicated robotic suites and human factors-informed planning strategies may enhance predictability, reduce variability, and mitigate stress amplification.

This review has several limitations. The included studies were heterogeneous in design, measurement tools, and outcome definitions, limiting direct comparability. Most investigations were observational, precluding definitive causal inference. Furthermore, reliance on existing literature frameworks may have restricted the inclusion of newly emerging evidence. Nevertheless, the consistency of findings across diverse settings supports the interpretation that OR design represents a modifiable system-level factor influencing surgical performance.

Future research should move beyond descriptive disruption analysis and towards predictive modeling of spatial-cognitive interactions. Prospective studies integrating behavioral mapping, physiological stress monitoring, and simulation-based architectural testing are needed to clarify causal pathways between OR configuration and safety outcomes. In an era of rapidly evolving surgical technology, the OR design should shift from static space planning to a dynamic evidence-based approach capable of supporting increasingly complex operative environments.

REFERENCES

[1]. Wiegmann DA, ElBardissi AW, Dearani JA, Daly RC, Sundt TM. Disruptions in surgical flow and their relationship to surgical errors: an exploratory investigation. Surgery. 2007;142:658–665.

[2]. Palmer G, Abernathy JH, Swinton G, Allison D, Greenstein J, Shappell S, et al. Realizing improved patient care through human-centered operating room design: a human factors methodology for observing flow disruptions in the cardiothoracic operating room. Anesthesiology. 2013;119(5):1066–1077.

[3]. Randell R, Honey S, Hindmarsh J, Alvarado N, Greenhalgh J, Pearman A, et al. A realist process evaluation of robot-assisted surgery: integration into routine practice and impacts on communication, collaboration and decision-making. Health Serv Deliv Res. 2017;5(20):1–140.

[4]. Cao CG, Taylor H. Effects of new technology on the operating room team. In: Khalid HM, Helander MG, Yeo AW, editors. Work with computing systems. Damai Sciences; 2004. p. 309–312.

[5]. Kanji F, Cohen T, Alfred M, Caron A, Lawton S, Savage S, et al. Room size influences flow in robotic-assisted surgery. Int J Environ Res Public Health. 2021;18(15):7984.

[6]. Catchpole KR, Hallett E, Curtis S, Mirchi T, Souders CP, Anger JT. Diagnosing barriers to safety and efficiency in robotic surgery. Ergonomics. 2018;61(1):26–39.

[7]. Cofran L, Cohen T, Alfred M, Kanji F, Choi E, Savage S, et al. Barriers to safety and efficiency in robotic surgery docking. Surg Endosc. 2021;36(1):206–215.

[8]. Moorthy K, Munz Y, Sarker SK, Darzi A. Objective assessment of technical skills in surgery. BMJ. 2003;327(7422):1032–1037.

[9]. Wetzel CM, Kneebone RL, Woloshynowych M, Nestel D, Moorthy K, Kidd J, et al. The effects of stress on surgical performance. Am J Surg. 2006;191(1):5–10.

[10]. Grantcharov PD, Boillat T, Elkabany S, Wac K, Rivas H. Acute mental stress and surgical performance. BJS Open. 2019;3(1):119–125.

[11]. Paré G, Trudel MC, Jaana M, Kitsiou S. Synthesizing information systems knowledge: a typology of literature reviews. Inf Manag. 2015;52(2):183–199.

[12]. Ahmad N, Hussein AA, Cavuoto L, Sharif M, Allers JC, Hinata N, et al. Ambulatory movements, team dynamics and interactions during robot-assisted surgery. BJU Int. 2016;118(1):132–139.

[13]. Catchpole K, Perkins C, Bresee C, Solnik MJ, Sherman JF, Fritch J, et al. Safety, efficiency and learning curves in robotic surgery: a human factors analysis. Surg Endosc. 2016;30:3749–3761.

[14]. Yu D, Dural C, Morrow MMB, Yang L, Collins JW, Hallbeck S, et al. Intraoperative workload in robotic surgery assessed by wearable motion tracking sensors and questionnaires. Surg Endosc. 2017;31:877–886.

[15]. Weber J, Catchpole K, Becker AJ, Schlenker B, Weigl M. Effects of flow disruptions on mental workload and surgical performance in robotic-assisted surgery. World J Surg. 2018;42(11):3599–3607.

[16]. Klein MI, Mouraviev V, Craig C, Salamone L, Plerhoples TA, Wren SM, et al. Mental stress experienced by first year residents and expert surgeons with robotic and laparoscopic surgery interfaces. J Robot Surg. 2014;8(2):149–155.

[17]. Kayani B, Konan S, Pietrzak JR, Huq SS, Tahmassebi J, Haddad FS. The learning curve associated with robotic-arm assisted unicompartmental knee arthroplasty: a prospective cohort study. Bone Joint J. 2018;100-B(8):1033-1042.

[18]. Kayani B, Konan S, Huq SS, Tahmassebi J, Haddad FS. Robotic-arm assisted total knee arthroplasty has a learning curve of seven cases for integration into the surgical workflow but no learning curve effect for accuracy of implant positioning. Knee Surg Sports Traumatol Arthrosc. 2019;27(4):1132–1141.

[19]. Kayani B, Konan S, Huq SS, Ibrahim MS, Ayuob A, Haddad FS. The learning curve of robotic-arm assisted acetabular cup positioning during total hip arthroplasty. Hip Int. 2021;31(3):311–319.