

# Healthcare 5.0 Technologies: A Socio-Technical Readiness Theoretical Framework for Service Robot Integration

Sujatha Alla

sall1a@odu.edu

Old Dominion University <https://orcid.org/0000-0003-2824-4528>

Steven Cotter

Old Dominion University

Krishnanand Kaipa

Old Dominion University

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## Research Article

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# Healthcare 5.0 Technologies: A Socio-Technical Readiness Theoretical Framework for Service Robot Integration

Sujatha Alla<sup>1\*</sup>, Steven Cotter<sup>1†</sup>, Krishnanand Kaipa<sup>2†</sup>

<sup>1</sup>Engineering Management and Systems Engineering, <sup>2</sup>Aerospace and Mechanical Engineering, Old Dominion University, Hampton Blvd, Norfolk, 23508, Virginia, United States.

Sujatha Alla ORCID ID: 0000-0003-2824-4528

\*Corresponding author(s). E-mail(s): [salla001@odu.edu](mailto:salla001@odu.edu); Contributing authors: [tcotter@odu.edu](mailto:tcotter@odu.edu), [kkaipa@odu.edu](mailto:kkaipa@odu.edu)

<sup>†</sup>These authors contributed equally to this work.

## Abstract

The integration of service robots into healthcare has the potential to address workforce shortages, reduce burnout, and enhance patient care by automating repetitive and hazardous tasks. However, successful implementation requires a comprehensive understanding of the technical, human, and organizational readiness of healthcare institutions. This study develops a theoretical framework to guide future research toward the assessment of healthcare systems' capability for service robot integration. Utilizing content analysis, this research examines key factors and their interrelations influencing readiness, including Technology Readiness Levels (TRLs), Human Readiness Levels (HRLs), and healthcare organizational readiness. The study employed a systematic literature review to identify manifest factors, text mining to identify additional latent factors, and thematic content analysis to examine relationships among manifest and latent factor themes. A combination of dictionary-based content analysis and Latent Dirichlet Allocation (LDA) was applied to extract additional explicit and latent dimensions of healthcare service robot integration. Findings indicate that while technology maturity is advancing, gaps remain in human and organizational preparedness, emphasizing the need for structured implementation strategies. The theoretical framework provides the basis for future research toward a domain taxonomy and ontology of healthcare systems' capability for service robot integration. The goal of this research is the development of a technology-human-organizational readiness assessment instrument of healthcare systems' capability for service robot integration.

**Keywords:** Healthcare Service Robots, Human Robot Interaction (HRI) in Healthcare, Healthcare Readiness for Robotics Integration

# 1 Introduction

The integration of social service robots in healthcare is gaining increasing attention as hospitals and medical institutions seek to address critical workforce shortages, improve efficiency, and enhance patient outcomes. The demand for healthcare services has grown exponentially due to aging populations, an increase in chronic illnesses, and global health crises such as the COVID-19 pandemic, which exposed significant vulnerabilities in healthcare systems [1, 2]. While autonomous service robots have demonstrated potential in assisting with repetitive, labor-intensive, and hazardous tasks, their adoption has been hindered by concerns surrounding technological readiness, human-robot interaction (HRI), and organizational integration [3, 4].

This research contributes to the field of social robotics by offering a theoretical multi-dimensional readiness assessment theoretical framework that integrates technological, human, and organizational factors. Key contributions include:

- Development of a comprehensive theoretical framework to guide research into robotic integration in healthcare.
- Identification of barriers and enablers in healthcare service robot adoption, including trust, technical maturity, and regulatory considerations.
- Recommendations for healthcare decision-makers on optimizing robotic deployment strategies.

By addressing the social, technical, and ethical challenges of robotic integration, this study provides a theoretical framework for considering service robot deployment in healthcare environments. The findings are expected to support future research in human-robot interaction (HRI), autonomous robotics policy development, and healthcare robotics integration.

# 2 Related Works

Service robots have been successfully utilized in manufacturing and logistics, but their deployment in healthcare settings remains limited due to the complexity of human-centric environments [3]. The healthcare sector presents unique challenges where robots must operate in dynamic and unpredictable environments, often requiring real-time decision-making and close collaboration with human staff [5].

The COVID-19 pandemic demonstrated the potential benefits of service robots by reducing human exposure to infectious diseases and easing the burden on healthcare workers. For instance, robots were used to disinfect surfaces, deliver medications, transport specimens, and monitor isolated patients [2]. These applications highlighted the advantages of robotic automation in mitigating health risks and enhancing efficiency in clinical workflows. However, despite these benefits, many hospitals remain hesitant to adopt service robots due to concerns related to technological limitations, cost, and workforce displacement [5].

The adoption of service robots in healthcare requires a multi-faceted readiness assessment framework, encompassing technological, human, and organizational dimensions. While Technology Readiness Levels (TRLs) are commonly used to evaluate the maturity of emerging technologies [6, 7], they do not sufficiently account for human and organizational factors, which are critical for successful integration [8].

In 2015, IEEE released Standard 1872-2015 IEEE Standard Ontologies for Robotics and Automation as the general core reference ontology for robotics and automation (CORA) across domains. IEEE 1872-2015 defines general axioms for robotics automation. [9] reported work by the IEEE Robot Task Representation Subgroup to develop a broad standard for a suite of domain-specific robotic automation ontologies to extend CORA to manufacturing robotics automation. [10] presented a *Shared Ontology for Human Robot Collaboration* (SOHO) as a production domain ontology. To date, however, an application-level healthcare autonomous service robot-human collaboration ontology or knowledge representation does not exist.

## 2.1 Technological Challenges

Technological challenges in healthcare robot integration primarily stem from the immaturity of certain robotic systems and the lack of standardized guidelines for their deployment [11]. While NASA’s TRL scale provides a structured method to assess technological maturity [12], it does not address the socio-technical complexities inherent in healthcare environments [13]. Several factors must be considered, including [14]:

**Autonomy and Reliability:** Many service robots require constant supervision or frequent human intervention, limiting their ability to function independently [3].

**Safety and Compliance:** Robots interacting with patients must adhere to strict safety standards such as ISO 13482:2014, which regulates personal care robots [15].

**Data Security and Interoperability:** Robots must seamlessly integrate with existing healthcare IT systems while ensuring patient data privacy and cybersecurity [16].

## 2.2 Human Readiness and Acceptance Challenges

Human factors are among the most significant barriers to service robot adoption in healthcare. Trust, acceptance, and perceived usability are critical determinants of successful integration [5]. The Human Readiness Level (HRL) scale, derived from TRLs, “... the level of readiness or maturity of a given technology as it relates to its usability and its refinement to be used by a human(s)” [13, 17]. However, healthcare professionals often express concerns regarding:

**Loss of Human Touch:** There is apprehension that robotic automation may reduce human-to-human interaction, potentially impacting patient care quality [4].

**Training and Adaptation:** Many healthcare workers lack adequate technical training to operate and troubleshoot service robots effectively [18].

**Workforce Displacement Fears:** Some professionals fear that increasing automation may lead to job reductions or changes in professional roles [19].

## 2.3 Organizational Readiness and Cultural Fit Challenges

Beyond technological and human factors, organizational culture plays a vital role in the adoption of autonomous systems in healthcare. The successful integration of service robots requires alignment between institutional values, policies, and operational workflows [20]. Research has identified several key organizational factors influencing readiness for robotic adoption:

**Leadership and Change Management:** Institutional support from executives and healthcare managers is crucial for overcoming resistance to change [21].

**Infrastructure and Workflow Adaptation:** Robotic systems require modifications in hospital layouts, automated logistics systems, and interoperability with healthcare IT platforms [22].

**Regulatory and Ethical Considerations:** The introduction of robotic systems must comply with medical ethics, patient rights, and national healthcare regulations [23].

## 3 Proposed Framework

To address the challenges associated with robotic integration, this research proposes a comprehensive theoretical framework that integrates three key dimensions of readiness assessment:

- **Technology Readiness Levels (TRLs):** Evaluates the maturity and performance of robotic systems in real-world healthcare applications.
- **Human Readiness Levels (HRLs):** Assess healthcare professionals' preparedness, training needs, and psychological acceptance of robots.
- **Organizational Readiness:** Examines the institutional, cultural, and policy-related factors influencing successful service robot adoption.

To guide the theoretical and empirical application of the H.STAR framework, we derive a set of propositions that reflect key relationships across its three readiness dimensions. These propositions are informed by literature synthesis, thematic patterns observed in the corpus, and interdisciplinary

perspectives from technology adoption, human-robot interaction, and healthcare management. The propositions serve as hypothetical linkages that can be empirically tested or further refined through case studies and future deployment assessments.

**Proposition 1: S2 (technical-human)** - Service robot human interface capabilities increase with the level of research and development, technology demonstration, and production and deployment (NASA). This proposition subsumes taxonomic structural ANSI/HFES 400-2021 technology Human Readiness Levels definitions.

**Proposition 2: S2 (technical)** - Service robot systems design maturity increases with the presence of efficient human-technology interactions, enhanced transparency to users, and optimized human-system function allocations. This proposition subsumes the taxonomic structural NASA Technical Readiness Levels definitions.

**Proposition 3: S1 (human-technical)** - Healthcare staff readiness increases with pre-conditioned technical knowledge of service robot capabilities and functional role in clinic processes.

**Proposition 3a: S1 (human)** - Healthcare staff readiness increases with pre-conditioned non-technical explicit and tacit emotional knowledge of service robot capabilities and functional role in clinic processes.

**Proposition 4: S3 (organization)** - Healthcare organizational pre-conditioned cultural readiness increases with increases in coordination of policies, planning, and coordination of processes, and communication protocols within and between organizational departments and external healthcare organizations.

**Proposition 5: S1 vs. S2 (technical - human interaction)** - The greater the service robot technology integration maturity and the greater the healthcare staff's technical awareness, the higher the probability of successful service robotic implementation. This proposition subsumes ontological axiomatic technological development and technology capability processes of NASA Technical Readiness Level definitions and ANSI/HFES 400-2021 technology Human Readiness Levels definitions. Taxonomic structural properties and ontological axiomatic processes are confounded in the NASA TRL definitions and in the ANSI/HFES 400-2021HRL definitions.

**Proposition 6: S2 vs. S3 (technical - organization interaction)** - The higher the service robot technological maturity and the higher organizational cultural readiness, the higher the service quality (performance, reliability, durability, and serviceability) provided.

**Proposition 7: S1 vs. S3 (human - organization interaction)** - The greater the healthcare staff's technical and emotional readiness and organizational cultural readiness, the greater the knowledge transfer regarding service robots' design limitations and workload expectations.

**Proposition 8: S1 vs. S2 vs. S3 (technical - human - organization interaction)** - The higher joint healthcare staff readiness, service robot technical and human readiness, and healthcare cultural readiness, the greater the knowledge transfer, possibility of successful service robot integration, benefit/cost justification, and quality of healthcare service provided.

These propositions jointly specify the technical-human-organization concept lattice in Figure 1, which provides the foundation of the **socio-technical alignment** required for service robot integration in healthcare and serves as the analytical foundation for the research methodology presented in Section 4.

In Figure 1, the symbol  $\wedge$  represents the minimal infimum technology-human-organization (**t**, **h**, **o**) concept set forth in 4.1 Definitions below. The symbols  $(\perp, \mathbf{t})$ ,  $(\perp, \mathbf{h})$ , and  $(\perp, \mathbf{o})$  respectively represent the nominal technology, human, and organization concepts, recognizing that at any point in economic sector evolution, the nominal technology, human, and organization vary from some lower viable bound  $LB_v > \wedge$  to a supremum upper bound  $UB_v < \vee$ . The proposed technical-human-organization concept lattice meets all definitions set forth below in the essential concept lattice theory definitions below, and is complete and closed. The research propositions map to the technical-human-organization concept lattice as follows.

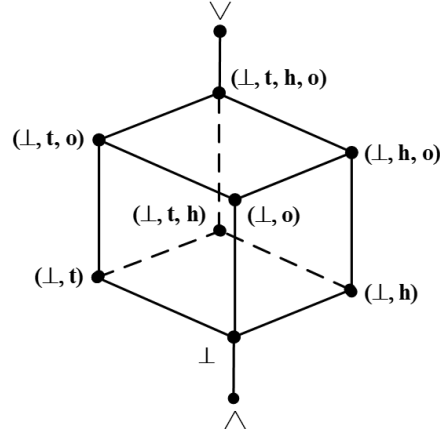


**Fig 1** Technical-human-organization concept lattice.

- **P1: S2 (technical-human) and P2: S2 (technical)**  $\in (\perp, t)$ . Innovative technology must possess the required end-use functional behavior and aesthetic, ergonomic, and anthropomorphic functionality to integrate into human processes [24]. The P1:S2 proposition represents designing technology to interoperate with humans, and the P2:S2 proposition represents designing new technology to interoperate with existing technologies or other new technologies.
- **P3: S1 (human-technical) and P3a: S1 (human)**  $\in (\perp, h)$ . Humans must possess the prerequisite emotional and learned technical knowledge necessary to accept and work with innovative technology. The P3:S1 proposition represents preparing humans to interoperate with technology, and the P3a:S1 proposition represents preparing humans to interoperate with other humans.
- **P4: S3 (organization)**  $\in (\perp, o)$ . Reference the organization definition below. Innovative technology must integrate into human roles and tasks and contribute to achieving goals and objectives.
- **Proposition 5: S1 vs S2 (technical vs human interaction)**  $\in (\perp, t, h)$ .
- **Proposition 6: S2 vs S3 (technical vs organization interaction)**  $\in (\perp, t, o)$ .
- **Proposition 7: S1 vs S3 (human vs organization interaction)**  $\in (\perp, h, o)$ .
- **Proposition 8: S1 vs S2 vs S3 (technical vs human vs organization interaction)**  $\in (\perp, t, h, o)$ .

In Figure 1, P1: S2 (technical-human) and P2: S2 (technical)  $\in (\perp, t)$ . P3: S1 (human-technical) and P3a: S1 (human)  $\in (\perp, h)$ , and P4: S3 (organization)  $\in (\perp, o)$  are designed or undesigned taxonomic properties of the systemic  $(\perp, t)$  technology,  $(\perp, h)$  human, or  $(\perp, o)$  organization structural elements and relationships within those elements. Propositions 5: S1 vs. S2 (technical - human interaction)  $\in (\perp, t, h)$ , 6: S2 vs. S3 (technical - organization interaction)  $\in (\perp, t, o)$ , 7: S1 vs. S3 (human - organization interaction)  $\in (\perp, h, o)$ , and 8: S1 vs. S2. vs. S3 (technical - human - organization interaction)  $\in (\perp, t, h, o)$  are the ontological axioms that define functional relationships among the taxonomic elements.

## 4 Methodology

### 4.1 Definitions

To build a theoretical framework of healthcare autonomous service robot integration, we must begin with primitive definitions of the framework entities. For this research, the following entity definitions are set forth.

**Definition – Technology:** engineered artifacts used to replace or leverage human physical or reasoning capabilities.

**Definition – Infimum Technology** – naturally occurring artifacts used to leverage human capabilities.

**Definition – Supremum Technology** – scientifically engineered artifacts of new technical maturity that provide incremental leverage to human capabilities over existing technical artifacts.

**Definition – Human:** an entity of the species *Homo sapiens*, distinguished from other members of the species by superior mental development of abstract reasoning, articulate speech, and upright stance.

**Definition – Infimum Human:** an entity of the species *Homo sapiens*, distinguished from other members of the species by incrementally minimal differential mental development, inarticulate speech, and possibly but not necessarily upright stance.

**Definition – Supremum Human:** an entity of the species *Homo sapiens*, distinguished from other members of the species by superior mental development of abstract reasoning approaching the 100<sup>th</sup> percentile, fluent articulate speech, and upright stance.

**Definition – Organization:** a set of human beings with self-assigned roles and tasks designed to achieve a particular purpose, objective, or goal.

**Definition – Infimum Organization:** a set of human beings and relations among them.

**Definition – Supremum Organization:** a set of human beings with assigned roles and tasks designed to achieve the maximum benefit/cost return in achieving a particular purpose, objective, or goal over an extended time.

Likewise, this work sets for the following working definitions of healthcare and autonomous robot

**Definition – Healthcare:** the organized provision of acute, chronic, preventive, restorative, and rehabilitative human welfare services delivered to individual human beings or communities of human beings.

**Definition – Autonomous Robot** – a machine capable of self-reasoning, independent movement, and human-like interactions with humans, other machines, and environmental infrastructure that can take on tasks toward the achievement of a particular purpose, objective, or goal [25, 26].

## 4.2 Essential Concept Lattice Theory

To assure theoretical rigor in the resultant healthcare autonomous service robot-human collaboration theoretical framework, this research built its propositions on Formal Concept Analysis (FCA) lattice theory. This section presents the minimal set of FCA definitions and propositions necessary to demonstrate the rigor of the developed healthcare autonomous service robot-human collaboration theoretical framework.

### 4.2.1 Relations

Definition 1: A **relation**  $R$  over any set  $A$  is a subset of  $A \times A$ .

Definition 2: A relation  $R$  is **reflexive** if for each  $a \in A$ ,  $(a, a) \in R$ .

Definition 3: A relation  $R$  is **irreflexive** if for each  $a \in A$ ,  $(a, a) \notin R$ .

Definition 4: A relation  $R$  is **symmetric** if for all  $a, b \in A$ ,  $(a, b) \in R$  implies  $(b, a) \in R$ .

Definition 5: A relation  $R$  is **antisymmetric** if for all  $a, b \in A$ ,  $(a, b) \in R$  and  $(b, a) \in R$  implies  $a = b$ .

Definition 6: A relation  $R$  is **asymmetric** if for all  $a, b \in A$ ,  $(a, b) \in R$  implies  $(b, a) \notin R$ .

Definition 7: A relation  $R$  is **transitive** if for all  $a, b, c \in A$ ,  $(a, b) \in R$  and  $(b, c) \in R$  implies  $(a, c) \in R$ . The relations ‘less than’ and ‘equal to’ are transitive.

Definition 8: A relation  $R$  is an **equivalence** relation if it is reflexive, symmetric, and transitive.

Definition 9: A relation  $R$  on a set  $A$  is **irreflexive transitive closure**,  $R^+$ , if for all  $a, b \in A$ ,  $(a, b) \in R^+$ , iff there exists a sequence  $a_0, a_1, \dots, a_j, j > 1$  with  $a_0 = a$  and  $a_j = b$  such that  $\forall i : 0 \leq i < j : (a_i, a_{i+1}) \in R$ . Thus, if  $(a, b) \in R^+$ , there is a nonempty path from  $a$  to  $b$  in the graph relation  $R$ . The **reflexive transitive closure**,  $R^*$ , is defined as  $R^* = R^+ \cup \{(a, a) \mid a \in A\}$ .

### 4.2.2 Partial Orders

Definition 10: A relation  $R$  is a **reflexive partial order** (non-strict partial order poset,  $a \leq_R b$ ) if it is reflexive, antisymmetric, and transitive. A reflexive partial order is denoted  $(A, \leq)$ .

Definition 11: A relation  $R$  is an **irreflexive partial order** (strict partial order poset,  $a <_R b$ ) if it is irreflexive and transitive. An irreflexive partial order is denoted  $(A, <)$ .

Definition 12: A relation  $R$  is a total order if  $R$  is a partial order for all distinct  $a, b \in A$ , either  $(a, b) \in R$  or  $(b, a) \in R$ .

Definition 13: For any two elements in a poset,  $a, b \in A$ ,  $b$  **covers**  $a$  if  $a < b$  and  $\forall c \in a \leq c < b$  implies  $c = a$ . The notation  $a \uparrow b$  denotes that  $b$  covers  $a$ . The element  $b$  is denoted an **upper cover** of  $a$ , and the element  $a$  is denoted **the lower cover** of  $b$ .

Definition 14: Two elements  $a, b$  of an ordered set  $(A, \leq)$  are called **comparable** if  $a \leq b$  or  $b \leq a$ . Otherwise, they are **incomparable**.

Definition 15: A subset of  $(A, \leq)$  in which any two elements are comparable is termed a **chain**; a subset in which any two elements are incomparable is termed an **antichain**. A chain  $B$  of a poset  $(A, \leq)$ , is a **maximum chain** if no other chain contains more elements than  $B$ . An antichain  $C$  of a poset  $(A, \leq)$ , is a **maximum antichain** if no other antichain contains more elements than  $C$ . The **length** of a poset is the number of elements in the maximum chain, and the **width** of a poset is the number of elements in the maximum antichain.

### 4.2.3 Completeness and Closure

Definition 16: Let  $A \subseteq B$ , where  $(B, \leq)$  is a poset. For any  $n \in B$ ,  $n = \text{infimum of } A$  (**meet**) iff  $\forall a \in A : n \leq a$  and  $\forall n' \in B : (\forall a \in A : n' \leq a) \Rightarrow n' \leq n$ .

Definition 17: Let  $A \subseteq B$ , where  $(B, \leq)$  is a poset. For any  $s \in B$ ,  $s = \text{supremum of } A$  (**join**) iff  $\forall a \in A : a \leq s$  and  $\forall s' \in B : (\forall a \in A : a \leq s') \Rightarrow s \leq s'$ . The element  $n$  is called the **greatest lower bound** of  $\{a, b\}$ , denoted  $a \sqcap b$ , and the element  $s$  is called the **least upper bound** of  $\{a, b\}$ , denoted  $a \sqcup b$ .

Definition 18 (**Lattice**): A poset  $(A, \leq)$  is a lattice iff  $\forall a, b \in A : a \sqcup b$  and  $a \sqcap b$  exist.

Definition 19 (**Distributive Lattice**): A lattice  $L$  is **distributive** if  $\forall a, b, c \in L : a \sqcap (b \sqcup c) = (a \sqcap b) \sqcup (a \sqcap c)$ . All antichains in a finite lattice  $L$  can be given join and meet operations making them into a distributive lattice.

Definition 20 (**Complete Lattice**): An ordered set  $L, (L, \leq)$ , is a **complete lattice** if the supremum  $\vee A$  and the infimum  $\wedge A$  exist for any subset  $A$  of  $L$ . Every complete lattice  $L$  has a largest element,  $\vee L$ , termed the **unit element**  $1_L$ , and a smallest element  $\wedge L$ , termed the **zero element**  $0_L$ . A complete lattice is a finite lattice.

Definition 21 (**Closed Lattice**): A lattice  $L$  is defined to be closed (continuous), if it is a distributive lattice.

Note that definitions 1 through 21 are only a minimally sufficient set to support the development of the finite lattice theoretical framework to be set forth by this research. All lattice definitions, axioms, theorems, and propositions set forth in [27], [28], and [29] apply to subsequent taxonomic, ontological, and instrument development.

## 4.3 Healthcare Service Robot Framework Research Methodology

To construct the proposed socio-technical readiness framework for healthcare service robot integration, this study employed a mixed-methods approach grounded in thematic content analysis, computational text mining, and conceptual theory development. The goal was to identify and synthesize key factors that inform the readiness of healthcare institutions across technology, human interaction, and organizational integration domains.

This research followed a ten-phase methodology:

1. **Scoping and Systematic Literature Review:** An initial review of over 120 peer-reviewed articles was conducted to identify core themes for each proposition's literature corpus associated with healthcare service robot deployment. This review focused on identifying the concepts relevant to Technology Readiness Levels (TRLs), Human Readiness Levels (HRLs), and Organizational Readiness.
2. **Corpus Construction and Preprocessing:** Articles were filtered based on relevance and recency (2000-2023). The selected corpus was preprocessed using natural language processing techniques, including tokenization, stemming, and stop-word removal.
3. **Text Mining:** Term frequency-inverse document frequency (TF-IDF) analysis and clustering algorithms were applied to detect high-frequency concepts and latent patterns in the combined corpus. These findings informed the latent factor structure within the framework.
4. **Thematic Content Analysis:** A manual coding process was employed for each proposition's literature corpus using Formal Concept Analysis (FCA) principles. This helped identify manifest themes and

validate the thematic alignment between textual data and theoretical propositions [37].

5. **Latent Dirichlet Allocation (LDA):** LDA topic modeling was used to further surface hidden themes and topic distributions. These computationally derived themes were then mapped back to framework dimensions to ensure coverage of latent readiness factors.
6. **Synthesis and Alignment:** Both manifest and latent factors were triangulated to ensure consistency and thematic saturation. Themes were classified under TRL, HRL, and Organizational Readiness concepts.
7. **Framework Operationalization:** The validated themes and concepts were integrated into the H.STAR (Healthcare Socio-Technical Assessment of Readiness) framework. The result is a unified, multi-dimensional readiness model suited for application in healthcare contexts.

This structured and theory-informed methodology ensures that the resulting framework reflects both empirical depth and conceptual rigor, making it suitable for guiding future development of assessment tools and taxonomies for healthcare robotics readiness.

## 5 Research Results

This research applied a systematic literature review to identify manifest conceptual themes, text mining to identify additional latent conceptual themes, and content analysis to establish structural relationships among the identified manifest and latent technical, human, and organizational conceptual themes.

### 5.1 Systematic Literature Review

Literature search prompts were designed based on keywords in each proposition’s literature corpus. The terms searched in the databases were different according to the focus of the database. For instance, IEEE Xplore included a combination of the following keyword prompts.

1. Healthcare AND Interface AND [Robot OR Automated]
2. Human AND Interface AND [Robot OR Automated]
3. Research AND Interface AND [Robot OR Automated]

For each proposition, a combination of relevant keywords was used as demonstrated in Table 1. Concept saturation was used as the standard for sampling adequacy [30, 31]. Literature review continued until no new concepts emerged implying that the concept information was sufficient in depth to support trustworthy analysis [32]. For each proposition, the top 80% terms represented power law saturation, while the remaining 20% are considered noise and excluded. Table 2 summarizes the power law important concepts by saturation and the cumulative percentage saturation coverage.

**Table 1** Summary of prompt search query results.

| Keywords and Query Database     | “Healthcare”  |               | “Interface” + “Health care” or Healthcare” + “Robot” or “Automated” |              | Total Number of Reviewed |
|---------------------------------|---------------|---------------|---------------------------------------------------------------------|--------------|--------------------------|
|                                 | Search Result | Reviewed      | Search Result                                                       | Reviewed     | Papers                   |
| IEEE Xplore                     | 58            | 6             | 1                                                                   | 1            | 7                        |
| SciTech Premium Collection      | 102           | 10            | 23                                                                  | 5            | 15                       |
| ScienceDirect                   | 14            | 14            | 8                                                                   | 3            | 17                       |
| ABI/INFORM Global               | 56            | 10            | 8                                                                   | 4            | 14                       |
| ProQuest Engineering Collection | 4             | 4             | 11                                                                  | 2            | 6                        |
| Medline/PubMed                  | 14            | 0 (duplicate) | 0                                                                   | 0            | 0                        |
| Science Citation Index Expanded | 0             | 0             | 20                                                                  | 0(duplicate) | 0                        |
| <b>Total</b>                    | <b>248</b>    | <b>44</b>     | <b>71</b>                                                           | <b>15</b>    | <b>59</b>                |

Proposition 1 (technical-human) research focuses primarily on robot-human interface design. Proposition 2 (technical) research likewise focused on robot-human interface design but with modifier concepts of cognitive workload management, customizable seamless user interaction (personalization), and ergonomic design. Proposition 3 (human-technical) research focuses on robotic proficiency and capabilities, workflow integration and optimization, and human understanding and comfort with the robot’s role in the process. Proposition 3a

(human) research focuses on human emotional awareness, trust, and acceptance of robots in process workflows and integrating robots into human teams. Proposition 4 (organizational) research focuses on cultural acceptance of and adaptation to robots in process workflows, integrating stakeholders' views and legal/regulatory compliance into organizational policy, and change management to standardize robot-human processes and decision making. Proposition 5 (technical x human) focuses more sharply on robot maturity and technological integration, readiness, safety, and maintenance. Proposition 6 (technical x organization) likewise focuses more sharply on organizational readiness, standardization, performance excellence, reliability, serviceability, and durability. Proposition 7 (human x organization) focuses more sharply on competency, confidence, and comfort through technical preparedness, staff emotional readiness, and training effectiveness in a culturally conducive support environment. Proposition 8 (technical x human x organization) focuses on the systemic problem of interacting components with concepts mapping from the two-way interactions. Concept two-way interaction mapping includes the following: (technical x human) technical systems

**Table 2** Pareto Distribution of 80% Concepts for Each Proposition.

|                                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
|--------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Proposition 1<br>(technical – human) | Innovative interface design, Interface technologies advancement, User-friendly interface development, R&D investment in interface design, Technology demonstration, Interface technological breakthroughs, Prototype testing/evaluation, Interface capabilities demonstration, Novel interface interactions, Testbed interface development, Robot advanced interface deployment, Technology barriers, User-centered design, User needs assessment<br>Power Sat. = 81.41% |
| Proposition 2<br>(technical)         | Technological readiness, Customizable interface, Robot interface design, Users experience design, Ergonomic design principles, Personalization options, Seamless interaction, Cognitive workload management, User feedback mechanisms, Explanation of robot capabilities, Intuitive controls, User-friendly interfaces, Usability/accessibility, Safety features, Limitations disclosure, Task allocation efficiency, Redundancy mechanisms<br>Power Sat. = 77.08%       |
| Proposition 3<br>(human – technical) | Technical proficiency, Understanding robot capabilities, Functional understanding, Knowledge of robotic features, Comfort with technology use, Awareness of robot limitations, Robot operation familiarity, Understanding robot's role, Workflow integration, Workflow optimization, Role clarification.<br>Power Sat. = 72.12%                                                                                                                                          |
| Proposition 3a<br>(human)            | Awareness of robot functions, Robot emotional awareness, Robot roles in clinical processes, Robot-workforce integration, Robot teamwork, Emotions connection with robots, Transition management, Pre-conditioning, Empathy toward robots, Trust in robots, Confidence in robot performance, Robot reliability.<br>Power Sat. = 75.71%                                                                                                                                    |
| Proposition 4<br>(organizational)    | Organizational culture, Cultural acceptance, Innovation culture, Strategic alignment, Stakeholder engagement, Policy alignment, Regulatory compliance, Change implementation, Decision-making process, Legal framework, Workflow optimization, Process standardization, Process integration, Automation planning, Process improvement Information sharing, Cultural adaptation . Power Sat. = 79.61%                                                                     |

**Table 2** (continued) Pareto Distribution of 80% Concepts for Each Proposition

|                                             |                                                                                                                                                                                                                                                                                                                                                                                                                                               |
|---------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Proposition 5<br>(technical x human)        | Robust technical design, Technological advancement, Integration readiness, Robot technology maturity, System interoperability, Seamless integration, Technical proficiency, Robot operation familiarity, Maintenance knowledge, Robot integration challenges, Existing systems compatibility, Evaluation criteria, Safety protocols awareness, Strategic planning, Technological infrastructure, Maintenance resources<br>Power Sat. = 77.78% |
| Proposition 6<br>(technical x organization) | Innovation maturity, Robotic deployment maturity, Robot system robustness, Organizational readiness, Standards conformity, Workflow optimization, Process efficiency, Performance excellence, Reliability assurance, Durability enhancement, Serviceability optimization, Quality improvement<br>Power Sat. = 79.21%                                                                                                                          |
| Proposition 7<br>(human x organization)     | Technical preparedness, Workflow management, Staff emotional readiness, Training effectiveness, Confidence & comfort, Competency development, Support environment, Information dissemination, Knowledge sharing, Educational                                                                                                                                                                                                                  |

|                                                     |                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|-----------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                     | intervention, Role clarity, Confidence in technology<br>Power Sat. = 80.00%                                                                                                                                                                                                                                                                                                                                                          |
| Proposition 8<br>(technical x human x organization) | Human-Robot collaboration, Staff shortages, Technical systems, Robot facilitating conditions, Organizational learning, Functional readiness, Collaboration skills, Budget allocation, Integration into healthcare network, Communication proficiency, Social influence, Trust & rapport, Compatibility assessment, Organizational alignment, Information dissemination, Performance expectancy, Safety concerns. Power Sat. = 75.54% |

and robot facilitating conditions (maturity), technological integration, readiness, and maintenance (performance), and safety; (technical x organization) organizational learning, budget allocation, compatibility, integration, functional readiness, and trust (organizational readiness); and (human x organization) alignment, collaboration skills, communications proficiency, information discrimination (competency, confidence, and comfort) and social influence (emotional readiness).

Note in Table 2 that concept phrase counts ranged from 11 (72.12%) to 17 (75.54%) per proposition, and Pareto significant percentages ranged from 72.12% (count 11) to 81.41% (count 14) per proposition. Also note that multiple phrases within and across propositions were synonymous in meaning. This strongly suggests that the healthcare service robot application-level body of knowledge is diffuse and still not succinctly specified.

## 5.2 Text Mining

Text mining of the combined literature corpus revealed meta-level latent concept dimensions centered on technical maturity, physical aspects, human factors dimensions, human-robot performance, and human-computer interaction user experience. High-frequency terms such as “automation,” “sensors,” “ISO standards,” and “clinical validation” corroborated Propositions 1 and 2, highlighting that perceived readiness was closely tied to demonstrated safety and regulatory compliance. Additionally, the lack of system integration with electronic health records (EHRs) emerged as a consistent barrier, supporting Proposition 1. Topic clusters confirmed that TRL-aligned maturity (particularly TRLs 7–9) was more prevalent in surgical and transport robotics, while lower readiness levels were noted in eldercare and assistive robots still under prototype evaluation [33]. Optimum K-means clustering analysis ( $k = 5$ ) of the literature corpus identified the systemic dimensions in Figure 2.

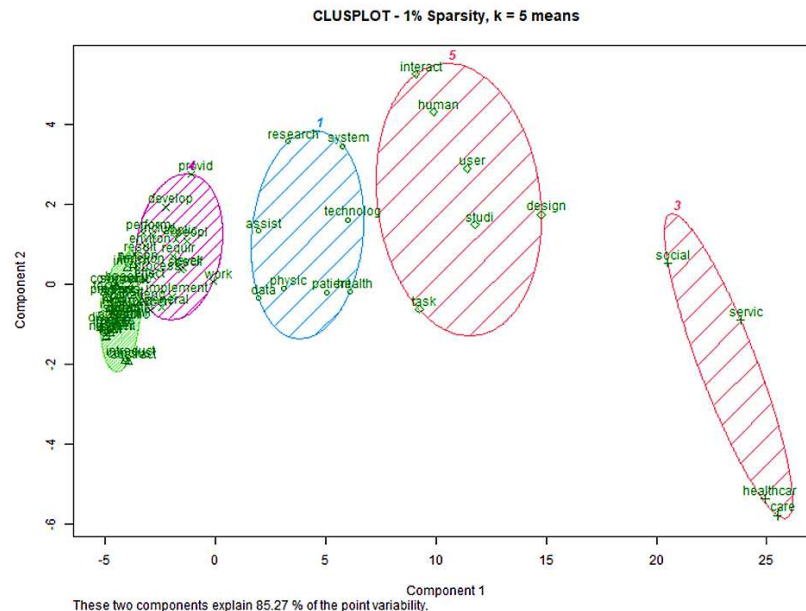


**Fig 2** Optimum K-means ( $k = 5$ ) Clustering Latent Dimensions.

Centroid 1 {research, assistance, physical systems, data, health, patient, system, technology} latent dimension Technology, is concerned with interdisciplinary research in technology. It highlights the role of research in

developing and integrating technological systems to assist healthcare. This centroid's center of mass loads moderately positive on both principal components, indicating a moderate positive concept importance. Variance (major axis) in interdisciplinary research meaning loads primarily onto principal component 2. Centroid 1 can be interpreted as focusing on technology development, deployment, and implementation maturity concepts.

Centroid 2 {provides, performs, executes, repairs, controls, inspect, maintain, plus noise terms} latent dimension Physical, focuses on operational and technical tasks execution, maintenance, and quality control processes, which are crucial for maintaining and improving technical systems. This centroid's center of mass loads moderately negatively onto principal component 1 reflecting the moderate importance of technical maturity in the context of healthcare organization processes. Variance in operational and technical tasks meaning is centered on and loads primarily onto principal component 2, but the prediction interval range is small relative to the other centroids.

Centroid 3 {social, service, healthcare, care} latent dimension Human Factors, is concerned with social services and healthcare. It emphasizes the provision of care and support within the healthcare sector, highlighting the importance of organizational readiness in enhancing patient outcomes. This centroid's center of mass shows significant loading on the first principal component, indicating a strong focus on delivering social care as well as healthcare. Centroid 3's center of mass loads moderately negative onto principal component 2, but its variance in meaning loads heavily onto principal component 2. Note that centroid 3's axes are rotated negatively relative to the principal component axes indicating residual interaction between social care and healthcare.

Centroid 4 {interact, human, user, study, design, project, team, manage, plan, develop, resource} latent dimension Performance, is concerned with planning and implementing human-robot performance within the healthcare work environment. Sub-Centroid 4 {interact, human, user, study, design, task} focuses on human-computer interaction and user experience. It represents the design and study of interactions between humans and systems, aiming to improve user experience and system usability. Sub-Centroid 4 {project, team, manage, plan, develop, resource} is concerned with project management and team coordination. This centroid's center of mass loads mildly negatively onto principal component 1 and mildly positively onto principal component 2 with its variance of concept meaning loading onto principal component 2. This suggests that consideration of human-robot performance in the design of healthcare autonomous service robots has only a mild impact on technology adoption. The variance prediction interval range is small relative to the other centroids.

Centroid 5 {interact, human, user, study, design, task}, latent dimension Interaction, focuses on human-computer interaction tasks and user experience. It represents the design and study of interactions between humans and systems, aiming to improve user experience and system usability. Centroid 5's center of mass loads strongly positive onto principal component 1, moderately positive onto principal component 2, and its variance in concept meaning loads heavily onto principal component 2 suggesting a focus on the organizational aspects of project management. Centroid 5 can be interpreted as focusing on human-robot interactions.

Principal component 1 represents latent dimension concept locations, while principal component 2 represents the concept precision (inverse of the variance). Note that centroids 2 and 4, with larger numbers of concept terms and higher precision (lower variability), load negatively onto principal component 1, counterbalancing centroids 1, 5, and 3, which load positively on principal component 1 with fewer numbers of and less precision (more variability) in concept terms. This suggests that the physical and resultant human-robot performance dimensions are counterbalanced against the technology, human factors, and human-robot user experience dimensions. Also note that principal components 1 and 2 explain 85.27% of point variability, indicating that the five centroids are power law sufficient [34].

The first of two final questions to be addressed for the text mining results was how the systematic literature review manifests taxonomic dimensions' ( $\wedge$ , t), ( $\wedge$ , o), and ( $\wedge$ , h) properties map to the text mining latent dimensions. To assess these mappings, Figure 3(a) maps propositions P1(technical x human) through P4(organization) design intent to centroids 1 through 5 terms definitions. The second question was how the text mining latent dimension centroids' definitions mapped to the systematic literature review manifest axiomatic interaction relationship dimensions ( $\wedge$ , t, h), ( $\wedge$ , t, o), ( $\wedge$ , h, o), and ( $\wedge$ , t, h, o). To assess these mappings, Figure 3(b) maps the text mining latent dimension centroids' definitions to propositions P5 (technical x human), P6 (technical x organization), P7 (human x organization), and P7 (technical x human x organization). Multiple correspondence analysis (MCA) was performed on each table to assess the associations and their strengths.

| C term | C1 | C2 | C3 | C4 | C5 | P1 | P2 | P3 | P3A | P4 |
|--------|----|----|----|----|----|----|----|----|-----|----|
| C1:    | 1: |    |    |    |    |    |    |    |     |    |
| :      | :  |    |    |    |    |    |    |    |     |    |
| :      | :  |    |    |    |    |    |    |    |     |    |
| C1     | 1  |    |    |    |    |    |    |    |     |    |
| C2:    |    | 1: |    |    |    |    |    |    |     |    |
| :      |    | :  |    |    |    |    |    |    |     |    |
| :      |    | :  |    |    |    |    |    |    |     |    |
| C2     |    | 1  |    |    |    |    |    |    |     |    |
| C3:    |    |    | 1: |    |    |    |    |    |     |    |
| :      |    |    | :  |    |    |    |    |    |     |    |
| :      |    |    | :  |    |    |    |    |    |     |    |
| C3     |    |    | 1  |    |    |    |    |    |     |    |
| C4     |    |    |    | 1: |    |    |    |    |     |    |
| :      |    |    |    | :  |    |    |    |    |     |    |
| :      |    |    |    | :  |    |    |    |    |     |    |
| C4     |    |    |    | 1  |    |    |    |    |     |    |
| C5     |    |    |    |    | 1: |    |    |    |     |    |
| :      |    |    |    |    | :  |    |    |    |     |    |
| :      |    |    |    |    | :  |    |    |    |     |    |
| C5     |    |    |    |    | 1  |    |    |    |     |    |

3(a) Taxonomic mapping.

| C term | C1 | C2 | C3 | C4 | C5 | P1 | P2 | P3 | P3A | P4 | P5 | P6 | P7 | P8 |
|--------|----|----|----|----|----|----|----|----|-----|----|----|----|----|----|
| C1:    | 1: |    |    |    |    | 1: |    |    |     |    |    |    |    |    |
| :      | :  |    |    |    |    | :  |    |    |     |    |    |    |    |    |
| :      | :  |    |    |    |    | :  |    |    |     |    |    |    |    |    |
| C1     | 1  |    |    |    |    | 1  |    |    |     |    |    | O  |    |    |
| C2:    |    | 1: |    |    |    |    | 1: |    |     |    |    |    |    |    |
| :      |    | :  |    |    |    |    | :  |    |     |    |    |    |    |    |
| :      |    | :  |    |    |    |    | :  |    |     |    |    |    |    |    |
| C2     |    | 1  |    |    |    |    |    |    |     |    |    |    |    |    |
| C3:    |    |    | 1: |    |    |    |    | 1  |     |    |    |    |    |    |
| :      |    |    | :  |    |    |    |    |    |     |    |    |    |    |    |
| :      |    |    | :  |    |    |    |    |    |     |    |    |    |    |    |
| C3     |    |    | 1  |    |    |    |    |    |     |    |    |    | 1: |    |
| C4     |    |    |    | 1: |    |    |    |    |     |    |    |    | :  |    |
| :      |    |    |    | :  |    |    |    |    |     |    |    |    | :  |    |
| :      |    |    |    | :  |    |    |    |    |     |    |    |    | :  |    |
| C4     |    |    |    | 1  |    |    |    |    |     |    |    |    | 1  |    |
| C5     |    |    |    |    | 1: |    |    |    |     |    |    |    | :  |    |
| :      |    |    |    |    | :  |    |    |    |     |    |    |    | :  |    |
| :      |    |    |    |    | :  |    |    |    |     |    |    |    | :  |    |
| C5     |    |    |    |    | 1  |    |    |    |     |    |    |    | 1  |    |

3(b) Axiomatic mapping.

**Fig 3** (a) Taxonomic Mappings Table. (b) Axiomatic Mappings Table.

Multiple correspondence analysis for the taxonomic property mappings showed that dimension one accounts for 67.5% of the information variation, and dimension two accounts for 8.6% of the information variation for a total of 76.1%. This meets the definition of Pareto significance set for this research. The conclusion is that the taxonomic technology ( $\wedge$ , t), organization ( $\wedge$ , o), and human ( $\wedge$ , h) dimensions of Figure 1 are sufficient in support of the text mining centroid manifest and latent dimensions. The systemic dimensions map to the lattice dimensions as follows: Technology  $\textcircled{R}$  ( $\wedge$ , t), Human Factors  $\textcircled{R}$  ( $\wedge$ , h), and {Physical, Performance, Interaction}  $\textcircled{R}$  ( $\wedge$ , o). Dimensional analysis of “1” associations in Figure 4 show the propositions to centroids mappings in Table 3. The taxonomic dimensions of technology ( $\wedge$ , t), organization ( $\wedge$ , o), and human ( $\wedge$ , h) are sufficient for future readiness level instrument development.

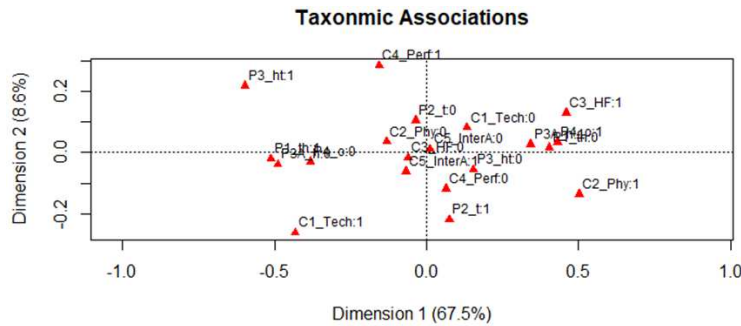


**Fig 4** MCA Taxonomic Proposition-Centroid Properties Associations.

**Table 3** Taxonomic Manifest Proposition to Latent Centroid Properties Dimension Mappings.

|                        |     | Systemic Dimensions |      |     |      |      |
|------------------------|-----|---------------------|------|-----|------|------|
|                        |     | C1                  | C2   | C3  | C4   | C5   |
| Mani-<br>fest<br>Dim's | P1  | -1,-2               |      |     |      |      |
|                        | P2  |                     | 1,-2 |     |      | 1,-2 |
|                        | P3  |                     |      |     | -1,2 |      |
|                        | P3a |                     | 1,0  | 1,2 |      |      |
|                        | P4  |                     | 1,0  | 1,2 |      |      |

Legend: 1 = Dim 1 mapping; 2 = Dim 2 mapping.

Multiple correspondence analysis for the axiomatic structural and functional relationships mappings showed that dimension one accounts for 26.6% of the information variation, dimension two 14.3%, and dimension three 10.3% for a total 51.2% of the total variation. Dimensions four and higher added only 2.4% or less to explaining information variation. The explained total variation of 51.2% does not meet the definition of Pareto significance set for this research. This strongly suggests that the central problem in implementing service robots into healthcare systems is the “how” represented by the axiomatic dimensions and not the “what” represented by the taxonomic dimensions. Note in Figures 5 (dimension 2 vs 1) and Figure 6 (dimension 3 vs 2) that the centroid-proposition axiomatic mappings are more tightly grouped around the barycenter of mass than those of the taxonomic proposition-centroid mappings in Figure 4. Dimensional analysis

of “1” associations in Figures 5 and 6 shows the centroids to propositions mappings in Table 4

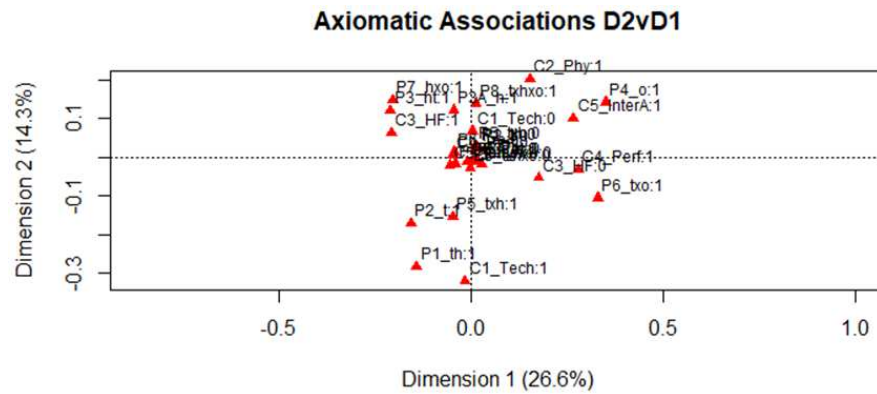


**Fig 5** MCA Axiomatic Dimensions 1 and 2 Centroid-Proposition Associations.

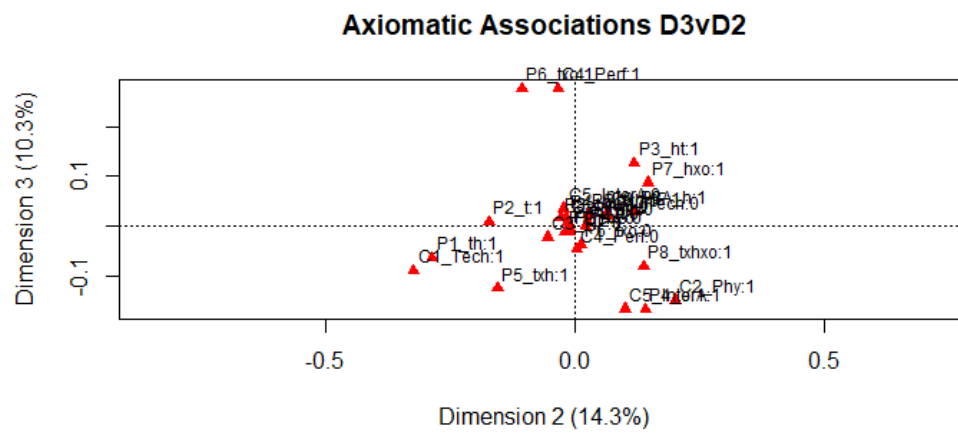


**Fig 6** MCA Axiomatic Dimensions 2 and 3 Centroid-Proposition Associations.

**Table 4** Axiomatic Latent Centroid to Manifest Proposition Dimension Mappings.

|                        |     | Systemic Dimensions |             |      |              |             |
|------------------------|-----|---------------------|-------------|------|--------------|-------------|
|                        |     | C1                  | C2          | C3   | C4           | C5          |
| Mani-<br>fest<br>Dim's | P1  | -1,-2<br>-2,-3      |             |      |              |             |
|                        | P2  | -2,-2               |             |      |              |             |
|                        | P3  |                     |             | -1,2 |              |             |
|                        | P3a |                     | 1,1         |      |              |             |
|                        | P4  |                     | 2,-3        |      |              | 1,1<br>2,-3 |
|                        | P5  | -1,-2<br>-2,-3      |             |      |              |             |
|                        | P6  |                     |             |      | 1,-2<br>-2,3 |             |
|                        | P7  |                     |             | -1,2 |              |             |
|                        | P8  |                     | 1,1<br>2,-3 |      |              | 2,-3        |

Legend: 1 = Dim 1 mapping; 2 = Dim 2 mapping; 3 = Dim 3 mapping.

### 5.3 Content Analysis

Dictionary-based content analysis evidential coding was used to extract the manifest dimension concepts from the systematic literature review of each proposition's literature corpus. The dictionary-based approach allows the

quantification and systematic analysis of text data, providing insights into patterns, trends, and underlying themes in the content. This approach involves the use of a lexicon or a list of words, where each word is associated with specific themes, sentiments, or concepts. The primary steps in dictionary-based content analysis include:

1. Text Preparation: Texts are cleaned and preprocessed to remove any irrelevant information, such as punctuation and stop words, ensuring that the analysis focuses on meaningful words. In the context of this research, the lexicon was derived during the systematic literature review and text mining phases.
2. Dictionary Matching: Each concept word identified for each corresponding proposition in the systematic literature review and text mining is compared against the predefined dictionary. When a match is found, the word is categorized according to the themes or concepts defined in the dictionary.
3. Frequency Counting: The occurrence of words from each proposition and manifest concept dimension was counted to determine the prevalence of specific concepts and relationships among concepts within the text.
4. Interpretation: The frequency data were analyzed to draw conclusions about the content. Pareto high-frequency words and phrases reveal key concepts and relationship patterns among concepts.

#### **Content Analysis Principal Components for Proposition 1**

Interestingly, content analysis of the evidential coding of proposition 1 (technology-human) literature corpus yielded the same concept dimensions of Technology, Physical, Human Factors, Performance, and Interaction identified in text mining. Content analysis principal components of proposition 1 dimensions in Table 5 indicated that the first three dimensions explain 84.2% of the information variation. in the manifest concept dimensions of Technology, Physical, Human Factors, Performance, and Interaction. The principal components biplot in Figure 7 shows the relationships among different themes related to service robot human interface capabilities and their associated variables. In the dimension 2 versus 1 biplot, dimensions Interactions and Human Factors load positively into quadrant one, Physical loads negatively onto dimension 1 and mildly positive onto dimension 2, and Performance loads negatively onto dimension 1 and mildly negative onto dimension 2. The lengths of the arrows indicate that Interaction, Physical, Performance, and Technology carry relatively equal weights, with Human Factors carrying slightly less weight. Technology is orthogonal to Interaction and Performance, and opposing the joint weights of Human Factors and Physical. Interaction and Human Factors are collinear, as are Physical and Performance. In dimension 3 versus 2, latent dimension Human Factors is essentially orthogonal to collinear Interaction-Physical with Technology dominating Performance and collinear Performance-Technology. The weights of Technology and Human Factors are essentially equal, with Interaction and Physical having lesser weights. This suggests that in designing the technical-human aspects of healthcare service robots, primary tradeoffs must be made between opposing Technology and collinear Physical-Human Factors and between Performance and Interaction. In dimension 3 versus 2, secondary design tradeoffs must be given to opposing collinear Interaction-Physical versus collinear Performance-Technology, with Human Factors being independent.

**Table 5** Content Analysis Principal Components of Proposition 1

|                        | PC1   | PC2    | PC3    | PC4     | PC5     |
|------------------------|-------|--------|--------|---------|---------|
| Standard deviation     | 1.387 | 1.2177 | 0.8965 | 0.69748 | 0.54966 |
| Proportion of Variance | 0.385 | 0.2965 | 0.1607 | 0.09729 | 0.06042 |
| Cumulative Proportion  | 0.385 | 0.6815 | 0.8423 | 0.93958 | 1.0000  |

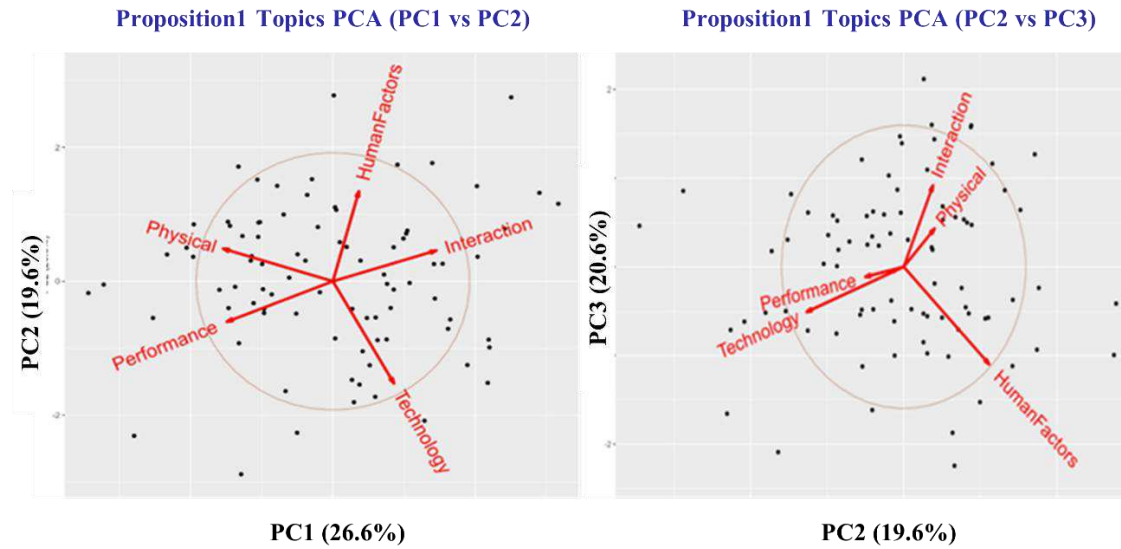


**Fig 7** Content Analysis Principal Components Proposition 1 Biplots – Dim 2 v1 and Dim 3 v 2.

### Content Analysis Principal Components for Proposition 2

Content analysis, evidential coding of proposition 2 (technology) literature corpus, yielded concept dimensions Capabilities, Development, Performance, Readiness, and Technology. Content analysis principal components of proposition 3 literature corpus dimensions in Table 6 indicated that the first three dimensions explain 81.2% of the information variation. in the identified manifest concept dimensions. The principal components biplot of dimension 2 versus 1 in Figure 8 shows that the concept dimensions are essentially orthogonal, with Interaction loading on the positive dimension 1 axis, collinear Healthcare and Performance loading negative on dimension 1, Users loading on the positive axis of dimension 2, and Technology loading negatively on the negative axis of dimension 2. The weights for Interaction, Healthcare, Users, and Technology are approximately equal. The principal components biplot of dimension 3 versus 2 shows the same essential orthogonality with Users loading onto the positive axis of dimension 2, Technology loading onto the negative axis of dimension 2, Healthcare loading onto the positive axis of dimension 3, and collinear Interaction and Performance loading negatively onto the negative axis of dimension 3. The weights of Users, Healthcare, and Technology are essentially equal, with Performance and Interaction having lesser weights. This suggests that in designing the technical aspects of healthcare service robots, primary tradeoffs must be made between opposing Technology and Users and between opposing Interaction and collinear Performance-Healthcare. In dimension 3 versus 2, secondary design tradeoffs must be given to opposing Users versus Technology and opposing Healthcare versus collinear Interaction-Performance. Designing the technical aspects must consider the meta-level latent dimensions of Technology, Performance, and Interaction, plus the applied level Healthcare and Users aspects.

**Table 6** Content Analysis Principal Components of Proposition 2

|                        | PC1    | PC2    | PC3    | PC4    | PC5     |
|------------------------|--------|--------|--------|--------|---------|
| Standard deviation     | 1.3651 | 1.2043 | 0.8627 | 0.7961 | 0.55525 |
| Proportion of Variance | 0.3727 | 0.2900 | 0.1489 | 0.1268 | 0.06166 |
| Cumulative Proportion  | 0.3727 | 0.6627 | 0.8116 | 0.9383 | 1.0000  |

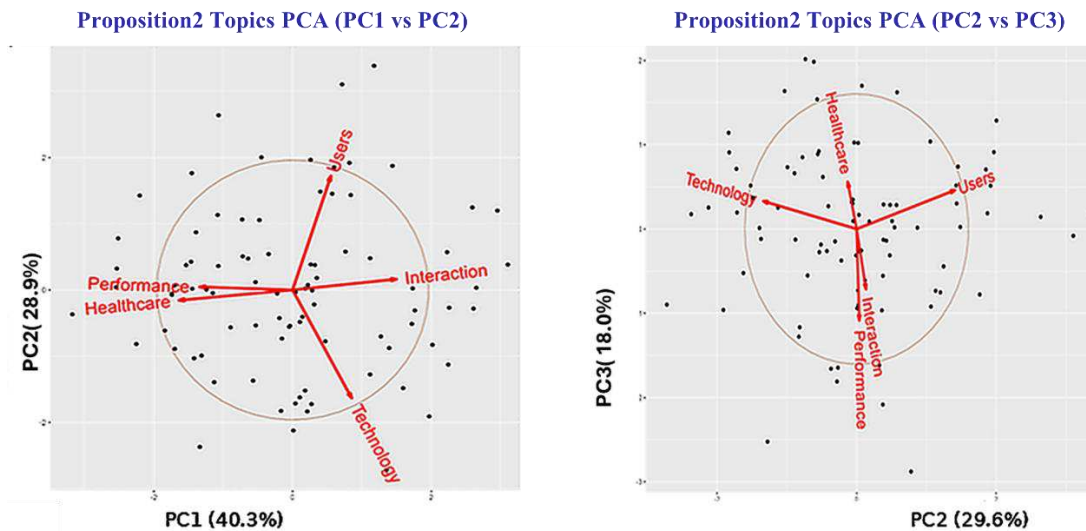


**Fig 8** Content Analysis Principal Components Proposition 2 Biplots – Dim 2 v1 and Dim 3 v 2.

### Content Analysis Principal Components for Proposition 3

Content analysis evidential coding of proposition 3 (human-technical) literature corpus yielded concept dimensions Capabilities, Development, Performance, Readiness, and Technology. Content analysis principal components of proposition 3 literature corpus dimensions in Table 7 indicated that the first three dimensions explain 88.3% of the information variation. in the identified manifest concept dimensions. The principal components biplot of dimension 2 versus 1 in Figure 9 show that the concept Performance, loading onto the negative dimension 1 axis, is essentially opposed to collinear dimensions Readiness and Development, loading onto the positive dimension 1 axis and positive dimension 2 axis, and colinear dimensions Capabilities and Technology, loading essentially onto the positive dimension 1 axis and negative dimension 2 axis. The joint Readiness-Development and the joint Capabilities-Technology dimensions are essentially orthogonal. The dimensions Performance, Readiness, and Technology exhibit essentially the same weights with Capabilities and with Development less weights. The principal components biplot of dimension 3 versus 2 indicates that concept Readiness loads into the positive dimension 2 and positive dimension 3 quadrant opposing Technology, which load into the negative-negative third quadrant. The concept Capabilities loads into the negative-positive second quadrant opposing Development, which loads into the positive-negative fourth quadrant. Readiness carries slightly more weight than Technology, and Capabilities carry slightly more weight than Development. The concept Performance carries almost no loading weight into dimensions 2 and 3. This suggests that Performance is an important consideration in preparing humans to interoperate with Technology (service robots) and is traded off against Development-Readiness and Technological-Capabilities. Secondary design considerations (latent dimension 2-3) are given to Readiness traded off against Technology benefits and to Capabilities traded off against Development. In preparing humans to interoperate with technology, the meta-level latent dimensions of Technology and Performance must be supplemented with technological Capabilities and human Readiness Development.

**Table 7** Content Analysis Principal Components of Proposition 3

|                        | PC1    | PC2    | PC3    | PC4     | PC5     |
|------------------------|--------|--------|--------|---------|---------|
| Standard deviation     | 0.1313 | 0.1199 | 0.1122 | 0.06144 | 0.04539 |
| Proportion of Variance | 0.3444 | 0.2783 | 0.2516 | 0.07544 | 0.04117 |
| Cumulative Proportion  | 0.3444 | 0.6318 | 0.8834 | 0.95883 | 1.0000  |

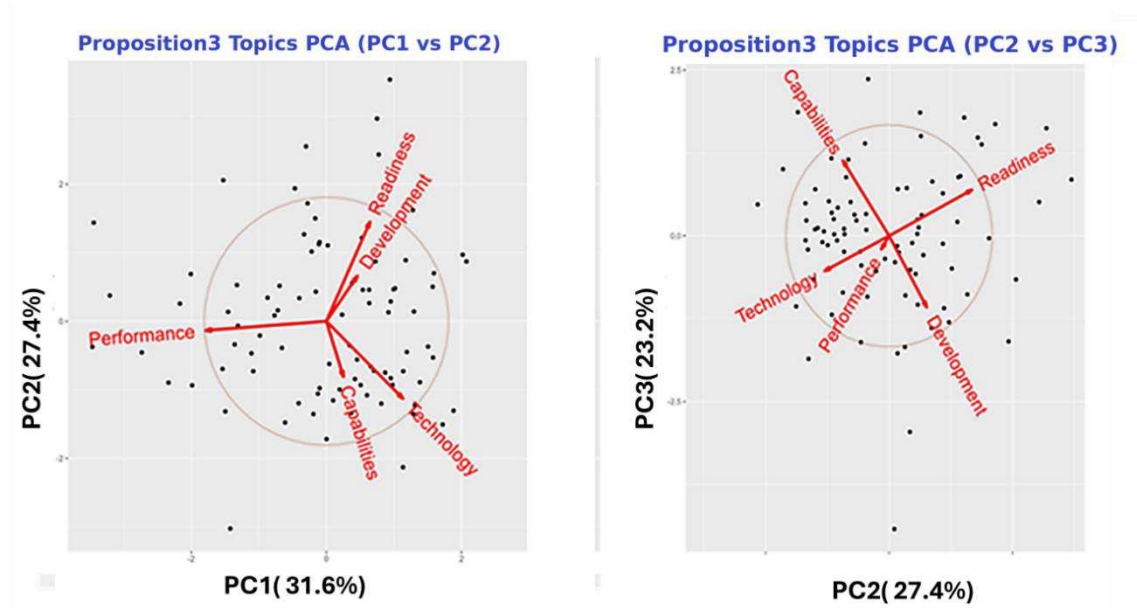


**Fig 9** Content Analysis Principal Components Proposition 3 Biplots – Dim 2 v1 and Dim 3 v 2.

### Content Analysis Principal Components for Proposition 3a

Content analysis evidential coding of proposition 3a (human) literature corpus yielded concept dimensions Behavior, Quality, Research, Stakeholders, and Technology. Content analysis principal components of proposition 3a literature corpus dimensions in Table 8 indicated that the first three dimensions explain 82.8% of the information variation. in the identified manifest concept dimensions. The principal components biplot of dimension 2 versus 1 in Figure 10 shows that collinear concept dimensions Quality and Research jointly load primarily onto the dimension 1 positive axis opposing Technology loads mostly onto the negative dimension 1 axis and somewhat onto the positive dimension 2 axis in the second quadrant. Dimension Behavior loads into quadrant 1 and opposes dimension stakeholders, which load into the third quadrant. Dimensions Quality-Behavior and Technology are essentially orthogonal to dimensions Behavior-Stakeholders. Dimensions Technology and Stakeholders carry the most weight, with Behavior, Quality, and Research carrying less weight. The principal components biplot of dimension 3 versus 2 in Figure 10 shows that concept dimension Behavior loads equally into the positive-positive first quadrant and opposes Research, which loads primarily onto the negative dimension 2 axis. Concept dimension Stakeholders loads into the negative-positive quadrant 2 and opposes Technology, which loads into the positive-negative third quadrant. Concept dimension Stakeholders carry the most weight with Behavior, Research, and Technology carrying less weight. Concept dimension Quality carries almost no loading weight in principal components dimensions 2 and 3. These loading suggests that primary consideration must be given to preparing Stakeholders to accept service robot Technology. The integration of advanced technology is viewed negatively in terms of stakeholder acceptance but may also be seen positively concerning system behavior [35]. Concept dimensions “Research” and “Quality” are essentially collinear and must be considered jointly when implementing service robots. This indicates that while research and quality improvements are seen positively in terms of system development, there may be underlying challenges or concerns that impact their perceived effectiveness. Concept dimension Behavior loading positively into positive-positive first quadrant underscores the importance of behavioral research and management in achieving maturity in service robot healthcare systems.

**Table 8** Content Analysis Principal Components of Proposition 3a

|                        | PC1    | PC2    | PC3     | PC4     | PC5     |
|------------------------|--------|--------|---------|---------|---------|
| Standard deviation     | 0.1255 | 0.1035 | 0.08373 | 0.06234 | 0.05450 |
| Proportion of Variance | 0.3898 | 0.2652 | 0.17351 | 0.09804 | 0.07352 |
| Cumulative Proportion  | 0.3898 | 0.6549 | 0.82844 | 0.92648 | 1.0000  |

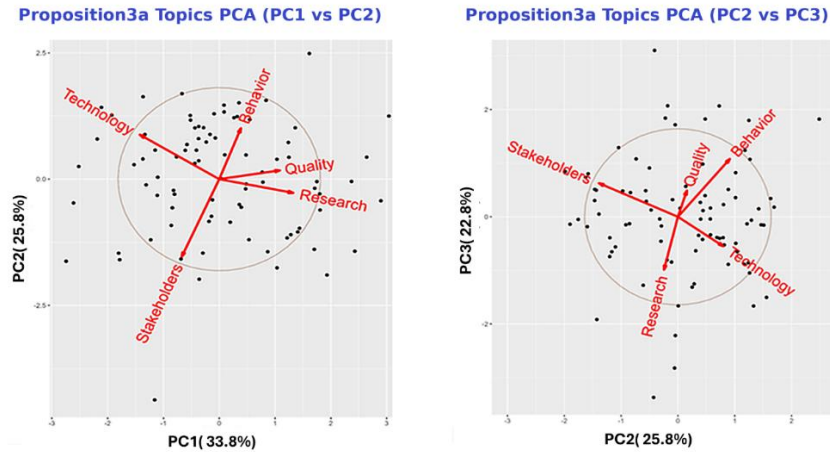


**Fig 10** Content Analysis Principal Components Proposition 3a Biplots – Dim 2 v1 and Dim 3 v 2.

#### Content Analysis Principal Components for Proposition 4

Content analysis evidential coding of proposition 4 (organization) literature corpus yielded concept dimensions Adoption, Challenges, Culture, Evaluation, and Organizational. Content analysis principal components of proposition 4 literature corpus dimensions in Table 9 indicated that the first three dimensions explain 83.9% of the information variation. in the identified manifest concept dimensions. The principal components biplot of dimension 2 versus 1 in Figure 11 shows that the collinear concept dimension Organizational and Challenges essentially load onto the dimension 1 positive axis and oppose concept dimension Culture, which loads primarily onto the dimension 1 negative axis and mildly onto the dimension 2 positive axis in the second quadrant. Concept dimensions Organizational and Culture directly oppose. Concept dimension Adoption loads onto the dimension 2 positive axis. Concept dimension Evaluation loads equally onto the dimension 1 negative axis and dimension 2 negative axis and opposes the joint effects of concept dimensions, Adoption and Challenges. Culture and Evaluation carry the most weight, Adoption and Organizational carry the next weight, and Challenges carry the least weight. This suggests that cultural evaluation considerations are essential for the successful implementation of service robots in healthcare.

**Table 9** Content Analysis Principal Components of Proposition 4

|                        | PC1    | PC2    | PC3    | PC4     | PC5     |
|------------------------|--------|--------|--------|---------|---------|
| Standard deviation     | 0.1400 | 0.144  | 0.1048 | 0.07886 | 0.04682 |
| Proportion of Variance | 0.3762 | 0.2514 | 0.2109 | 0.11937 | 0.04208 |
| Cumulative Proportion  | 0.3762 | 0.6277 | 0.8386 | 0.95792 | 1.0000  |

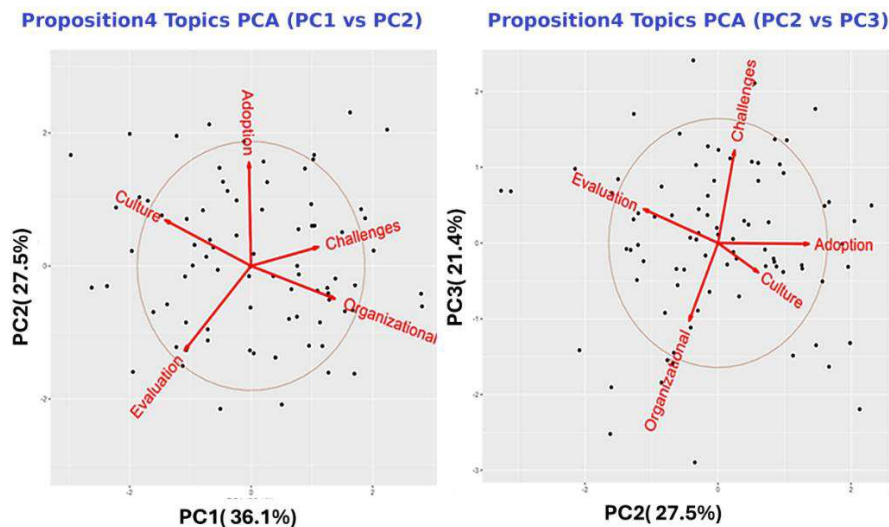


**Fig 11** Content Analysis Principal Components Proposition 4 Biplots – Dim 2 v1 and Dim 3 v 2.

The principal components biplot of dimension 3 versus 2 in Figure 11 shows that concept dimension Adoption, collinear with Culture, loads onto the dimension 2 positive axis and essentially opposes Evaluation, which loads primarily onto the dimension 2 negative axis and mildly onto the dimension 3 positive axis. Concept dimension Challenges load essentially onto the dimension 3 positive axis and oppose concept dimension Organizational, which essentially loads onto the dimension 3 negative axis. Joint concept dimensions, Adoption-Culture and Evaluation, are essentially orthogonal to joint concept dimensions, Challenges and Organizational. Concept dimensions, Adoption, Challenges, Evaluation, and Organizational carry essentially equal weights, with concept dimension Culture carrying less weight. This suggests that the latter four concept dimensions should receive secondary joint consideration after designing for cultural evaluation considerations in principal components dimensions 1 and 2.

#### Content Analysis Principal Components for Proposition 5

Content analysis evidential coding of proposition 5 (technical x human interaction) literature corpus yielded axiomatic relations Assessment, Capability, Interaction, and Practice. Content analysis principal components of proposition 5 literature corpus dimensions in Table 10 indicated that the first three dimensions explain 88.4% of the information variation. in the identified manifest relationship dimensions. The principal components biplot of dimension 2 versus 1 in Figure 12 shows that Interaction and Practice are collinear, jointly loading into the positive-positive first quadrant and opposing Assessment, which loads essentially on the dimension 1 negative axis, and Capability, which loads essentially onto the dimension 2 negative axis. Assessment and Capability relations carry the greatest weights with the collinear Interaction-Practice relationships carrying slightly less weight. These rotations suggest that assessment plays a complex role in shaping the maturity of service robot systems. Although the primary purpose of assessment is to provide critical evaluations that drive improvements, assessments can also highlight technology or human limitations that may hinder progress. The collinear relationship of Interaction-Practice suggests that improving technical - human interactions in practice is a major focus area and is perceived as beneficial across healthcare service robot system design. Capability loading negatively onto both dimensions highlights ongoing concerns regarding the existing capabilities within service robot systems. This negative loading suggests that current capabilities are seen as insufficient or lacking in some key areas, thus representing a significant barrier to achieving full maturity in healthcare service robot systems. The principal components biplot of dimension 3 versus 2 in Figure 12 shows that Capability loads essentially onto the dimension 2 negative axis and opposes the joint relationships of Interaction, which loads into the positive-negative fourth quadrant, and Practice, which loads into the positive-positive first quadrant. The Capability, Interaction, and Practice are separated, essentially 120 degrees, suggesting some mild negative interactions. Capability carries the largest weight, followed by Interaction and Practice. Assessment loads into dimension 2-3 with little weight. These rotations and weights suggest that secondary design tradeoffs must be made in the design of human - technical robotic interactions to achieve best joint practice capabilities.

**Table 10** Content Analysis Principal Components of Proposition 5

|                        | PC1    | PC2     | PC3    | PC4     |
|------------------------|--------|---------|--------|---------|
| Standard deviation     | 0.1146 | 0.09778 | 0.0727 | 0.06068 |
| Proportion of Variance | 0.4150 | 0.30186 | 0.1699 | 0.11625 |
| Cumulative Proportion  | 0.4150 | 0.71688 | 0.8838 | 1.00000 |

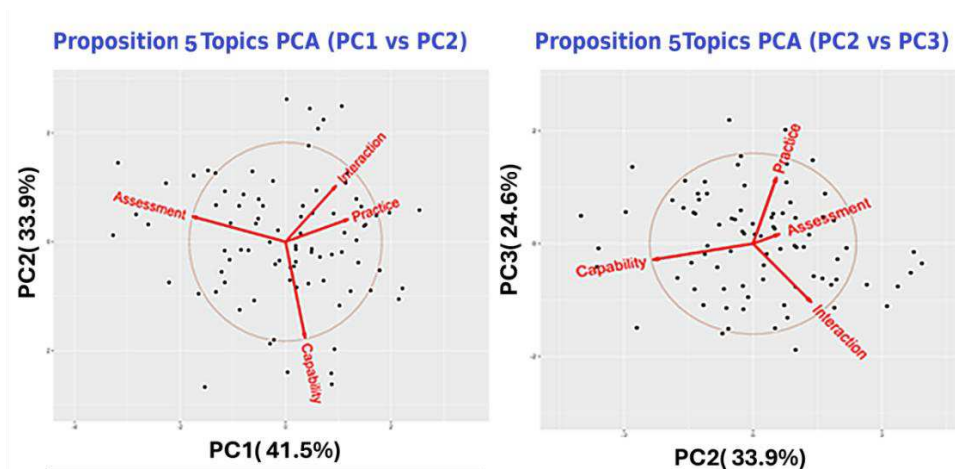


**Fig 12** Content Analysis Principal Components Proposition 5 Biplots – Dim 2 v1 and Dim 3 v 2.

### Content Analysis Principal Components for Proposition 6

Content analysis evidential coding of proposition 6 (technical x organization interaction) literature corpus yielded axiomatic relations Analysis, Autonomy, Experience Level, and Technology Interaction. Content analysis principal components of proposition 6 literature corpus dimensions in Table 11 indicated that the first two dimensions explain 80.5% of the information variation in the identified manifest relationship dimensions. The principal components biplot of dimension 2 versus 1 in Figure 13 shows Experience Level and Analysis, which are highly collinear, loading onto the dimension 1 positive axis and can be considered as representing parallel relationships. The Technology-Interaction relationship loads into the negative-positive second quadrant and suggests that while technological interactions within the organization are critically important, their current state is seen as lacking, particularly in relation to other aspects like autonomy and experience level. Autonomy loads into the negative-negative third quadrant, suggesting that, as currently implemented robot autonomy may be insufficient or problematic in organizational settings, requiring focused efforts to enhance this aspect. Technology Interaction and Autonomy exhibit the most weight with the Analysis/Experience Level relationship slightly less weight. These three relationships are approximately 120 degrees apart suggesting opposing and mildly negative interactions.

**Table 11** Content Analysis Principal Components of Proposition 6

|                        | PC1    | PC2     | PC3     | PC4     |
|------------------------|--------|---------|---------|---------|
| Standard deviation     | 0.1463 | 0.09148 | 0.06734 | 0.05193 |
| Proportion of Variance | 0.5786 | 0.22608 | 0.12250 | 0.07286 |
| Cumulative Proportion  | 0.5786 | 0.80465 | 0.92714 | 1.00000 |

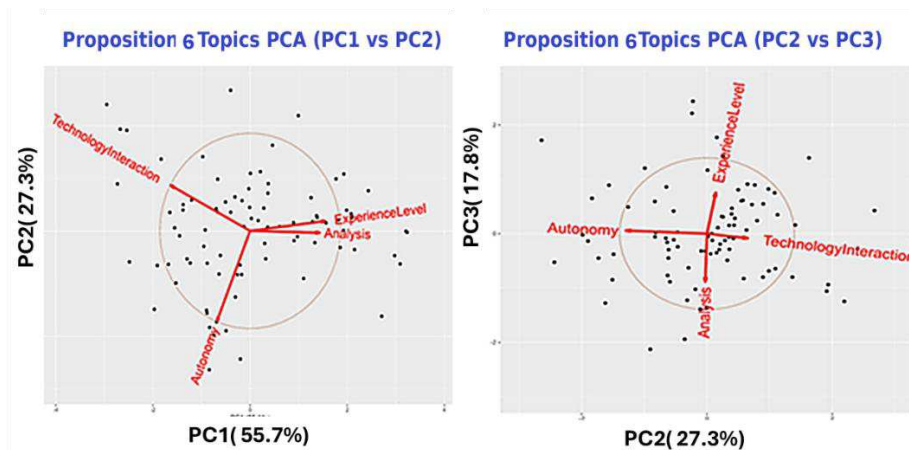


**Fig 13** Content Analysis Principal Components Proposition 6 Biplots – Dim 2 v1 and Dim 3 v 2.

Extending the relationships analysis to dimensions 2 and 3 explains 92.7% of the information variation, however no additional knowledge is gained regarding the axiomatic proposition relationships. As can be observed in the dimension 3 versus 2 biplot in Figure 13, the relationships are essentially orthogonal, with Technology Interaction opposing Autonomy and Experience Level opposing Analysis. Autonomy carries the largest weight, with the other three relationships carrying much less weight. The complex design tradeoff information is in a dimension 2 versus 1 biplot. In the dimension 3 versus 2 biplot, the relationships can be designed independently, given the opposing relationships.

### Content Analysis Principal Components for Proposition 7

Content analysis, evidential coding of proposition 7 (human x organization interaction) literature corpus yielded axiomatic relations: Development, Impact, Interaction, and Specification. Content analysis principal components of proposition 7 literature corpus dimensions in Table 12 indicated that the first three dimensions explain 95.7% of the information variation. in the identified manifest relationship dimensions. The principal components biplot of dimension 2 versus 1 in Figure 14 shows that relationship development loads into the positive-positive first quadrant and opposes Specification, which loads into the negative-negative third quadrant. Relationship Impact loads into the negative-positive second quadrant and opposes Interaction, which loads into the positive-negative fourth quadrant. Development-Specification is essentially orthogonal to Impact-Interaction. This suggests that there is an emphasis on development efforts that enhance knowledge transfer, particularly concerning service robots' design limitations and workload expectations. However, development work might be hindered by

inadequate specifications. For effective knowledge transfer to occur, it is crucial that specifications are refined to support ongoing development efforts, ensuring that healthcare staff can fully understand and manage service robots' design limitations. The positive loading of Impact on PC2 indicates that as readiness improves, there is potential for a more significant positive impact, particularly in how well staff and organizations manage and understand the implications of service robots on their workflows. Conversely, the theme "Interaction" loads positively onto PC1 but negatively onto PC2. The positive loading on PC1 indicates that interaction is seen as a critical component of the system's maturity, with improved interaction capabilities being key to better knowledge transfer. However, the negative loading on PC2, and the fact that "Impact" and "Interaction" are nearly 180 degrees apart, suggest that while interaction is essential, it might conflict with the current impact of the system. This opposition indicates a need for careful management of interaction improvements to ensure they align with the desired impact, particularly in terms of understanding and addressing design limitations and workload expectations. Relationships Specification, Impact, and Interaction carry the greatest weights with Development carrying less weight. In principal component dimensions 3 versus 2, Development loads into the positive-positive first quadrant and opposes Interaction, which loads into the negative-negative third quadrant. Relationship Specification loads into the negative-positive second quadrant and opposes Impact, which loads into the positive-negative fourth quadrant. Development-Interaction is orthogonal to Specification-Impact. In dimensions 3 versus 2, Development carries the greatest weight, with Specification and Impact carrying less weight, and Interaction carrying the least weight. This suggests that in preparing healthcare organizations to integrate service robots, primary consideration must be given to developing adequate robot and process specifications to assure positive interactions that produce positive impacts on organizational operations.

**Table 12** Content Analysis Principal Components of Proposition 7

|                        | PC1    | PC2    | PC3    | PC4     |
|------------------------|--------|--------|--------|---------|
| Standard deviation     | 0.1589 | 0.1463 | 0.1197 | 0.05226 |
| Proportion of Variance | 0.3964 | 0.3358 | 0.2249 | 0.04289 |
| Cumulative Proportion  | 0.3964 | 0.7322 | 0.9571 | 1.00000 |

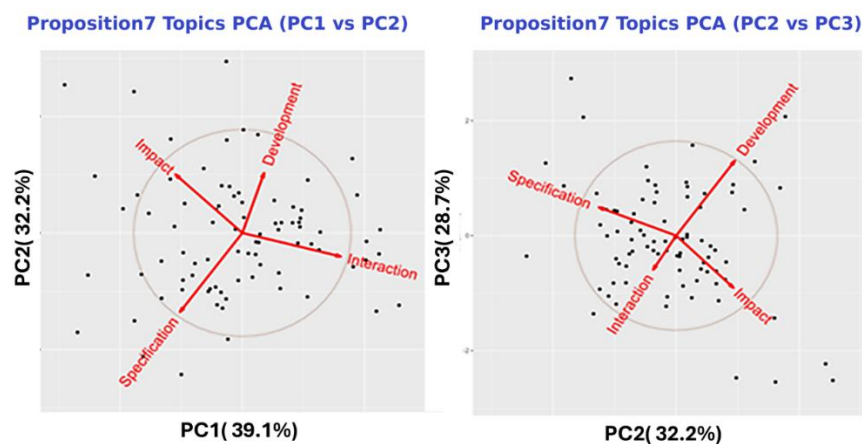


**Fig 14** Content Analysis Principal Components Proposition 7 Biplots – Dim 2 v1 and Dim 3 v 2.

### Content Analysis Principal Components for Proposition 8

Content analysis evidential coding of proposition 8 (technology x human x organization interaction) literature corpus yielded axiomatic relations Acceptance, Economic Analysis, Technology, User, and Work. Content analysis principal components of proposition 8 literature corpus dimensions in Table 13 indicated that the first three dimensions explain 89.4% of the information variation. In the identified manifest relationship dimensions. The principal components biplot of dimension 2 versus 1 in Figure 15 shows that collinear relationships Technology and Work load onto the dimension 1 positive axis and essentially oppose collinear User and Acceptance, which is just above the dimension 1 negative axis in the negative-positive quadrant 2. Economic Analysis loads just off the dimension 2 negative axis in the negative-negative third quadrant. Economic Analysis is essentially orthogonal to Technology-Work and User-Acceptance. Economic Analysis carries the greatest weight, with Technology-Work and User-Acceptance carrying less weight. A similar loading occurs in dimension 3 versus 2. Here, Economic Analysis loads primarily onto the dimension 2 negative axis, whereas User and Technology are collinear, loading into the positive-positive first quadrant, and Work and Acceptance are collinear and load onto the negative dimension 3 axis. Economic Analysis is essentially orthogonal to Work and

Technology, but essentially opposes User and Acceptance. At the healthcare systemic level, this suggests that successful service robot integration is jointly influenced by the perceived financial benefits of economic factors traded off against healthcare work task completion and user acceptance. This suggests that economic and work-related aspects, such as the nature and distribution of human and robotic tasks, play a complex role in readiness and integration. While technological factors are crucial, there may be challenges that need to be addressed to achieve successful integration and high-quality healthcare services. This highlights the importance of optimizing work processes and roles to facilitate successful service robot integration while achieving required economic benefits.

**Table 13** Content Analysis Principal Components of Proposition 8

|                        | PC1    | PC2    | PC3     | PC4     | PC5    |
|------------------------|--------|--------|---------|---------|--------|
| Standard deviation     | 0.1266 | 0.1060 | 0.08874 | 0.05391 | 0.0354 |
| Proportion of Variance | 0.4079 | 0.2858 | 0.20037 | 0.07397 | 0.0319 |
| Cumulative Proportion  | 0.4079 | 0.6938 | 0.89414 | 0.96810 | 1.0000 |

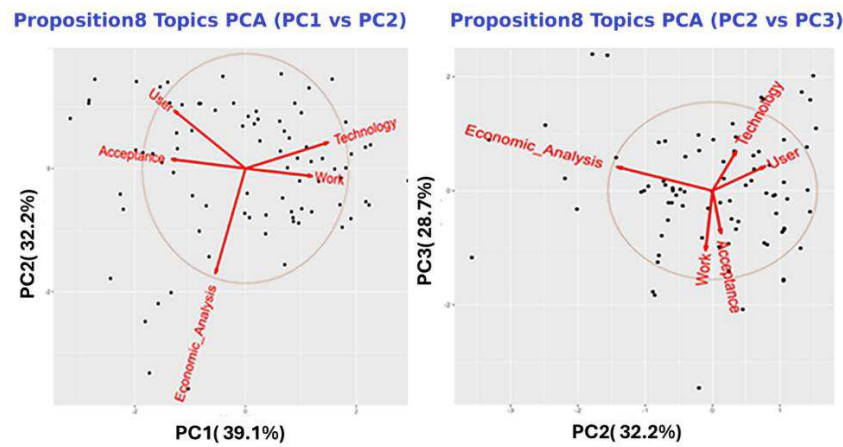


**Fig 15** Content Analysis Principal Components Proposition 8 Biplots – Dim 2 v1 and Dim 3 v 2.

#### Systemic Design of Proposition 5 Through 8 Service Robot Integration Axiomatic Relations

As illustrated in the content analysis of propositions 5 through 8, preparation of service robot technology, humans, and organizational culture to interoperate  $[(^, t, h), (^, t, o), (^, h, o), \text{ and } (^, t, h, o)]$  interactions] must consider multiple axiomatic relationships across at two levels for each interaction. These relationships are set forth in the concept matrix in Table 14 and illustrated in the axiomatic relationships graph in Figure 16. The upper node is the supremum V in Figure 1, and the lower node is the joint connection to the taxonomic dimensions of technology, human, and organization in Figure 1. Figure 16 confirms that the axiomatic relationships are complete and closed under lattice theory, Definitions 20 and 21.

**Table 14** Axiomatic Interactions Relationships Concept Matrix

|                    | EconAnal | Tech-Work | User-Accept | Tech-User | Work-Accept | Development | Impact | Interaction | Specification | Autonomy | ExpAnal | TechInteract | Assessment | Capability | Interact | Practice | PracticeInteract |
|--------------------|----------|-----------|-------------|-----------|-------------|-------------|--------|-------------|---------------|----------|---------|--------------|------------|------------|----------|----------|------------------|
| P8 (txhxo) Dim 1,2 | X        | X         | X           |           |             |             |        |             |               |          |         |              |            |            |          |          |                  |
| P8 (txhxo) Dim 2,3 | X        |           |             | X         | X           |             |        |             |               |          |         |              |            |            |          |          |                  |
| P7 (hxo) Dim 1,2   |          |           |             |           |             | X           | X      | X           | X             |          |         |              |            |            |          |          |                  |
| P7 (hxo) Dim 2,3   |          |           |             |           |             | X           | X      | X           | X             |          |         |              |            |            |          |          |                  |
| P6 (txo) Dim 1,2   |          |           |             |           |             |             |        |             |               | X        | X       | X            |            |            |          |          |                  |
| P5 (txh) Dim 1,2   |          |           |             |           |             |             |        |             |               |          |         |              | X          | X          |          |          | X                |
| P5 (txh) Dim 2,3   |          |           |             |           |             |             |        |             |               |          |         |              | X          | X          | X        | X        |                  |

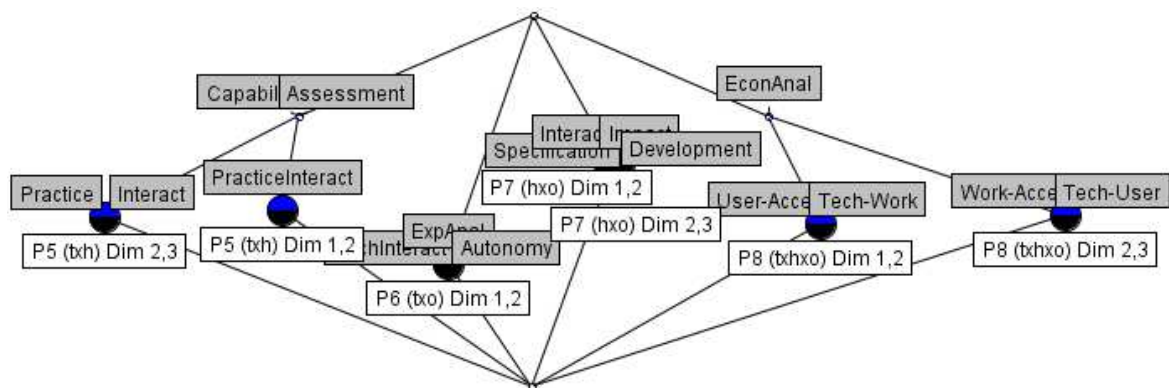


**Fig 16** Content Analysis Axiomatic Relationships Lattice

As illustrated in the content analysis of propositions 1 through 4, the design of healthcare service robot technology, human, and organization taxonomic dimensions'  $[(^{\wedge}, t), (^{\wedge}, o), \text{ and } (^{\wedge}, h)]$  properties must consider multiple hierarchical relationships across two levels for each dimension. These relationships are set forth in the concept matrix in Table 14 and illustrated in the dimension-properties relationships concept graph in Figure 17. The upper node is the joint connections to the interaction relationships in Figure 1, and the lower node is the  $^{\wedge}$  minimal infimum technology-human-organization (t, h, o) concept in Figure 1. Figure 17 confirms that the dimension-property relationships are complete and closed under lattice theory, Definitions 20 and 21. Table 14 and Figure 17 also illustrate that the design of the healthcare service robot technology, human, and organizational dimensions, and subsequent readiness level scales cannot be considered independently. Property Technology creates a concept block congruence across propositions 1 through 3a technology-human dimensions. Property Performance creates a concept block congruence across propositions 1 and 3 technology design for humans, and humans' preparation for technology. Property Interaction creates a concept block congruence across propositions 1 and 2 technology design for humans and for technology.

**Table 15** Taxonomic Dimensions-Properties Relationships Concept Matrix



A recurrent pattern across the literature was the moderating role of perceived benefit; robots that clearly reduced workload or improved patient safety were more favorably received. However, studies consistently flagged concerns over loss of human touch, especially in direct patient interaction roles, reinforcing the importance of designing robots that enhance rather than replace interpersonal care.

## 5.6 Healthcare Service Robots Organizational Readiness Themes

Thematic analysis of Proposition 4 (organization) identified emergent themes of evaluation, challenges, organizational culture, and adoption. The principal finding is that organizational readiness improves with evaluation, addressing challenges, and fostering an innovative culture. The key design interpretation is that there is a strong association between an organization's readiness for innovation and its ability to address challenges related to robot integration. Organizations that prioritize evaluation and continuous improvement are more likely to successfully adopt and benefit from service robots.

Content analysis mapped institutional readiness onto themes such as leadership support, change readiness, workflow alignment, and ethics/governance structures, providing strong support for Proposition 4. Institutions that adopted a top-down strategy for digital transformation demonstrated greater preparedness for robot integration.

In contrast, resistance was evident in organizations lacking standardized digital processes or those with rigid hierarchical decision-making. Articles discussing successful implementation often cite interdepartmental collaboration, flexible budgeting, and early stakeholder involvement as enablers of readiness.

## 5.7 Healthcare Service Robots Axiomatic Relationships Insights

Thematic analysis identified several characteristics of the axiomatic interaction relationship dimensions ( $\perp$ , t, h), ( $\perp$ , t, o), ( $\perp$ , h, o), and ( $\perp$ , t, h, o). Proposition 5 (technical x human interaction) emergent axiomatic themes include technology (as a verb describing what technology does), maturity, staff awareness, and integration. The principal finding is that successful robotic implementation correlates with higher technology maturity and staff technical awareness. The key design interpretation is that mature technologies with well-understood functionalities are more easily integrated into clinical settings.

Proposition 6 (technology x organization interaction) emergent axiomatic themes include technological maturity, cultural readiness, and service quality. The principal finding is that higher service quality is linked to higher technological maturity and cultural readiness. The key design interpretation is that service quality improves when both the technology is mature, and the organizational culture is ready to embrace innovation.

Proposition 7 (human x organization interaction) emergent axiomatic themes include staff readiness, organizational readiness, and knowledge transfer. The principal finding is that staff and organizational readiness enhance knowledge transfer regarding service robot integration. The key design interpretation is that organizations and staff who are more prepared for robot integration are better at disseminating knowledge and best practices. This facilitates smoother transitions and more effective use of the technology across the organization.

Proposition 8 (technology x human x organization interaction) emergent axiomatic themes include joint readiness, knowledge transfer, and service quality. The principal finding is that joint readiness in staff, technology, and organization improves knowledge transfer, cost-benefit justification, and service quality. The key design interpretation is that there is a synergistic effect when readiness is aligned across all levels. This joint readiness not only enhances knowledge transfer but also ensures that the implementation of service robots delivers measurable improvements in service quality and cost efficiency.

An integrative review of the manifest themes across all three readiness dimensions ( $\perp$ , t), ( $\perp$ , h), and ( $\perp$ , o) suggests that the Formal Concept Analysis technical-human-organization concept lattice of Figure 1 can be translated to the interdependent H.STAR socio-technical concept theoretical framework of Figure 18 [37]. For instance, technological maturity alone did not guarantee successful adoption unless paired with human trust and organizational capacity. This reinforces the framework's central proposition that readiness for service robot integration in healthcare is inherently socio-technical within a given organizational context. The H.STAR conceptual framework is useful both an evaluative and planning tool for healthcare institutions considering robotic integration.

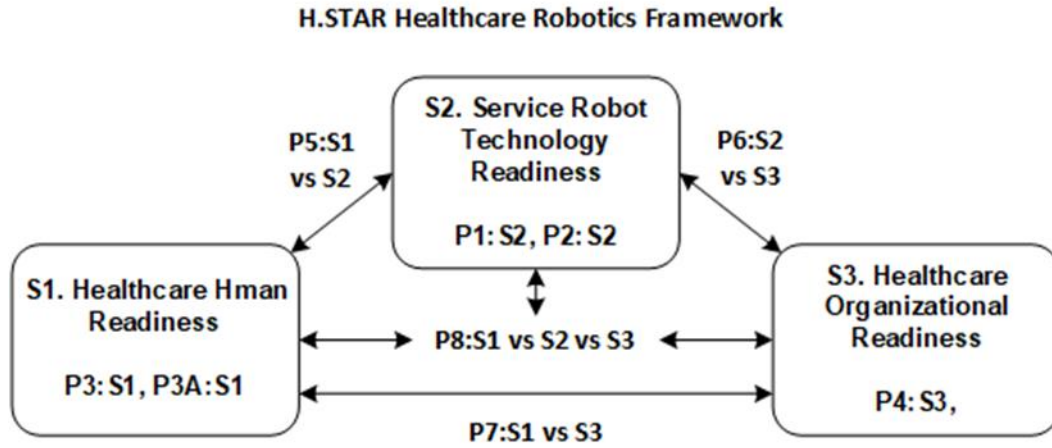


**Fig 18** Socio-Technical Concept Theoretical Framework for Healthcare Service Robots [37]

## 6 Interpretation: The Proposed Healthcare Service Robot Theoretical Framework Architecture

The findings of this study reinforce the significance of adopting a socio-technical perspective when evaluating readiness for service robot integration in healthcare. The H.STAR (Healthcare Socio-Technical Assessment of Readiness) framework not only unifies previously siloed dimensions, technology, human factors, and organizational capacity, but also illustrates how these components interact to influence adoption outcomes. Perceived intelligence and trust significantly influence healthcare robot adoption, and recent studies show that robots capable of estimating and modeling user values alter perceptions of animacy and intelligence in human–robot interaction [38]. The reference framework shows how the HRI can be parsed to independent “Readiness Level” dimensions to reinforce the findings from systematic literature review, text mining, and content analysis [39].

## 6.1 Socio-Technical Interdependence

At its core, the H.STAR architecture emphasizes that readiness for healthcare robotics is not linear or unidimensional. A robot's technical maturity (high TRL) does not ensure successful deployment if healthcare staff lack the training or trust required for operational engagement (low human-robot readiness level), or if organizational processes are not adaptable to accommodate robot-assisted workflows.

This interdependence is especially evident in implementation case studies from the literature. For example, hospitals with high technology capacity still struggled with adoption due to cultural resistance or lack of leadership alignment, affirming the central claim that robotic integration is a function of aligned readiness across all three taxonomic dimensions [40].

## 6.2 Theoretical and Practical Implications

From a theoretical standpoint, the H.STAR framework extends existing models such as Technology Readiness Levels (TRL) by embedding Human Readiness Levels (HRL) and Organizational Readiness Concepts within a unified architecture. This integrated approach allows researchers and practitioners to:

- Diagnose readiness gaps using structured criteria across TRL, HRL, and organizational enablers.
- Predict implementation challenges based on multi-dimensional misalignment (e.g., high technological readiness level but low human readiness level).
- Develop tailored intervention strategies such as change management programs, training protocols, or policy reforms to support robotic deployment.

Practically, the framework supports decision-making in healthcare settings by offering a strategic lens through which robotics integration can be evaluated, not solely based on performance but also on institutional and human readiness to adapt.

## 7 Future Research Toward Development of a Healthcare Service Robot Readiness Instrument

This study presents the H.STAR (Healthcare Socio-Technical Assessment of Readiness) framework as a comprehensive theoretical model for evaluating the integration of service robots in healthcare environments. Grounded in socio-technical systems, the framework synthesizes insights from technology maturity, human readiness, and organizational preparedness to offer a multi-dimensional view of adoption feasibility.

By combining systematic literature review thematic analysis, computational text mining, content analysis within Formal Concept Analysis lattice theory, the research contributes a validated and extensible architecture that reflects the complex inter dependencies between robotics design and healthcare delivery systems. The findings emphasize that technological advancement alone is insufficient for successful implementation. alignment across human and institutional dimensions is equally critical.

The propositions developed within the framework provide a basis for future empirical testing, enabling researchers and practitioners to assess specific readiness dimensions, anticipate barriers, and design targeted interventions. Future research includes (1) translating the H.STAR lattice into a publishable taxonomy for the taxonomic dimensions ( $\perp$ , t), ( $\perp$ , h), and ( $\perp$ , o), (2) integrating the axiomatic interaction relationship dimensions ( $\perp$ , t, h), ( $\perp$ , t, o), ( $\perp$ , h, o), and ( $\perp$ , t, h, o) into a publishable ontology, and (3) applying the ontology to guide testing and development of a H.STAR technology-human-readiness level instrument for healthcare service robots. Beyond readiness instrument development, the H.STAR framework offers a strategic planning tool for healthcare leaders, policymakers, and developers aiming to navigate the ethical, operational, and cultural challenges of robotics adoption. Ultimately, this study advances the field of social robotics by shifting the focus from robot-centric innovation to a more holistic understanding of system-wide readiness supporting responsible, equitable, and effective integration of robotic technologies in healthcare.

## Statements and Declarations

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

## Data Availability Statement

The datasets and related software code used and/or analyzed during the current study are available from the corresponding author upon reasonable request from qualified researchers.

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### **Author Contributions**

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Sujatha Alla, T. Steven Cotter, and Krishnanand Kaipa. The first draft of the manuscript was written by Sujatha Alla, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

### **Ethics Declaration**

Not Applicable.

## References

- [1] Höpfl F, Peisl T, Greiner C. Sustainable Technology and Entrepreneurship.
- [2] Holland J, Kingston L, McCarthy C, Armstrong E, O'dwyer P, Merz F, McConnell M. Service robots in the healthcare sector. *Robotics*. 2021 Mar 11;10(1):47.
- [3] Mettler T, Sprenger M, Winter R. Service robots in hospitals: new perspectives on niche evolution and technology affordances. *European Journal of Information Systems*. 2017 Sep 1;26(5):451-68.
- [4] Riek LD. Healthcare robotics. *Communications of the ACM*. 2017 Oct 24;60(11):68-78.
- [5] Cresswell K, Cunningham-Burley S, Sheikh A. Health care robotics: qualitative exploration of key challenges and future directions. *Journal of medical Internet research*. 2018 Jul 4;20(7):e10410.
- [6] Mankins JC. Technology readiness levels.
- [7] Tapia-Siles SC, Coleman S, Cuschieri A. Current state of micro-robots/devices as substitutes for screening colonoscopy: assessment based on technology readiness levels. *Surgical endoscopy*. 2016 Feb;30(2):404-13.
- [8] Sauser B, Ramirez-Marquez JE, Magnaye R, Tan W. A systems approach to expanding the technology readiness level within defense acquisition. 2009 Mar 20.
- [9] Fiorini SR, Bermejo-Alonso J, Gonçalves P, De Freitas EP, Alarcos AO, Olszewska JI, Prestes E, Schlenoff C, Ragavan SV, Redfield S, Spencer B. A suite of ontologies for robotics and automation [industrial activities]. *IEEE Robotics & Automation Magazine*. 2017 Mar 24;24(1):8-11.
- [10] Umbrico A, Orlandini A, Cesta A. An ontology for human-robot collaboration. *Procedia CIRP*. 2020 Jan 1;93:1097-102.
- [11] Kazanzides P. Safety design for medical robots. In 2009 Annual International Conference of the IEEE Engineering in Medicine and Biology Society 2009 Sep 3 (pp. 7208-7211). IEEE.
- [12] NASA (2017, 08/07/2017). "Technology Readiness Level." Technology Readiness Level. Retrieved 05/01/2020, 2020, from [https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt\\_accordion1.html](https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html).
- [13] Phillips EL. The development and initial evaluation of the human readiness level framework.
- [14] Ge Z, Jiang J, Coombes M, Liang S. Enhancing swift and socially-aware navigation with continuous spatial-temporal routing. *International Journal of Social Robotics*. 2025 Jan;17(1):87-98.
- [15] International Organization for Standardization. (2014). Robots and robotic devices -- Safety requirements for personal care robots (Standard No. ISO 13482:2014). Retrieved from <https://www.iso.org/standard/53820.html>
- [16] Pikkarainen M, Kempainen L, Xu Y, Jansson M, Ahokangas P, Koivumäki T, Hong Gu H, Francis Gomes J. Resource integration capabilities to enable platform complementarity in healthcare service ecosystem co-creation. *Baltic Journal of Management*. 2022 Sep 30;17(5):688-704.
- [17] Garcia A, Ganey N, Wilbert J. Human readiness assessment: A multivariate approach. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting 2017 Sep (Vol. 61, No. 1, pp. 106-109). Sage CA: Los Angeles, CA: SAGE Publications.
- [18] Veloso M, Aisen M, Howard A, Jenkins C, Mutlu B, Scassellati B. WTEC Panel Report on Human-Robot Interaction: Japan, South Korea, and China. World Technology Evaluation Center, Inc., Arlington. 2012.
- [19] Hradecky D, Kennell J, Cai W, Davidson R. Organizational readiness to adopt artificial intelligence in the exhibition sector in Western Europe. *International journal of information management*. 2022 Aug 1;65:102497.

- [20] Schmiedel T, Jäger J, Zhong VJ. Social Robots in Organizational. New Trends in Business Information Systems and Technology: Digital Innovation and Digital Business Transformation. 2020 Jul 7;294:163.
- [21] Robertson MM, Tubbs D, Henning RA, Nobrega S, Calvo A, Murphy LA. Assessment of organizational readiness for participatory occupational safety, health and well-being programs. Work. 2021 Aug 27;69(4):1317-42.
- [22] Sahoo SK, Choudhury BB. Challenges and opportunities for enhanced patient care with mobile robots in healthcare. Journal of Mechatronics and Artificial Intelligence in Engineering. 2023 Dec 31;4(2):83-103.
- [23] Javaid M, Haleem A, Pratap Singh R, Rab S, Suman R, Kumar L. Utilization of robotics for healthcare: a scoping review. Journal of Industrial Integration and Management. 2025 Mar 13;10(01):43-65.
- [24] Andrighetto L, Sacino A, Cocchella F, Rea F, Sciutti A. Cognitive processing of humanoid robot faces: Empirical evidence and factors influencing anthropomorphism. International Journal of Social Robotics. 2025 Jan;17(1):117-31.
- [25] Apraiz A, Lasa G, Mazmela M, Arana-Arexolaleiba N, Serrano Muñoz A, Elguea Í, Etxabe A. Evaluating the Effect of Speed and Acceleration on Human Factors during an Assembly Task in Human–Robot Interaction (HRI). International Journal of Social Robotics. 2025 Feb;17(2):211-56.
- [26] Mahmud F, Cotter TS. Human-intelligence/machine-intelligence decision governance: An analysis from ontological point of view.
- [27] Birkhoff G. Lattice theory. American Mathematical Soc.; 1940 Dec 31.
- [28] Gratzer G. Lattice theory: First concepts and distributive lattices. Courier Corporation; 2009.
- [29] Ganter B, Wille R, Wille R. Formal concept analysis. Berlin: Springer-verlag; 1999.
- [30] Bowen GA. Naturalistic inquiry and the saturation concept: a research note. Qualitative research. 2008 Feb;8(1):137-52.
- [31] Saunders B, Sim J, Kingstone T, Baker S, Waterfield J, Bartlam B, Burroughs H, Jinks C. Saturation in qualitative research: exploring its conceptualization and operationalization. Quality & quantity. 2018 Jul;52(4):1893-907.
- [32] Guest G, Bunce A, Johnson L. How many interviews are enough? An experiment with data saturation and variability. Field methods. 2006 Feb;18(1):59-82.
- [33] Alla S. A statistical analysis of surgeons' preference on robot-assisted surgeries. In IISE Annual Conference. Proceedings 2019 (pp. 1385-1390). Institute of Industrial and Systems Engineers (IISE).
- [34] Thakur A, Kaipa K, Banerjee AG, Cappelleri DJ, Krovi VN, Gupta S. Physical artificial intelligence for powering the next revolution in robotics. Journal of Computing and Information Science in Engineering. 2025 Dec 1;25(12):120809.
- [35] Cotter TS. EMBOK 5.0-Industry 4.0/5.0 Manifest and Latent Dimensions Mapping to the ASEM EMBOK.
- [36] Skubis I. Exploring the potential and perceptions of social robots in tourism and hospitality: Insights from industry executives and technology evaluation. International Journal of Social Robotics. 2025 Jan;17(1):59-72.
- [37] Alla S. *An Integrated Theoretical Socio-Technical Framework for Implementing Service Robots' Integration in Healthcare* (Doctoral dissertation, Old Dominion University).
- [38] Sakamoto Y, Uchida T, Ishiguro H. Effectiveness of conversational robots capable of estimating and modeling user values. International Journal of Social Robotics. 2025 Jun;17(6):1003-17.

- [39] Raggioli L, D'Asaro FA, Rossi S. Deep reinforcement learning for robotic approaching behavior influenced by user activity and disengagement. *International Journal of Social Robotics*. 2025 May;17(5):903-15.
- [40] Alla S, Pazos P. Healthcare robotics: Key factors that impact robot adoption in healthcare.