Review

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Review

Bridging Medical Simulation and Robotics: A Systematic Analysis of Manikin Adaptation for Advanced Applications

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Abstract: Introduction: Medical simulation manikins have evolved to include advanced sensor networks, actuators, and physiological modeling capabilities. However, their potential applications in robotics remain underexplored, and there is a lack of comprehensive analysis of opportunities and implementation challenges. **Methods:** This scoping review examined research from the IEEE Xplore, PubMed, ACM Digital Library, SpringerLink, and Elsevier databases (1969-2024). Out of 156 initial studies, 64 met the inclusion criteria, focusing on adapting medical manikins for robotics. The analysis investigated hardware modifications, software integrations, and hybrid implementation strategies. **Results:** Analysis revealed three main development paths: hardware adaptation evolving from basic sensor integration to intricate musculoskeletal frameworks (15 studies); software integration progressing from rule-based responses to biomimetic control architectures (22 studies); and hybrid approaches that combine physical manikins with mixed reality interfaces (18 studies). Nine additional studies investigated convergent applications in humanoid robotics and dynamic tactile systems. **Discussion:** Findings indicate significant potential for cross-disciplinary innovation in biomimetic control systems and human-robot interaction. Major challenges include achieving seamless hardware-software integration while upholding anatomical accuracy. Future development should emphasize standardized integration frameworks and modular architectures supporting simulation and robotics applications. **Conclusion:** Repurposing medical manikins for robotics presents transformative potential for human-robot interaction and biomedical engineering. Achieving success requires tackling integration challenges through interdisciplinary collaboration and standardized frameworks.

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Introduction

Integrating robotics into medical, industrial, and research applications has created unprecedented opportunities for innovation in human-like systems. Medical simulation manikins, featuring anatomically accurate structures and embedded sensor systems, represent a promising yet underutilized platform for robotics development [1–3]. Adapting these manikins requires significant modifications across hardware components (actuators, sensors, materials), software systems (control architectures, physiological modeling), and system interoperability frameworks (robotic integration, biofeedback systems) [4–6].

Background and Motivation

Medical simulation technology has seen transformative development since the introduction of Sim One in 1969, the first computer-controlled patient simulator capable of breathing, blinking, and

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responding to administered drugs [7]. Modern manikins integrate sophisticated musculoskeletal models, real-time physiological simulations, and embedded feedback systems that enhance the effectiveness of medical training [8–10]. Recent advances in sensorized tissues, soft robotics, and real-time control systems have further expanded their capabilities and potential applications [5,11].

Parallel developments in humanoid robotics, biomimetic engineering, and human-robot interaction (HRI) research have made significant progress in replicating human-like motion, sensory perception, and interactive capabilities [3,12,13]. Innovations in musculoskeletal robotics [6], biomimetic control systems [14,15], and mixed reality interfaces [4,5] establish a strong foundation for integrating robotic functionalities into medical manikins. However, limited interdisciplinary collaboration between the medical simulation and robotics communities has resulted in significant knowledge gaps in effectively leveraging these technologies [16,17].

Research Gap and Rationale

Despite the structural and functional similarities between medical manikins and humanoid robotic platforms, there is no standardized framework for their adaptation [6,17]. Hardware adaptation requires improved actuation mechanisms and sensor integration while maintaining material durability for extended robotic operations [1,2,18]. Software integration must navigate proprietary control architectures to enable autonomous and interactive functionalities [14,15]. Additionally, human-robot interaction applications must utilize anatomical fidelity while supporting realistic robotic interactions across healthcare, rehabilitation, and teleoperation scenarios [19–21].

Current research efforts remain fragmented, with isolated advances in modular hardware design [1,2], robotic sensorimotor control [3,12], and real-time physiological simulation [15]. Bridging these gaps could enable innovative applications in human-robot collaboration, telemedicine, and emergency response systems [19–21]. The absence of comprehensive integration frameworks limits the potential to leverage the sophisticated features of medical manikins in robotics applications [16,17].

Objectives and Research Questions

This scoping review evaluates the current state of research on repurposing medical simulation manikins for robotic applications by synthesizing findings across three key domains: hardware adaptation, software integration, and hybrid approaches [1–4,12]. The review addresses four primary research areas:

First, hardware adaptation requirements involve necessary modifications to actuators, sensors, and materials [1,2,6], as well as assessing how structural and material properties affect suitability for repeated robotic tasks [5,18,22]. Second, software integration challenges center on existing system limitations and compatibility with autonomous control frameworks [6,14,15], which include adapting real-time physiological models and biofeedback mechanisms for robotics applications [15].

Third, the review examines potential applications ranging from human-robot interaction platforms to autonomous medical robots [21]. It also includes strategies for modularizing manikins to test specific robotic subsystems [4,5]. Finally, it discusses current barriers to collaboration between the medical simulation and robotics fields [16,17], identifying opportunities to leverage anatomical fidelity and embedded physiological simulations for broader robotics research [3,12,13].

This review systematically analyzes the intersection of medical simulation and robotics technologies to establish a foundation for future research and development. The findings will guide efforts to create standardized integration frameworks and promote cross-disciplinary innovation in this emerging field.

Methods

This scoping review employs a systematic approach to identifying, selecting, and synthesizing research on adapting medical simulation manikins for robotics applications. The methodology

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adheres to established scoping review protocols [23] and implements a five-stage process that includes study identification, selection, data extraction, synthesis, and reporting.

Search Strategy and Information Sources

The review conducted thorough searches across five major academic databases chosen to encompass a wide range of relevant research: IEEE Xplore for literature on robotics and engineering, PubMed for biomedical and medical simulation studies, ACM Digital Library for contributions in computer science and software engineering, SpringerLink for interdisciplinary studies in medical technology, and Elsevier (ScienceDirect) for broader research in engineering and robotics. The search period spanned from January 1969 to December 2024, covering the development of the first computer-controlled medical manikin [7] to recent advancements in robotics integration. The primary search string combined key concepts using Boolean logic operators: ("medical manikin" OR "simulation manikin") AND ("robot" OR "robotics") AND ("adaptation" OR "repurposing"). Additional targeted searches incorporated terms including "soft robotics," "biomimetic robotics," "human-robot interaction," and "physiological modeling" to ensure comprehensive coverage [3,12].

Selection Process

The study selection employed a structured three-stage approach. Initial screening identified 156 potentially relevant studies. Two independent reviewers evaluated these studies against predefined eligibility criteria, with a third reviewer addressing any disagreements. The full-text review phase yielded 64 studies that met all inclusion criteria requirements. Studies were classified into three categories:

- Direct relevance: Studies explicitly addressing medical manikin adaptation for robotics
- Partial relevance: Research focusing on either medical simulation manikins or robotics adaptation independently
- Contextual relevance: Studies providing broader insights into medical simulation or robotics methodologies

Data Extraction and Analysis

A standardized data extraction template captured crucial information from each study, including publication details, methodology, hardware modifications, software integration methods, and application domains. Two reviewers independently conducted data extraction and carried out regular reliability checks to ensure their accuracy consistency. The analysis framework organized findings into four primary themes:

- Hardware adaptation strategies for robotic implementation
- Software integration approaches and control architectures
- Application domains and emerging use cases
- Cross-disciplinary challenges and opportunities

Quality Assessment

Each study was evaluated for methodological rigor, practical implementation value, and relevance to the research objectives. Studies demonstrating successful real-world implementation [1,2,4,5] received priority in the analysis, while theoretical contributions helped identify emerging trends [2,5,7].

Limitations

The review acknowledges several methodological limitations. Industry-driven developments may be underrepresented in published literature. Many studies focus on conceptual frameworks instead of validated implementations, complicating the assessment of practical feasibility [3,12].

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Additionally, the historical disconnect between the medical simulation and robotics communities may have resulted in gaps in integrated approaches [16,17]. Despite these limitations, this comprehensive methodological approach establishes a solid foundation for analyzing medical manikin adaptation's current state and future directions for robotics applications.

Results

The analysis of 64 studies published between 1969 and 2024 revealed significant advancements in adapting medical simulation manikins for robotics applications. The findings demonstrate progress in hardware adaptation, software integration, and hybrid approaches.

Hardware Adaptation Trajectory

Hardware modifications for medical manikins have evolved through three distinct phases. From 1969 to 2000, research primarily focused on basic sensor integration, with twelve studies documenting the implementation of force feedback sensors for medical training applications [1,2,7]. These early adaptations emphasized passive monitoring systems rather than active robotics functionality.

The period from 2000 to 2015 marked a transition toward advanced mechanical modifications. Eighteen studies explored the integration of joint actuation systems, musculoskeletal frameworks, and comprehensive sensor arrays [5,6]. This phase introduced modular joint designs that enhanced motion control and force distribution capabilities, establishing foundational elements for robotic actuation in anatomically accurate structures [18,22].

Recent developments from 2015 to 2024 have highlighted material innovation and advanced robotic integration. Fifteen studies have contributed to implementing dynamic tactile synthetic tissues, hybrid musculoskeletal systems, and bio-inspired actuation technologies [5,22]. These innovations have improved haptic feedback capabilities and durability for robotic applications, although integration challenges remain concerning standardization and compatibility with existing robotic frameworks [16,17].

Software Integration Advances

Twenty-two studies demonstrated the progression in software development from basic automation to sophisticated biomimetic control systems. Early implementations relied on predefined response patterns, with eight studies using rule-based decision trees for automated physiological responses [1,2]. These systems offered limited adaptability and remained confined to structured training scenarios. Seven studies advanced the field by developing real-time physiological models and biofeedback-driven control architectures [4,5,15]. These systems enabled dynamic adaptation to sensor inputs, particularly in cardiovascular and respiratory simulations. However, integration with robotic autonomy frameworks has remained limited [47,49].

Recent research has focused on biomimetic control systems, with seven studies implementing machine learning approaches and cerebellum-inspired control architectures [14]. While these advances show potential for improved robotic motion control, integrating them with standard robotics frameworks remains a significant challenge, as only four studies have investigated direct implementation with the Robot Operating System (ROS) [17,47].

Hybrid Approaches and Emerging Applications

Eighteen studies explored hybrid solutions that combine physical manikins with digital interfaces and robotic systems. These approaches have shown promise in mixed reality-enhanced training simulations and teleoperation applications [4,5]. Integrating haptic feedback mechanisms has improved precision in robot-assisted procedures, while teleoperation capabilities have broadened potential applications for remote medical intervention [16,17]. Seven studies specifically targeted teleoperation systems, integrating robotic manipulators with sensorized manikins [4,16,17].

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Although these implementations show promise for remote medical procedures, technical challenges remain regarding latency reduction and force feedback accuracy [14,50].

Synthesis of Findings

The analysis reveals three primary trends in manikin adaptation for robotics. Hardware development has advanced from simple sensor integration to complex musculoskeletal frameworks, though material durability and standardization challenges persist [1,2,5,6]. Software integration has progressed toward biomimetic control systems, providing opportunities to expand real-time adaptation capabilities [14,15]. Hybrid approaches have shown significant potential, particularly in mixed reality and teleoperation applications while emphasizing the need for improved interdisciplinary collaboration [11,20,50]. These findings highlight the significance of creating standardized integration frameworks to close the gap between medical simulation technologies and robotics research. Future development should focus on modular architectures supporting simulation and robotic applications while ensuring anatomical accuracy and functional reliability [2,31,47].

Discussion

The findings from this scoping review demonstrate significant progress in adapting medical simulation manikins for robotics applications while highlighting critical areas for future development. This section examines key implications across technical domains and identifies strategic priorities for advancing the field.

Evolution of Hardware Integration

Hardware adaptation has advanced significantly from basic sensor integration to complex biomimetic systems. Recent progress in musculoskeletal frameworks and dynamic tactile materials has improved the potential for realistic human-robot interaction [5,22]. These advancements align with broader trends in soft robotics and bio-inspired design, indicating promising pathways for further development [5,7].

Material science innovations have enhanced haptic feedback and durability, which is particularly important for surgical training and rehabilitation applications [20,21]. However, considerable challenges remain in developing materials that preserve anatomical fidelity while enduring repeated robotic actuation. Future research should focus on hybrid materials that integrate realistic tissue properties with mechanical resilience [8,31].

Software and Control Systems Advancement

The evolution of control systems from static responses to adaptive architectures represents a fundamental shift in capability. Recent implementations of biomimetic control models, especially those incorporating machine learning and physiological simulation, demonstrate the potential for enhanced autonomous operation [14,15]. These advances enable more sophisticated human-robot interaction scenarios, although integration challenges with standard robotics frameworks remain significant. Software interoperability poses a persistent challenge, with limited success in implementing industry-standard platforms like ROS. Developing standardized interfaces between medical simulation systems and robotics frameworks should be prioritized, facilitating broader adoption and innovation [31,47].

Impact of Hybrid Approaches

The emergence of hybrid solutions that combine physical manikins with digital interfaces has created new possibilities for medical training and robotic intervention. Mixed reality integration has enhanced training effectiveness, while teleoperation capabilities have expanded potential applications in remote healthcare [4,5]. These developments align with broader trends in healthcare digitalization and remote service delivery.

Technical challenges in latency reduction and force feedback precision require continued attention [21]. Addressing these limitations could enable the more widespread adoption of manikin-based robotic systems in clinical and educational settings [19,20].

Future Research Priorities

Based on the analysis, several key research priorities emerge for advancing the field. The development of standardized integration frameworks should focus on modular architectures that support both simulation and robotic applications [6,15]. Research in biofeedback-driven control systems should emphasize real-time adaptation and learning capabilities [14]. Material science research should prioritize durability while maintaining anatomical fidelity [5,22]. Integration with existing robotics ecosystems requires careful attention to compatibility with established platforms and development tools [6,17]. Additionally, research should consider ethical implications regarding hyper-realistic robotic systems, including effects on patient trust and privacy [16,21].

Practical Implementation Considerations

Successful implementation requires careful attention to maintaining anatomical accuracy while incorporating robotic functionality [6,14]. As demonstrated in early studies [1,2], a modular development approach offers the most promising path toward scalable integration. Future development efforts should emphasize collaboration among robotics engineers, medical educators, and human factors researchers [3,12,17]. This interdisciplinary approach will be crucial for creating standardized frameworks that enhance both medical training and robotic applications.

Synthesis and Future Outlook

Adapting medical simulation manikins for robotics applications presents a significant opportunity for human-robot interaction and medical technology innovation. Success demands addressing technical challenges through coordinated, cross-disciplinary research efforts. Developing standardized frameworks and modular architectures will be crucial for unlocking the full potential of this emerging field. The findings suggest that future success depends on balancing technological innovation with practical implementation considerations. The field can advance toward more sophisticated and widely applicable robotic systems based on medical simulation platforms by addressing current limitations and focusing on end-user needs.

Conclusion

This scoping review demonstrates the significant potential of repurposing medical simulation manikins for robotics applications. By analyzing 64 studies from 1969 to 2024, clear trajectories emerge in hardware adaptation, software integration, and hybrid approaches that combine physical and digital elements.

Hardware development has evolved from simple sensor integration to advanced musculoskeletal frameworks, including dynamic tactile materials and bio-inspired actuation systems [1,2,6,18]. Software advancements have progressed from fixed pre-programmed responses to adaptive control architectures utilizing machine learning and physiological modeling [14,15]. Hybrid approaches integrating mixed reality and teleoperation capabilities have broadened potential applications in medical training and remote healthcare delivery [4,5,21].

Despite these advances, several critical challenges remain. Integrating medical manikin systems with standard robotics frameworks requires further development [6,17]. Innovations in material science must balance anatomical fidelity with mechanical durability [5,22]. Additionally, the field needs standardized protocols for implementing autonomous control systems while ensuring reliable operation [16,17].

Future research should focus on developing modular architectures that support both simulation and robotic applications. Emphasis must be placed on enhancing biofeedback-driven control models,

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improving material resilience, and establishing standardized integration frameworks. Success in these areas will require ongoing collaboration among robotics engineers, medical educators, and human factors researchers [3,12,17].

The findings indicate that successfully adapting medical manikins for robotic applications could transform human-robot interaction and biomedical engineering approaches. By addressing current technical challenges through coordinated interdisciplinary efforts, the field can advance toward more sophisticated and widely applicable robotic systems that leverage the unique advantages of medical simulation platforms.

The convergence of medical simulation and robotics technologies presents unprecedented opportunities for innovation in healthcare delivery, medical education, and human-robot interaction. To realize this potential, continued investment in research and development is essential, particularly in maintaining anatomical accuracy while expanding robotic capabilities. By carefully addressing integration challenges and fostering cross-disciplinary collaboration, the field can progress toward standardized frameworks that enhance both medical training and robotic applications.

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