

Review Article

Thermal Management Optimization for Robotic Surgical Systems in Clinical Applications in Mongolia

Chao Liu¹ , Hongxing Hai^{1,*,†} , Batbold Baasanjav^{1,†} , Baasanjav Nachin^{1,2} 

¹Department of General Surgery, Ach Medical University, Ulaanbaatar, Mongolia

²Department of General Surgery, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia

Abstract

In the clinical application of robotic surgical systems, optimizing thermal management is crucial for improving surgical efficiency and ensuring system reliability. The rapid development of flexible robotics has introduced enhanced flexibility and adaptability in surgical procedures, opening new clinical possibilities while simultaneously imposing more stringent thermal management requirements. Furthermore, thermal management in implantable medical devices has become increasingly critical, demanding advanced optimization strategies to guarantee both safety and operational stability. This study conducted a systematic review and analysis of research indexed in major databases, including Web of Science (WoS), Scopus, and CNKI. The investigation focused on three key areas: (1) thermal management optimization in robotic surgical systems, (2) the design and clinical applications of flexible robotic technologies, and (3) thermal management strategies for implantable devices. By synthesizing findings from these domains, the study aimed to identify effective approaches to enhance thermal performance in surgical robotics. Thermal Management: Increasing heat dissipation surface area and optimizing thermal conduction pathways—such as using copper or aluminum materials under cryogenic conditions—significantly improved cooling efficiency. However, while iron/nickel-based alloys and ceramics demonstrated superior thermal stability in high-temperature environments, challenges related to corrosion resistance and long-term durability remained unresolved. Flexible Robotics: Magnetic actuation and smart material-based actuators enhanced reconfigurability, enabling more adaptable surgical interventions. Additionally, probability model-based online learning algorithms facilitated control optimization independent of specific robotic designs. Thermal Performance: Finite-state machine control combined with proportional-integral (PI) strategies effectively minimized temperature gradients to below 0.5°C. Liquid cooling systems proved highly efficient in battery thermal management, though integration complexities and control challenges persisted. The integration of multidisciplinary approaches—spanning materials science, thermodynamic modeling, and intelligent control—has significantly advanced thermal management in robotic surgical systems. Flexible robotics technologies offer safer and more precise surgical solutions, while thermal management strategies for implantable devices can be rigorously validated through computational simulations and experimental studies. Future research should explore novel nanomaterials, dynamic thermal management algorithms, and cross-disciplinary collaborations to further optimize the performance and reliability of robotic surgical systems. These advancements will be pivotal in meeting the growing demands of next-generation surgical robotics and implantable medical technologies.

*Corresponding author: ulaanod@ach.edu.mn (Hongxing Hai)

† Hongxing Hai and Batbold Baasanjav are co-first authors

Received: 26 November 2025; **Accepted:** 31 December 2025; **Published:** 23 January 2026



Copyright: © The Author(s), 2026. Published by Science Publishing Group. This is an **Open Access** article, distributed under the terms of the Creative Commons Attribution 4.0 License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution and reproduction in any medium, provided the original work is properly cited.

Keywords

Mongolia, Robotic Surgical System, Thermal Management Optimization, Heat Dissipation System, Clinical Value, Intelligent Robot

1. Introduction

In clinical applications of robotic surgical systems, research on thermal management optimization has become pivotal for enhancing surgical efficiency and system reliability. The following presents a review of relevant studies. First, research on integrated thermal management models has provided a theoretical foundation for heat dissipation optimization in robotic surgical systems. For instance, a 2019 study proposed a vehicle-level integrated thermal management system for helicopters, analyzing the structural characteristics, operational principles, and energy/mass flow relationships of rotor subsystems, engine subsystems, fuel subsystems, oil subsystems, and environmental control subsystems. This model exhibits strong scalability, enabling optimization at the vehicle level rather than merely at the subsystem level [1]. Regarding heat transfer enhancement technologies, a separate study reviewed techniques for improving thermal performance in latent heat thermal energy storage systems, investigating combinations of different technologies to enhance efficiency while providing recommendations for current system designs and future research directions [2]. For specific equipment optimization, such as solar collector arrays, Yuan et al. (2019) introduced a design methodology and algorithm tailored to given installation sites and spatial constraints, laying the groundwork for software-based solar collector array design [3]. In research on magnetron cooling technology, Chen and Wang demonstrated through theoretical analysis and simulations that increasing the heat dissipation surface area and elevating the Reynolds number of the cooling system significantly improves thermal performance [4]. Finally, thermal performance enhancement techniques for solar air heating systems have also been extensively studied. Chamarthi and Singh (2021) comprehensively reviewed experimental investigation procedures and thermal enhancement technologies, including static and dynamic testing standards, thermodynamic parameters, thermofluidic and enthalpy efficiency metrics, as well as heat transfer surface augmentation methods such as fins, baffles, and ribs [5-9]. By extension, research on thermal management optimization in robotic surgical systems spans multiple domains-from integrated thermal modeling to device-specific optimization and heat transfer enhancement techniques-providing critical insights for improving clinical application efficiency.

2. Research Methodology

This study conducts a comprehensive summary and analysis of research indexed in databases such as Web of Science (WOS), Scopus, and CNKI, focusing on thermal management optimization in robotic surgical systems, the design and clinical applications of flexible robots, and thermal management strategies for implantable devices.

3. Results

3.1. Advances in Flexible Robotics Technology

The design and control of flexible robots are critical aspects in the field of soft robotics [10]. In terms of design, flexible robots typically employ soft materials and compliant components to achieve shape adaptability in complex environments and enable safer interactions with humans [11]. Some researchers highlight magnetic control as a promising approach due to its ability to enhance the reconfigurability and untethered manipulation of soft robots [12]. This study summarizes novel fabrication techniques for magnetic soft robots, including chemical and physical methods, and provides a detailed discussion on reconfigurability and deformation mechanisms. In modeling and control, flexible robots face multiple challenges in control strategies. Some scholars have reviewed recent advances in soft robotic manipulators, covering device architectures, actuation, stiffness modulation, and sensing technologies [13]. Actuation techniques are broadly categorized into three types: tendon-driven actuation, fluidic actuation, and stimulus-responsive actuation based on smart materials. Stiffness modulation strategies are divided into two approaches: leveraging interactions between structural elements and direct material stiffness adjustment. Additionally, sensing technologies are functionally classified into proprioceptive and exteroceptive sensing. Design optimization plays a crucial role in improving the performance of flexible robots. Some studies emphasize next-generation soft robot designs that prioritize adaptability, compliance, and reliability [14, 15]. These optimization efforts focus on enhancing soft robots' ability to adapt and perform tasks across diverse application scenarios. In control strategies, one study proposes a probabilistic model-based online learning optimal control algorithm for soft pneumatic actuators [16]. This method derives optimal control policies by learning the mapping between the actuator's state and its subsequent state transitions. A key advantage of this algorithm is its inde-

pendence from specific structural designs, offering a promising design-agnostic control approach for the soft robotics community. The design and control of flexible robots encompass multiple aspects, including material selection, structural design, stiffness modulation, sensing, and functional control. With continuous technological advancements, flexible robots are increasingly being applied across various domains, making design optimization and control strategy research a growing focus in the field.

3.2. Clinical Value of Soft Robots

The emergence of flexible surgical robotic systems is attributed to the trend toward minimizing trauma during surgery and recent advancements in robotic technology. These soft robots can navigate through narrow and tortuous pathways to reach surgical sites, extending the reach of robotic surgery and potentially reducing incision sizes. Some scholars have reviewed key technical issues related to flexible surgical robots and introduced emerging flexible surgical robotic systems organized according to their target applications in the field of intracavitary surgery [6]. These systems not only demonstrate their technical features but also exhibit significant clinical value. The clinical applications of soft robots, particularly in rehabilitation and assisted therapy, show great potential. Research indicates that flexible electronic interfaces and soft robotic technologies have garnered considerable attention in the medical robotics field due to their high biocompatibility, functionality, adaptability, and low cost [17]. The application of flexible human-machine interfaces in soft robots may serve as alternatives to traditional rigid devices, potentially transforming the paradigms of medical robotics in rehabilitation feedback and user experience, as well as shaping future development directions. Additionally, advancements in wearable robotic technology offer possibilities for functional substitution, rehabilitation, assistance, and strength augmentation for patients with motor impairments. Despite recent scientific and technological achievements, further research is still required to develop intuitive, easy-to-wear, safe, and effective wearable robots. Some scholars have outlined the progress and challenges in the field of wearable robotics [18]. Medical robotics stands at the forefront of transformation, impacting various aspects of medicine—from surgical interventions to targeted therapy, rehabilitation, and hospital automation. Some researchers have analyzed the evolutionary development of interventional robotics and discussed how the integration of imaging, sensing, and robotic technologies influences patient care pathways, steering them toward precise interventions and patient-specific treatments [11]. This tightly integrated perception, decision-making, and action can enhance dexterity, improve precision, and reduce invasiveness. The clinical value of soft robots is reflected not only in their technical features but also in their ability to provide patients with more personalized and precise treatments. As technology continues to advance, soft robots are expected to play an

increasingly vital role in the medical field.

3.3. Training and Use of Flexible Robots

An analysis of the usability of flexible robots in training and application indicates that their design aims to enhance the flexibility and precision of surgical operations. In head and neck surgeries, flexible robots demonstrate unique advantages, particularly in adapting to complex anatomical structures and providing flexibility in surgical pathways [19]. During training, operators of flexible robots need to master the fundamental principles and operational techniques of the robotic system. According to scholarly research, the widespread application of surgical robots in the field of neurosurgery, including procedures such as deep brain lesioning or electrical stimulation, highlights their value in precise and minimally invasive surgeries [20]. During training, operators must gradually familiarize themselves with the robot's motion control and path planning through simulators and hands-on practice. Additionally, scholars have noted in their research that the growing interest in soft robotics technology is attributed to the potential of soft materials in creating highly adaptable robots, whose flexibility far surpasses that of rigid-component devices [7]. Therefore, during training, operators must also learn how to leverage these characteristics of flexible robots to achieve better surgical outcomes [21]. In clinical settings, the use of flexible robots requires consideration of their integration with existing surgical workflows. Some scholars have pointed out that while the feasibility of robotic surgery in pediatric head and neck procedures has been validated, its adoption remains limited [22]. Through advanced preoperative surgical planning and the design of new robotic platforms, robotic surgery may be better incorporated into practice. This means that during application, surgeons need to combine advanced computer-assisted surgical planning technologies, such as 3D printing and virtual reality, to optimize surgical pathways. The application of flexible robots in head and neck surgeries, particularly in complex procedures, has been highlighted by many scholars as transformative for neurosurgical practices [23-26]. Robots are not only capable of performing linear trajectory guidance similar to stereotactic frames but can also serve as surgical assistants in endoscopic procedures, providing functions such as camera holding and illumination. Furthermore, robots can perform remote surgical operations with enhanced precision, which is crucial for improving surgical efficiency and safety.

3.4. Skill Retention in Soft Robots

Skill retention in soft robots within clinical settings is a critical factor, determining whether the robot can maintain its operational skills after training. During the training process, soft robots gradually acquire the ability to perform complex surgical tasks by simulating and learning the movements of human surgeons. However, skill retention involves not only

the robot's memory and learning capabilities but also its ability to recover skills after prolonged periods of disuse. According to scholarly research, soft robotics technology has made significant advancements over the past two decades, with its high flexibility and adaptability granting soft robots broad application prospects in minimally invasive surgery. The ability of soft robots to conform to environmental changes has generated considerable interest in the field of surgical robotics research [17]. This compliance is crucial for maintaining the robot's surgical skills, as it allows the robot to preserve operational precision and flexibility across different surgical environments. One study introduced a real-time dynamic model capable of simplifying computational requirements and improving algorithm speed, which is particularly important for continuum robots with multiple joint segments [27]. The development of such models helps enhance the robot's operational performance, enabling it to recover its skills more quickly after extended periods of inactivity. Research in the field of soft robotics has highlighted that the application scope of soft robots is continuously expanding, enabling them to perform various tasks in unstructured environments. This flexibility and adaptability are equally important for skill retention in clinical settings, as they allow the robot to adjust to potential variations during surgical procedures [28]. Additionally, scholars have discussed the importance of determining optimal soft tissue preservation techniques, which are crucial for surgical skill training [29]. The application of these techniques not only enhances the realism of training but also maximizes the utility of each donor. This principle similarly applies to robots, as they need to simulate real surgical conditions to maintain their skills.

4. Discussion

4.1. Research on the Thermal Transfer Performance of Robot Thermal Insulation Materials

The evaluation of thermal properties in insulation materials is crucial for ensuring the stable operation of robotic surgical systems in clinical applications in Mongolia, where thermal management is a key factor. This study investigates the thermal transfer performance of robotic insulation materials, particularly analyzing the heat transfer rates of different insulation materials under high- and low-temperature conditions. Under ultra-low-temperature conditions, experimental research by Luo Wei et al. shows that high-purity copper and aluminum exhibit excellent thermal conductivity below 40K. By increasing the cross-sectional area of thermal connectors, shortening heat conduction paths, and reducing the thermal capacity of connectors, the cooling time of cryogenic shields can be effectively reduced [30-34]. Additionally, flexible thermal connectors enable non-directional structural optimization of cryogenic shields, which is significant for the design

of deep-cryogenic radiation sources and non-directional cryogenic radiators [35]. Under high-temperature conditions, the design and material selection of high-temperature heat exchangers are key research focuses. Scholars have conducted comprehensive reviews on high-temperature heat exchangers, noting that iron- and nickel-based alloys, as well as ceramics, are the most commonly used materials. Critical issues in high-temperature heat exchangers include corrosion, material degradation over time, quality deterioration, and limited service life. The study also provides a concise yet comprehensive overview of high-temperature heat exchanger design, discussing gaps in each parameter and offering a clear roadmap for future research [32]. Yi Peng et al. investigated heat transfer and permeability in dendritic branching networks, finding that when considering the temperature difference between the wall and fluid at each branching level, thermal convection plays a significant role in heat transfer. Moreover, the temperature difference at each branching level has a major impact on heat transfer. Neglecting these temperature differences would lead to significant errors in heat transfer calculations [36]. Jun Shinoda et al. reviewed surface heat transfer coefficients in radiative heating and cooling systems, analyzing measurement data from various authors to compare heat transfer rates and estimated coefficients. The study found substantial deviations in total and convective heat transfer values, while radiative heat transfer errors remained within $\pm 20\%$ in the literature. The primary sources of error include computational procedures for each heat transfer mechanism, the selection of reference temperatures, measurement heights and positions, and room dimensions [37].

4.2. Selection and Application of Thermal Insulation Materials

When selecting thermal insulation materials suitable for robotic surgical systems, the thermal transfer performance of the materials must be considered, particularly their behavior under extreme temperature conditions. Scholars conducted a theoretical analysis of nineteen different insulation materials and experimentally tested three of them (asbestos, fiberglass, and extruded polyurea) [30]. Experimental results showed that at 40°C, the heat transfer rates were 120W for asbestos, 126W for fiberglass, and 173.9W for extruded polyurea, while at -25°C, the rates were 97W for asbestos, 107.8W for fiberglass, and 127.8W for extruded polyurea. These data indicate that asbestos and fiberglass exhibit relatively better thermal transfer performance, making them suitable for robotic surgical systems requiring lower heat transfer rates. Additionally, the thermal rating of electrical insulation materials is another factor to consider when selecting insulation materials [33]. Although this study primarily focuses on materials in electrical insulation systems, its principles for determining and applying thermal ratings are equally applicable to the selection of insulation materials in robotic surgical systems. In terms of insulation material applications, research on heat

transfer processes involving nanomaterial suspensions in refrigerants and lubricants provides insights into thermo-physical property behavior and heat transfer enhancement [38]. While this study mainly targets refrigeration and HVAC systems, its understanding of the impact of nanomaterials on heat transfer offers valuable references for developing new high-efficiency insulation materials [39]. Finally, regarding the application of magnetic soft materials in robotics, although the primary focus is on the design and application of magnetically driven soft robots, it also provides some inspiration for developing novel insulation materials [40]. Understanding the physical properties and behavior of magnetic soft materials may offer new design approaches for insulation materials in robotic surgical systems [41-45].

4.3. Adaptive Thermal Management for Implantable Devices

The design and implementation of thermal management methods. In designing the thermal management system for implantable devices, the key lies in achieving effective temperature control and optimization. The design principles of the thermal management system include analyzing the temperature characteristics of the device and regulating the operating temperature while minimizing temperature gradients to control temperature distribution [46]. For example, in air-cooled proton exchange membrane (PEM) fuel cells, a three-dimensional numerical model was constructed to predict the temperature distribution along the cooling channel direction under different wind speeds. Additionally, a multi-node control model was developed through simulation and controller design to reflect the differences in temperature distribution of the fuel cell along the cooling channel direction. In terms of implementation, the proposed thermal management system employs finite state machine control to adjust the direction of coolant flow and uses traditional proportional-integral control to regulate airflow velocity. Experiments conducted on a 1.2-kilowatt PEM fuel cell system verified that the proposed temperature control scheme improves battery performance and reduces the temperature gradient to within 0.5 degrees Celsius [46]. On the other hand, some scholars have discussed the factors influencing the thermal performance of batteries, as well as battery modeling methods and thermal management strategies [47]. This literature presents a systematic review of liquid-based thermal management systems, emphasizing the importance of integrated systems with appropriate energy allocation and control units [47]. In the process of designing and implementing thermal management methods, practical operational constraints must also be considered. Some researchers have proposed a work and heat integration method that accounts for real-world operational constraints. This method solves the optimization model using metaheuristic approaches and validates it against benchmark and industrial cases to identify low-cost and energy-efficient solutions [48].

4.4. Performance Evaluation of Thermal Management Methods

Through in-depth analysis of simulation studies and in vitro experiments, this paper evaluates the performance of thermal management methods. The results demonstrate that effective thermal management strategies are crucial for maintaining devices within safe and optimal operating temperature ranges [49]. In a critical review of battery thermal performance and liquid-based battery thermal management strategies, Weixiong Wu et al. discussed the impact of temperature on battery performance and presented a systematic evaluation of liquid-based thermal management systems [47]. The study emphasized the importance of integrated systems, which include appropriate energy allocation and control units, as essential for optimizing thermal management performance. Wei-Wei Yuan et al., in their study on the thermal management of air-cooled proton exchange membrane fuel cells, constructed a three-dimensional numerical model to predict the temperature distribution of the fuel cell stack under different wind speeds and designed control strategies through simulation to reflect temperature distribution differences along the cooling channel direction [46]. Experiments verified that the proposed thermal management system, using finite state machine control and traditional proportional-integral control to adjust the direction and speed of cooling airflow, improved battery performance and reduced temperature gradients [50, 51]. In research on determining energy parameters in pulsed reactor experiments, Vladimir Vityuk and Alexander Vurim developed a solution based on heat balance equations to determine the energy parameters of fuel assemblies during pulsed tests [52]. This method was validated through a series of in-reactor experiments, improving the accuracy of energy parameter determination in pulsed tests. Hajin Song et al. developed a multi-layer food temperature prediction model for real-time food quality assessment [53]. The model considers spatial temperature distribution within food and was validated by comparing it with experimental measurements. This food temperature model was integrated with a freshness monitoring model to create a real-time food quality monitoring system. Carla Menale et al. conducted an experimental study to better understand the thermal behavior of lithium-ion batteries under load and the effectiveness of different cooling fluids in maintaining safe operating conditions [53]. The study noted that while many theoretical models exist in the literature, experimental data are scarce. Using two experimental setups, they investigated the ability of different cooling fluids to remove excess heat generated in lithium-ion battery modules, thereby safely examining the possibility of thermal runaway under extreme operating conditions.

5. Conclusion

In the study of thermal management optimization for robotic surgical systems, the integration of multidisciplinary

technologies-such as materials science, thermodynamic modeling, and intelligent control-has significantly enhanced system performance. Advances in flexible robotics have provided safer and more precise surgical solutions for clinical applications, while the reliability of thermal management strategies for implantable devices has been validated through simulations and experiments. Future research should further explore novel nanomaterials, dynamic thermal management algorithms, and interdisciplinary collaboration to drive comprehensive optimization of robotic surgical systems.

Abbreviations

WOS	Web of Science
CNKI	China National Knowledge Infrastructure

Author Contributions

Chao Liu: Conceptualization, Formal Analysis , Writing – review and editing

Hongxing Hai: Data curation

Batbold Baasanjav: Writing – original draft

Baasanjav Nachin: Writing – review and editing

Data Availability Statement

The study data were provided by the Robotic Surgery Center of the Affiliated Hospital of the Ach.

Hongxing Hai and Batbold Baasanjav made equal contributions to this study.

Conflicts of Interest

All authors declare no conflicts of interest.

References

- [1] Li Y, Xuan Y. Integrated Thermal Modeling of Helicopters. *Appl Therm Eng*. 2019; 154: 458-468. <https://doi.org/10.1016/j.applthermaleng.2019.03.069>
- [2] Mahdi JM, Lohrasbi S, Nsofor EC. Hybrid heat transfer enhancement for latent-heat thermal energy storage systems: A review. *Int J Heat Mass Transf*. 2019; 137: 630-649. <https://doi.org/10.1016/j.ijheatmasstransfer.2019.03.134>
- [3] Yuan J, et al. [Analysis of optimal design of solar collector array in heating system]. *arXiv preprint arXiv:201908013*. 2019: 8-73, 47.
- [4] Chen W, Wang XY. Research on heat dissipation technology of magnetron and its performance improvement method. *Shinku*. 2019; 56(1): 63-66. <https://doi.org/10.3131/jvsj2.56.63>
- [5] Chamarthi S, Singh S. A Comprehensive Review Of Experimental Investigation Procedures And Thermal Performance Enhancement Techniques Of Solar Air Heaters. *Int J Energy Res*. 2021; 45(4): 5098-5164. <https://doi.org/10.1002/er.6155>
- [6] Kim J, et al. Advancement of Flexible Robot Technologies for Endoluminal Surgeries. *Proc IEEE*. 2022; 110(7): 909-931. <https://doi.org/10.1109/JPROC.2022.3162476>
- [7] Kwok KW, et al. Soft Robot-Assisted Minimally Invasive Surgery and Interventions: Advances and Outlook. *Proc IEEE*. 2022; 110(7): 871-892. <https://doi.org/10.1109/JPROC.2022.3162475>
- [8] Boskoski I, Costamagna G. Endoscopy Robotics: Current and Future Applications. *Dig Endosc*. 2018; 31(S1). <https://doi.org/10.1111/den.13269>
- [9] Aitzetmueller MM, et al. Robotic-Assisted Microsurgery and Its Future in Plastic Surgery. *J Clin Med*. 2022; 11(11): 3378. <https://doi.org/10.3390/jcm11123378>
- [10] Liounakos J, et al. Robotics in Spine Surgery and Spine Surgery Training. *Oper Neurosurg*. 2021; 21(2): 35-40. <https://doi.org/10.1093/ons/opab195>
- [11] Troccaz J, et al. Frontiers of Medical Robotics: from Concept to Systems to Clinical Translation. *Annu Rev Biomed Eng*. 2019; 21: 193-218. <https://doi.org/10.1146/annurev-bioeng-060418-052502>
- [12] Ning L, et al. Engineering Magnetic Soft and Reconfigurable Robots. *Soft Robot*. 2024; 11(1): 2-20. <https://doi.org/10.1089/soro.2022.0172>
- [13] Dou W, et al. Soft Robotic Manipulators: Designs, Actuation, Stiffness Tuning, and Sensing. *Adv Mater Technol*. 2021; 6(9). <https://doi.org/10.1002/admt.202001383>
- [14] Nurzaman SG, et al. Design Optimization of Soft Robots [from the Guest Editors]. *IEEE Robot Autom Mag*. 2020; 27(4): 10-11. <https://doi.org/10.1109/MRA.2020.3033208>
- [15] Chen F, Wang MY. Design Optimization of Soft Robots: A Review of the State of the Art. *IEEE Robot Autom Mag*. 2020; 27(4): 27-43. <https://doi.org/10.1109/MRA.2020.3033210>
- [16] Tang ZQ, et al. A probabilistic model-based online learning optimal control algorithm for soft pneumatic actuators. *IEEE Int Conf Robot Autom*. 2020; 5.2: 1437-1444. <https://doi.org/10.1109/ICRA40945.2020.9196696>
- [17] Heng W, et al. Flexible electronics and devices as human-machine interfaces for medical robotics. *Adv Mater*. 2022; 4(16): 107307. <https://doi.org/10.1002/adma.202107307>
- [18] Moreno JC, et al. Introduction to the special section on wearable robots. *IEEE J Robot Autom*. 2022; 8(3): 338-1342. <https://doi.org/10.1109/JRA.2022.3163598>
- [19] Howard AM, et al. Socially assistive robots [from the guest editors]. *IEEE Robot Autom Mag*. 2019; 6(2): 0-110. <https://doi.org/10.1109/MRA.2019.2908066>
- [20] Qiao L, et al. [Application status of surgical robots in neurosurgery]. *Chin J Neurosurg*. 2020; 6(12): 286-1289.

- [21] Zhu S, et al. Assessing the learning curve associated with a novel flexible robot in the pre-clinical and clinical setting. *Surg Endosc.* 2021; 6: 563-1572.
<https://doi.org/10.1007/s00464-021-08644-2>
- [22] Konuthula N, et al. Robotics in pediatric otolaryngology-head and neck surgery and advanced surgical planning. *Otolaryngol Clin North Am.* 2020; 3(6): 005-1016.
<https://doi.org/10.1016/j.otc.2020.07.009>
- [23] Meek RD, et al. Machine learning for the interventional radiologist. *AJR Am J Roentgenol.* 2019; 13(4): 82-784.
<https://doi.org/10.2214/AJR.19.21192>
- [24] Touloupoulos E, et al. The cognitive load of learning anatomy in a virtual world. *FASEB J.* 2022; 6(S1).
<https://doi.org/10.1096/fasebj.2022.36.S1.R3701>
- [25] Adida S, et al. Machine learning in spine surgery: a narrative review. *Neurosurgery.* 2024; 4(1): 3-64.
<https://doi.org/10.1227/neu.0000000000002678>
- [26] Ball T, et al. Robotic applications in cranial neurosurgery: current and future. *Neurosurgery.* 2021; 1: 71-379.
<https://doi.org/10.1093/neuros/nyab009>
- [27] Barrientos-Diez J, et al. Real-time kinematics of continuum robots: modelling and validation. *Robot Comput Integr Manuf.* 2021; 7: 02042. <https://doi.org/10.1016/j.rcim.2020.102042>
- [28] Nurzaman SG, et al. Soft robotics: the journey thus far and the challenges ahead [TC spotlight]. *IEEE Robot Autom Mag.* 2020; 7(4): 5-77. <https://doi.org/10.1109/MRA.2020.3033213>
- [29] Le E, et al. Determining the optimal soft tissue preservation techniques for surgical skills training. *FASEB J.* 2022; 6(S1).
<https://doi.org/10.1096/fasebj.2022.36.S1.R3702>
- [30] Sevinchan E, et al. Investigation of heat transfer performance of various insulating materials for robots. *Int J Heat Mass Transf.* 2018; 31: 07-919.
<https://doi.org/10.1016/j.ijheatmasstransfer.2018.11.104>
- [31] Liu M, et al. Numerical studies on effective thermal conductivities of the glass/polyimide composite materials under the conditions of conduction & radiation. *Int J Heat Mass Transf.* 2021; 180: 121781.
<https://doi.org/10.1016/j.ijheatmasstransfer.2021.121781>
- [32] Vooren EV. Thermal ratings of electrical insulation materials-how are they determined and used? *IEEE Electr Insul Mag.* 2021; 7(5): 6-33. <https://doi.org/10.1109/MEI.2021.9447993>
- [33] Yu X, Chen C. A simulation study for comparing the cooling performance of different daytime radiative cooling materials. *Sol Energy Mater Sol Cells.* 2020; 09: 10459.
<https://doi.org/10.1016/j.solmat.2020.110459>
- [34] Wei L, et al. Experimental study on thermal connection mode in ultra-low temperature region. *Vacuum.* 2022; 9(1): 4-67.
<https://doi.org/10.1016/j.vacuum.2021.110678>
- [35] Peng Y, et al. Heat transfer and permeability of the tree-like branching networks. *Int J Heat Mass Transf.* 2019; 29: 01-811.
<https://doi.org/10.1016/j.ijheatmasstransfer.2018.09.115>
- [36] Shinoda J, et al. A review of the surface heat transfer coefficients of radiant heating and cooling systems. *Build Environ.* 2019; 59: 06156.
<https://doi.org/10.1016/j.buildenv.2019.106156>
- [37] Yang L, et al. A review of heating/cooling processes using nanomaterials suspended in refrigerants and lubricants. *Int J Heat Mass Transf.* 2020; 53: 19611.
<https://doi.org/10.1016/j.ijheatmasstransfer.2020.119611>
- [38] Gaberson PC. Do the methods used to determine the thermal class of rotating machine insulation systems make sense? *IEEE Electr Insul Mag.* 2021; 7(3): 8-26.
<https://doi.org/10.1109/MEI.2021.9399072>
- [39] Kim Y, Zhao X. Magnetic soft materials and robots. *Chem Rev.* 2022; 22(5): 317-5364.
<https://doi.org/10.1021/acs.chemrev.1c00481>
- [40] Usmonkulov A, et al. [Some aspects of automatic regulation of thermal conditions in multi-story buildings equipped with exhaust ventilation systems]. *Sci Educ.* 2020; (8): 62-168.
- [41] Xia G, et al. Thermal management solution for enclosed controller used in inverter air conditioner based on heat pipe heat sink. *Int J Refrig.* 2019; 9: 9-79.
<https://doi.org/10.1016/j.ijrefrig.2018.11.011>
- [42] Cui H, Overend M. A review of heat transfer characteristics of switchable insulation technologies for thermally adaptive building envelopes. *Energy Build.* 2019; 99: 27-444.
<https://doi.org/10.1016/j.enbuild.2019.06.029>
- [43] Qi SS, et al. Design and analysis of temperature control heat sink for thermal vacuum test equipment. *Vacuum.* 2020; 7(2): 2-65. <https://doi.org/10.1016/j.vacuum.2019.108955>
- [44] Liu G, et al. A temperature and time-sharing dynamic control approach for space heating of buildings in district heating system. *Energy.* 2021; 21: 19835.
<https://doi.org/10.1016/j.energy.2021.119835>
- [45] Yuan WW, et al. Thermal management for an air coolant system of a proton exchange membrane fuel cell using heat distribution optimization. *Appl Therm Eng.* 2020; 67: 14715.
<https://doi.org/10.1016/j.applthermaleng.2019.114715>
- [46] Wu W, et al. A critical review of battery thermal performance and liquid based battery thermal management. *Energy Convers Manag.* 2019; 82: 62-281.
<https://doi.org/10.1016/j.enconman.2018.12.051>
- [47] Pavão LV, et al. An extended method for work and heat integration considering practical operating constraints. *Energy Convers Manag.* 2020; 06: 12494.
<https://doi.org/10.1016/j.enconman.2020.112494>
- [48] Gil JD, et al. A review from design to control of solar systems for supplying heat in industrial process applications. *Renew Sustain Energy Rev.* 2022; 63: 12461.
<https://doi.org/10.1016/j.rser.2022.112461>
- [49] Li Y, et al. Swimming pool heating technology: a state-of-the-art review. *Build Simul.* 2020; 4(3): 21-440.
<https://doi.org/10.1007/s12273-020-0690-6>

- [50] Shin DU, et al. Simultaneous heating and cooling system with thermal storage tanks considering energy efficiency and operation method of the system. *Energy Build.* 2019; 05: 09518. <https://doi.org/10.1016/j.enbuild.2019.109518>
- [51] Vityuk V, Vurim A. Method for determining the energy parameters in pulse reactor experiments. *Ann Nucl Energy.* 2019; 33: 27-433. <https://doi.org/10.1016/j.anucene.2019.05.034>
- [52] Song H, et al. Development of a food temperature prediction model for real time food quality assessment. *Int J Refrig.* 2018; 8: 68-479. <https://doi.org/10.1016/j.ijrefrig.2018.11.006>
- [53] Menale C, et al. Thermal management of lithium-ion batteries: an experimental investigation. *Energy.* 2019; 82: 7-71. <https://doi.org/10.1016/j.energy.2019.06.012>