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REVIEW ARTICLE

State-of-the-art: A taxonomy of artificial intelligence-assisted robotics for medical therapies and applications

Jinyang Wang[1], Lei Zhu[2], Po Yang[3], Ping Li[4,5], Jihong Wang[1]*, Huating Li[6]*, and Bin Sheng[7]*

[1]Shanghai University of Sport, Shanghai, China

[2]ROAS Thrust, The Hong Kong University of Science and Technology (Guangzhou), Guangzhou, China

[3]Department of Computer Science, University of Sheffield, Sheffield, U.K.

[4]Department of Computing, The Hong Kong Polytechnic University, Hong Kong, China

[5]School of Design, The Hong Kong Polytechnic University, Hong Kong, China

[6]Shanghai Jiao Tong University Affiliated Sixth People's Hospital, Shanghai, China

[7]Department of Computer Science and Engineering, Shanghai Jiao Tong University, Shanghai, China

Abstract

This paper presents a review on the development and major advances in artificial intelligence-assisted robotics for medical therapeutic tasks by focusing on the current challenges emerging from the clinical application process and the research efforts mitigating the problems. In this review, we searched Nature, Science, and Cell using specific keywords (*i.e.*, medical artificial intelligent robots), categorized research works over the past three decades based on therapeutic applications, and discuss the latest development and bottleneck problems of each subtopic. We first present a chronology of the artificial intelligence-assisted techniques developed for medical therapeutic tasks over the past three decades and classify them according to the principles of the algorithm and its corresponding type of medical therapeutic tasks. Artificial intelligence technologies have evolved from classic machine learning methods in the early nineties to data-driven deep learning methods. We subsequently derive a taxonomy of artificial intelligence-assisted therapeutic tasks in the past three decades based on the types of therapeutic tasks and the trending topics in relation to the problems. Using certain search criteria with Nature and Cell databases, one prosperous trend has been abstracted from highly cited research papers and the interpretation of our taxonomy. This unprecedented trend embodies the revolutionary development of artificial intelligence, a closer integration with therapeutic tasks, and a more comprehensive human-robot interaction, all of which benefit sophisticated telesurgery and microsurgery by providing surgeons with higher imaging accuracy and human-like tactile sensation. Our survey discusses the current challenges and future trends of artificial intelligence-assisted therapeutic tasks for the convenience of clinical research and applications, hoping that they would help bridge the gap between entrepreneurial translation and research.

Keywords: Artificial intelligence; Chronic disease management; Laparoscopic robots; Medical robotics; Medical therapies; Wearable medical robots

***Corresponding authors:**
Jihong Wang
(cylwsy@163.com)
Huating Li
(huarting99@sjtu.edu.cn)
Bin Sheng
(shengbin@sjtu.edu.cn)

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1. Introduction

The past decade has witnessed the advancements achieved by artificial intelligence-assisted robotics for therapeutic tasks (AI-ART). In consideration of commercial translational requirement and better artificial intelligence application to therapeutic tasks, AI-ART can be categorized into three groups based on their applications and underlying principles. The nascent application of artificial intelligence-assisted robotics for therapeutic tasks, which includes the exploration application of robotic manipulators to fulfill standard surgical procedures and the incorporation of early artificial neural network or statistics-based algorithms, has had its ups and downs. In this review, we regard medical artificial intelligent robots, such as laparoscopic robots, medical wearable equipment that has benefited from artificial intelligent algorithms, and intelligent soft medical robots, as AI-ART. The chronological development of AI-ART based on methodology and milestones is shown in Figure 1.

2. Taxonomy of artificial intelligence-assisted robotics for therapeutic tasks

By setting the search criteria and selecting influential journals, such as Web of Nature, Cell, and other journals, involving AI-ART in various aspects over a long time span, we identified the taxonomy range. The topics of the taxonomy are related to specific clinical therapeutic tasks (*e.g.*, laparoscopy surgical robots in Section 2.1) or enabling technologies that help to remove urea for dialysate regeneration for wearable artificial kidney (*e.g.*, medical wearable robots in Section 2.3). A detailed exposition of each clinical therapeutic task itself warrants a survey, but in this work, we focus on the problems during the integration process and the latest trending methods proposed in AI-ART for each clinical therapeutic task. We also survey the clinical artificial intelligence improvement in robots, which empower the effective monitoring and update of the applied AI-ART in specific clinical therapeutic task. In this section, we focus on summarizing the development of each subtopic of laparoscopy surgical robots and discuss the current challenges to lay a foundation for the three major trending research in Section 3, as shown in Figure 2.

2.1. Surgery automation

2.1.1. Gripper contact force sensing

Due to the limitations in the development of physical sensors, the contact force sensing techniques that are used in current commercial or academical research tend to "isolate" the hands of surgeons from the tissues or skin of the patients[45,47]. The tactile sensation isolation from manual instruments or artificial intelligence-assisted medical robots could be disastrous, especially in surgical tasks like tissue retraction surgery, during which deformable connective tissues would be manipulated recurrently[48]. To sense and control the interaction force while using artificial intelligence-assisted robotic techniques for therapeutic tasks, researchers are exploring the recreation of tissue palpation, temperature, and even corrosive sensing with improved gripper design[49].

To address the technical sensing problem, advancements have been made. Luca *et al.*[50] presented a simulation of Ruffini receptors with deep neural networks and optical gratings, which could be applied to manufacture tactile-sensitive skin. This bio-inspired polymetric matrix skin might be a novel research direction to implementing tactile sensation while owning a different principle with that of human. The researchers employed the convolutional neural network (CNN) to decode the fiber Bragg grating sensor signals, achieving median errors of 35 mN and 3.2 mm, and demonstrating the advantages of CNN algorithm. Tae *et al.*[51] proposed the use of leech-inspired dry electrodes for auxiliary blood pressure sensing through surgical robots. Although their work was not directly meant to sense the interaction force between the contact point of the robotic gripper and the patient's tissue or skin, it provides an optional method to monitor the fluctuations in blood pressure during the whole surgical procedure, as shown in Figure 3.

2.1.2. Automated surgery

Prolonged operation is often indicated in research or review works as the major risk for complications after surgery.

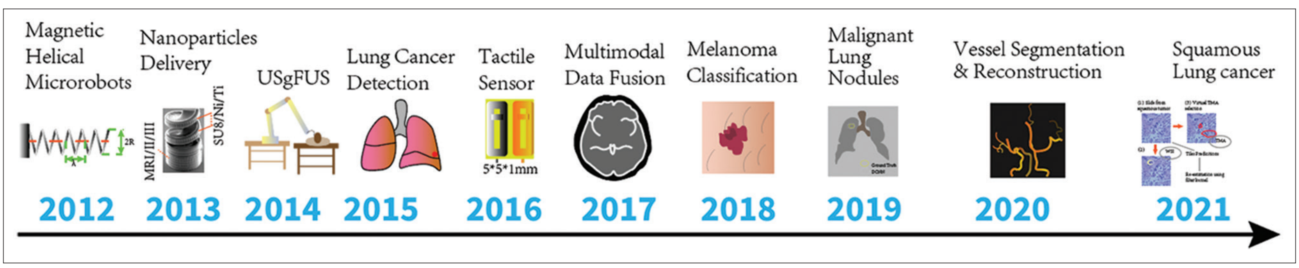

Figure 1. Chronological development of AI-ART in the past decade from the early 2010s' magnetic helical microrobots to squamous lung cancer detection and therapeutic tasks. The illustrations in each year are recreated and referenced as follows: 2012[1], 2013[2,3], 2014[4,5], 2015[6-9], 2016[10-13], 2017[14-17], 2018[18-21], 2019[22-27], 2020[28-32], and 2021[33-38].

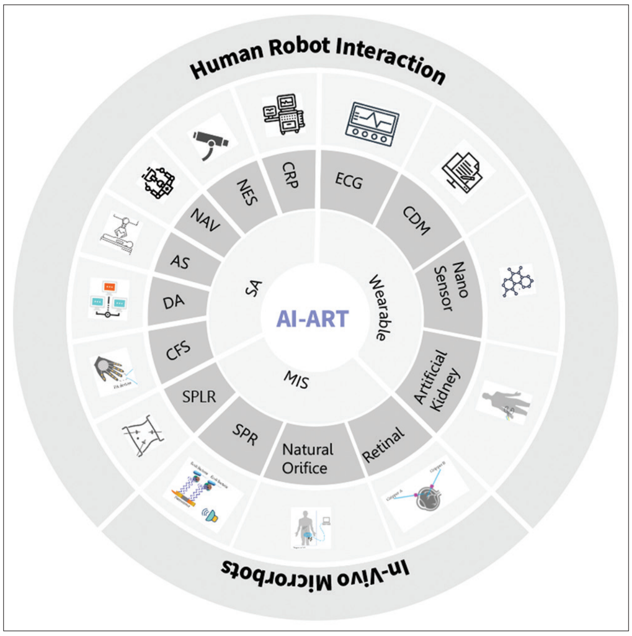

Figure 2. Taxonomy of AI-ART in three major scenarios for medical therapies. The innermost circle embodies the three major scenarios. The outermost circle states the two most trending topics through AI-ART. The middle tiles are the subbranches (from the innermost circle to the adjacent tiles surrounding it): MIS refers to minimally invasive surgery; SA refers to surgery automation; Wearable refers to medical wearable robots; CFS refers to contact force sensing, with an illustration shown[38]; DA refers to distributed architecture, with an illustration taken from the Robotic Surgery Center at Szpital na Klinach; SPLR refers to single port laparoscopy robot, with an illustration taken from intuitive surgical; AS refers to automated surgery; NAV refers to navigation techniques, with an illustration shown[39]; NES refers to naked-eye scopy, with a reprinted illustration shown[40]; CRP refers to collaborative research platform, with an illustration taken from Applied Dexterity; ECG refers to electrocardiogram, with an illustration shown[41]; CDM refers to chronic disease management, with an illustration taken from the American Society of Hematology; Nano Sensor refers to nanotechnology-based medical sensors, with an illustration shown[42]; artificial kidney refers to the artificial intelligence-assisted kidney devices, with illustration shown in[43]; Retinal refers to robots used in retinal surgeries, with an illustration shown[44]; Natural orifice refers to surgical robots that can gain access through natural orifices, with an illustration shown[45]; SPR refers to self-propelling robots, with an illustration shown[46].

Prolonged surgery mainly occurs in reconstructive surgical tasks, such as in cancer reconstruction, birth defects, full or partial mastectomy, limb salvage, and so on. Therefore, automated surgical robots are required to perform a wide range of surgical tasks, including standard and non-standard procedures. Surgeries with standard procedures are viewed as super-states, which could be decomposed into finer-grained sub-states, such as dynamic imaging of different views, pull, loop, cutting through, and so on[56]. However, a precise and robust detection of incision remains one of the biggest challenges, as point cloud generated by stereo vision is significantly affected by various light conditions.

These standard procedures could be learned through AI-ART[56]. Wang *et al.*[56] developed a medical robot system equipped with stereo vision, incision detection, and staple positioning algorithms for surgical suturing and staples removals. Lu *et al.*[54] presented an in-house vision system with efficient trajectory planning algorithms. They successfully addressed the automatic suturing problem with two collaborative grippers through visual detection algorithms, which also eliminated the risk of collisions between the two gripers. In fact, their work does not include the full automation of medical robots, but rather only as a sub-state semi-automatic assistant for surgeons. Moreover, the tactile sensation between the operated tissue or organ and the robotic gripper does not provide any feedback to the surgeons or have a monitoring module of the computer unit.

Even with artificial intelligence assistance for laparoscopic surgery, full-automation medical robots have not been approved by the Food and Drug Administration (FDA), due to the trust attitudes of patients and surgeons toward these technologies. In addition, career dilemmas and anxieties associated with full-automation smart medical robots among skilled surgeons still exist. Another issue to be considered is personal information security protection, which is either exposed to the surgeons in charge or big data, and sometimes even a virtual AI doctor outputting the treatment. Hence, governmental departments and researchers have begun to establish laws, standards, and instructions during the AI-ART process.

2.1.3. Navigation

Navigation plays a crucial role for AI-ART, providing fundamental functions such as real-time self-localization and dynamic map building. The relative positional coordinates of the abdominal cavity vary with time and breathes. The classic navigation methods used for other non-medical robots in most cases are not suitable for AI-ART, as the workspace and volume of medical robots are limited, namely, the aforementioned miniaturization challenge. Based on specific operative scenarios, corresponding navigation algorithms are leveraged with homologous hardware and sensors by AI-ART.

The commonly used sensors for AI-ART include visual charge coupled device (CCD) camera, three-dimensional (3D) laser, and time-of-flight (ToF) camera. Ebihara *et al.*[39] performed real-time vessel navigation through indocyanine fluorescence during artificial intelligence-assisted gastric tube reconstruction. Each patient was followed-up, with no reported post-operative complications, such as ischemia or adhesion of gastric tube. Although the navigation method adopted by Ebihara *et al.* was a classic approach, they

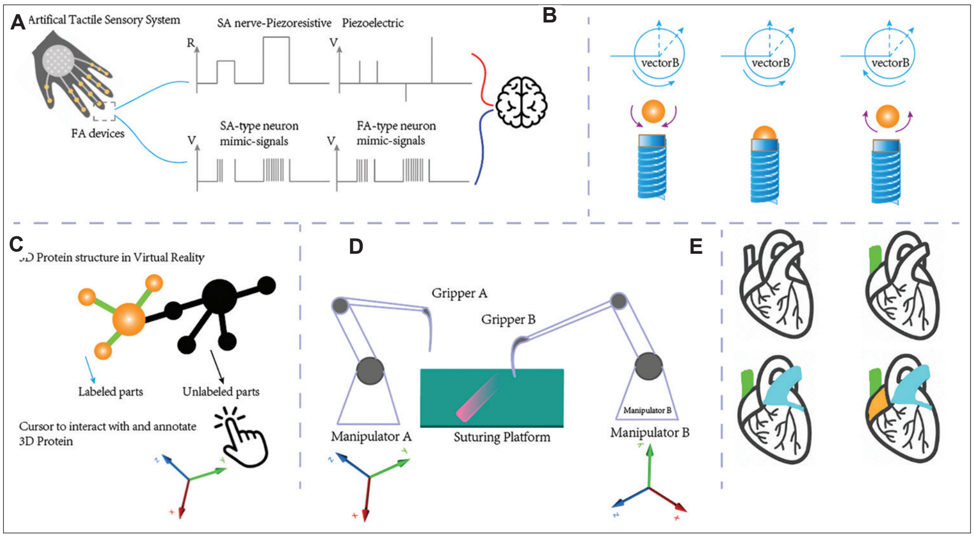

Figure 3. Representative surgery automation applications with AI-ART. (A) Mimicking human tactile sensing for laparoscopy gripper[50]. (B) A capsule robot that is capable of picking, dropping, and assembling particles and drugs[52]. (C) Augmented reality (AR)-assisted biological annotation[53]. (D) Vision-assisted suturing robots[54]. (E) Ground truth atrium (first, at top left) and predicted results (the other three) of CNN[55].

recognized the elementary function of navigation, which is to provide localization signal. Affected by the fluorescence dosage, imaging accuracy, and the positioning precision of visual algorithm, the actual relocalization and robustness of the navigation have room for further improvement. Taking the dynamics and deformability of the abdominal cavity into account, Zhang *et al.*[57] attempted to address the problems of invasive external tags and the difficulties of deformable tissue mapping and segmentation through modified 3D-3D iterative closest point (ICP), Mask R-CNN, and semi-global block matching (SGBM) algorithms. The method presented by Zhang *et al.* is suitable for the distributed form of AI-ART, as the deep learning segmentation algorithm would cost expensive computation during real-time inference. SGBM algorithm relies on the complex texture of the surgical region, which may be polluted by disinfectants or residual bloodstains. Therefore, surgery automation is expected to improve when the navigation algorithm is invariant to the slight texture variations.

The current state-of-the-art navigation technologies prefer to fuse multi-modality sensor data together to achieve accurate and multiple aspects imaging of the patients, including ultrasound, computed tomography (CT), magnetic resonance imaging (MRI), and the two-dimensional (2D) visual images of inner tissue and organs. We will discuss sensor data fusion in Section 3.2.

2.1.4. Collaborative research platform

To produce comparable and reproducible results of AI-ART, researchers of different organizations seek to construct a collaborative research platform of laparoscopic robots[57]. A collaborative laparoscopy platform would eliminate the enormous amount of duplicate work for a small or new medical research team. The bootstrapping team or experienced peers can gain access to existing and open works as well as use their own laparoscopic robots for specific therapeutic tasks[58]. On identifying this requirement and the benefits for subsequent product development, two organizations have developed their own respective collaborative laparoscopy platform for researchers. The first one is Raven II, an open-architecture laparoscopic robot, from Applied Dexterity, which has seven degrees of freedom (six DoF plus one grasp) through two cables containing monitoring, power supply, and control signals[58]. The second open platform for laparoscopy surgery is from the collaboration of intuitive surgery with practicing surgeons to perform non-clinical trials with animals for verification or proof of certain therapeutic approaches[59]. After in-depth investigation, the weakness of Raven II applied for automatic surgery lies in state estimation, as it lacks accurate encoders to indicate each coarse state. The lack of relevant evaluation standards and metrics may be a serious problem for collaborative research platforms. As a consequence, the experimental results and data produced by these collaborative research platforms lack comparability with equipment, granted by the FDA. The two collaborative platforms are verified only for research use, in which human clinical trials are not permitted.

2.2. Minimally invasive surgical (MIS) robots

MIS has evolved as a popular alternative to open-ended surgeries, due to reduced trauma and a much faster recovery. Another reason for its popularity is an increasing proportion of the elderly. The elderly has a weaker immunity and wound healing ability than the young. Therefore, it is crucial to invest energy and money in MIS now and in the future. We have witnessed the progress made by researchers in MIS in recent years; the seminal ones are illustrated in Figure 4.

2.2.1. Self-propelling robots for endoluminal surgery

Traditional endoscopic equipment used in clinical therapeutic tasks tends to cause pain and agitate the stomach as a soft cable, containing imaging or small scalpels, would be pushed through the stomach or intestine. Therefore, several types of self-propelling endoluminal robots with different performances have been proposed by researchers[60].

Researchers have designed a new propelling method inspired by wasp ovipositor, which squeezes its tail needle into the rind of tree through multiple sliding body parts[61]. The propelling endoluminal robot is able to drive itself forward in the intestine with a rotatable camera mounted on one of its body parts. Further research is needed even after testing the novel self-propelling endoluminal robots for the risk of insufficient energy, which would cause these robots to remain inside the body, and the image sticking algorithm of the rotating camera in the dynamic human intestine is susceptible to peristalsis and breathing. To overcome the possible adverse effects produced by the friction between the sliding body part and the intestinal mucosa, researchers have turned to a new direction: Extracorporeal magnetic actuator[46,62]. Endoluminal robots that are propelled by body parts or extracorporeal magnetic actuator depend on the natural opening of the intestine or stomach, which is dynamic and continuously changing along with the heartbeat and respiration. Hence, a reliable support structure is needed for endoluminal robots to obtain better imaging of its surroundings deep inside the human body. At present, self-propelling robots are mainly developed for endoluminal examinations. They have yet to meet the requirements of drug delivery, which has higher demands for accurate localization and resistance to gastrointestinal peristalsis.

2.2.2. Surgical robots through the natural orifice

As a minimally invasive surgical approach, natural orifice transluminal endoscopic surgery (NOTES) robots are gaining widespread attention for bare skin incision, faster recovery time, and fewer complications after surgery[62,65]. The main challenge of NOTES is the localization and navigation ability when deep inside the human body. A number of surgical robots are now able to carry out natural orifice tasks. With regard to NOTES, the focus is on development of tools for multitasks and compact-sized soft continuum robots with multiple articulations and more power.

Shen *et al.* devised a multitasking robot with two hands, like humans, but equipped with multifunctional manipulators, aiming at on-site tool exchange based on the type of surgery[65]. Another important feature is the motor-like actuator with two spatial independent articulated curvature sections. They attempted to address the power deficit problem, which constrains the degree-of-freedom motion inside the lumen of the stomach, intestine, *etc.* The research team also rearranged the operation sequence

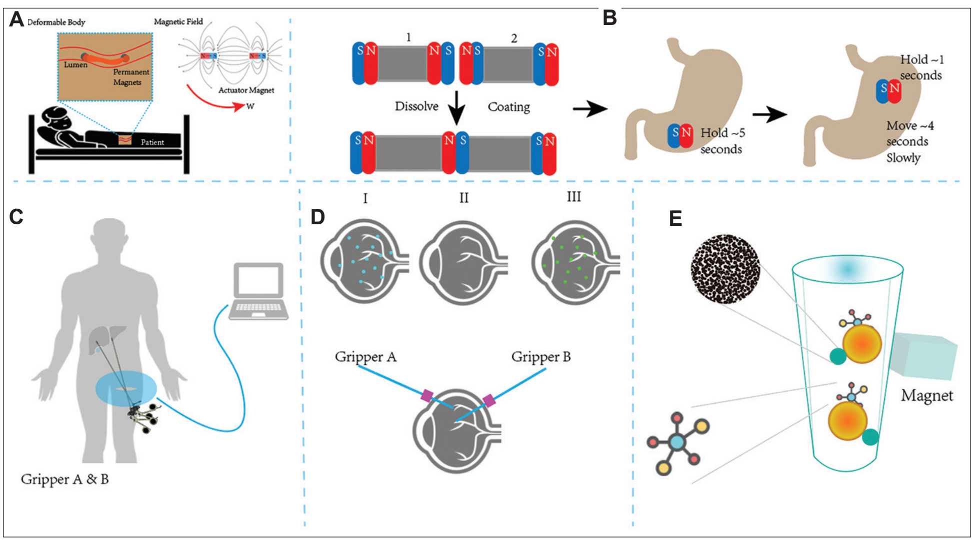

Figure 4. Three interpretations of minimally invasive surgical robots with AI-ART. (A) Soft endoluminal *in vivo* robot propelled by rotating magnetic field[60]. (B) Deglutible capsule robot propelled by rotating magnetic dipole fields[61]. (C) Operative illustration through natural orifice[62]. (D) Retinal robot with AI-ART[63]. (E) Illustration of self-propelling magneto-fluorescent nanorobot capturing tumor cells[64].

configuration to reduce the trade-off between size and power, reflecting their comprehensive efforts toward the exploration of NOTES. The navigation of NOTES robots within the lumen would be a topic of interest considering the synthesis of multiple AI technologies, such as visual semantic segmentation and recognition, inertial information fusing, and so on. The integration of NOTES and soft-bodied robots would be another technical direction, as conventional NOTES tends to cause injuries and discomfort to the natural orifices of the body. The soft-bodies design adjusts the integral positions and speed based on the pressure to the orifice. Hence, the tactile sensing technique plays a crucial role for the further development of NOTES.

2.2.3. Robots for retinal surgery

The innovation of AI-ART robots for retinal surgery predominantly aims at reducing the risk of injury to the crystalline lens, corneal injury, and retinal tearing, all of which may lead to serious consequences and pose a challenge for surgeons[63,66]. The additional benefit of AI-ART robots for retinal surgery lies in the increased dexterity and lower incidence of ocular hypotony. In the treatment of retinal vein occlusion, severe visual loss may occur; hence, retinal cannulation of retinal veins using a smaller-diameter cannula is the best approach thus far. Within the past few years, there has been an increasing interest in ultra-high precision positioning mechanism and image segmentation algorithms. In 2021, Jinno[66] proposed the use of snake-like robots to address the problem of restrained motion within a confined workspace from an appropriate direction, in which multiple surgical tasks were performed on the delicate cornea and retina. In 2020, Suzuki[44] designed a miniature remote center of motion manipulator (RCM) with a positional precision of 26.4 mm for teleoperated microsurgery. Retinal surgery robots continue to be the best assistance for surgeons. Considering the complexity of retinal surgery, automated robots can contribute from three perspectives: (1) Understanding the current semantic processing; (2) learning the control patterns or rules based on the semantic process; (3) conducting semantic processing when the surgeon requires.

2.2.4. Single-port laparoscopy

A standard laparoscopy surgical robot usually consists of 3–4 ports to supply accesses for the robotic arms, including several manipulators and one planar or stereo imaging endoscopy. Compared with manual open procedures of standard specifications, the standard laparoscopy surgical robot can effectively reduce the invasiveness of surgery. The incision is small as single-port laparoscopy robot integrates the robotic manipulation arms and the endoscopy into one trocar through the abdominal wall.

The difficulties in using single port-laparoscopic robots lie in the solvability and theoretical formula derivation of multi-arm single-port surgical coordinates trajectory mapping. As we know, the singularities of artificial intelligence-assisted robotic arms with a confined workspace are major issues. Notable innovative single-port laparoscopic robot prototypes have been proposed over the past 5 years[67,68]. Bai *et al*. proposed an optimized anthropomorphic coordinated control approach through dual-step optimization based on the dexterous arms in human boxing maneuvers[67]. Bai's method has shown to achieve higher efficiency and less invasiveness apart from addressing the issue of control. Wang *et al*. designed a comprehensive system, made up of three 6-DoF robotic arms and a camera-mounted endoscopy, which could be inserted into the abdominal cavity through one trocar with diameter <20 mm. Bai *et al*. attempted to address the miniaturization of laparoscopic robots and the sophisticated control of robotic arms[67].

2.3. Medical wearable robots

Medical wearable robots are primarily for the improvement of body functionality, including the normal functioning of internal organs and limb movement. In medical therapeutic scenarios, exoskeleton robots generally refer to rehabilitation robots. The focus now is on human-robot interaction to improve the cognition ability and physical assistance provided by robots to humans. Another aspect of medical wearable robots is wearable artificial organs, which include microfluidic lung, bioartificial heart, artificial hemodialysis (artificial kidney), artificial liver, and so on[69,70]. The representative medical wearable robots are illustrated in Figure 5.

2.3.1. Assisted chronic disease management

Compared with wearable nanosensors for medical signal collection, AI-ART for chronic disease management mainly focuses on stage distinction and leveraging more powerful artificial intelligent algorithms to support the decision-making process. For instance, patients with chronic lymphocytic leukemia (CLL), which is a type of cancer that originates from the lymphocytes in the bone marrow and spreads to the blood, causing infections and lowering the immunity, may endure the transformation into the next stage: Aggressive malignant lymphoma. However, determining whether the patient is in the first stage or second stage is challenging due to limited guidelines and insufficient morphologic experience of biopsy specimens. Therefore, researchers from University of Rochester Medical Center, Rochester and University of

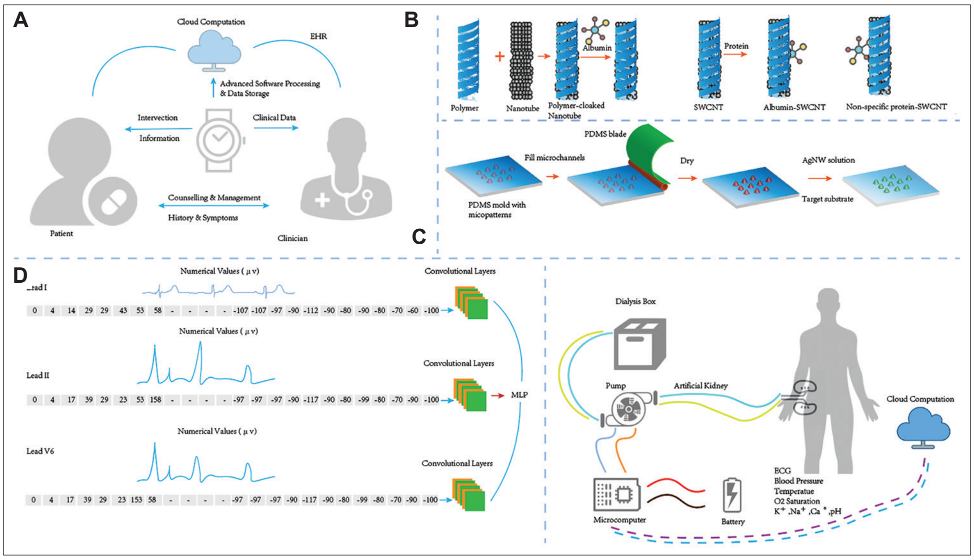

Figure 5. Data collection and flow of medical wearable robots. (A) Intelligent wearable robot with AI-ART[71]. (B) Formation process, and a proposed interaction model[72]. (C) Fabrication process of epidermal electronics with nanocomplex[71]. (D) Cardiovascular disease management method and architecture with AI-ART[73]. (E) Smart artificial kidney incorporated with proteomics, hematology, and engineering techniques of AI-ART[70].

Texas MD Anderson Cancer Center seek to establish an approach to improve the diagnostic accuracy and probe the stage or degree of CLL with artificial intelligence algorithms[73]. Besides the mainstream application for stage distinction, there are two supplementary branches of AI-ART for chronic disease management. The first is to optimize chronic disease management, involving fusion of multi-modality medical big data, patient-oriented risk evaluation, and decision support assistance[71]. Compared with the former, the second branch involves imposing the prediction function of artificial intelligence algorithms onto post-operative recovery. In spite of that, the third branch is in its infancy, involving a comprehensive framework with enormous amount of multi-modality medical data of specific diseases from wearable medical robots, multilevel progressive data mining algorithms, official guidelines, and relevant laws. One of the most important goals of chronic disease management is to recapitulate the corresponding short-term and long-term therapies for the patient in the future. The chronic disease management system collects comprehensive data from daily examination and wearable sensors, such as ECG and so on. Valuable data mining from the massive information are the key for subsequent treatment formulation.

2.3.2. Wearable electrocardiogram monitoring

Predicting when a patient would suffer from an unexpected heart attack is difficult. Wearable ECG is a revolution toward 24 h or longer ECG monitoring, which assists the doctors in detecting cardiovascular diseases before they become serious and uncontrollable. At present, wearable ECG monitor is growing as a supplementary tool of conventional heavy and costly ECG monitor[71]. AI-ART human-like interpretation, which is massively unrecognizable to human interpreters, reveals the associations between electrical signals and various phenotypes, such as patents' ages, sexual distinction, atrial fibrillation, ventricular dysfunction, and so on. Wearable ECG monitor is expected to become a potential, ubiquitous, and non-invasive biomarker[74]. Long-lasting power supply for wearable ECG monitoring can be mitigated by the rapid development of new-energy chargeable battery. Perhaps, integrating important first-aid strategies, such as defibrillation by electric shock and so on, into the ECG monitor would be beneficial.

2.3.3. Artificial kidney

The innovation of artificial kidney (portable hemodialysis) to some extent represents a center translation substantially from in-center to patient-center[75]. The kidneys remove toxic and excessive water from the blood. Hence, wearable artificial kidney plays an extremely important role for kidney failure patients. Although artificial kidney has been envisioned in 1960s, until now, artificial kidney has not been approved by the FDA for clinical use.

Researchers are gaining interest in the barriers hindering research development and commercial productization. The main challenge is how to effectively remove toxic salutes from the blood, while decreasing the dosage of dialysate, which is also an impediment for hemodialysis. The reason behind the necessity to solve the substantial usage of dialysate is that even if the patient is able to afford a wearable artificial kidney, the patient may not have access to dialysis storage or caregiver at any time[70].

The main direction is the study of sorbent adsorption, in which highly effective activated charcoals can inherently absorb uremic toxins. Historically, the exclusive sorbents system has been proven ineffective in binding and eliminating urea. Hence, researchers have developed five types of sorbents, to the best of our knowledge, for urea adsorption. One of the five types includes TPA-COF (covalent organic framework) nanosheets and TPA-COF nanoparticle modified with -OH, which have been verified to have better urea adsorption based on molecular study. Other directions of wearable artificial kidney include enzymatic removal of urea, electro-oxidation, photo-oxidation, blood compatibility, and human factors[69]. Artificial intelligence-assisted analysis would improve the search for more efficient materials relating to the development of sorbents in three aspects: (1) Effective combination of candidate structures; (2) more reliable dynamics simulation for liquid circuit system; and (3) accurate prediction of the recharge of consumable materials.

3. Human-robot interaction for automation or telesurgery

We searched Nature, Cell, and Science website pages using keywords "medical artificial intelligent robots" to index all the related papers with a time range from 1990s to the latest issues. We then conclude that the main research trend is human-robot interaction for automation or telesurgery, as shown in Figure 6.

3.1. Feedback of tactile sensation

The application of either classic laparoscopy or AI-ART for medical robots isolates the surgeon's tactile sensation from the patient's deformable tissue or skin. However, either the surgical robot with on-site surgeons or telesurgery through 5G communication technologies is required to hold or pull the tissue with proper force without secondary classic laparoscopic injury. Researchers have explored new sensation technologies for the interaction between medical robots and soft tissue[76]. The fundamental work of AI-ART for medical robots is undoubtedly the calibration of force sensor or torque sensor, which transforms raw electrical signal into force or torque values with real physical meaning. With regard to the progress of calibration, the main focus is on end-to-end neural networks as the multi-axis data and their mutual coupling. Deep learning algorithms have been leveraged for the calibration of force and torque sensors. On the basis of calibration works, the skin-like sensor that is able to attach to arbitrary surface has drawn interests, as it can be manufactured into non-array arrangement as well as sense and transmit signals even with partial damages. Four artificial neural networks have been adopted to determine their slippage and accuracy data output as well as compared for cross-verification, with their weaknesses illustrated[50]. Generative adversarial network (GAN) learning algorithms and its variants as GAN exploits generator and discriminator can be used for searching an effective tactile sensing material to produce better generator in an adversarial manner. The produced generator by GAN

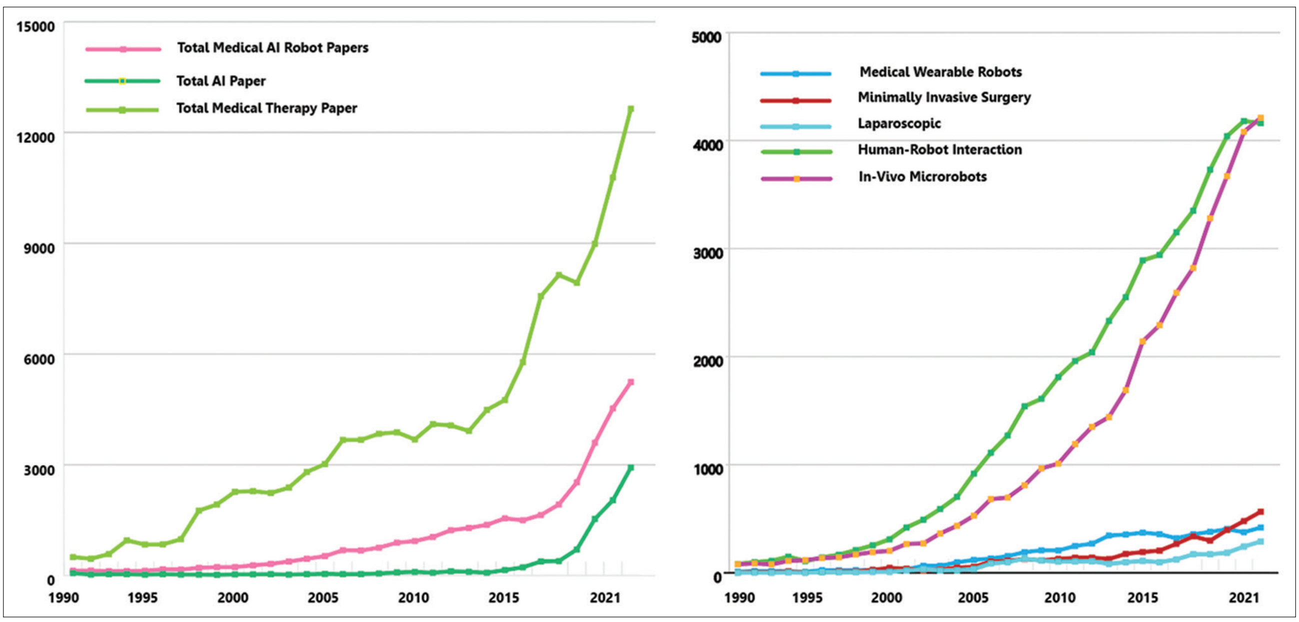

Figure 6. The left curves describe the total artificial intelligence, total medical therapy, and total medical applications combined with AI-ART papers published each year. The right curves are the trending topics associated with AI-ART medical therapies and applications. From the highest two trends of the right chart, we extract the two most trending topics: Human-robot interaction for automation or telesurgery and *in vivo* microrobots.

possesses the ability to generate candidate structures to sense different surfaces and materials. The signals collected from the sensing system can be sent to processing neural networks to extract the valid tactile sensing patterns.

3.2. Multi-sensor fusion

Recognizing and understanding the various behaviors of surgeons under different scenarios may improve the cognition and assistive ability of medical robots. The traditional data fed to assistive medical robots are often single modal, such as robotic imaging information from CT or MRI[16]. One of the focuses of current research on human-robot interaction is sensor fusion based on multi-modality information collected during or after the surgery process. For instance, in a surgery with the assistance of a laparoscopic robot, the robot must be able to comprehend the term "hemostasis" spoken by the surgeon, segment the images collected by the camera sensors mounted on the robot and obtain semantic understanding of organs or tissues of the patient, recognize the bleeding vessels, and use the correct size of hemostatic forceps to implement the action within a short period of time. The construction of a multimodal information framework is necessary for flexible interfaces of various sensor types, accuracy improvement, haptic sensation, diverse vital signs, surgeons' spoken words and gestures, and decoupling of internal modules and external software interfaces. Concrete gesture recognition incorporates the kinematics of grippers, grasping different tissues, with proper fine-grained tissue or organ segmentation under different surgical types[77,78]. Multi-sensor fusion has greatly contributed to the commercial translation from AI-ART, such as the combination of CT and MRI to obtain more precise spatial scanning results in relation to the location of lesions. However, CT and MRI images require diverse configuration parameters under different conditions to ensure a better fusion. Therefore, more emphasis should be placed on adaptive fusion by AI-ART.

3.3. Augmented reality for telemanipulated medical robot

In the past 3 years, COVID-19 has posed unprecedented challenges to both, patients who have underlying diseases and surgeons with long-distance or safety isolation concerns. As a result of the considerable advancements in both, AI-ART and hardware computing power, medical applications integrated with augmented reality are growing exponentially[57]. In cardiovascular surgery, complicated anatomical structures make the surgery more challenging. For instance, in obstructive hypertrophic cardiomyopathy, the surgeon needs to open a small slot without damaging the upper cardiac aorta, which is only a few millimeters away from it. Therefore, in cases such as this, the interactive augmented reality technique supported by robotic endoscope camera provides useful functions, such as magnified stereo imaging of the ventricle internal structure, dynamic segmentation of ventricle parts, and automatic annotation on the screen for surgical decision-making. Another challenge to accurate segmentation and annotation is the deformable tissue and organs at the operation area. The 2D shape silhouettes of the tissue or organs are extracted from images from a monocular camera to assist the 3D deformable registration models through several projective constraints of multiview geometry[53,57,76]. The allocation of communication channels by AI-ART, such as 5G, ensures real-time video transfer of the surgery process. This lays a solid foundation for telemanipulated medical robots. Simulated sensing is obtained through the tactile sensing technique equipped on these robots. AI-ART also enables multi-views of a patient through cameras mounted at different positions. The fusion of these multi-views, in which the images are stitched together, forms a panoramic view by convolutional neural network (CNN)[50,78].

4. Challenges and directions

4.1. Future challenges

The past decades have witnessed the tremendous progress of AI-ART in the fabrication of various medical robots, such as laparoscopy surgical robots, single-port laparoscopy robots, naked-eye imaging laparoscopy, capsule robots, wearable medical robots, and so on, as shown in Figure 7. Due to the breakthrough of parallel computation chips, such as graphics processing unit (GPU) and field programmable gate array (FPGA), as well as artificial intelligence algorithms like multi-layer perceptron (MLP), convolutional neural network (CNN), deep learning (DL), and the latest knowledge distillation techniques, various medical therapies and applications have been uncovered.

New surgical tool manipulation modeling and navigation methods are made feasible with more powerful artificial intelligence algorithms and computation hardware. However, the main obstacle to surgical robot automation is the interaction between surgeons and robots. Another challenge lies in *in vivo* microrobots, which have shown potential for target drug and cell delivery, bacteria killing, vascular cleanup, and other therapeutic applications. The 6-DoF motion control and navigation of the microrobots *in vivo* are pushed forward by the rotating magnetic field technique. The challenges are listed below.

i. Vision segmentation accuracy and robustness: Is the medical robot's vision algorithm capable of precisely and robustly segmenting dynamic tissue or organs from complex backgrounds with the given required metrics? This is crucial in automatic surgery and human-robot interaction.

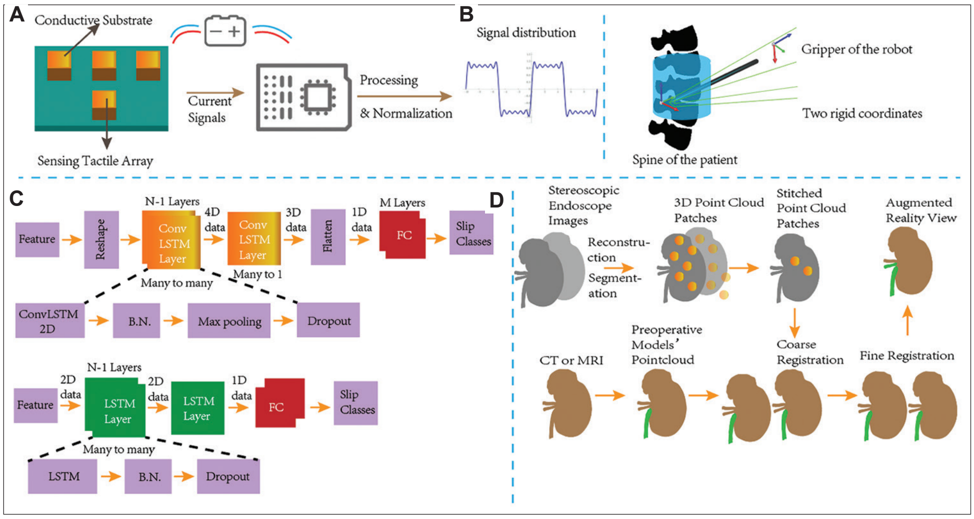

Figure 7. Trending topics and advancements over the past decades. (A) 3-DoF force feedback apparatus[76]. (B) Spinal operation robot with AI-ART constrained by a safe light cylinder workspace[78]. (C) Tactile sensing feature processing neural networks from[50]. (D) Non-marker virtual reality (VR) navigation approach[57].

ii. 6-DoF motion control: How to guarantee the robustness of real-time 6-DoF motion control, especially when the microrobot is approaching the target position?

iii. Smarter tactile sensation of surgical robot: How to apply appropriate pinching force onto different tissues or organs during surgery to prevent post-operative complications?

iv. Multi-modal data fusion: How to better fuse data generated from different sensors, such as vision sensor, robotic arms control, MRI, and ultrasound, to obtain a better integration for navigation *in vivo* or imaging?

v. Binding mechanism of nanoparticles and microrobots: In target drug or cell delivery scenarios, how to bind nanoparticles efficiently with the organic membrane of the transporter microrobot without mismatching?

vi. Formal self-verification of AI-ART: How to verify the output through AI-ART used by surgical robots, especially the recognition or segmentation results?

4.2. Technical directions

It is challenging to predict the long-term technical direction for surgical therapies and applications using AI-ART, but it is possible to predict the mid-term technical direction based on the established trends, as shown in Figure 8.

1) Gripper contact force sensing would not directly rely on the progress of AI-ART but rather the development of the structural design of the force sensor and on novel material producing electrical signals. Researchers are now seeking for arbitrary shape coverage and human-like simultaneous pressure and temperature sensation. Hence, the novel calibration methods and concrete application scenarios using AI-ART would be fairly different from the previous routines.

2) Since the navigation, control, computation, and surgical tool functional modules are suitable for spatially independent mounting, the distributed architecture of laparoscopy surgical robots would be the mainstream design for *in vitro* surgical robots. The development of 5G in the coming years would bring about improvements to the complex arrangement of cables inside surgical robots and linking modules, eventually replacing them with wireless communication.

3) In the next decade, single-port laparoscopy would progressively erode the market of natural orifice surgical robots due to its reaching limitations and the significant physical (orifice) and psychological discomforts associated with the procedure. Single-port laparoscopy also requires peritoneal membrane penetration with an extra incision.

4) The navigation of AI-ART would continue to progress toward robust segmentation and reliable depth value estimation. This fundamental technique also serves as the basis of self-propelling *in vivo* robots for target cell or drug delivery and the advancement human-robot interaction.

5) The technical directions of artificial wearable kidney could be divided into the advancements of new dialysis material and the methods of using less dialysate. Wearable chronic disease management would embody remote databases, cloud computing platforms, and the monitoring devices worn by patients, such as ECG monitor and medical nanosensor network.

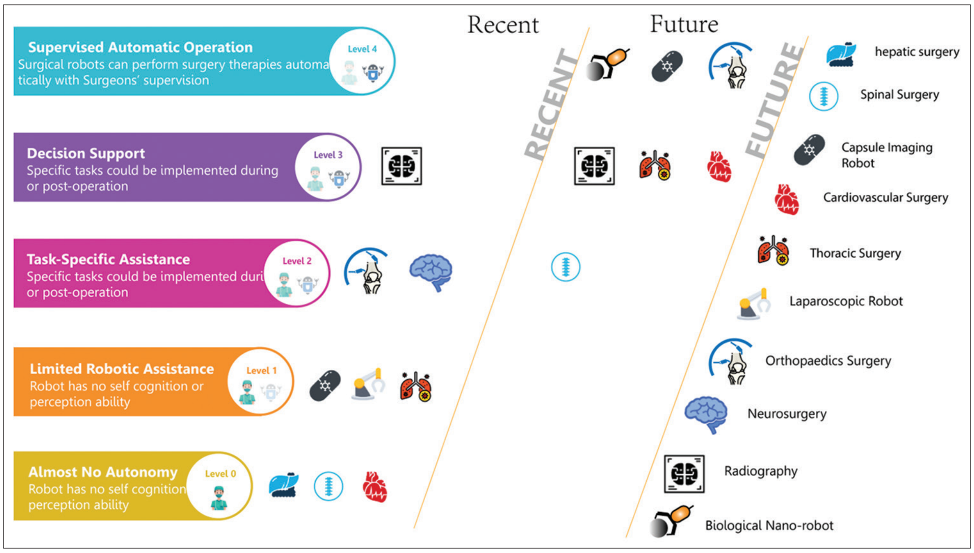

Figure 8. Recent advancements and future technical directions of medical robots with higher autonomy. The left column represents the recent stages and applications of surgical therapies with AI-ART. The middle column represents the future surgical applications with more automated assistance. The right column shows the annotations of the graphic icons adopted in left and middle columns.

6) Target drug and cell delivery microrobots weave another promising area for precision medicine, instead of the traditional one-size-fits-all approach. To ensure the goal of using the right treatment (targeted treatment) for the right patients at the right time, the patients' genetic information and the genetic profile of specific tumors would be taken into account by microrobots carrying suitable doses of drugs or functional cells.

5. Conclusion

To bridge the gap between AI-ART and commercial applications, a taxonomy of major scenarios of AI-ART was derived with three divisions: Surgery automation, minimally invasive surgery, and medical wearable robots. Surgery automation mainly focuses on the progress and challenges of artificial intelligence-assisted techniques used in automated surgeries, such as gripper contact force sensing, navigation, and collaborative research platform. Considering that minimally invasive surgery results in rapid recovery and less physical injury, we discuss its development from four aspects: Self-propelling robots, surgical robots through natural orifice, high-precision retinal surgical robots, and single-port laparoscopy. In light of the pressing demand for chronic disease management and wearable life support equipment, we also explore the applications of AI-ART in artificial kidneys and ECG monitoring, as well as the use of AI as a powerful analysis for chronic diseases. By ranking the research results, we identify the latest trend of AI-ART as human-robot interaction. Although we have witnessed the great achievements in AI-ART, there are still many challenges ahead. Accurate vision segmentation and localization would affect the quality of surgery automation. Meanwhile, the efficiency and reliability of drug or cell delivery at certain time and location within the body are determined by the spatial six-DoF control of self-propelling robots. Based on the problems encountered both, in research and commercial applications, we also discuss the promising technical directions for AI-ART.

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Conflict of interest

The authors declare no conflicts of interest.

Author contributions

Conceptualization: Huating Li, Bin Sheng
Formal analysis: Jinyang Wang, Lei Zhu
Investigation: Jinyang Wang, Lei Zhu, Ping Li
Methodology: Po Yang, Bin Sheng
Writing – original draft: Jinyang Wang, Lei Zhu

Writing – review & editing: Jinyang Wang, Ping Li, Huating Li, Bin Sheng

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

The data that support the findings of this work are available from the corresponding author on reasonable request.

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