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Review

A systematic review of image-guided, surgical robot-assisted percutaneous puncture: Challenges and benefits

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Abstract: Percutaneous puncture is a common medical procedure that involves accessing an internal organ or tissue through the skin. Image guidance and surgical robots have been increasingly used to assist with percutaneous procedures, but the challenges and benefits of these technologies have not been thoroughly explored. The aims of this systematic review are to furnish an overview of the challenges and benefits of image-guided, surgical robot-assisted percutaneous puncture and to provide evidence on this approach. We searched several electronic databases for studies on image-guided, surgical robot-assisted percutaneous punctures published between January 2018 and December 2022. The final analysis refers to 53 studies in total. The results of this review suggest that image guidance and surgical robots can improve the accuracy and precision of percutaneous procedures, decrease radiation exposure to patients and medical personnel and lower the risk of complications. However, there are many challenges related to the use of these technologies, such as the integration of the robot and operating room, immature robotic perception, and deviation of needle insertion. In conclusion, image-guided, surgical robot-assisted percutaneous puncture offers many potential benefits, but further research is needed to fully understand the challenges and optimize the utilization of these technologies in clinical practice.

Keywords: percutaneous puncture; surgical robot; imaging technology; clinical practice; cancer diagnosis

1. Introduction

Cancer, a prevalent chronic disorder, has the potential to affect any organ or tissue and may disseminate to other areas of the body, finally perishing with the host [1, 2]. Despite cancer patients having a high mortality rate, multiple studies have shown that early detection is key to improving patient outcomes and increasing survival rates [3–6]. Moreover, it has been found that early detection can provide access to less invasive and more efficacious treatment options, reducing side effects and improving the quality of life for patients. Consequently, it is crucial to be cognizant of the signs and symptoms of cancer and to undergo regular screenings as advised by a healthcare provider. In the diagnosis of cancer, imaging technologies permit medical practitioners to visualize the internal structure of the body and identify abnormalities that may be indicative of cancer [7]. Some common imaging technologies used for the diagnosis of cancer include X-ray, computed tomography (CT), magnetic resonance imaging (MRI), ultrasound, and positron emission tomography (PET) [8].

While imaging technologies can identify abnormalities that may be suggestive of cancer, a definitive diagnosis of cancer can only be made through the results of percutaneous puncture, which involves the direct examination of cells or tissue for the presence of cancerous cells [9]. Depending on the location and size of the target tissue, different imaging techniques are used to guide the surgeons to position the focus and ensure accuracy. In general, the percutaneous puncture is well tolerated by patients and can be performed on an outpatient basis. However, as with any medical procedure, there is a risk of complications, such as infection, bleeding or damage to surrounding tissues [10]. There are several factors that may influence the successful execution of percutaneous puncture. For example, image-guided percutaneous puncture is the limited visualization provided by traditional imaging technologies, such as X-ray and ultrasound, which may make it difficult to accurately place the needle and avoid damaging surrounding tissues [11]. Additionally, the procedure requires superb operator skill and expertise, including precise hand-eye coordination and a thorough understanding of anatomy, which poses challenges for inexperienced operators.

In order to mitigate the risk of complications and optimize the outcome, surgical robots have been studied and applied to assist the process of percutaneous puncture. As a matter of fact, the 21st century has witnessed a wide range of technological advancements that facilitate the evolution of the surgical robot, and some of them are as shown in Figure 1 [12–16]. Advanced imaging technology has improved the accuracy of preoperative planning and intraoperative guidance, providing a clearer view of the surgical site and allowing for more precise interventions. The integration of 5G technology into surgical robots has increased the speed and reliability of data transmission during surgeries, providing real-time information to support decision-making. Improved control systems have also allowed for more intuitive and ergonomic control of surgical robots, making it easier for surgeons to manipulate the devices during procedures. Force sensors in surgical robots have increased sensitivity and precision in the application of force, reducing the risk of tissue damage and improving surgical outcomes. Assistant robots in medicine are computer-controlled devices that are designed to assist in various medical procedures and tasks. They are equipped with a range of instruments and sensors and can be programmed to perform a variety of tasks, such as handling and manipulating instruments, assisting in surgery and providing patient care [17]. When it comes to percutaneous puncture, robots can be guided by imaging technologies, such as X-ray or ultrasound, and perform precise and accurate procedures [18]. The benefits of using assistant robots in percutaneous puncture are evident. Due to many surgical robots being equipped with high-resolution cameras and other imaging technologies, they can provide a more detailed view of the internal structures of the body, leading to improved accuracy and precision during the procedure [19, 20]. In addition, surgical robots are equipped with a range of instruments that can be manipulated with a high degree of precision and stability, facilitating the successful completion of complex procedures [21]. Furthermore, the use of surgical robots in percutaneous puncture may improve patient outcomes by minimizing the invasiveness of the procedure and decreasing the need for large incisions, thereby reducing the risk of infection, bleeding and other complications [22, 23]. Overall, the impact of surgical robots on image-guided, surgical robot-assisted percutaneous puncture is significant and has the potential to make the procedure more accurate, more preciser and safer.

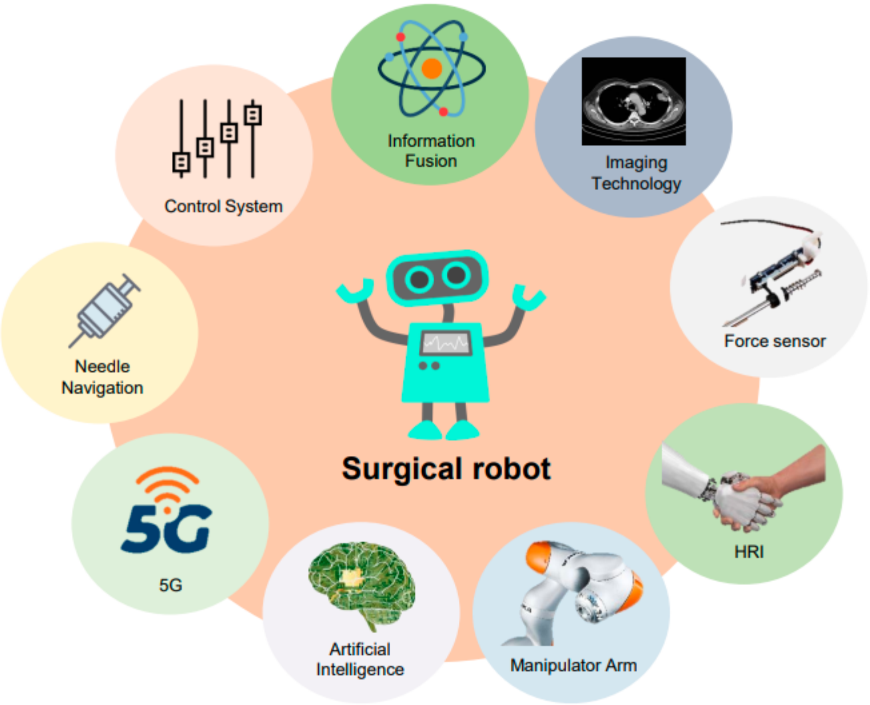


Figure 1. Technologies related to surgical robots (processed by authors).

The systematic review provides a comprehensive and up-to-date analysis of the current state of research on image-guided, surgical robot-assisted percutaneous puncture. A diverse range of studies is brought together in a systematic manner, offering a comprehensive evaluation of the benefits and challenges of advanced technologies in this medical area. The contribution of this systematic review can be summarized as follows: identification of gaps in research, improved understanding of image-guided, surgical robot-assisted percutaneous puncture and practical implications for healthcare. As far as the unique advantages of this work over other related reviews, this review is based on the most recent research, ensuring that the findings are up-to-date and relevant to current clinical practice. Moreover, the study is conducted from the perspective of the assistant surgical robot, which is innovative and groundbreaking.

2. Materials and methods

This systematic review conformed to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement [24].

2.1. Literature search

A comprehensive systematic search was conducted on December 10, 2022. The following online electronic databases were searched, including PubMed, Cochrane Library, Scopus, Web of Science and EMBASE. Due to the dramatic development of surgical robots in recent years, the review only includes the literature published over the past five years, from 2018 to 2022. Moreover, the review's scope was also restricted to surgical robots employed in percutaneous puncture. Accordingly, the search terms were as follows: ”image-guided” or ”ultrasound” or ”X-ray” or ”computed tomography” or ”magnetic resonance imaging” or ”positron emission tomography” or ”CT” or ”MRI” or ”PET” and ”robot*” and ”surgery” or ”percutaneous puncture” or ”minimally invasive surgery” or ”biopsy” or ”needle insertion”, which are the most frequently used terms or expressions in the publications. Two researchers took part in the search for the literature.

2.2. Inclusion and exclusion criteria

In this study, the inclusion criteria were (1) studies that provide empirical evidence, (2) original research, (3) published in a peer-reviewed journal in English, (4) studies that validate the effectiveness of surgical robots employed in percutaneous puncture. The exclusion criteria were (1) review articles and (2) studies that did not use robot technology. A total of 471 studies were identified through a database search. After a thorough selection, there were 56 articles satisfying the eligibility criteria.

2.3. Quality assessment

We conducted the quality assessment of the selected scholarly articles by using the Cochrane Risk of Bias tool. In addition, we consulted two senior researchers regarding the quality rating. At last, 53 studies were included to be reviewed and analyzed. The PRISMA flow diagram for this study is shown in Figure 2.

3. Results

3.1. Surgical assistant robots

Surgical assistant robots are specialized devices designed to assist surgeons in performing complex procedures [25]. These robots typically have a range of instruments, such as scalpels, forceps and suture needles, which can be manipulated with high precision and stability [25]. Surgical assistant robots are typically controlled by a surgeon who sits at a console and uses joystick-like controls to guide the instruments. The robot is equipped with a high-resolution camera and other imaging technologies, which fit the surgeon with a detailed view of the surgical field.

Surgical assistant robots are increasingly being used in various procedures, including laparoscopic surgery, neurosurgery and thoracic surgery [26–28]. There are several benefits to using surgical assistant robots in surgery, including improving the accuracy and precision of the procedure, which can lead to better patient outcomes. They can also reduce the invasiveness of the surgery, which can reduce the occurrence of complications and improve the recovery process [29]. For example, a systematic review of robotic-assisted surgery has proved the potential advantages of employing surgical robotics over standard laparoscopic approaches for patients undergoing rectal cancer surgery [30].

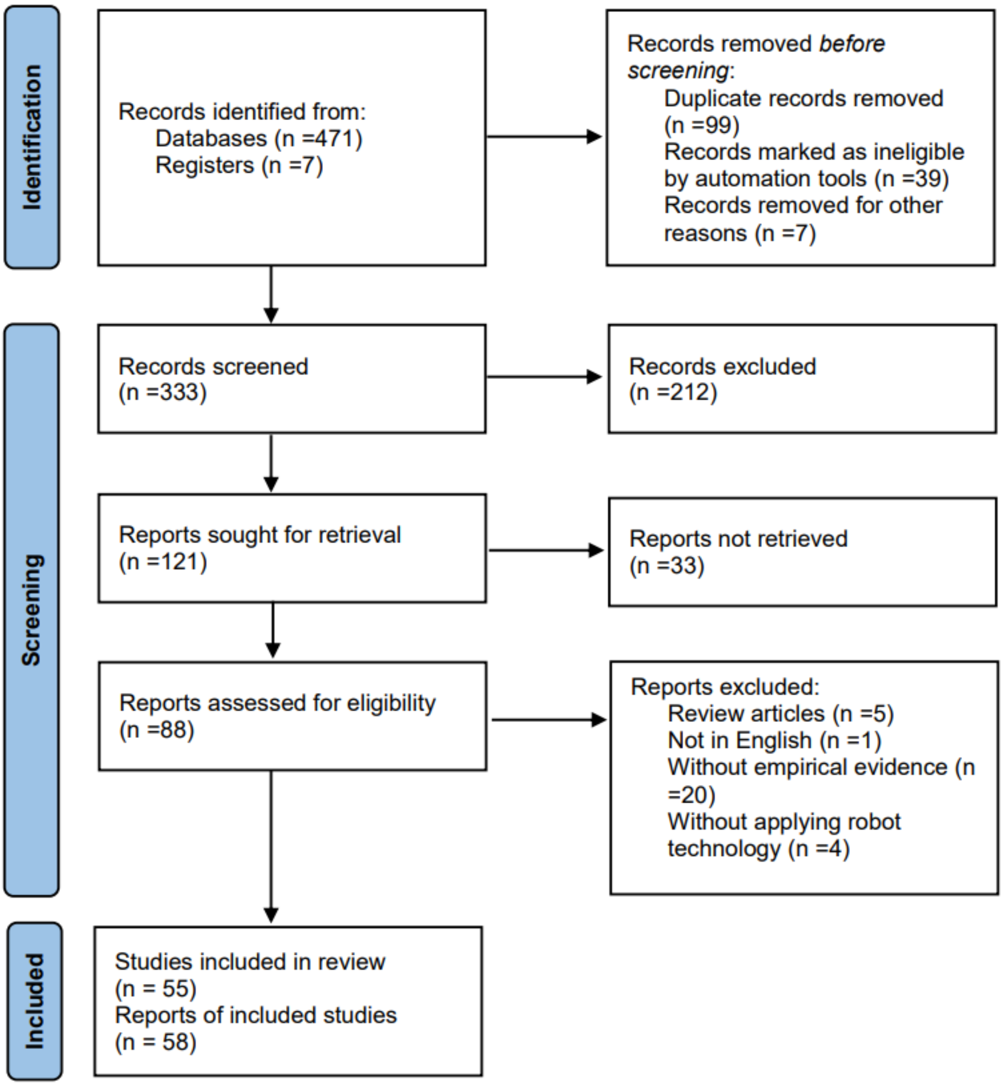


Figure 2. PRISMA flow diagram of studies on image-guided, surgical robot-assisted percutaneous puncture.

Regarding percutaneous puncture, surgical assistant robots also play a critical role. Their advanced imaging technologies allow for a more detailed view of the internal structures of the body, which can help to improve the accuracy of needle placement and minimize the risk of damage to surrounding tissues [31]. In addition, the improved dexterity and stability of the instruments can facilitate the successful completion of complex procedures. The results of the needle insertion showed improvement in both placement and orientation accuracy as compared to the outcomes obtained through a traditional, free-hand puncture method [18].

3.2. Image-guided, surgical robot-assisted percutaneous puncture

In this part, a systematic review of recent image-guided, robot-assisted surgical percutaneous punctures is made for the five primary imaging technologies of X-ray, ultrasound, PET, MRI and CT. In Table 1, we list the representative examples of the robotic system or robotic devices designed for assisting image-guided percutaneous puncture.

3.2.1. Surgical robot-assisted percutaneous puncture under X-ray guidance

Radiography, commonly referred to as X-ray, is a diagnostic imaging modality that utilizes ionizing radiation to produce visual representations of the internal anatomy. Surgical robots can improve the accuracy and precision of the percutaneous puncture through enhanced visualization. Additionally, surgical robots manage to improve the dexterity and stability of the instruments.

In percutaneous puncture, interventional radiologists can perform treatments or diagnoses based on an imaging device, such as a high-spatial-resolution CT scanner. However, to reduce radiation exposure to patients and practitioners, X-rays or low-risk radiation devices, will be used to guide percutaneous procedures. Han et al. [47] presented a method for robot-assisted needle placement using C-arm fluoroscopy, which allows for the computation of movement and evaluation of targeting accuracy with one X-ray image, resulting in reduced radiation exposure and operation time. The method has been validated for accuracy and reliability in clinical applications through pre-clinical experiments and robot-assisted pedicle screw placement surgery, whose setup is as shown in Figure 3. Because the tactile sensation of surgical robots is underdeveloped, it is inconvenient to use a robotic system in the operating room. To cope with that, Park et al. [32] renovated a robotic device with newly-developed intraoperative X-ray imaging devices, which would facilitate the localization of lesions. Besides, with endoscopic marking, their device has the potential to become a viable method in laparoscopic gastrointestinal surgery.

Mammography, a special X-ray, uses a low dose of X-ray radiation to create images of the breast tissue. These images can show abnormalities that may indicate the presence of cancer or other breast conditions. In 2021, Said et al. [48] proposed a novel approach to matching MRI and spot mammograms in order to identify breast lesions that may not be visible in traditional mammography. Initial results from one patient showed promising accuracy, with a total target registration error of 7.3 mm. By combining a biomechanical model and image-based registration, this method could enhance early breast cancer diagnosis, particularly in women with dense breast tissue. In view of the suspicious characteristics of lesions, Said et al. [49] developed their previous method so that it could optimize a matching tool. The results of their work demonstrate that image-based registration between full X-ray mammograms and spot mammograms can provide accurate matching between the images, with a

Table 1. Representative robotic systems or robotic devices described in this article (processed by authors)

System/Device	Experiments	Imaging modality	Reference
In situ ultra-low-dose X-ray imaging device	Animal experiments using ex vivo pig lungs	X-ray	[32]
Prostate coordinate system	Five clinical cases	ultrasound	[33]
Dual-armed robotic puncture system	Simulations and animal tests	ultrasound	[34]
Flexible ultrasound probe clamping device (FUPCD)	Clinical cases	ultrasound	[35]
PET-CT-guided robotic arm-assisted system	Clinical cases	PET	[36]
MRI-guided light puncture robot (LPR)	Clinical cases	MRI	[37]
Image-Guided Automated Robot (IGAR)	Clinical trials	MRI	[38]
Integrated navigation system (INS)	Phantom studies	MRI	[39]
Robotic MRI device	Clinical cases	MRI	[40]
CT-guided robotic system	Animal experiments using Yorkshire pigs	CT	[41]
Zerobot	Animal experiments	CT	[42]
Robotic assistance system (RAS)	Phantom studies	CT	[43]
Interventional robotic system	Aantom studies and animal experiments	CT	[44]
Robotic system and a tumour respiratory motion simulation platform	Simulations	CT	[45]
Advanced robot-assistant device	Cadaver studies	CT	[46]

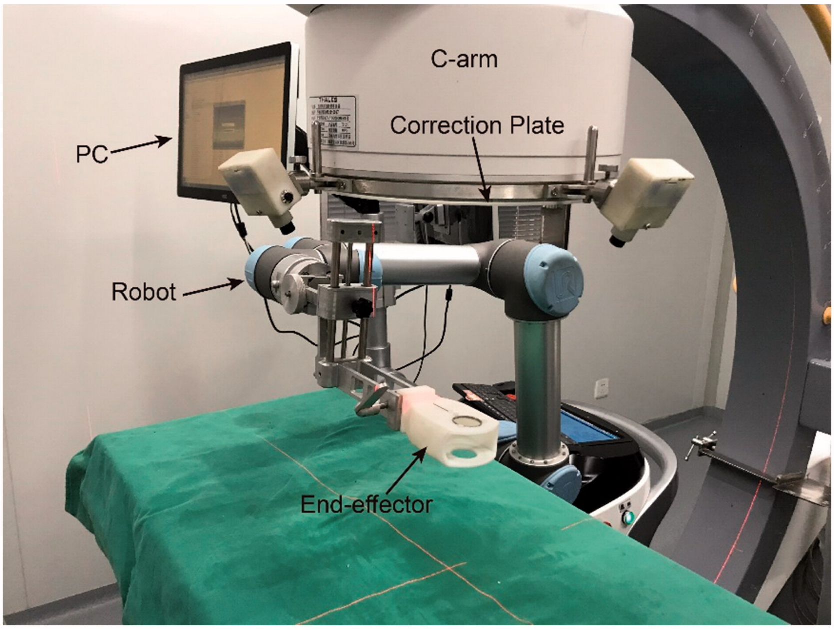


Figure 3. Pre-clinical experimental setup [47].

median target registration error of 21.7 mm and a standard deviation of 9.3 mm.

Although X-ray is widely available and easy to access, as well as inexpensive, X-ray imaging is seldom used in percutaneous puncture procedures because of its limited visualization. However, it should be noted that mammography is widely used to guide percutaneous breast puncture. Assisted by a robotic system, the precision and accuracy of X-ray image-guided percutaneous puncture can be improved.

3.2.2. Surgical robot-assisted percutaneous puncture under ultrasound guidance

Ultrasound is a medical imaging technique that transmits high-frequency sound waves to capture images of the internal body and it is usually used to guide the placement of a needle or other instrument during the percutaneous puncture. The application of robots in ultrasound-guided percutaneous puncture not only allows for them to be programmed to make repeatable movements, but it also helps to help reduce operator fatigue. With the aid of robots, medical professionals are able to perform more complex procedure.

A great number of robotic systems have been developed to assist with ultrasound-guided percutaneous punctures. For a transrectal ultrasound-guided prostate biopsy, a novel robot-assisted technique was proposed [33]. In total, five clinical cases were conducted with minimal prostate deformations, which signified that the prostate biopsy is practicable and safe with the assistance of the robot. In 2020, Welleweerd et al. [50] presented a novel robotic system and methodology that aids radiologists in targeting magnetic resonance (MR)-detected breast lesions using ultrasound guidance, the setup of which is as shown in Figure 4. The system accounts for tissue deformations and offers a high degree of accuracy. The proposed workflow was demonstrated on a breast phantom, with results indicating that lesions as small as 2.9 mm in radius can be successfully targeted. Around a year later, Chen et al. [18] developed another robotic system and evaluated it by performing five groups of puncture tests.

The results showed that the robotic system was able to improve the accuracy and reduce the number of needle insertions relative to free-hand punctures. A novel robotic control scheme for ultrasound imaging was proposed, and it could optimize the image quality of the ultrasonogram by utilizing variable impedance control [51]. The experimental results revealed the feasibility of the proposed approach and foresaw that the investigation could positively influence current ultrasound image-guided procedures. To enhance the success rate of renal puncture surgery, Gao et al. [34] developed a robotic puncture system with two arms, i.e., an ultrasound scanning arm and a puncture arm, both of which have a compliant positioning function and master-slave control function.

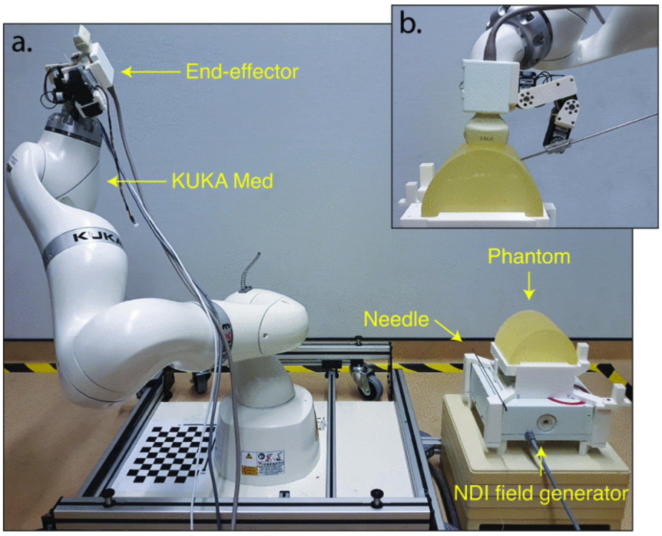


Figure 4. Robitic setup [50].

Apart from various studies on the design of the robotic system, there are also novel strategies for optimizing the implementation of the robotic system. Two robust optimization strategies were proposed to optimize the automatic placement of an ultrasound robot in radiation therapy [52]. The experimental results showed that the automatic scheme could facilitate collaboration with the robot setup. In light of the complexities associated with integrating robots into the operating room and the limited opportunities for doing so, Berger et al. [53] devised and confirmed a medical robotic device system to assess and regulate the cooperation of two KUKA robots during ultrasound-guided needle insertions, as shown in Figure 5.

As a result of increased accessibility to population-based screening for breast cancer, the number of related studies on robot-assisted breast biopsies has increased significantly [54]. In [55], Welleweerd et al. designed an end-effector tool for a robotic arm that helps with performing ultrasound-guided biopsies on the breast with high accuracy. Thereafter, the system was validated on a cuboid phantom and achieved a needle placement accuracy of 0.3 1.5 mm in and 0.1 0.36 mm out of the US plane and a Euclidean distance error of 3.21 mm between the needle tip and the target, while the radiologist maintained control over the procedure like in the traditional method. In order to enhance breast ultrasound imaging, Tan et al. [35] proposed a flexible and robotic ultrasound scanning system. The proposed system is a successful implementation that can streamline the breast ultrasound examination, optimize the ultrasound imaging system and promote the stability and repeatability of the ultrasound image by stabilizing the contact force.

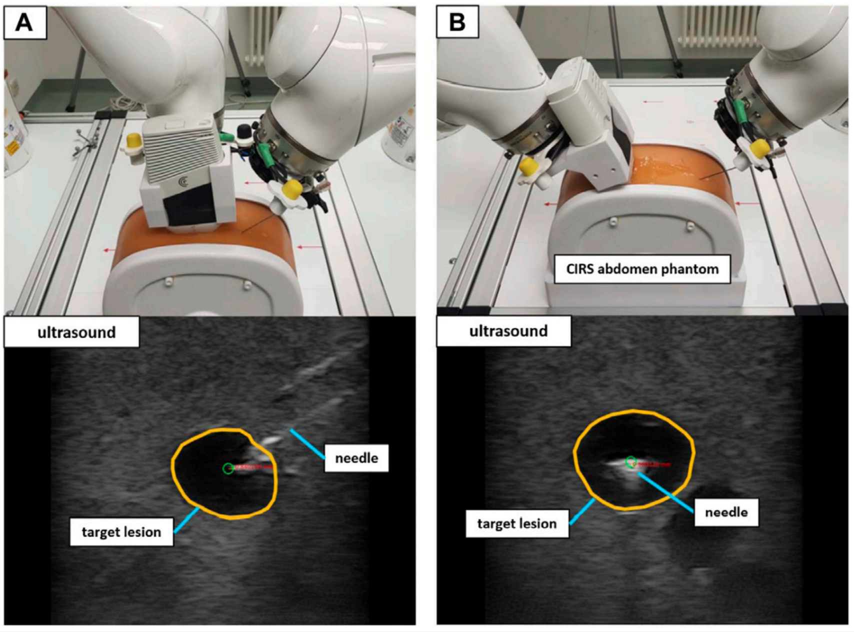


Figure 5. Validation setup to puncture lesions inside an abdominal phantom with trajectory hand guidance. Shown are the in-plane positioning (A) and orthogonal positioning (B) for the same target lesion. The green circle marks the planned needle tip position [53].

3.2.3. Surgical robot-assisted percutaneous puncture under PET guidance

PET is a medical imaging technique that utilizes a small amount of radioactive tracer to create detailed images of the body's metabolism and physiological functions. It can be used in conjunction with CT to create images that show both the structure and function of the body's tissues and organs [56]. The tracer used in the percutaneous puncture emits positrons, which are detected by the scanner and used to create images of the target area. Surgical robots can enhance the image quality by reducing the amount of motion artifacts in images.

By reviewing recent surgical robot-assisted percutaneous punctures with PET, it can be easily found that PET is often used in conjunction with CT. In [57], the feasibility of using an automated robotic arm (ARA) for Ga-68 labeled tracer PET/CT-guided biopsies were evaluated. Thirteen patients underwent the procedure, with diagnostic results yielded in all cases, and no immediate complications were observed. The study found that utilizing ARA-assisted Ga-68 tracer PET/CT-guided percutaneous real-time sampling provides a technically feasible diagnostic method, with a notably high yield, particularly in individuals exhibiting focal abnormal tracer uptake. In [58], Kumar et al. conducted a prospective study that evaluated the feasibility of using an ARA, in combination with PET and CT, for percutaneous biopsies of lesions that appear bright on Ga-68 scans; they compared its accuracy and safety to a manual biopsy. The study included 25 patients with a 100% diagnostic yield, and the results showed no immediate or delayed procedure-related complications. Due to the high energy of the annihilation radiation, shielding measures are indispensable to protect the personnel who perform PET biopsies. Lakhanpal et al. [36] found that the mean whole-body exposure per procedure to the interventionist and an assistant was 1.88 0.82 μ Sv and 1.04 0.75 μSv, respectively, with the assistance of robotic arm. The results showed that the PET/CT-guided biopsies were safe from a radiation protection point of view. Three years later, Deva et al. [59] did a similar study that evaluated the radiation exposure to patients undergoing PET/CT-guided biopsies; they found that PET/CT-guided biopsy was a safer interventional procedure than routine whole-body PET/CT imaging.

Above all, robotic assistance in PET/CT-guided percutaneous puncture provides a high diagnostic yield with no immediate complications and minimal radiation exposure, making it an invaluable tool for medical professionals. Moreover, the combination of PET and CT can not only provide more detailed internal structure diagrams, but it can also identify and diagnose the physiological condition of the target tissue.

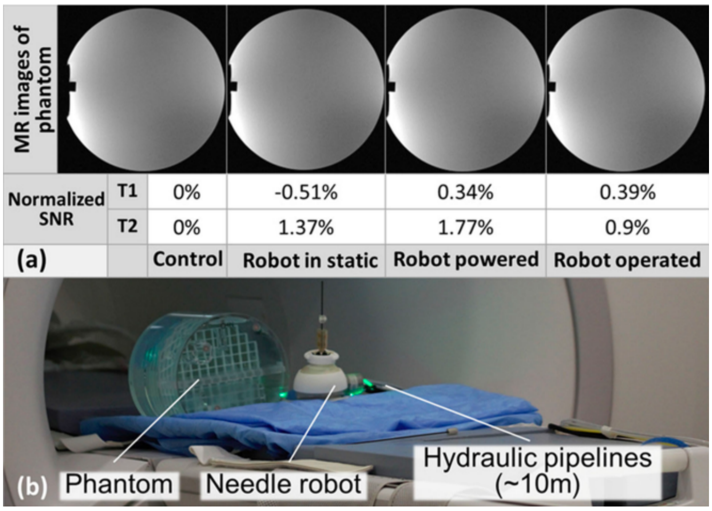
3.2.4. Surgical robot-assisted percutaneous puncture under MRI guidance

As a medical imaging technique, MRI combines a magnetic field, radio waves and computer processing to produce high-contrast images of the inside of the body. By analyzing the information provided by the MRI images, the surgical robots can be programmed to position the needle with high precision, minimizing the chance of complications or errors.

Many MRI-guided robotic systems have been developed to increase the accuracy of intra-tumor probe placement and decrease the risk to patients. In general, iterative positioning and imaging are involved due to insufficient physician grasp on patients in the MR scanner bore, which may increase the risk to patients. To this end, Mendoza and Whitney [60] designed a robust teleoperated system and instrumented testing platform for robotic MRI-guided percutaneous puncture, and it showed promising performance. Percutaneous ablation is a typical therapy for curing hepatocellular carcinoma. In this way, how to place the intra-tumor probe precisely matters. For MRI-guided percutaneous needle practices, He et al. [61] designed a semi-automated robotic system where valid needle navigation was accomplished with an error of 0.89 0.31 mm, and they conducted relevant MRI-compatibility testing, whose results and setup are as shown in Figure 6. Patel et al. [62] designed and implemented a robotic system for transperineal prostate biopsy guided by MRI directly. Preclinical evaluation of the system was performed using phantom studies in a 3-T MRI scanner, demonstrating an in-plane targeting error of 1.5 mm. Besides, a preliminary clinical study was conducted with patient consent, with the targeting errors at two biopsy target sites being 4.0 mm and 3.7 mm, which is adequate for targeting clinically significant tumor foci.

In terms of the assistant robots in MRI-guided percutaneous puncture, many researchers have put forth an effort to evaluate their performance. In [37], Ghelfi et al. evaluated the accuracy of an MRI-guided light puncture robot (LPR) in placing a needle and found the LPR accuracy to be satisfactory. In [63], Patel et al. found that MRI-guided robotic-assisted targeted biopsies (RA-TB) resulted in higher cancer detection rates than cognitive targeted biopsies (C-TB) for clinically significant prostate cancer and any other cancer, and the results still stood as the score of regions of interest ascended, as is presented in Figure 7. Additionally, RA-TB resulted in fewer complications and shorter biopsy times, suggesting the benefits of using the robotic procedure. However, Sandahl et al. [64] compared the detection rates of prostate cancer between manually operated and robot-assisted in-bore MRI-targeted biopsy, and they detected no statistically remarkable difference in the detection rates of prostate cancer between the two methods.

As far as MRI-guided brain biopsies, Giannakou et al. [65] developed and tested a robotic system that utilizes MRI guidance for brain biopsy and, potentially, brain cancer ablation, by incorporating a



Normalized SNR		Control	Robot in static	Robot powered	Robot operated
	T1	0%	-0.51%	0.34%	0.39%
	T2	0%	1.37%	1.77%	0.9%

Figure 6. (a) MR images of an MRI phantom put beside the robot showing the negligible EM interference under four operating conditions. The normalized SNR results are summarized in the table. (b) Experimental setup of the robot in the 1.5T MRI scanner [61]

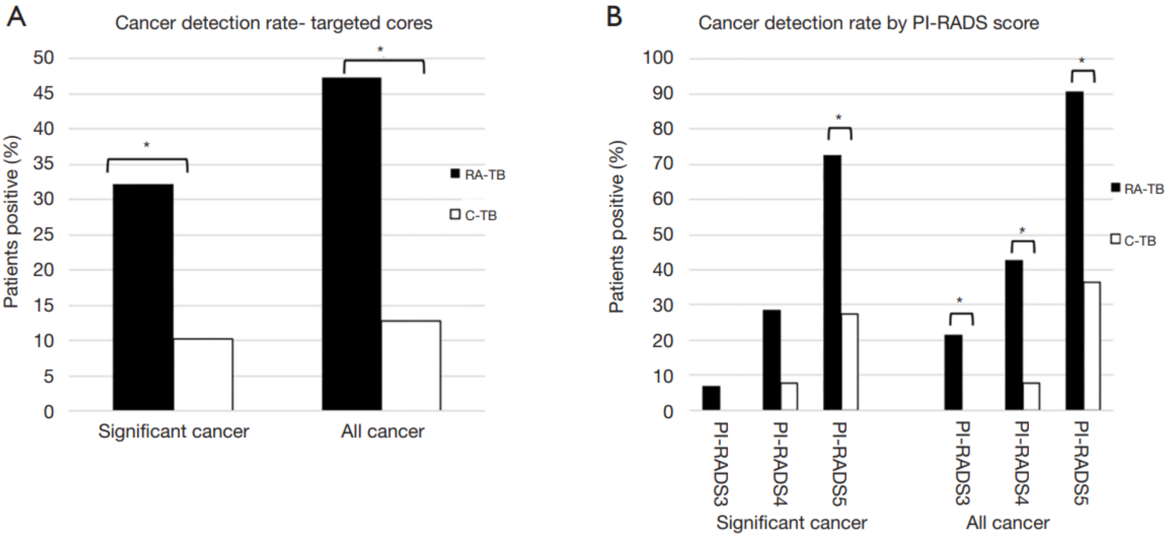


Figure 7. Cancer detection rates from (A) targeted cores stratified by significant and all cancers and (B) from targeted cores stratified by the PI-RADS score and by significant and all cancers. *, P<0.05. RA-TB, robotic-assisted targeted biopsy; C-TB, cognitive targeted biopsies; PI-RADS, Prostate Imaging Reporting and Data System [63]

small rectangular unfocused ultrasonic transducer. In the case of the agar-based phantom, the system was demonstrated to have the potential to perform frameless brain biopsy and potentially ablate small and localized brain tumors in the future. Johnston et al. [66] designed a robotic MRI/CT fusion biopsy method using a specially designed interventional phantom. The technique was tested, and the results showed that it was highly accurate, reliable and practicable in clinically acceptable timescales, making it suitable for clinical application.

Numerous studies have demonstrated growing attention and interest from the research community toward robot-assisted MRI-guided breast biopsy. A new cable-driven robot for MRI-guided breast biopsy has been designed and implemented; it has a compact three-degree-of-freedom semi-automated robot driven by ultrasonic motors, a novel insertion trajectory planning algorithm and kinematic analysis and accuracy compensation methods to improve accuracy [67]. An experimental study was conducted to verify the execution of the new robot, with conclusions showing an average position accuracy of 0.7 0.04 mm. In 2022, Anvari et al. [38] evaluated the safety and efficacy of an image-guided automated robot (IGAR) in performing breast biopsies compared to manual procedures. It can be concluded that the IGAR system is safe and efficient and could be a feasible option for manual breast biopsy procedures. Song et al. [39] developed an integrated navigation system based on a grid-shaped dedicated breast support device to assist doctors in MRI-guided breast biopsy, with the aim of increasing accuracy and reducing the procedure time. The robotic system was tested in experiments and found to be feasible and accurate, with a latency of 0.30 0.03 s and puncture error of 1.04 0.15 mm. An automated robot support technology, called IGAR for MRI-guided breast biopsy, was developed as a therapeutic method for breast cancer [68]. The robot is safe for use in an MRI environment and can accurately locate lesions, reducing tissue injury and the risk of false negatives. The IGAR system is unique, as it is compliant with MRI, maintains safe operation, proper protection, high image quality and high accuracy, even in an imaging environment.

Transrectal MRI-guided biopsy is a type of biopsy procedure that is used to diagnose prostate cancer. Many researchers have dedicated themselves to evaluating the benefits of robotic-assisted percutaneous puncture. By analyzing the needle path during the procedure, the performance of robot-assisted MRI-guided prostate biopsy was evaluated, and the findings are expected to improve preoperative planning of transperineal prostate biopsies [69]. As for prostate biopsies in a Chinese population, the use of semi-robotic navigation in combination with multiparametric MRI and transrectal ultrasound was examined; the initial results of this approach were presented [70]. Barral et al. [71] analyzed the feasibility and potential role of robot-assisted transrectal MRI-guided biopsy for the diagnosis of prostate cancer with a sample of 57 patients. The findings demonstrate that the procedure exhibited a 100% technical success rate, a brief occupancy time within the MRI room, a high rate of cancer detection through the utilization of either one or two cores and a complete absence of any adverse events. Later, Vilanova et al. [40] evaluated the potential clinical and technical utility of using a robotic MRI-guided in-bore prostate biopsy in the current diagnosis of prostate cancer. In total, 30 patients with a single cancer-suspicious lesion interpreted on MRI using PI-RADS version 2.1 category ≥ 3 underwent an in-bore robotic transrectal MRI remote-controlled-guided biopsy. The authors found a cancer detection rate of 73% and reported that all lesions were reachable with the robotic MRI device, and that the procedure was efficient and feasible with one self-limited rectal hemorrhagic complication reported. These studies indicate that the use of robotic assistance in MRI-guided prostate biopsy has been the most widely researched topic within the field.

In summary, the use of robotic assistance in MRI-guided percutaneous puncture has been shown to have potential benefits in increasing accuracy and reducing procedure time in the biopsy, especially for breast biopsy and prostate biopsy. Studies have also demonstrated that the robot is safe for use in an MRI environment and can accurately locate lesions, reducing tissue injury and the risk of false negatives. Additionally, robotic surgery in tissue repair and regeneration has been found to have potential benefits, such as an increased accuracy of skin flaps and a shorter harvest time, as well as minimal tissue trauma and scarring. However, it is important to note that the technology is still under development, and that more research is needed to confirm the benefits and potential limitations of using robotic assistance in MRI-guided percutaneous puncture.

3.2.5. Surgical robot-assisted percutaneous puncture under CT guidance

CT is a medical imaging technique that combines X-rays and computer processing to create detailed cross-sectional images of the internal body. In percutaneous puncture, surgical robots allow the operator to control the procedure in a remote mode, which can be of particular importance in procedures where the patients might be unable to move or there is higher risk [46, 72].

By using a CT-assisted robot system, precise needle puncture can be achieved in the treatment of percutaneous fractures, but there is still a certain risk. Ben-David et al. [41] assessed the accuracy and precision of a CT-guided robotic system for percutaneous needle insertions in common target sites such as the retroperitoneum, kidneys, liver and lungs by using a small, patient-mounted, CT-guided robotic system with five degrees of motion in a porcine model. In their test, an overall targeting accuracy of 1.2-1.4 mm was reached, with the system compensating for 52.9% of intraprocedural target movement, and 91% of the target being achieved with a single insertion. Numerous evidence has suggested that using a CT-guided robotic assistance system is beneficial for performing needle insertions in cases of metastatic carcinoma of the vertebrae. However, the risk of bone fracture should be noticed. Nagao et al. [42] proposed a method for measuring the angle offset of the robot by using CT equipment and a compensation method to prevent injury to surrounding areas during the procedure, with effectiveness being confirmed through experiments which led to the development of a surgery support robot, dubbed 'Zerobot', to minimize the radiation exposure to the doctor. Levy et al. [73] designed a CT-guided robotic approach that is capable of precise needle positioning with an error of less than 2 mm. In [74], a swine kidney model demonstrated that robotically aided needle insertion was feasible, safe and precise, but complications are still inevitable. A multistage retractable needle guide unit was developed to overcome the risk, which made the robotic assistance system a useful tool for precise needle insertion during percutaneous vertebroplasty treatment [75].

Guided by cone-beam CT, a novel robotic assistance system for percutaneous needle placement was assessed by performing 16 needle insertion trials, with a mean deviation of 2.14 mm in depth and a mean deviation of 2.74 mm between needle tip position and target point [43]. The results showed that the proposed robotic assistance system was accurate and efficient. In 2022, Chen et al. [44] developed an automated robotic system and evaluated its precision and safety. Animal experiments were conducted in the swine lung, showing that CT-guided robotic operation is comparable to manual operation in terms of accuracy and is superior to manual needle insertion in terms of radiation exposure, confirmatory scans and the number of needle insertions. A commercially CT-guided robotic assistance machine for percutaneous puncture was evaluated by a clinical experiment that included 55 patients [72]. Compared with manual needle insertion, the device with robotic assistance reached a minor mean deviation in a shorter mean intervention time. At the same time, the radiation exposure to the physician was cut down to zero when applying the robotic navigation system. Human trials are usually hard to implement, unlike regular phantom and animal trials. However, Hiraki et al. [76] conducted a prospective and first-in-human experiment to evaluate the performance of biopsy introducer needle insertion with robotic assistance. Finally, the robotic insertion was verified to be feasible and safe.

Among specific cancer diagnoses in different parts of the body, CT is most frequently used to guide the needle biopsy in the lung and diagnose lung cancer. To diagnose the lesion in the lung, Zhang et al. [77] developed a lesion positioning method by using three noncollinear markers and an omnidirectional needle positioning method with virtual remote center of motion technology. In vitro experiments were conducted, and the findings showed that the accuracy of the lesion positioning method was within 3 mm and the average calculation error was 0.997 mm, with improved positioning efficiency by about 40%, demonstrating that the designed surgical robot can provide a good precision basis for robot-assisted puncture surgery. Due to respiratory motion, it is hard to realize effective puncture procedures for lung tumors. Therefore, Wei et al. [78] proposed a robotic needle insertion technique for velocity adjustment to enhance the visualization of lung puncture, which lessened respiratory motion's effect on accuracy (Figure 8). With the same purpose as the previous study, Lei et al. [45] constructed a robotic system and a tumor respiratory motion simulation platform to cope with inconsistent breath-holding. Contrastive experiments were done, proving that the novel method can enhance the precision and efficiency of puncture operation. To assess the precision and feasibility of a robotic system in combination with CT under the condition that the mechanical arm can implement automatic trajectory execution, Fong et al. [79] conducted a trial in a porcine lung and acquired an overall accuracy of 1.36 mm 0.53.

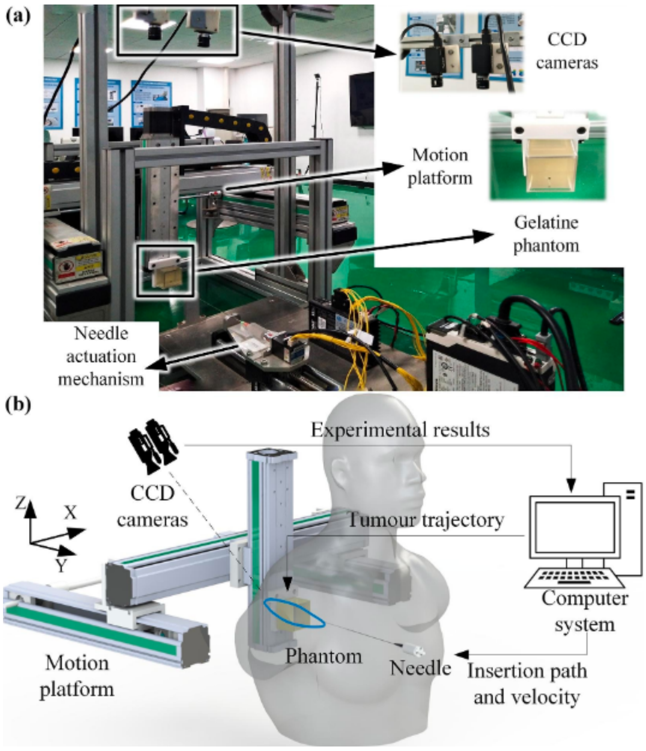


Figure 8. Environment of the phantom experiment (a) and the experimental scheme (b) [78].

Moreover, robotic assistance also facilitates percutaneous needle placement in the liver. In 2021, Guiu et al. reported a study regarding the impact of robots on CT-guided percutaneous needle placement [80]. In order to validate the feasibility, safety and accuracy of the robot's operation, a swine liver model was used to conduct experiments. It should be mentioned that the trajectory angulations, trajectory length and operator experience had no bearing on accuracy. During the thermal ablation of liver tumors, robots also play a critical role in needle insertion, as proved by a bicentric pilot study and a randomized controlled experiment [81, 82]. Apart from the thermal ablation of liver tumors, another similar study concluded that robotic insertion of various ablation needles under CT guidance was accurate regardless of needle type or location in the swine, such as a kidney, lung or hip muscle, and the experimental device is as shown in Figure 9 [83].

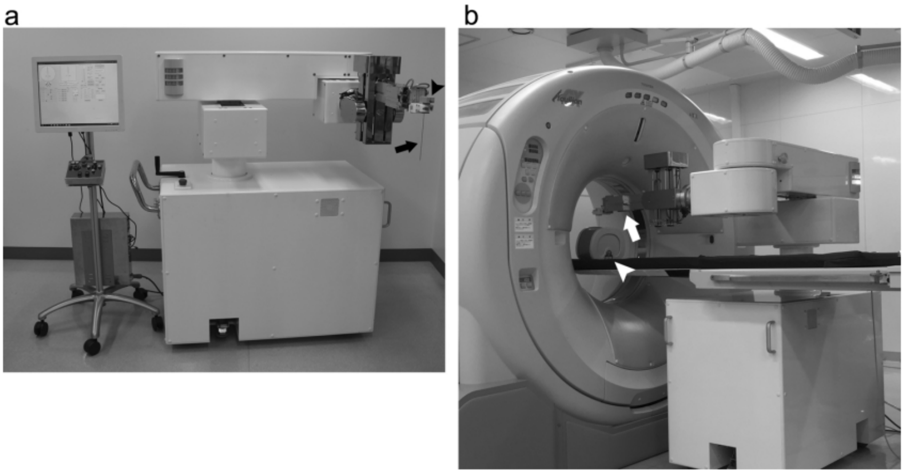


Figure 9. Photographs of the robot used for the insertion of ablation needles in swine. (a) The robotic system comprises a robot (right) and an operating interface (left). Attached to the end of the robot arm is the needle holder (arrowhead), to which the ablation needle (arrow) is attached. (b) The robot is set to the CT table with its arm (arrow) inside the CT gantry. The arrowhead indicates a phantom [83].

In the CT-guided diagnosis of other parts of the body, robots also play an important role. Burovik et al. [84] describes the first experience of using a CT-guided robotic system for percutaneous interventions, specifically the biopsy of an adrenal tumor and cryoablation of a renal cell carcinoma, and they found that it was convenient, effective and safe to use. In [85], Kumar et al. evaluated the performance of PET/CT-guided percutaneous biopsy that received assistance from an ARA. Clinical experiments for pelvic and abdominal lesions were conducted, demonstrating the ARA-based percutaneous biopsy's efficiency, precision and safety. If lesions occur inside the thorax, the assistant robot also contributes to the diagnostic yield of CT-guided percutaneous puncture [56]. Clinical trials have proved that robot-assisted CT-guided biopsy is a reliable method for diagnosing intrathoracic neoplasms, which resulted in minimal complications. Another clinical trial was conducted to evaluate the accuracy and feasibility of robot-assisted stereotactic biopsy for a neurosurgical procedure [86]. Clinical results showed that the robot-assisted technique is useful and effective in stereotactic neurosurgery. As for image-guided percutaneous K-wire insertion in the spine, Croissant et al. [46] evaluated the accuracy and time requirements associated with using an advanced robot-assisted device. The study utilized a cadaveric specimen, and the results demonstrated the successful completion of all procedures without any incidents of pedicle wall perforation. Additionally, the study revealed a high level of accuracy in robot-assisted K-wire insertion during spinal interventions while minimizing the operator's exposure to radiation.

4. Discussion

X-ray, ultrasound, PET, MRI and CT are primary imaging modalities that can be employed to facilitate percutaneous puncture interventions. Nevertheless, each modality has its own advantageous and disadvantageous aspects. When evaluating potential robotic systems for image-guided percutaneous puncture procedures, the selection of imaging technology can profoundly affect the efficacy and functionality of the system.

X-ray is a widely available and inexpensive technology that can demonstrate the internal structures of the body in images. Robotic systems that use X-ray imaging typically involve a robotic arm that is equipped with a fluoroscope, which is used to guide the procedure [47]. However, due to its limited visualization capabilities and the poor soft tissue contrast, it is difficult to accurately identify certain structures. Ultrasound is particularly useful for visualizing soft tissues, but it can be limited in its ability to visualize deep structures or those obscured by bone. Robotic systems in ultrasound-guided percutaneous punctures are able to improve accuracy and reduce the number of needle insertions relative to free-hand punctures [18]. In particular, robotic technologies have been widely employed in the workflow of breast examinations. In terms of surgical robots for PET-guided percutaneous puncture, previous studies showed that PET/CT-guided biopsy is a technically feasible method with a high diagnostic yield, with no immediate complications and low radiation exposure [57]. When it comes to PET techniques, studies have found that robot-assisted targeted biopsies result in higher cancer detection rates [63]. MRI provides detailed images of internal organs and tissues; however, it can be time-consuming and expensive, and it may cause discomfort or anxiety for some patients due to the confinement of the MRI machine. The integration of surgical robots with MRI provides improved accuracy and precision in the targeting of lesions, leading to increased patient safety and improved clinical outcomes [67]. Finally, CT-guided robotic systems are being developed well. These systems can provide high-resolution images and detailed information about the target lesion and anatomy. Moreover, robot-assisted needle placement procedures have been demonstrated to be an accurate, safe and effective method for various diagnoses and treatments, such as those for lung and liver cancers. However, the high dose of ionizing radiation and the high cost of CT scanners make them less accessible.

Integrating robotic technology and imaging equipment into a surgical environment can be a complex task, necessitating collaboration between the surgical team, imaging team and robot operator [53, 87]. Furthermore, certain imaging modalities used in robot-assisted procedures, such as X-ray and CT, may expose patients and surgeons to ionizing radiation, which can be detrimental [32]. Additionally, deviation of needle insertion, caused by poor robot perception and tissue deformation, is another challenge commonly encountered during these procedures [32]. The future of image-guided, surgical robot-assisted percutaneous puncture lies in improving robot perception and needle insertion accuracy and minimizing exposure to radiation. Research efforts are focused on developing strategies to reduce errors in robot perception, including the use of advanced imaging modalities and real-time feedback systems. Additionally, there is growing interest in exploring the potential of artificial intelligence and machine learning algorithms to improve robot accuracy and reduce exposure to ionizing radiation [88].

Based on a systematic review of more than 50 pertinent studies, we have ascertained the advantages of utilizing robotic systems for percutaneous puncture to be higher accuracy and precision in both lesion localization and puncture implementation, a decrease in radiation exposure for patients and medical personnel and a reduction in the risk of complications. Challenges associated with this field include the combination of the robot and operating room, poor robotic perception and deviation of needle insertion. These findings can be utilized to inform clinical operations and future research. However, there are several limitations associated with conducting the systematic review. For example, despite efforts to search multiple databases and sources, there is always a risk of missing some important studies that could have an impact on the results of the systematic review. Therefore, further research is needed to fully understand the benefits and limitations of image-guided, surgical robot-assisted percutaneous puncture.

5. Conclusion

This systematic review examines a subset of literature on the utilization of robotic systems incorporating imaging technology to facilitate percutaneous puncture, and it elucidates the advantages and difficulties associated with robotic assistance. Image-guided, surgical robot-assisted percutaneous puncture has been demonstrated to have potential advantages over more traditional, manually performed procedures, including increased accuracy and efficiency, as well as reduced risk of complications and physical strain on the operator. Advanced imaging modalities such as ultrasound, CT and MRI can provide detailed, high-resolution images to aid in the diagnosis and treatment of various conditions. Despite certain challenges associated with this procedure, such as integration of the robot and surrounding environment, inadequate robotic perception and variable needle insertion, with appropriate training and further exploration, image-guided, surgical robot-assisted percutaneous puncture can be a valuable asset in a surgeon's resource pool.

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Conflict of interest

The authors declare that there is no conflict of interest.

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