

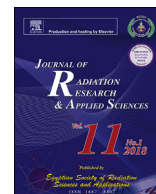


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## Evolution of Robot-assisted ultrasound-guided breast biopsy systems

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## ABSTRACT

Robot-assisted ultrasound-guided breast biopsy combines ultrasound (US) imaging with a robotic system for medical interventions. This study was designed to provide a literature review of a robotic US-guided breast biopsy system to delineate its efficacious impact on current medical practice. In addition, the strengths and limitations of this approach were also addressed. Articles published in the English language between 2000 and 2016 were appraised in this review. A wide range of systems that bind robotics with US imaging and guided breast biopsy were examined in this article. The fundamental safety and real-time imaging capabilities of US, together with the accuracy and maneuverability of robotic devices, is clearly an effective association with unmatched capabilities. Numerous experimental systems have obvious benefits over old-fashioned techniques, and the future of robot-assisted US-guided breast biopsy will be characterized by increasing levels of automation, and they hold tremendous possibility to impact doctor achievement, patient recovery, and clinical management.

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## 1. Introduction

Breast malignancy and other breast complaints, particularly in females, present considerable health risks for all humans around the world. Breast cancer is the second most commonly diagnosed cancer in the world and the most common among women. An estimated 1.67 million new cancer cases were diagnosed in 2012, representing approximately 25% of all cancer cases (Ferlay et al., 2015). Breast cancer is growing strongly in South America, Africa and Asia. Studies show that early detection of breast cancer has an important role in reducing the mortality rate and improving the prognosis of the disease (Rahimzadeh, Baghestani, Gohari, & Pourhoseingholi, 2014). In developed countries, more than 50 percent of eligible women are being screened but in these countries, immigrant women and the ones who have low economic status are being deprived of screening (Vahabi, Lofters, Kumar, & Glazier, 2015). Breast cancer constitutes the most frequent

malignancy among American females, and it is the second-leading cause of cancer deaths in women; however, the early detection of this cancer has been shown to diminish mortality by about 20%–35% (Elmore, Armstrong, Lehman, & Fletcher, 2005). In 2008, the American Cancer Society (ACS) estimated that 182,460 females will be diagnosed with breast malignancy and that 40,480 females will die of breast malignancy in the United States alone. One in eight women is likely to be diagnosed with breast malignancy at some point in her life. Although these results are discouraging, there have been positive developments in diagnostic and therapeutic innovations over the past decade (Desai & Gullapalli, 2009).

The maximum effectiveness of the diagnostic precision in breast cancer is accomplished by three approaches: clinical investigation, imaging with fine-needle aspiration cytology (FNAC), and a core biopsy of suspected abnormal breast tissues (Tanaiutchawoot, Treepong, & Wiratkapan, 2014). Of the two main approaches to breast biopsy FNAC and core biopsy FNAC is the most frequently practiced due to the fact that it is quick, secure, accurate, affordable, less vulnerable, it generates slight or no scars, it is associated with a quicker recovery, and the outcomes compare well with the results of tissue biopsy when the FNAC is executed by an expert practitioner. However, given that few experts accomplish and render FNAC, and even fewer are also available for on-site sufficiency assessments, the usage of core needle biopsy has increased for deep-

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seated non-palpable lesions, and for palpable masses in the breast, thyroid, lymph nodes, and soft tissue (Berner, Davidson, Sigstad, & Risberg, 2003).

Needle biopsies are directed by either stereotactic mammography, magnetic resonance imaging (MRI), or ultrasound (US) imaging. Among these, US is the most extensively applied imaging technique due to its real-time capabilities and cost effectiveness (Mallapragada, Sarkar, & Podder, 2008). However, breast biopsies are accomplished with handheld and stereotactic biopsy procedures, which are operator dependent; moreover, they require extensive training standards, are difficult to regulate, and they are more challenging to perform when smaller lesions are found. As a result, handheld diagnostic methods do not always yield ideal results. Thus, the early discovery of breast malignancies requires more accurate and precise instruments (Nelson, Tran, Fakourfar, & Nebeker, 2012). Despite the numerous advantages of needle biopsy, US-guided biopsy techniques are highly dependent on a doctor's expertise. Furthermore, as the needle is inserted, the mass tends to move away from the line of insertion given the huge transformation of the breast tissue. If the mass moves out of the plane of the US transducer, the doctor has to continuously reorientate the US transducer to keep the needle and the target in the imaging plane, while also introducing the needle into the tissue. In addition, since stabilization of the breast is problematic, and steering the needle within the breast is extremely difficult to achieve, many insertion efforts may be needed to properly sample the mass. This may harm the architecture of the breast tissue, resulting in excessive hemorrhaging, obscuring the guiding images, and resulting in operator fatigue and pain for the patient (Mallapragada et al., 2008).

Over the past two decades, robotic systems have been integrated with US imaging to facilitate the discovery and management of breast cancer; these systems have been of increasing interest within the medical and research communities (Morris, 2005). The benefits of robotic manipulators can be applied to improve the acquisition and usage of real-time US (Fenster, Downey, & Cardinal, 2001). In addition, robots are able to precisely trace and handle the US transducer, and they can also produce uniformly spaced slices, facilitating three-dimensional (3D) volume reconstruction that is greater than that of unassisted or free-handed techniques. Moreover, these robots were not subjected to human afflictions such as hand tremors, fluctuating relevancy forces, or lapses in concentration, which often confound the results of lengthy US examinations (Priester, Natarajan, & Culjat, 2013). US-guided robots have been shown to prevent error bias while reducing the degree of invasiveness when compared with manual needle insertion (Boctor, Choti, Burdette, & Webster III, 2008). Therefore, breast biopsy is an ideal pursuit for robotic procedures. Table 1 summarized the advantages and drawbacks of these different breast biopsy techniques.

Since the start of the current millennium, there has been a significant breakthrough in RUS, particularly when applied to breast biopsy. Therefore, this paper reviews the current RUS-guided breast biopsy systems and it delineates their efficacious impact on modern medicine.

## 2. Literature review

An inclusive literature review was conducted to revise the scientific foundation of RUS-guided breast biopsy, as well as to describe its powerful impact on modern medicine. In addition, the strengths and limitations of these approaches are also addressed.

The ScienceDirect, PubMed, MEDLINE, National Center for Biotechnology Information (NCBI), and SAGE databases were searched in January 2017 for publications containing information about RUS-guided breast biopsy for the purpose of this report.

Abstracts arising from this search were reconsidered for their applicability to the clinical outcomes associated with the procedure. Full manuscripts were retrieved and considered for inclusion if they featured data that evaluated the evidence on the role of RUS-guided breast biopsy and assessed the possible impact of this approach on modern medicine, and if clinical literature was published on this topic.

Only those studies published between 2000 and 2016 were included in the outcomes analysis; this was due to the tremendous evolution of the association between US imaging and robotic systems that occurred in medical interventions at the beginning of the new millennium. With respect to the location of the research or the types of journals included in this study, all valid sources of experience were incorporated. There were no restrictions with respect to the country of origin of the publications, which supplied a range of opinions and experiences. Articles obtained in the refined search were resurveyed on an individual basis to further explore their content.

## 3. Robotic needle guidance systems

The beginning of the robotic age was marked by the development and integration of computers, when in 1954 the first robot used play back memory. The first master-slave robotic system was used to manipulate radioactive substances, invented by Goertz and Thompson (1954). Robots for medical applications have been initially derived from industrial robots. In 1985, the PUMA 560 (Unimation, Danbury, CT, USA), the first medical robot was released by Kwoh, Hou, Jonckheere, and Hayati (1988) and was used to perform neurosurgical biopsies under computed topography guidance. Robots for interventions with needles or other slender probes or instruments can be connected to an imaging modality (computed tomography (CT), MRI, US, fluoroscopy, etc.). Targets and paths are defined in the image based on planning algorithms and the robot aligns and may insert the needle accordingly. The true potential of needle delivery mechanisms relies on their ability to operate with, be guided by, and use feedback from medical imaging equipment. This may compensate for organ reposition during the procedure caused by patient movement or by simple breathing (Badaan & Stoianovici, 2011).

Numerous procedures required precise needle positions, from central venous admittance and biopsies to more complicated interventions, such as brachytherapy and thermal ablation. Many of these procedures utilize US guidance, either freehand or with a needle attached to the transducer, to increase their accuracy. One of the obstacles to these approaches, especially for freehand techniques, is the demand to continuously handle the US transducer and needle using both hands. Several robotic systems have thus been improved to accomplish needle insertions, as directed by US imaging. These computer-aided design (CAD) and computer-aided manufacturing (CAM) systems complete part or all of the needle-insertion tasks autonomously, thereby preventing the difficulties accompanied by manual methods. CAD/CAM systems are fitted with positioning needles with sub-millimeter accuracy, counterbalancing patient motion, tracking multiple targets, and updating complicated panel paths in real time (Priester et al., 2013; Singh et al., 2009).

## 4. Achievements in RUS-guided breast biopsy systems

Robotic biopsy systems imitate common biopsy procedures. First, an extracorporeal US transducer is applied to examine the region of interest by producing a 3D volume. Secondly, the operator recognizes the biopsy target in the US image, and an insertion point is indicated. Before the robot can situate the needle, however, the

**Table 1**  
Advantages and drawbacks of different breast biopsy techniques.

Breast biopsy techniques	Advantages	Disadvantages
breast biopsy FNAC and core biopsy FNAC	<ul style="list-style-type: none"> <li>- Quick.</li> <li>- Secure.</li> <li>- Accurate.</li> <li>- Affordable.</li> <li>- Less vulnery.</li> <li>- Generates slight or no scars.</li> <li>- Quicker recovery.</li> </ul>	<ul style="list-style-type: none"> <li>- Operator dependent.</li> <li>- Require extensive training standards.</li> <li>- Difficult to regulate.</li> <li>- Challenging to perform when smaller lesions are found.</li> <li>- Not always yield ideal results.</li> </ul>
Needle biopsies directed by US	<ul style="list-style-type: none"> <li>- Real-time capabilities.</li> <li>- Cost effectiveness.</li> </ul>	<ul style="list-style-type: none"> <li>- Dependent on a doctor's expertise.</li> <li>- Transformation of the breast tissue.</li> <li>- Steering the needle is extremely difficult to achieve.</li> <li>- Harm the architecture of the breast tissue.</li> <li>- Excessive hemorrhaging.</li> <li>- Cause operator fatigue and pain for the patient.</li> </ul>
Robotic US (RUS) systems	<ul style="list-style-type: none"> <li>- Improve the acquisition and usage of real-time US.</li> <li>- Able to precisely trace and handle the US transducer.</li> <li>- Produce uniformly spaced slices, facilitating 3D volume reconstruction.</li> <li>- Not subjected to human afflictions.</li> </ul>	<ul style="list-style-type: none"> <li>- High initial investment.</li> </ul>

robotic and US coordinate systems must be coregistered through optical tracking, electromagnetic tracking, or rigid coupling. Once transformation of the needle and identification of the biopsy target's position have been determined, the robot orientates the needle along the prescribed course and a doctor completes its insertion. Real-time US tracking systems permit monitoring of the needle insertion, and adjustments can be made as the needle nears its target (Priester et al., 2013).

It could be argued that the system for US-guided biopsy (Fig. 1) designated by Megali et al. (2001) was one of the first attempts to employ RUS-guided breast biopsy. The system consists of a robotic arm that handles the biopsy needle, an US system, a 3D localizer, and a personal computer (PC) with a main processing unit (MPU), which presents the graphical user interface (GUI).

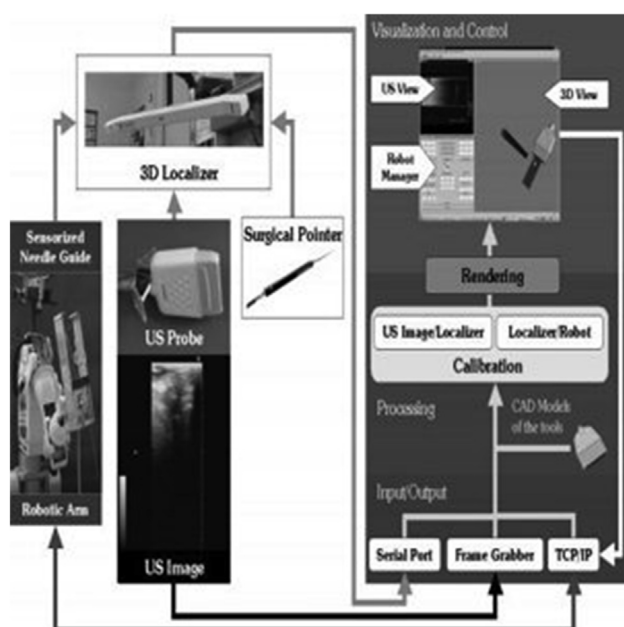
The biopsy needle is placed at the end effector of the robot arm with the aid of a needle guide (Fig. 2). When the robot arm is placed in position, the guide permits movement of the needle to 1-degree of freedom (DOF) along its axis. The doctor immediately selects the

biopsy target on the US image, and the point of insertion is located on the breast. The robotic arm subsequently places the biopsy needle along the determined course. This system improves upon the modern biopsy process by offering a perceptive choice of the biopsy target point, and it facilitates machine-controlled and precise placement of the biopsy needle (Megali et al., 2001).

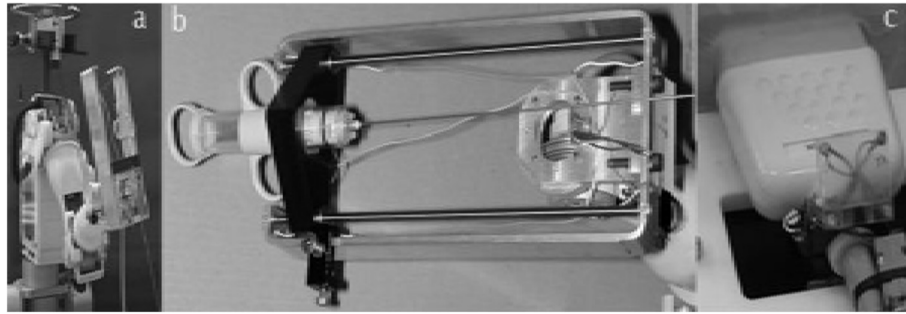
In more recent years, there has been a growing interest in robot-assisted US-guided breast biopsy approaches. The primary findings from in vitro experiments were gained using US-guidance robot-assisted biopsy (Kettenbach et al., 2005). A complete robotic system, B-Rob I, contains an optical tracking system (NDI Polaris; Spectra, Waterloo, ON, Canada) to enable the real-time localization of the US transducer, the phantom bag's position, and the robot position; a LINUX-based industrial PC equipped with a video-capture card, including medical planning software; a 4-DOF robotic arm for gross positioning; a 3-DOF needle positioning unit, including a needle holder; and a robot control system, which contains custom input devices and safety switches to govern the robot's movements. Once a suitable position is reached, the angulation and pitch are fitted, and the robotic arm is moved automatically with 7-DOF to the delineated panel path, aiming the needle-positioning unit at the middle of the target. Then, the biopsy is accomplished manually using a coaxial method (Fig. 3). It was demonstrated that this biopsy method was practicable, and it featured excellent precision, even when applying a single US image. These phantom experiments denote that B-Rob I can be employed for several percutaneous interventions (Kettenbach et al., 2005).

A study on robot-assisted real-time mass manipulation for breast biopsy satisfactorily depicted a mass manipulation technique, that uses externally controlled actuators to situate the mass in line with a needle during real-time insertion (Mallapragada, Sarkar, & Podder, 2009). The controller's achievement is examined on a phantom with stiff inclusion (Fig. 4). This provided a new technique that is essentially different from the existing method, where instead of steering the needle toward the mass during insertion, it directs the mass toward the line of insertion. The strength of this protocol is that it can decrease the number of attempts a doctor makes when trying to capture the required tissue specimen, while diminishing the potential for texture changes, improving biopsy speed, and decreasing patient pain.

Liang, Rogers, Light, von Allmen, and Smith (2010a) investigated the practicability of a real-time three-dimensional (RT3D) US-guided approach featuring an autonomous robotic needle biopsy of resected tissue. In their study, they used a turkey breast with



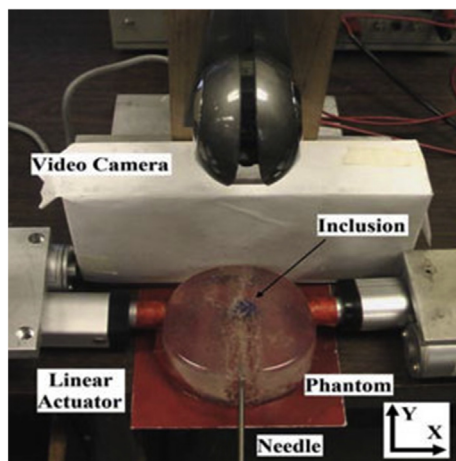
**Fig. 1.** System design and intercommunication between the parts (Megali et al., 2001).



**Fig. 2.** Hardware components of the system. (a) Dexter arm holding the (b) sensorized needle guide and (c) sensorized US transducer (Megali et al., 2001).



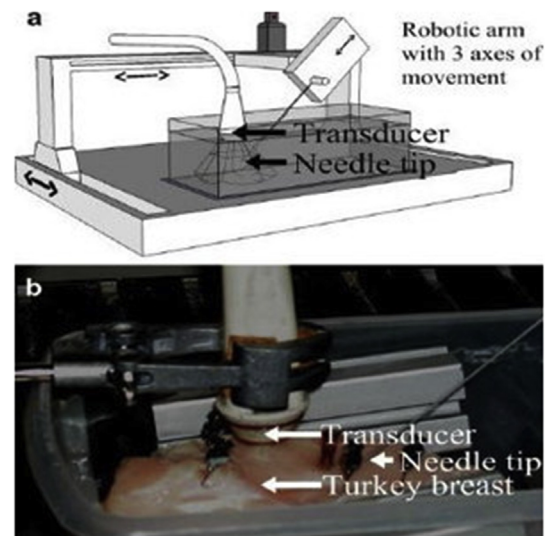
**Fig. 3.** Once the puncture needle was introduced into the phantom, the stylet of the piercing needle was removed (a, b), and the 18-gauge biopsy needle (c) was introduced (Kettenbach et al., 2005).



**Fig. 4.** Needle-insertion process employing robot-assisted, real-time mass manipulation for breast biopsy (Mallapragada et al., 2009).

counterfeit calcification and a fluid-filled cyst. The autonomous robot was successful at making contact with the metal tip and targeting the interior of the cyst. The robot applied was a gantry III Cartesian robot linear motion system (Techno, Inc.; Techno-Isel, New Hyde Park, NY, USA) using an automated controller that understands input orders and 3D coordinates from a PC (Fig. 5).

The robot was moderated such that the Z-axis slide was inclined at a 45° angle, while staying in the X-Z plane. Thus, the researchers more closely counterfeited a real biopsy protocol where the biopsy needle typically reaches the target obliquely to prevent nipple-/areola involvement. The biopsy needle was settled to the slide, such that its movements were restrained by the X, Y, and diagonal axes



**Fig. 5.** Schematic (a) and photograph (b) of trial configuration using a gantry III Cartesian robot linear motion system (Liang et al., 2010a).

of the robot. The robot first autonomously processed 3D image volumes gained from the US scanner to locate a metal rod target that was fixed in the turkey breast tissue, mimicking a calcification; in another attempt, the core of a water-filled void in the breast tissue simulated a cyst. In both experiences, the robot then inserted a needle in the requested area, with no user input needed. By replicating simple procedures, which is frequent in typical breast biopsies, Liang et al. (2010a) demonstrated that autonomous leading might ultimately be expanded to many relatively straight



forward surgical issues that are commonly encountered in hospitals.

An autonomous, multiple-core biopsy system directed by real-time 3D US and managed by a robotic arm with  $6 + 1$  DOF has been improved (Liang, Rogers, Light, von Allmen, & Smith, 2010b). Using a turkey breast model as a tissue phantom, the system was competent at autonomously locating the phantom in the image volume and then executing needle rods in each of eight sectors in the phantom in a single session, with no need for human intervention. The robot that was applied was an iARM assistive robotic manipulator (Exact Dynamics BV; Didam, the Netherlands). The robot arm was designed to be mounted on a wheelchair or bed, as it can be directed by a person with a physical disability using a keypad or joystick; this robotic arm can also approve input orders and coordinates from a PC using separate software (Fig. 6).

The tip of the biopsy needle was connected within the needle port on the probe, mimicking a clinical end-firing US probe with an attached biopsy needle guide, such as the one employed in *trans*-rectal US-guided (TRUS) biopsy (Fig. 7). The probe was held in the robot gripper and fastened tightly with cable connections to ensure that the transducer and its needle did not diverge during the biopsy. Once the robot reached its primary unfolded position during 3D scanning of the phantom, and upon user-controlled triggering, the entire 3D image volume featuring the echo data (depth, azimuth angle, and elevation angle) was transmitted from the 3D scanner, without requiring image slice selection by the user, and using the MATLAB image division algorithmic program (Mathworks, Natick, MA, USA), which was run on a PC. Based on the eight sectors that were properly sampled over the course of five attempts, a succession percentage of 93% was registered. This system could hold significance in clinical procedures that require multiple needle core specimens, such as in the case of breast or prostate biopsy (Liang et al., 2010b).

A positional calibration of a US image-guided robotic breast biopsy system was managed by Nelson et al. (2012). The authors arranged a volume breast biopsy system that contained a biopsy table, a biopsy device, a robotic arm (F3 robot; CRS Robotics Corporation, Burlington, ON, Canada), a robot controller, and a doctor-targeting and guidance console (Fig. 8). Specifically, during clinical manipulation, the biopsy robot would accomplish a breast biopsy with the patient lying in the ventral decubitus position on the biopsy table. The table-top has a round opening for the pendant breast. The base of the robot is positioned immediately below the patient; it is focused around the table aperture and aligned with the

patient coordinate system in a perpendicular position. A mean of biopsy (Mammotome; Devicor Medical Products, Pleasant Prairie, WI, USA) was attached to the effector at the end of the robot. After being adjusted to the breast's surface, the biopsy needle was introduced by applying a linear actuator (Phidgets Inc; Calgary, AB, Canada) under doctor supervision. The breast biopsy device is mounted on a silicon strain gauge force/torque sensor (ATI Industrial Automation; Apex, NC, USA) to provide insertion feedback to the doctor during the procedure. The doctor decides the target coordinates, which are sent from the control console to the robot controller after being programmed using a dedicated software program (RobComm3); the programming details are inputted into the control console and sent to a robot controller, which controls the power and movement of the robotic arm. As a result, a completely automated, dedicated breast volume US scanner featuring a compact robotic design was refined, so it could be precisely positioned to test a mass within  $\pm 1$  mm of the breast volume. In addition, the overall precision and reproducibility of the compact robotic device were attractive and well within the breast biopsy requirements (Nelson et al., 2012).

Vrooijink, Abayazid, and Misra (2013) executed a research study, that demonstrated the real-time 3D tracking of flexible needles following insertion into a soft-tissue simulator using a 2D US probe. The transducer was positioned vertically to the needle tip to measure its position. Once the needle was introduced, the probe was automatically repositioned to track the needle tip using a Cartesian robotic system. Positioning of the probe was established by a compensator that uses the needle's insertion velocity, corrected by needle-tip velocities, to determine out-of-plane movement (Fig. 9). The experiments were completed to confirm the needle tip's position during tracking. The highest mean errors of the needle tip placement within the X-, Y-, and Z-axes were, 0.64 mm, 0.25 mm, and 0.27 mm, respectively. Moreover, Vrooijink et al. (2013) showcased how the needle-tip position can be calculated by applying a 2D US probe. The tip position can be used to automatically steer needles, thereby boosting the overall efficiency of the biopsy process.

Tanaiutchawoot et al. (2014) advanced a brand new breast biopsy exploration arrangement with a 5-DOF passive robotic needle holder (Fig. 10) and graphical user interface (GUI) on MATLAB, as well as a 3D slicer interface based on an optical tracking system that generates real-time data. The robot is sketched depending on the breast shape, while its motion depends on the friction mode employed. The GUI is necessary to guide the doctor during the operating breast biopsy procedure. The trajectory passage, which is determined by the short length between the breast's surface, the mass, and the adjustment of the biopsy needle, is presented in the GUI on MATLAB and on a 3D slicer in real time (Fig. 11). In their study, a phantom breast and breast simulation were performed; the models were hemispheric in architecture, which is a basic requirement when rating the robot's performance. The authors' findings indicated that there was an immediate and high succession percentage of 92% to conduct a simulated breast biopsy, as the robot expanded the certainty and aptitude of the needle insertion as well.

On a technical note about US-guided 3D needle steering in biological tissues with curved surfaces, Abayazid et al. (2015) designed a system that accommodates the automatic steering of a bevel-tipped flexible needle under US guidance toward a physical target, while simultaneously preventing the physical restrictions associated with gelatin phantoms and biological tissues with curved surfaces (Fig. 12). In their research, a robot was used to manage the US probe to initiate contact between the probe and the curved surface of the soft tissue phantom, applying force feedback. Complete 3D tracking, passage planning, and control algorithms



Fig. 6. The iARM robotic arm may be folded into a compact configuration or expanded as requested; it has a length of 80 cm and may rotate a full 360° (Liang et al., 2010b).

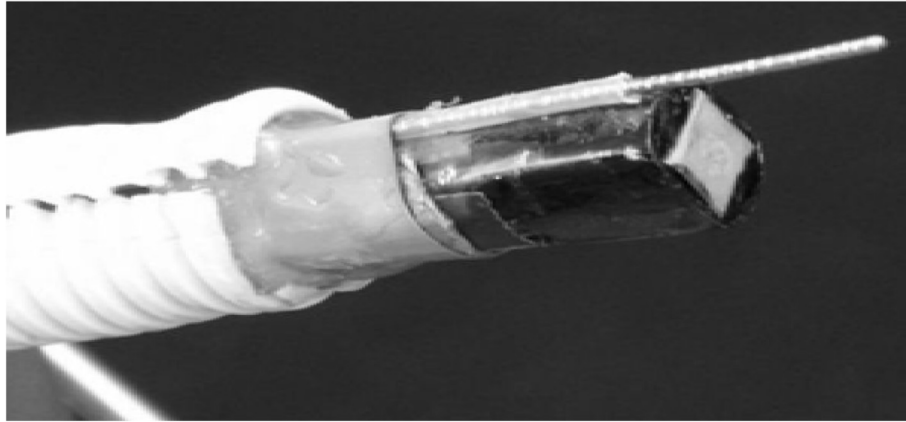


Fig. 7. The tip of the biopsy needle was connected to the needle port on the probe, similar to the one applied for TRUS biopsy (Liang et al., 2010b).

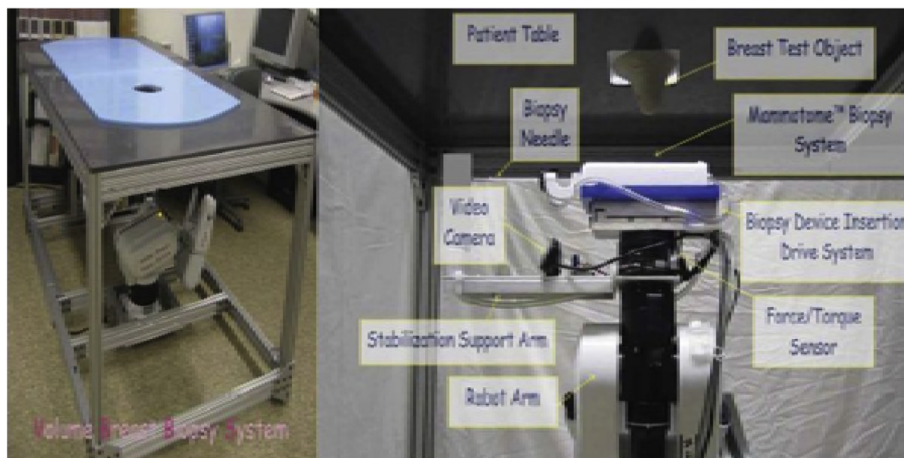


Fig. 8. Left, robot table assembly. A round opening provides space for the pendant breast. Right, appearance from beneath the table, which presents a breast exam object and the biopsy system attached to the robotic arm (Nelson et al., 2012).

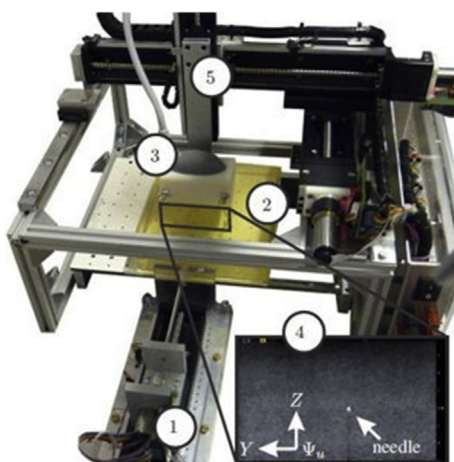


Fig. 9. Real-time 3D flexible needle tracking while applying 2D US. (1) The needle-introducing device, (2) a soft-tissue simulator supported on a gelatin mix, (3) a US probe, (4) a US image with a radial short-axis view of the needle, and (5) a robotic positioning device for the US probe (Vrooijink et al., 2013).

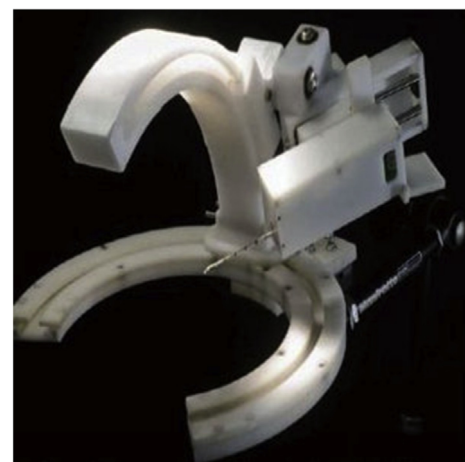


Fig. 10. The prototype of the passive robotic needle holder, as sketched by Tanaiutchawoot et al. (2014).

were applied to steer a bevel-tipped flexible needle into a curved phantom to reach the localized target in a 3D space, while

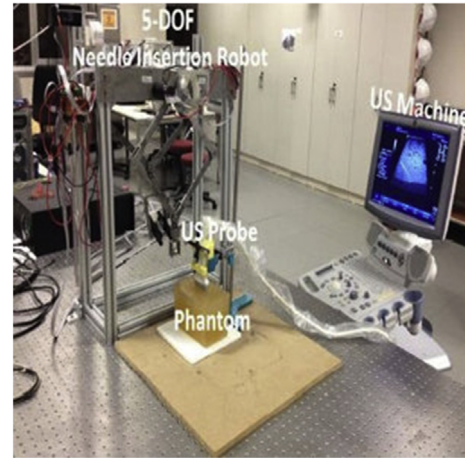
preventing physical hindrance. A 5-DOF system was constructed to accurately scan the curved surfaces using a 2D US probe. The mechanical design grants the probe the ability to scroll and angle at distinct speeds. The footprint of the probe is supposed to be the end



**Fig. 11.** Performance of a passive robotic needle holder (Tanaiutchawoot et al., 2014).

effector. The revolving mechanism (Maxon Motor, Sachseln, Switzerland) was governed by an Elmo Whistle 2.5/60 motor controller (Elmo Motion Control Ltd, Petach-Tikva, Israel). The system has a force/torque detector (ATI Nano-17; Industrial Automation, Apex, NC, USA) to measure the contact forces subjected to the probe. The force measurements are applied to adjust the probe's footprint with the curved phantom surface. Mean targeting errors of  $1.46 \pm 0.37$  mm,  $1.29 \pm 0.29$  mm, and  $1.82 \pm 0.58$  mm were achieved for phantoms with inclined, curved, and combined (inclined and curved) surfaces, respectively, to reach an insertion distance of 86–103 mm. The attained targeting errors propose that our protocol is acceptable for targeting masses with a 3 mm radius that can be detected using clinical US imaging systems (Abayazid et al., 2015).

Kaya, Senely, Ahmad, Orhanz, and Bebekz (2015) further demonstrated a real-time needle-tip tracking system employing 2D US images for robotic biopsies. The needle tip is estimated with the Gabor filter-based image processing algorithm, and the estimated noise is minimized by the Kalman filter. To conduct the proposed method in real time, the bin-packing method is applied, and the processing time is decreased by 56%, without a GPU. The robot

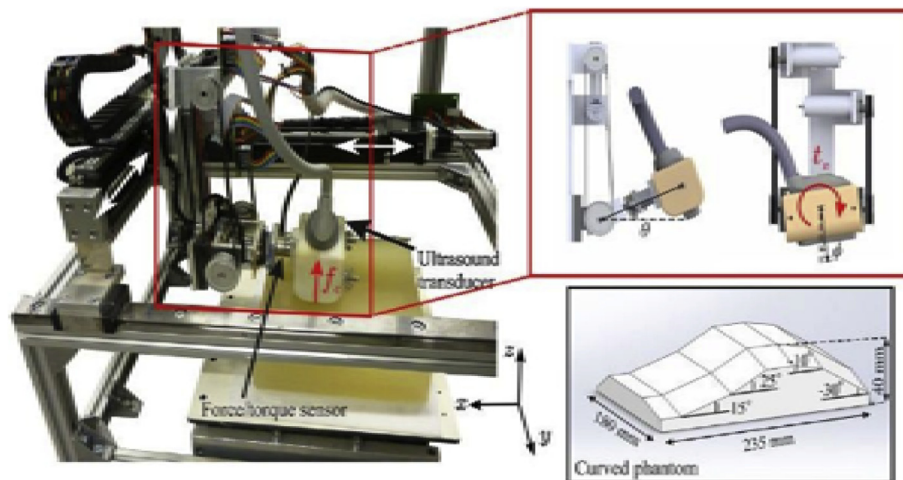


**Fig. 13.** View of percutaneous needle procedures using a 2D US-guided 5-DOF robotic system (Kaya et al., 2015).

employed in their investigation was an OzU biopsy robot (OBR), and it has 5-DOF (Fig. 13).

The US images were adopted by applying a LOGIQ P5 2D US scanner (General Electric, Boston, MA, USA) with a linear 2D US transducer (11L; General Electric). Four different models featuring phantoms and distilled water were applied during the needle-insertion process. Distilled water (25 °C), distilled water and ethanol mixture (25 °C), and gelatin-based, agar-based, and gelatin and agar mixture phantoms were used. The efficiency of the needle-tip assessment was calculated with an optical tracking process. The various attempts showed that the algorithm could track the needle tip in real time. The needle was introduced into each phantom at least 30 times and nearly three US images were captured in each process. Finally, a total of 1417 2D US images from different types of phantoms were used to evaluate the algorithm. In all US images, the needle passage and its tip were successfully determined. The algorithm managed to localize the biopsy needle passage and its tip in all of the phantoms models, thus reinforcing the robustness of this approach (Kaya et al., 2015).

The achievements in the RUS-guided breast biopsy systems detailed in this report are summarized in Table 2.



**Fig. 12.** US-guided 3D needle steering; the force/torque sensor is connected to the revolving mechanism to measure the contact force, and the geometry of the curved phantom consists of different angles of insonation (Abayazid et al., 2015).



**Table 2**

Summary of the listed achievements in RUS-guided breast biopsy systems from 2001 to 2015.

Authors and references	Country and year of publication	Robot	DOF	Accuracy
Megali et al. (2001)	Italy, 2001	Dexter arm robot; arm and needle-positioning unit (NPU)	8	2 mm
Kettenbach et al. (2005)	Austria, 2005	B-Rob I; arm and NPU	7	1.8 mm
Mallapragada et al. (2009)	USA, 2009	External linear actuators	—	—
Liang et al. (2010a)	USA, 2010	Gantry III Cartesian robot	—	1.15 mm
Liang et al. (2010b)	USA, 2010	Assistive robotic manipulator (iARM)	7	—
Nelson et al. (2012)	USA, 2012	F3 robot; gantry and arm	6	<1 mm
Vrooijink et al. (2013)	Netherlands, 2013	Cartesian robotic system	3	—
Tanaiutchawoot et al. (2014)	Thailand, 2014	Passive robotic needle holder	5	—
Abayazid et al. (2015)	Netherlands, 2015	Cartesian robotic system	5	3 mm
Kaya et al. (2015)	Turkey, 2015	OzU biopsy robot (OBR)	5	1.17 mm

## 5. Cost

High cost associated with robotic assisted surgery is a major concern primarily due to the monopoly in the manufacturing industry. Several studies has shown that robotic-assisted minimally invasive surgery does not appear to have any clinical benefit over conventional laparoscopic techniques in terms of outcomes and complication rates but is associated with significantly higher costs (Medscape, 2017). In a retrospective study comparing convectional laparoscopic surgery with robot-assisted procedure, there was up to 20% conversion rate and 10–30% higher cost for the Robot-assisted procedures (Pasic et al., 2010). However, both Robot-assisted and laparoscopic techniques seem to have better overall patient outcome compared with conventional open surgical procedures. Ultrasound guided Robot system for breast biopsy procedure is an emerging technology for a well-defined area of operation compared to other robot-assisted surgical procedures. After the initial investment, the operational cost of robot –assisted breast biopsy systems are expected to be the same or less than the cost of conventional procedure.

## 6. Future prospective in RUS-guided breast biopsy systems

As depicted by the progress reviewed here, RUS-guided breast biopsy systems are going to change the face of surgery in the near future. Robots are expected to become the standard modality for biopsy of suspected abnormal breast tissues. As a result, doctors have to become familiar with technology, and technology should come closer to the everyday needs of a biopsy team. Autonomous and semi-autonomous modes are increasingly being investigated and implemented in breast biopsy procedures, automating various phases of the operation. The complexity of these tasks is also shifting from the low-level automation early medical robots to high-level autonomous features. Future progress will require a continuous interdisciplinary work, with breakthroughs in RUS systems, particularly when applied to breast biopsy. RUS-guided breast biopsy systems is a fascinating field of research involving progress in artificial intelligence technology. However, it should always be faced with caution and never allow the exclusion of human supervision and intervention.

## 7. Conclusion

A wide range of systems that combine robotics and US imaging in guided breast biopsy was reviewed in this article. The inherent safety and real-time imaging capabilities of US, together with the maneuverability and precision of robotic devices, make for a potent combination that features exclusive capabilities. Safety metrics must often incorporate redundancy in control systems, emergency stop and restart methods, actual regulation of patient-contact force, and accurate design analysis. Despite these achievements,

controlled studies are required to demonstrate the adequacy of RUS-guided breast biopsy approaches, particularly when compared with conventional techniques. Over the past two decades, investigators have repeatedly found that robots are uniquely appropriate for US-guided breast biopsy. Experimental systems have definite benefits over conventional protocols, and the future of RUS-guided breast biopsy will be showcased by increasing levels of automation, enhancing doctor's diagnostic skills, facilitating patient recovery, and engaging in appropriate clinical management.

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## Conflicts of interest

The authors declare that there is no conflict of interest.

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