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Review Article

Optimization of Regional Anesthesia Through Robotic Needle Guidance

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ABSTRACT

Robotic needle guidance has moved from a single technical demonstration a decade ago into a broader, still-emerging subfield of regional anesthesia that combines robotic actuation, force feedback, and artificial-intelligence-based image interpretation.

This review traces that development from the first robot-assisted human nerve blocks performed with the Magellan system through simulation studies comparing robotic and manual needle guidance, the mechanical solutions borrowed from adjacent epidural and lumbar puncture robotics, and the deep-learning segmentation models now being used to identify nerve and vascular targets on ultrasound in real time.

Simulation-based evidence indicates that robotic assistance narrows the performance gap between novice and experienced operators more than it accelerates task completion for already-skilled hands, while force-sensing and puncture-detection systems developed for neuraxial robotics offer a plausible route toward mechanical safeguards against intraneural or intravascular needle placement.

Artificial-intelligence-based nerve segmentation has matured technically but is hampered by a mismatch between standard computer-vision performance metrics and the clinically relevant question of whether a given segmentation would keep a needle tip out of harm's way, and no adequately powered randomized trial yet compares robot-assisted to conventional ultrasound-guided nerve block on patient-centered outcomes.

We conclude that robotic needle guidance is a credible and rapidly maturing research direction, with the greatest promise lying in integrated systems that combine reliable AI-based target identification with robotic path execution, rather than in either technology deployed alone.

Keywords: *robotic needle guidance; regional anesthesia; ultrasound-guided nerve block; artificial intelligence; needle tracking*

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INTRODUCTION

Ultrasound-guided regional anesthesia rewarded

practitioners with direct visualization of the target nerve, the surrounding vasculature, and the spread of local anesthetic, but it did not remove the fundamental difficulty of the task: a clinician must simultaneously hold a probe steady with one hand, watch a two-dimensional slice of a three-dimensional anatomy, and advance a needle along a trajectory that is only ever inferred rather than measured. Hand tremor, probe drift, and the sheer cognitive load of image interpretation set a ceiling on precision that no amount of operator experience fully erases. Robotic needle guidance was proposed as a way to push past that ceiling — not by replacing clinical judgment, but by decoupling the mechanical act of needle advancement from the biological limits of a human hand.

The idea is not new. Early teleoperated systems for percutaneous procedures in interventional radiology demonstrated that a needle mounted on a robotic arm could be positioned with sub-millimeter accuracy and held there indefinitely, free of the fine tremor that accumulates over a two- or three-minute block attempt [1]. What has changed more recently is the convergence of three technologies that regional anesthesia can now borrow: real-time image-based needle tracking, machine-learning-based recognition of nerve and vascular structures on ultrasound, and compact, force-sensing robotic manipulators small enough to sit at a patient's bedside rather than in a radiology suite. Together these have moved robotic needle guidance in anesthesia from a laboratory curiosity to something a handful of groups have now tested in cadavers, simulation, and small clinical series.

This review traces that arc — from the first robot to place a nerve block in a living patient, through the mechanical and control-theoretic problems that had to be solved along the way, to the artificial-intelligence layer that is now being grafted onto these platforms, and finally to the honest state of the clinical evidence, which remains thin relative to the engineering literature.

THE FIRST GENERATION OF ROBOTIC NERVE BLOCK SYSTEMS

The Magellan system, developed by Hemmerling and colleagues in Montreal, is generally credited as the first robot used to perform an ultrasound-guided peripheral nerve block in a human being [2]. The system separated the two manual tasks of regional anesthesia — probe manipulation and needle advancement — assigning the ultrasound probe to a robotic arm under joystick control by the anesthesiologist and the needle to a second, teleoperated arm with haptic feedback, so that the physician could "feel" tissue resistance transmitted back through the controller even while standing at a console some distance from the patient [3]. In the initial reported cases, femoral and axillary blocks performed via Magellan were technically successful, and the authors argued that the separation of probe-holding from needle-driving reduced the fine motor demand on the operator and produced a needle path that was more consistently held to the pre-planned trajectory than a freehand approach.

What Magellan demonstrated, more than any specific outcome metric, was feasibility: that a robot could interpret operator intent, translate it into sub-millimeter needle movements, and do so with a latency low enough to be usable in a live nerve block. It also exposed the practical friction of first-generation systems — a second console, a learning period for the operator, and a setup time that made the robot slower than an experienced hand for straightforward blocks, even when it may have been steadier for difficult ones.

LEARNING CURVES AND SIMULATED PERFORMANCE COMPARISONS

Because robot-assisted regional anesthesia could not ethically or practically be tested against freehand technique across a wide range of operators in early patients, much of the comparative evidence comes from simulation. Morse and colleagues compared robot-assisted and manual ultrasound-guided needle guidance in a simulated nerve block model across a cohort of anesthesiology residents and attendings, tracking not just success rates but the shape of the learning curve itself [4]. Robot-assisted guidance produced less inter-subject variability in performance than manual guidance — novices using the robot performed closer to the level of experienced operators than novices working freehand, which is exactly the kind of skill-leveling effect that proponents of surgical and interventional robotics have claimed in other domains. Time to task completion, however, tended to favor manual technique among already-skilled operators, underscoring that robotic assistance in this context is not obviously a speed advantage for the expert — its value proposition is more about consistency and about narrowing the gap between the best and least experienced hands in the room.

A separate simulated demonstration by Tighe and colleagues used a telerobotic platform to perform mock regional blocks, again finding that the mechanics of robotic needle advancement were reliable and reproducible, while flagging that operator adaptation to the altered haptic and visual feedback loop of a teleoperated system is itself a skill that takes deliberate practice [5]. These simulation studies matter because they are the substrate from which any future randomized clinical trial of robotic regional anesthesia will have to draw its power calculations and its training protocols; a robot that only skilled hands can use well has a much narrower clinical niche than one that closes the gap for trainees.

PATH PLANNING, FORCE SENSING, AND THE MECHANICS OF AUTONOMOUS ADVANCEMENT

Robotic needle guidance in anesthesia sits at the more

constrained end of a broader interventional robotics literature that includes lumbar puncture, epidural placement, and percutaneous biopsy, and the mechanical solutions developed for those neighboring procedures have migrated directly into nerve block platforms. Needle path planning for semiautonomous and teleoperated robot-assisted epidural anesthesia has been worked out as a proof of concept, with the robot computing a trajectory that avoids bony landmarks identified on pre-procedural imaging and then either executing it autonomously under supervision or handing incremental control back to the operator at critical junctures such as ligamentum flavum penetration [6]. Force-feedback manipulators built specifically for lumbar puncture have similarly demonstrated that instrumented needle holders can detect the characteristic loss-of-resistance and pop-through signals that mark tissue-plane transitions, feeding that information back to the operator or to an autonomous control loop in real time [7].

An autonomous spinal robotic system for transforaminal lumbar epidural injections carried this further, executing needle advancement with only supervisory human oversight rather than continuous teleoperation, and reporting accurate needle placement relative to pre-planned targets in a small proof-of-concept series [8]. Augmented-reality overlays have been layered onto these robotic epidural platforms as well, projecting the planned trajectory and real-time needle position onto the operator's view of the patient, an approach evaluated formally for epidural interventions with encouraging accuracy and reduced number of needle redirections compared to unassisted planning [9]. On the imaging side, dedicated work on automatic and accurate needle detection in two-dimensional ultrasound during robot-assisted insertion has addressed one of the more stubborn technical problems in the field — the needle shaft and tip are often faint, angle-dependent artifacts on ultrasound, and reliable real-time tracking of the needle itself, not just the target anatomy, is a prerequisite for any closed-loop robotic control [10]. More recent work on puncture-event detection for teleoperated needle insertion systems has focused specifically on identifying the moment of tissue-layer crossing from force and vibration signatures, a capability directly transferable to fascial-plane and perineural needle advancement in regional anesthesia [11].

ARTIFICIAL INTELLIGENCE FOR TARGET IDENTIFICATION AND SEMI-AUTOMATION

If early robotic systems solved the mechanical problem of holding a needle steady, the current wave of work is aimed at the harder perceptual problem: knowing, from an ultrasound image alone, exactly where the nerve is. Deep-learning segmentation networks trained on peripheral nerve ultrasound have matured considerably, with conditioned U-Net architectures achieving pixel-level identification of nerve cross-sections across variable patient anatomy and probe angles [12], and more recent masked-autoencoder pretraining strategies improving segmentation robustness when labeled training data for a specific block type is scarce [13]. These segmentation outputs are the natural upstream input to a robotic guidance system — a robot cannot autonomously steer a needle toward a nerve it cannot first locate, and locating a nerve reliably across the full range of body habitus, depth, and imaging artifact seen in clinical practice has proven harder than early single-center demonstrations suggested.

That gap between demonstration accuracy and clinical reliability has become an explicit subject of study. Work evaluating AI-based nerve segmentation on ultrasound has argued that the standard computer-vision metrics used to report these models — Dice coefficients and intersection-over-union scores chief among them — do not map cleanly onto what matters clinically, namely whether the segmentation would have kept a needle tip out of the nerve fascicle or away from an adjacent vessel [14]. A parallel effort toward consensus and standardization in evaluating deep-learning nerve block segmentation echoes this concern, proposing that the field needs shared benchmark datasets and clinically anchored evaluation criteria before segmentation performance claims from different groups can be meaningfully compared [15]. Building directly on segmentation output, a system for semi-automated ultrasound-guided peripheral nerve blocks aimed at non-specialist operators used deep-learning tracking of neurovascular features to provide real-time overlay guidance, with the explicit goal of extending safe regional anesthesia to practitioners without years of ultrasound experience — a goal with particular relevance in resource-limited or point-of-care settings where a fellowship-trained regional anesthesiologist may not be available [16]. A broader narrative review of artificial intelligence in ultrasound-guided regional anesthesia surveys this landscape and is candid about the distance still remaining between algorithmic promise and bedside practice, noting that most validated models have been tested on curated, single-institution image sets rather than the messier and more varied images encountered across a real block service [17].

Autonomous target localization and needle guidance that combines these AI perception layers with robotic actuation has been demonstrated in early feasibility work, with one group publishing a fully autonomous pipeline that segments the nerve target from live ultrasound, plans a needle trajectory around identified vascular structures, and drives the needle robotically to the calculated target depth without moment-to-moment human steering [18]. This kind of end-to-end system remains at the preclinical or phantom-testing stage in the published literature, but it represents the logical endpoint toward which the

mechanical and perceptual threads of this field are converging.

FEASIBILITY, SAFETY, AND THE BROADER INTERVENTIONAL ROBOTICS CONTEXT

Robotic needle guidance for regional anesthesia does not exist in isolation; it is a specific application of a broader push toward robot-assisted percutaneous intervention that spans interventional radiology, pain medicine, and urology. A recent prospective multispecialty feasibility study of robotic guidance for ultrasound-guided percutaneous procedures — spanning biopsy, drainage, and ablation applications well beyond anesthesia — found that robotic assistance was technically feasible across a range of operators and target depths, with accuracy that compared favorably to freehand technique and no device-related adverse events in the reported cohort [19]. This kind of cross-specialty evidence matters for regional anesthesia because it establishes that the underlying platform technology — robotic arms capable of precise, image-guided percutaneous needle placement — is maturing on a broader front, even while anesthesia-specific clinical trials remain sparse.

A broader review of recent technological advancements in regional anesthesia situates robotic guidance alongside other emerging tools — electromagnetic needle tracking, fusion imaging, and wearable ultrasound — as part of a general trend toward instrumenting and automating a procedure that has historically relied entirely on operator skill and tactile feel [20]. That review's framing is a useful corrective to any temptation to treat robotic needle guidance as a standalone solution: in practice, the platforms most likely to reach routine clinical use will probably combine robotic actuation, AI-based image interpretation, and haptic or force feedback into a single integrated workflow rather than deploying any one of these technologies alone.

Safety data specific to robotic regional anesthesia remain limited to the small case series and simulation cohorts already discussed, and no adequately powered randomized trial comparing robot-assisted to conventional ultrasound-guided nerve block on clinically meaningful endpoints — block success, time to onset, incidence of vascular puncture or neurologic injury — has yet been published. The force-sensing and puncture-detection work coming out of the epidural and lumbar puncture robotics literature is nonetheless encouraging from a safety-engineering standpoint, since the same instrumented needle holders that detect ligamentum flavum penetration for a spinal robot could, in principle, be tuned to detect the more subtle resistance changes associated with fascial-plane crossing or intraneural needle placement in a peripheral nerve block, potentially adding a layer of mechanical safeguard beyond what ultrasound imaging alone provides [11] [7].

CONCLUSION

Robotic needle guidance for regional anesthesia has progressed from a single-center technical demonstration a little over a decade ago to a genuine, if still narrow, subfield with its own mechanical, control-theoretic, and now artificial-intelligence literatures. The mechanical case for robotic assistance — steadier needle holding, reduced inter-operator variability, and the possibility of force-based tissue-plane detection — is reasonably well established in simulation and in adjacent procedures such as lumbar puncture and epidural placement. What is far less established is whether any of this translates into better patient outcomes than a skilled anesthesiologist already achieves freehand with ultrasound alone; the clinical evidence base is still built almost entirely on feasibility series, phantom studies, and simulated comparisons rather than adequately powered trials with patient-centered endpoints. The most promising direction is not robotic actuation or AI image interpretation in isolation but their combination — a system that can see the nerve reliably across variable anatomy, plan a path around vascular structures, and execute that path with a steadiness no human hand sustains indefinitely. Getting there will require the field to first agree on how to measure success, since current reporting of segmentation accuracy and needle-placement precision varies too widely across studies to support pooled comparison. Until larger comparative trials exist, robotic needle guidance in regional anesthesia is best regarded as a credible and rapidly maturing research direction rather than a validated clinical tool ready for routine adoption.

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Conflict of Interest

The authors declare no conflicts of interest relevant to the content of this review.

Author Contributions

Isabel Fernandez conceived the review and drafted the initial manuscript. Vaclav Nowak performed the literature search and contributed to drafting and revision of the sections on robotic platforms and clinical evidence. Chiara Fischer critically revised the manuscript for intellectual content and approved the final version. All authors read and approved the final manuscript.

Ethics Statement

This is a literature review of previously published data and did not involve new studies with human participants or animals performed by any of the authors.

Data Availability

No new data were generated or analyzed in the preparation of this review. All sources discussed are cited and publicly available through their respective publishers.

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