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Systematic Review Article

Advancing Minimally Invasive Surgery with Magnetically Actuated Surgical Instrument

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ABSTRACT

Minimally Invasive Surgery (MIS) has profoundly impacted the field of patient care, although it still faces the challenges of limited dexterity and the constraints of distance posed by conventional surgical tools. The use of Magnetically Actuated Surgical Instruments (MASI) represents an exciting innovation capable of wireless, accurate manipulations in the complex, small spaces of the human body. The current literature on MASI developments from 2010 to 2025 in gastrointestinal, neurosurgical, vascular, and Magnetic Resonance Imaging (MRI)-guided MASI applications was assessed. Electromagnetic MASI offer the benefits of programmable actuation, precision, and real-time imaging, enabling the surgeon's intention to be executed with reduced tissue trauma. While issues of accurate localization, motion prediction in soft tissues, and installation costs, among others, remain, ongoing efforts in automation, force feedback, and image guidance appear to be addressing existing hurdles. MASI represents important technology in the development of next-generation surgical robots or patient-focused surgical approaches.

Keywords: Magnetic; Surgery; Minimally-Invasive; Systematic Review; Neurosurgery; Gastrointestinal; Cholecystectomy

INTRODUCTION

Minimally Invasive Surgery (MIS) has changed how surgeons approach patient care, with shorter recovery times and fewer infection risks making it the preferred option over open surgery in many cases (1). The problem is that traditional instruments, built around rigid mechanical linkages, were never really designed for the body's tighter spaces, often forcing larger incisions and sometimes damaging tissue unintentionally (2). Over the past 15 years, MASI have arrived as an alternative, using external magnetic fields to guide small wireless tools through areas that conventional instruments can't access (3). Early MASI development relied on permanent magnets to establish foundational clinical use, with subsequent work shifting toward precise localization and force sensing in more complex surgical environments (4, 5). Electromagnetic systems changed that, allowing programmable control and real-time imaging (6, 7). This matters most in procedures involving the abdomen, heart, and brain, where the margin for error is very low. This systematic review examines nine studies published between 2010 and 2025, spanning gastrointestinal, neurosurgical, vascular, and MRI-guided MASI applications. The included studies encompass both permanent magnet and electromagnetic approaches, which differ substantially in controllability, clinical readiness, and infrastructure requirements. Permanent magnet systems have achieved clinical validation in select domains, whereas electromagnetic platforms remain largely pre-clinical, and this distinction has not been

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systematically examined across surgical specialties. Yet despite growing interest, no comprehensive comparison of MASI systems across these surgical domains exists. This systematic review argues that recent advances in MASI have meaningfully improved the precision and effectiveness of MIS, and that a clearer picture of where each system stands is long overdue.

METHODS AND MATERIALS

Literature Search Strategy

A comprehensive literature search was conducted using PubMed, IEEE Xplore, Scopus, and Google Scholar in October 2025 for studies published between 2010 and 2025. These databases were selected as they collectively cover both the clinical and engineering literature relevant to magnetically actuated surgical instruments, with PubMed providing coverage of biomedical research and IEEE Xplore and Scopus covering engineering and technical studies. The following search terms were used individually and in combination using Boolean operators: “magnetically actuated surgical instruments” OR “magnetic actuation in minimally invasive surgery” OR “magnetic anchoring and guidance systems (MAGS)” OR “magnetically guided neurosurgery” OR “magnetic soft robots,” with additional combinations such as “magnetic actuation” AND “minimally invasive surgery” AND “magnetic soft robots” AND “surgical instruments” used to broaden the search. Two additional sources were identified through manual reference searching to support background claims in the Introduction and were not subject to the systematic inclusion criteria.

Screening Process and Study Selection Criteria

A total of 65 records were identified, of which 7 duplicates were removed, leaving 58 records screened by title and abstract by a single reviewer. Of the 58 screened records, 24 were excluded at the title and abstract stage, and the remaining 34 full-text articles were assessed for eligibility. A further 25 were excluded based on the defined criteria, leaving 8 studies included in the final review. The study selection process is illustrated in Figure 1.

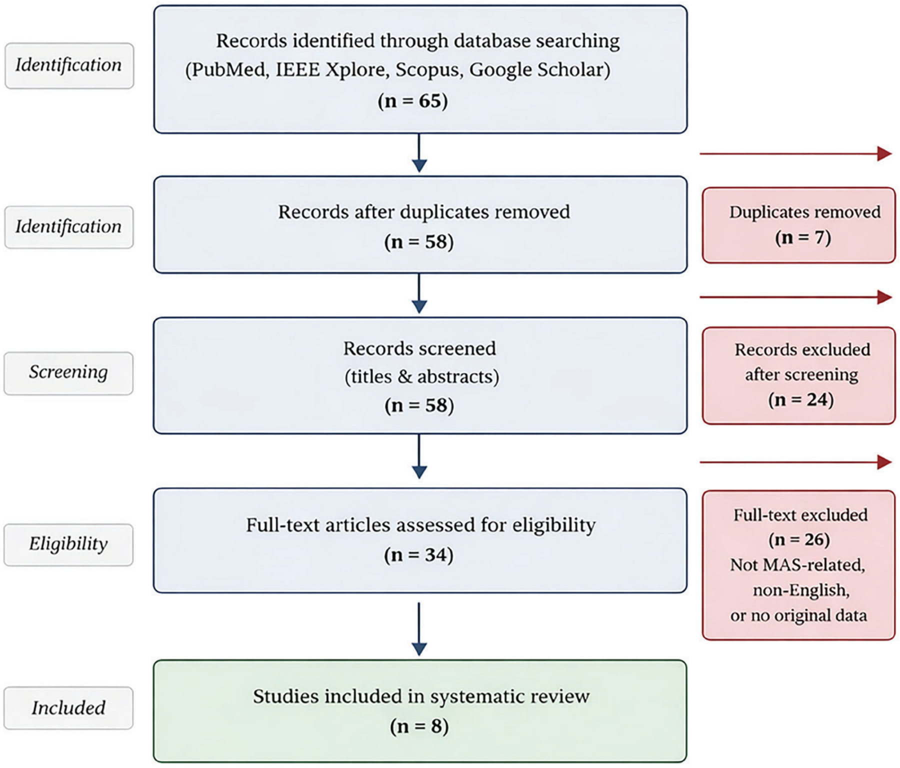

Figure 1. *PRISMA flow diagram showing identification, screening, eligibility, and inclusion of studies in the systematic review. A total of 65 records were identified, 58 screened, 34 screened in depth, and 8 included.*

Studies were included if they reported the development or testing of magnetically actuated surgical tools and were excluded if they were not written in English, did not report the development or testing of magnetically actuated surgical instruments, or did not present original data.

Data Extraction and Analysis

Data was collected on the type of tool, methods of control, target area, scanning or location strategy, and key outcomes such as accuracy, invasiveness, and patient safety. Both quantitative and qualitative data were considered, and the selected studies were organized into a comparison table with sections for tool type, actuation mechanism, precision, and testing environment. Other factors including size, wireless capability, imaging compatibility, and potential for automation were also noted. Common challenges identified included limitations in localization accuracy, stability, and limited evidence from real-world clinical use. All references are formatted in Vancouver style.

RESULTS

A systematic review was conducted to identify trends and advancements in MASI. Studies were included if they reported the development or testing of MASI in clinical, in vivo, or laboratory settings, focused on surgical applications, and were published in English between 2010 and 2025. Eight papers met these criteria (3-10). They span gastrointestinal, neurosurgical, vascular, and MRI-guided applications, reflecting both rapid technological development and clinical adoption. Summaries are presented in Table 1.

Table 1. *Summary of included studies and key contributions to the clinical application and development of MASI.*

Study Reference	Key Contribution	Actuation Type	Testing Level	Key Limitation
(3)	Reported findings from the first prospective clinical trial of robotic magnetic surgery. Shows safety and feasibility across procedures in a controlled clinical setting. Provides evidence supporting translation of MASI into real-world practice	Permanent magnet	Clinical (human)	Early feasibility only; limited procedural scope
(4)	Investigated localization and control of magnetic suture needles in surgical environments. Demonstrated that accuracy is affected by interference from blood and surrounding tissue. Identified critical limitations in realistic operative conditions.	Electromagnetic	Bench/phantom	Localization error increases significantly under occlusion
(5)	Developed a magnetic catheter with integrated force sensing for interventional procedures. Enabled real-time feedback on tissue interaction which improved control and safety. Addressed a major limitation of MASI by using haptic feedback capabilities.	Electromagnetic (solenoid)	Phantom	Tested in phantom only; not yet in vivo
(6)	Introduced MRI-compatible electromagnetic servomotors for image guided robotic procedures. Demonstrated operation without losing safety. Advanced integration of MASI within real-time imaging environments.	Electromagnetic	Bench/phantom	High infrastructure cost; limited to specialized centers
(7)	Proposed an under-table electromagnetic navigation system for microsurgical applications. Demonstrated precise magnetic control while maintaining an uncluttered surgical workspace. Improved practicality and clinical usability of electromagnetic actuation systems.	Electromagnetic	Prototype validation	Prototype only; not yet tested in vivo or clinically

Continued Table 1. *Summary of included studies and key contributions to the clinical application and development of MASI.*

Study Reference	Key Contribution	Actuation Type	Testing Level	Key Limitation
(8)	Demonstrated the clinical feasibility of a magnetic surgical device during laparoscopic cholecystectomy. Showed that magnetic retraction can reduce the need for additional incisions. Provided human validation of MASI in a surgical environment.	Permanent magnet	Clinical (human)	Limited to GI procedures; fixed magnetic properties
(9)	Evaluated magnetically assisted capsule endoscopy in randomized controlled trial. Demonstrated noninvasive diagnostic applications of magnetic actuation.	Permanent magnet	Clinical (human)	Did not improve small bowel completion rates
(10)	Developed magnetically actuated dexterous tools for minimally invasive neurosurgery procedures. Demonstrated high precision manipulation in confined spaces. Highlighted the potential of MASI for advanced neurosurgical applications.	Permanent magnet	In vivo (animal)	No human trials conducted yet

Gastrointestinal surgery has, so far, produced the strongest clinical evidence for MASI use. A 50-patient clinical trial of the Levita Magnetics device showed that an external magnet could safely control a detachable intraabdominal clip to retract the gallbladder. That removes the need for an additional port incision (8). The average hospital stay was 22 hours, the average pain scores were 0.6 out of 10 at seven days, and patients returned to work within five days (8). A later prospective trial of the Levita Robotic Platform across cholecystectomy and bariatric procedures extended these findings and supports future clinical use (3). A randomized controlled trial of 122 patients separately examined magnetic steering of the MiroCam Navi capsule endoscope for small bowel examination (9). Completion rates and gastric emptying were not significantly improved, but mucosal visualization and transit to the gastric antrum were both significantly better in the intervention group. This suggests the technique may be better suited to stomach-specific examination than small bowel screening (9).

In neurosurgery, the core challenge is reaching targets that conventional instruments cannot access without causing accidental damage. He *et al.* addressed this by developing three magnetically actuated tools, each under 3.2mm in diameter, with permanent magnets enabling wireless control via an external field (10). Testing on silicone brain phantoms and live piglets confirmed that the tools perform biopsies on brain tissue, with experiments demonstrating access to ventricular and corpus callosotomy sites (10). Human trials have not yet been conducted, although the animal data makes a case for further use.

Vascular studies were concerned with how to keep patients safe when navigating through narrow, delicate parts of the body. A solenoid-tipped catheter with an integrated soft force sensor demonstrated that bending direction and angle could be controlled by adjusting current direction and magnitude. The safety was confirmed in attraction mode (5). Phantom testing in a bifurcation model and aortic arch showed the catheter could guide a laser beam along stable paths on a cardiac chamber wall (5). A separate study tackled the localization problem for magnetic suture needles, combining neural network segmentation with classical image processing to achieve 0.73mm Root Mean Square (RMS) error in clean conditions and 2.72mm RMS error under blood and occlusion (4). Autonomous closed-loop control then allowed the needle to follow a suture path across four progressively harder conditions, with the tip tracking error between 2.6 and 3.7mm RMS (4).

Integrating MASI with active MRI scanners presented a set of engineering challenges, given that conventional motors are not safe near strong magnetic fields. Hofstetter *et al.* resolved this by building a servomotor entirely from non-magnetic materials and using the scanner's own superconducting field to generate torque (6). The system operated safely inside a 3

Tesla scanner during live imaging and was incorporated into a robot that could insert a large-diameter biopsy instrument into tissue (6). Schonewille *et al*. approached the problem differently, arranging eight electromagnets beneath the operating table to keep the workspace above fully accessible (7). Fields of up to 38 mT along the x and y axes and 47 mT along the z axis were generated at 120mm depth, which is sufficient to actuate millimeter-scale tools at neurosurgical targets, though the system has not yet moved beyond a prototype (7).

Taken together, gastrointestinal MASI stands out as the most clinically developed, backed by human trial data and regulatory approval. Neurosurgical and vascular platforms have demonstrated strong results in controlled settings but remain largely preclinical. MRI-compatible systems have proven that actuation and real time imaging can happen together, though the infrastructure costs involved limit their accessibility. Permanent magnet systems offer a practical and affordable entry point, while electromagnetic systems trade cost and complexity for significantly greater control precision. Across all domains, safety, localization accuracy, and imaging compatibility were the recurring priorities.

DISCUSSION

The reviewed studies point to magnetic actuation as a meaningful step forward in minimally invasive surgery, though the evidence is stronger in some domains than others. Permanent magnet systems were the first to reach patients, and their safety record in gastrointestinal procedures is backed by prospective trial data (8, 3). Their fixed magnetic properties, however, limit real-time adjustability, making them a poor fit for procedures that require dynamic, fine-grained control. Electromagnetic systems address this through programmable field generation, which has proven valuable in neurosurgical and vascular settings where millimeter-level precision is required (3, 7). Adding MRI compatibility extends this further, enabling continuous intraoperative imaging that conventional instrumentation simply cannot offer (6).

Despite these advances, a wide gap remains between laboratory performance and clinical deployment. Gastrointestinal MASI are the most developed, with multiple human trials and regulatory clearance in at least one case (8, 3). The capsule endoscopy trial by Hale *et al.* is an example of this gap in practice, as magnetic steering improved mucosal visualization but failed to enhance small bowel completion rates, suggesting that clinical benefit is highly procedure-specific and not guaranteed by magnetic control alone (9). Most neurosurgical and vascular platforms, including those developed by He *et al.* and Wang *et al.*, have been tested primarily in phantom models or limited animal studies, and haven't been exposed to the full range of conditions encountered in human surgery (10, 5).

Infrastructure cost remains a significant barrier to wider adoption, yet it receives little attention in literature. Electromagnetic systems like the MRI-compatible servomotors described by Hofstetter *et al.* and the under-table platform proposed by Schonewille *et al.* require substantial investment in coil arrays, power systems, and operating room modifications, which in practice limits them to large tertiary centers (6, 7). Permanent magnet systems are cheaper and more accessible, but their limited programmability makes them unsuitable for the complex neurosurgical and vascular procedures where electromagnetic systems are needed most.

The safety contributions across the reviewed studies are worth noting. Force-sensing catheters reduced vascular injury risk during navigation, and magnetic localization methods tracked instruments accurately even in blood-filled and occluded environments where optical imaging fails (4, 5). MRI-compatible actuators showed that high-field imaging and magnetic surgical tools can run concurrently without interfering with each other (6). These aren't incremental improvements and they tackle problems that current tools have no good answer for.

Moving forward, the most promising direction appears to be deeper integration of electromagnetic actuation with real-time imaging and automation. Thoracic and cardiac surgery represent realistic near-term targets, though widespread adoption will require multi-center trials that the field has not yet produced. Taken together, the reviewed evidence supports the central argument of this systematic review: that advances in MASI have improved the precision and effectiveness of minimally invasive surgery, particularly in gastrointestinal applications where clinical validation is most mature. The more pressing question is no longer whether magnetic actuation works, but how quickly can the engineering, economic, and clinical barriers be addressed to bring these tools into routine surgical practice across all domains.

Several limitations of this systematic review should be acknowledged. The database searches covered PubMed, IEEE Xplore, Scopus, and Google Scholar, but complete coverage of the available literature cannot be guaranteed. Some relevant studies may have been missed due to language restrictions or publication in sources not captured by these searches. The eight included studies also vary considerably in design, from randomized controlled trials to prototype bench validations, and this heterogeneity makes direct comparison difficult and limits the strength of overarching conclusions. Selection bias is a further concern given that study inclusion was handled by a single reviewer. Finally, many of the included platforms remain at early stages of development, and the absence of long-term outcome data means questions about real-world durability and safety are still largely unanswered.

CONCLUSION

Magnetically actuated surgical instruments (MASI) have demonstrated measurable progress toward clinical integration, with validated applications emerging in select procedural domains; however, the field remains in a developmental phase. Their wireless actuation, capacity to navigate constrained anatomical environments, and compatibility with real-time imaging modalities collectively address limitations inherent to conventional surgical tools. Electromagnetic actuation systems provide superior programmability and dynamic control relative to permanent magnet-based approaches, supporting their suitability for technically demanding neurosurgical and endovascular interventions. Notwithstanding these advancements, a translational gap persists between controlled experimental performance and consistent functionality in operative settings. Limitations in real-time localization accuracy, challenges associated with compensating for soft tissue dynamics, and the financial and logistical burden of electromagnetic infrastructure continue to restrict widespread adoption. While ongoing efforts in automation, haptic integration, and image-guided control aim to address these barriers, progress remains uneven across subdomains. The rationale for continued development of MASI extends beyond technical innovation to clinically relevant outcomes. Evidence suggests potential benefits including reduced invasiveness, decreased tissue disruption, and improved postoperative recovery profiles. As larger-scale studies are conducted and system costs decrease, the evidentiary basis for broader implementation is likely to strengthen. Although the transition from investigational systems to standard-of-care technologies is not assured, current evidence supports sustained advancement toward clinical viability.

CONFLICT OF INTEREST

The author declares that there are no conflicts of interest related to this work.

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