MEDICAL ROBOTS

Medical robots learn to be autonomous

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Medical robots have been in clinical use for more than a quarter of a century. In surgical interventions, they provide enhanced dexterity for minimally invasive procedures as well as increased accuracy during orthopedic procedures and needle insertions. In neurorehabilitation, they enable more intensive therapy, whereas assistive robots support the daily activities of those with disabilities. Although much progress has been made, it is notably less than what was anticipated. The major challenge is that existing medical robots rely heavily on the operator to perform their functions. Most surgical robots are teleoperated—they simply mimic the hand motions of the clinician. In this role, the robot's additional costs can be more substantial than any benefit provided to the patient. In rehabilitation, robots can relieve the therapist from applying physical loads to the patient and enable more intensive therapy, but they require the therapist to invest substantial time developing a patient-specific treatment plan. Assistive exoskeletons can enable the user to perform otherwise impossible tasks, but their capabilities are limited with regard to inferring the user's intent.

The common limitation of these systems is that they lack the capability to perform their functions autonomously. There are a variety of reasons why this is the case. These include ethical and legal concerns—who is responsible when an autonomous robot makes a mistake? Financial limitations are also important. The development and regulatory costs of nonautonomous medical robots are already among the highest of all medical devices. The most fundamental limitation, however, has been technological. The classical techniques in the autonomous robotics toolbox work well for processes that are highly structured and can be precisely modeled, but these methods struggle with the complexity that is typical in medicine. The manipulation of soft tissue is challenging and complex to model. There can be large variations in patient condition and anatomy. Image quality and viewpoint is also variable. To overcome these challenges using existing techniques, prior demonstration projects in medical automation relied on introducing artificial structure. Automated bowel anastomosis, for example, required manually suspending the bowel with stay sutures and using fluorescent fiducial markers on the tissue (*1*). Similarly, autonomous cardioscopically guided catheter navigation required the use of fiducial markers sewn into the annulus of an implanted heart valve (*2*).

The recent explosion in progress with large language models and vision-language models suggests that we are entering a new era in which the complexity of medical applications will no longer be a limitation to achieving autonomy. This special issue of *Science Robotics* reviews the current state of autonomy and artificial intelligence (AI) in medical robotics and explores how learning methods can transform the use of robots in medicine. With health care costs continuing to rise, the issue opens with a Focus article by Weber *et al.* examining the potential impact of autonomous medical robots on health care disparities in low- and middle-income countries. Although autonomy yields the potential to provide advanced medical care in regions lacking highly specialized clinicians, costs remain a major challenge, and the authors urge collaboration between the robotics and global surgery communities to identify opportunities for progress.

The papers comprising the remainder of the issue review the current state of medical robot autonomy and investigate how learning-based methods can advance the field. A Focus article by Michael Yip emphasizes that progress in automation will depend on leveraging results from foundation models given the relative scarcity of large medical training datasets. To compensate for the lack of domain-specific data, two strategies are suggested. First, a foundation model can be used as a high-level policy with middle-level domain-specific models below. The middle-level models may be learned or classical models could be more easily tuned to a specific medical application while still benefiting from the high-level foundation model. Alternatively, if medical applications can be performed with robot arms and grippers closer to those used for general manipulation, it may be possible to use foundation models built for general purpose manipulation.

Three Reviews detail the state of automation in laparoscopic surgery by Schmidgall *et al.*, needle steering by Alterovitz *et al.*, and exoskeletons by van der Kooij *et al.* The automation of laparoscopic soft tissue surgery is potentially the most challenging surgical domain given that it involves cutting and manipulating tissue in complex ways that are difficult to model and sense. Steering of a flexible needle along a curved three-dimensional path through compliant tissue to a millimeter-scale target is similarly challenging. Looking to the future, both Schmidgall *et al.* and Alterovitz *et al.* note that automation leveraging natural language as an input and output could provide an intuitive way for clinicians to interact with these systems. Correspondingly, van der Kooij *et al.* describe how large language models could be used with therapeutic robots to convert high-level treatment goals into personalized exercise plans and therapeutic games. Regarding how to train such models, Schmidgall *et al*. describe advances in reinforcement and imitation learning applied to surgery. For reinforcement learning, they describe the challenge of the sim-to-real gap—that a robot trained in simulation will often fail in the real world. For imitation learning, they explain the challenge of generating sufficiently large and rich sets of expert demonstrations. Van der Kooij *et al*. point out that assistive robots designed to detect user intent face a similar sim-to-real gap when trained with data from able-bodied experts instead of disabled patients.

Three Research Articles present substantial advances in medical robot automation while exploring three alternative approaches to implementing autonomy with learning methods. Kim *et al*. describe a system that uses imitation learning to perform a portion of a cholecystectomy. Long *et al*. used reinforcement learning to train a system to perform individual laparoscopic tasks such as gauze picking, tissue retraction, and vessel clipping. Liu *et al*. present a hybrid approach that combines imitation learning with classical searching and mapping techniques to demonstrate the bronchoscopic retrieval of aspirated foreign bodies. These three systems use only standard endoscopic imaging as input sensing, and the surgical scenarios were not simplified to facilitate the tasks. Furthermore, the latter two papers include in vivo demonstrations.

Although the articles in this special issue provide a glimpse of what will become possible using learning-based tools, many open questions remain, and we hope that these will form the basis for future research in the field. For example, what will be the best framework(s) for implementing autonomy that enables clinician intervention and provides safety guarantees? How will the best framework vary with the application, e.g., soft tissue surgery versus endovascular interventions versus assistive robotics? Will procedure-specific simulators and training datasets be required? Can autonomy serve to bring down the ever-growing cost of health care by raising clinician productivity? Or will the technology and the workforce required to maintain it continue to increase costs? These are questions that we hope our prospective authors at *Science Robotics* will explore and therefore enable autonomy and AI to help medical robotics realize its full potential.

—Pierre E. Dupont

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