MEDICAL ROBOTS

Augmented dexterity: How robots can enhance human surgical skills

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Advances in AI and robotics have the potential to enhance the dexterity of human surgeons.

Surgery is a highly respected profession for good reason: Surgery requires many years of training to acquire detailed knowledge of human anatomy and medicine. The best surgeons combine that knowledge with extraordinary manual dexterity that they use to treat their patients and help them recover. A surgeon's dexterity often separates the good surgeons from the great ones. Fortunately, emerging advances in artificial intelligence (AI) and robotics now have the potential to narrow this gap.

Last year, more than 2 million surgeries were performed with robotic systems like Intuitive's da Vinci (*1*), which facilitates minimally invasive ("keyhole") surgery to help reduce pain, blood loss, scarring, complications, and recovery time in many procedures involving the appendix, colon, gall bladder, prostate, and others. These robots are very sophisticated, but nearly every movement is determined by human surgeons. This is because surgery is extremely sensitive to errors—there are a vast number of rare but potentially dangerous edge conditions, and the consequences of even a single failure can lead to a serious adverse event, so it may be a very long time before fully autonomous robots are sufficiently safe and reliable for the operating room. Moreover, surgeons and patients may be fearful of fully autonomous surgical robots, and there may be substantial regulatory and legal barriers to getting them approved.

However, recent advances in AI are opening the door to augmenting surgeons' skills when performing specific subtasks, such as suturing, debridement, and resection. Instead of the term "autonomous," which can sound threatening to surgeons and patients, we propose the term "augmented dexterity" to describe systems in which surgical subtasks are controlled by a robot under the close supervision of a human surgeon who is ready to take over at a moment's notice.

Augmented dexterity is related to augmented reality, where digital images are overlaid on top of live images, and is related to human supervisory control (*2*). Augmented dexterity has the potential to elevate good surgeons to the level of the best surgeons, which could support safer, faster, and more reliable surgery. Intuitive Surgical's da Vinci X, Xi, and 5 systems are taking the first steps toward augmented dexterity, and researchers are exploring how emerging advances in AI and robotics can facilitate augmented dexterity (*3*, *4*).

Surgical robots are imprecise because the motors that drive them must remain outside the patient's body. The metal cables that adjust tool positions are long and prone to backlash. Human surgeons learn to compensate for these challenges, but we found that the da Vinci Research Kit (dVRK) was challenging to control accurately without human supervision. We recently showed that a deep neural network can learn how to compensate so that the robot could perform a common surgical training task called a peg transfer at accuracies and speeds on par with (and in some cases better than) those of an expert surgeon (*2*).

Suturing is a tedious subtask. It requires careful placement of sutures to balance tissue forces to reduce the chances of infection and scarring, to speed healing, to prevent the joined tissues from tearing apart, to prevent leaking of bodily fluids, and to avoid tissue necrosis. Currently, surgeons rely on intuition and a force model developed for straight lacerations to plan sutures. We recently developed an extension that works for straight and curved lacerations. Our software analyzes a photo of the laceration, then computes and displays an overlay showing the precise placement of each suture to optimally distribute forces across the laceration. The surgeon can use a mouse to adjust the resulting overlay and then use it to guide suturing (*5*).

Even with guidance, given that suturing skill varies widely between surgeons, it would be valuable to augment surgical suturing dexterity. Although initial results have been demonstrated in research laboratories (*6*, *7*), one challenge is to securely transfer a thin surgical needle back and forth between gripper tools and to manage the slack in surgical thread.

Another surgical subtask is debridement—the removal of damaged tissues or foreign fragments from a wound. Debridement can be very tedious and time consuming; it is very easy for a surgeon to overlook fragments, which can lead to infections. We conjecture that augmented dexterity could be applied to debridement by using a surgical camera and robot system to systematically identify and remove fragments under close supervision of the surgeon, who is ready to take over if the system misidentifies a discolored human tissue as a foreign fragment. Researchers have achieved limited augmented dexterity for suturing (*8*) and surgical debridement in laboratory conditions, but research is still needed to extend these results and evaluate them in vivo.

Augmented dexterity can also facilitate telesurgery by addressing the problem of inherent time delays of optical and electrical signals, which cause any direct control loop to be unstable. Remote mentoring allows an expert surgeon to mentor a remote surgeon to complete a complex robotic case. Today, the remote expert interacts using video and voice and overlays into the surgery through the cloud. In the future, telesurgery, which allows control of the robot at a distance, could provide access to skilled surgeons thousands of miles away, depending on a number of factors, including the availability of reliable infrastructure, regulatory approval and licensing, and experienced teams that can manage the new dynamics of a remote configuration (*9*).

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The field of robotics is evolving rapidly with advances in AI, including deep learning and generative AI (*4*, *10*). These advances have the potential to allow augmented dexterity to make surgery safer, faster, and more reliable for patients worldwide.

REFERENCES AND NOTES

1. Intuitive Surgical, "Environmental, social, and governance report 2023" (Intuitive Surgical, 2023); https://isrg.intuitive.com/static-files/8f873230-8cd5-419e-87e0-52bec95bcdab.
2. M. Hwang, J. Ichnowski, B. Thananjeyan, D. Seita, S. Paradis, D. Fer, T. Low, K. Goldberg, Automating surgical peg transfer: Calibration with deep learning can exceed speed, accuracy, and consistency of humans. *IEEE Trans. Autom. Sci. Eng.* **20**, 909–922 (2022).
3. C. Shin, P. W. Ferguson, S. A. Pedram, J. Ma, E. P. Dutson, J. Rosen, Autonomous tissue manipulation via surgical robot using learning based model predictive control, in *2019 IEEE International Conference on Robotics and Automation (ICRA)* (IEEE, 2019), pp. 3875–3881.
4. J. W. Kim, T. Z. Zhao, S. Schmidgall, A. Deguet, M. Kobilarov, C. Finn, A. Krieger, Surgical Robot Transformer (SRT): Imitation learning for surgical tasks. arXiv: 2407.12998 [cs.RO] (2024).
5. V. Kamat, V. Ramakrishnan, Y. Mohnot, H. Jalan, J. Isaac, V. Schorp, Y. Avigal, A. Adler, D. M. Fer, K. Goldberg, Automating 2D surgical suture placement, in *2023 IEEE 19th International Conference on Automation Science and Engineering (CASE)* (IEEE, 2023), pp. 1–8. 10.1109/CASE56687.2023.10260435.
6. H. Saeidi, J. D. Opfermann, M. Kam, S. Wei, S. Leonard, M. H. Hsieh, J. U. Kang, A. Krieger, Autonomous robotic laparoscopic surgery for intestinal anastomosis. *Sci. Robot.* **7**, eabj2908 (2022).
7. Z. Y. Chiu, A. Z. Liao, F. Richter, B. Johnson, M. C. Yip, Markerless suture needle 6D pose tracking with robust uncertainty estimation for autonomous minimally invasive robotic surgery, in *2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)* (IEEE, 2022), pp. 5286–5292.
8. K. Hari, H. S. Kim, W. Panitch, K. Srinivas, V. Schorp, K. Dharmarajan, S. Ganti, T. Sadjadpour, K. Goldberg, STITCH: Augmented dexterity for suture throws including thread coordination and handoffs. arXiv:2404.05151 [cs.RO] (2024).
9. P. J. Choi, R. J. Oskouian, R. S. Tubbs, Telesurgery: Past, present, and future. *Cureus J.* **10**, e2716 (2018).
10. C. D'Ettorre, A. Mariani, A. Stilli, F. R. y Baena, P. Valdastri, A. Deguet, P. Kazanzides, R. H. Taylor, G. S. Fischer, S. P. DiMaio, A. Menciassi, D. Stoyanov, Accelerating surgical robotics research: A review of 10 years with the da Vinci Research Kit. *IEEE Robot. Autom. Mag.* **28**, 56–78 (2021).

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