

MEDICAL ROBOTS

Remote magnetic navigation enables precision telesurgery

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Medical devices actuated by external magnetic fields can create opportunities for clinical adoption of precision telesurgery.

The projection of magnetic fields into the human body to create forces and torques on magnetized medical devices, such as microrobots, catheters, and endoscopes, is known as remote magnetic navigation or robotic magnetic navigation (RMN). The fundamental advantage of this approach is that forces and torques are exerted on devices without a direct physical connection to the device itself. This advantage has been recognized for centuries for removing metal filings embedded in eyes of workers using machining processes, as well as other uses (1). Research interest in the use of magnetic fields to guide the delivery of therapeutics to precise locations in the human body has substantially increased in the past two decades. There are many reasons for this. The discovery of the rare earth alloy NdFeB in the early 1980s dramatically improved the properties of readily available permanent magnets, allowing for the generation of stronger forces and torques on magnetized bodies. The adoption of magnetic resonance imaging over the past several decades increased our comfort level with projecting high-strength magnetic fields into the human body. The widespread acceptance of minimally invasive procedures has driven the development of smaller, efficacious medical devices that create less tissue trauma, which in turn forced device developers to reconsider how to actuate these devices. Micromanufacturing techniques have advanced, allowing engineers to design smaller, more complex devices. Finally, models of magnetic fields have improved, allowing engineers to design and control magnetic devices using electromagnetic navigation systems

(eMNSs) with higher precision and more complex motions than ever before.

Companies such as Stereotaxis, Aeon Scientific (2), and Levita (3) have used RMN to perform endocardial ablations and minimally invasive abdominal surgeries. Many microrobot research groups have also embraced the approach for guiding medical microrobots in vivo (4), and the literature in the field is rapidly growing (5).

An inherent advantage of RMN is that the approach effectively addresses the non-collocation problem for many medical robotics procedures that use flexible devices, such as catheters, guidewires, and endoscopes. Colocated control means that the sensors and actuators, essential components of any control system, are located near one another. For many endoluminal devices, this is impossible with the traditional approach in which the distal end is observed using, for example, fluoroscopy but is controlled from the proximal end by a surgeon pushing, pulling, and twisting the device. The sensing and actuation can be located over a meter from each other with a long, flexible catheter serving as a transmission between the actuation and the endpoint where the task is being performed. This represents a classic non-collocation problem, and control theorists are well familiar with the challenges this presents. RMN addresses this by colocating the sensed distal end with torques that are applied directly to this end with magnetic fields.

Although addressing the non-collocation problem with RMN makes controlling endoluminal devices easier for surgeons in the operating room, a less recognized but perhaps more important advantage is that it

creates an opportunity for improving tele-operator control during telesurgery (6). By simply looking at the x-ray image of the in vivo device and determining where the device needs to go in the image, the surgeon can directly control device motion without having to account for the difficult-to-model flexibility of the entire catheter, guidewire, or endoscope. This provides the surgeon with a more intuitive and effective control of the device so that the working end of the device can be guided to the location of interest, such as a blood flow-blocking thrombus or an aneurysm to be treated with an endoluminal approach.

The opportunities that telesurgery present have been recognized for decades and were a primary impetus for the initial development of robotic surgical systems (7). However, because most robotic surgeries currently performed are not time critical, the adoption of telesurgery has been slow. This is primarily because surgeons prefer being near their patient to provide direct supervision of the entire surgical workflow. For time-critical procedures in which treatment must be delivered as rapidly as possible, these considerations change. This is the case for diseases such as ischemic and hemorrhagic stroke, myocardial infarction, and twin-to-twin transfusion syndrome. In the case of stroke, the second leading cause of death in the world, “time is brain” as neurovascular surgeons say (8). Studies have shown that ischemic stroke patients treated within 150 min of the onset of systems have a 90% chance of functional independence after recovery (9). The longer the treatment is delayed, the more irreversible brain damage occurs, worsening patient outcome. Mechanical thrombectomy has been shown to be an effective treatment for many ischemic stroke patients and entails the insertion of guidewires and catheters into the patient’s blood vessels that are guided to the blood clot to be removed. Unfortunately, most of the world’s population does not

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have rapid access to the highly skilled surgeons that are able to perform thrombectomies. In the United States alone, 113 million people live more than an hour's drive from the nearest stroke center capable of performing mechanical thrombectomy (10), and the situation worsens in many parts of the world, particularly in the Global South. In the future, local clinics with teleoperated robotic surgical systems may connect to highly trained surgeons located far away in large hospitals that can support 24/7 stroke

centers. This approach has the potential to vastly increase the number of people that will have access to rapid treatment of ischemic stroke by mechanical thrombectomy. As a proof of concept, a demonstration of a complete 3D mechanical thrombectomy on a phantom in Zurich, Switzerland was performed in October 2023 by surgeons located at the Mayo Clinic in Phoenix, Arizona, USA, a distance of more than 9000 km (Fig. 1 and movie S1). Remote magnetic navigation by an electromagnetic navigation

system was an enabling technology. Adoption of RMN telesurgery will also lead to these types of procedures being performed using microrobots as these devices enter clinical use.

Supplementary Materials

This PDF file includes:
Legend for movie S1

Other Supplementary Material for this manuscript includes the following:
Movie S1

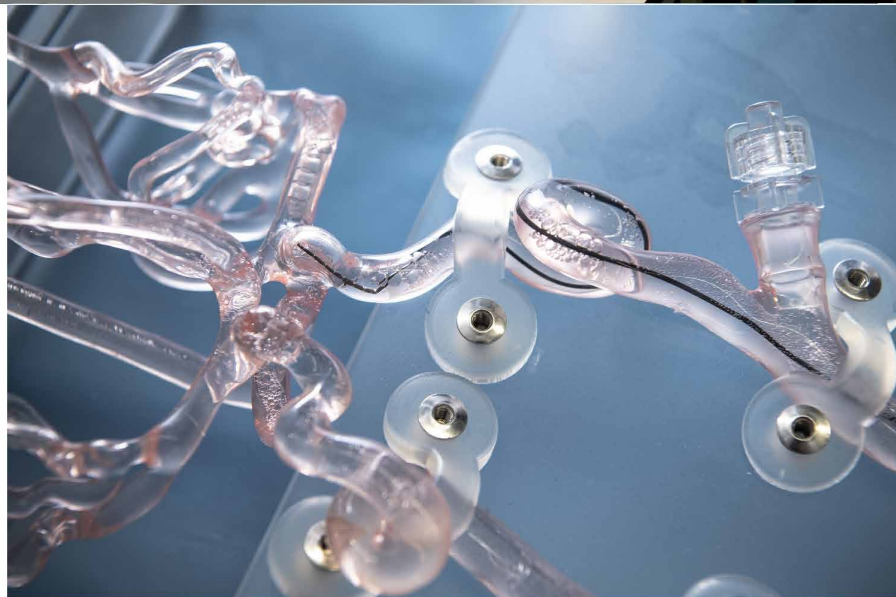
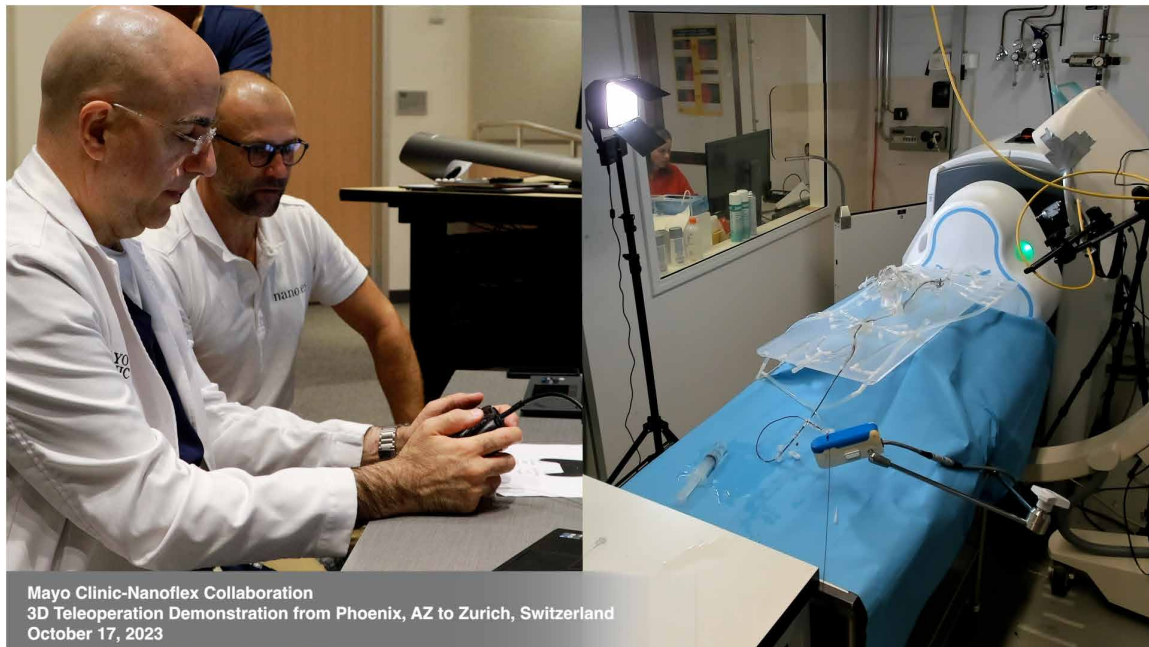


Fig. 1. Mechanical thrombectomy using telerobotics. A complete mechanical thrombectomy being performed on a phantom between Mayo Clinic in Phoenix, USA (top left) and Nanoflex Robotics in Zurich, Switzerland (top right), a distance of more than 9000 km. The bottom image shows a magnetic guidewire navigation through a phantom neurovasculature under teleoperator control.

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