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A decade retrospective of medical robotics research from 2010 to 2020

SMART Group Meeting - Paper Reading Sharing

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A decade retrospective of medical robotics research from 2010 to 2020

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Introduction

More than three decades ago, robot manipulators were tried for performing surgical procedures.

Two decades ago, the first commercial systems were installed in hospitals.

In the past decade, thousands of robotic surgical systems were installed in clinics around the world, and many millions of procedures have been performed.

surgical robots +

- pharmacy robots
- telepresence robots
- disinfecting robots
- rehabilitation robots
- ……

Introduction

The purpose of this article:

1. to identify the major research themes or "hot topics" in medical robotics over the decade.

2. to summarize the seminal research papers that concisely highlight these themes.

Introduction

Hot topic	Seminal references
1. Robotic laparoscopy	(7-18)
2. Nonlaparoscopic robots for minimally invasive surgery	(19-24)
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Introduction

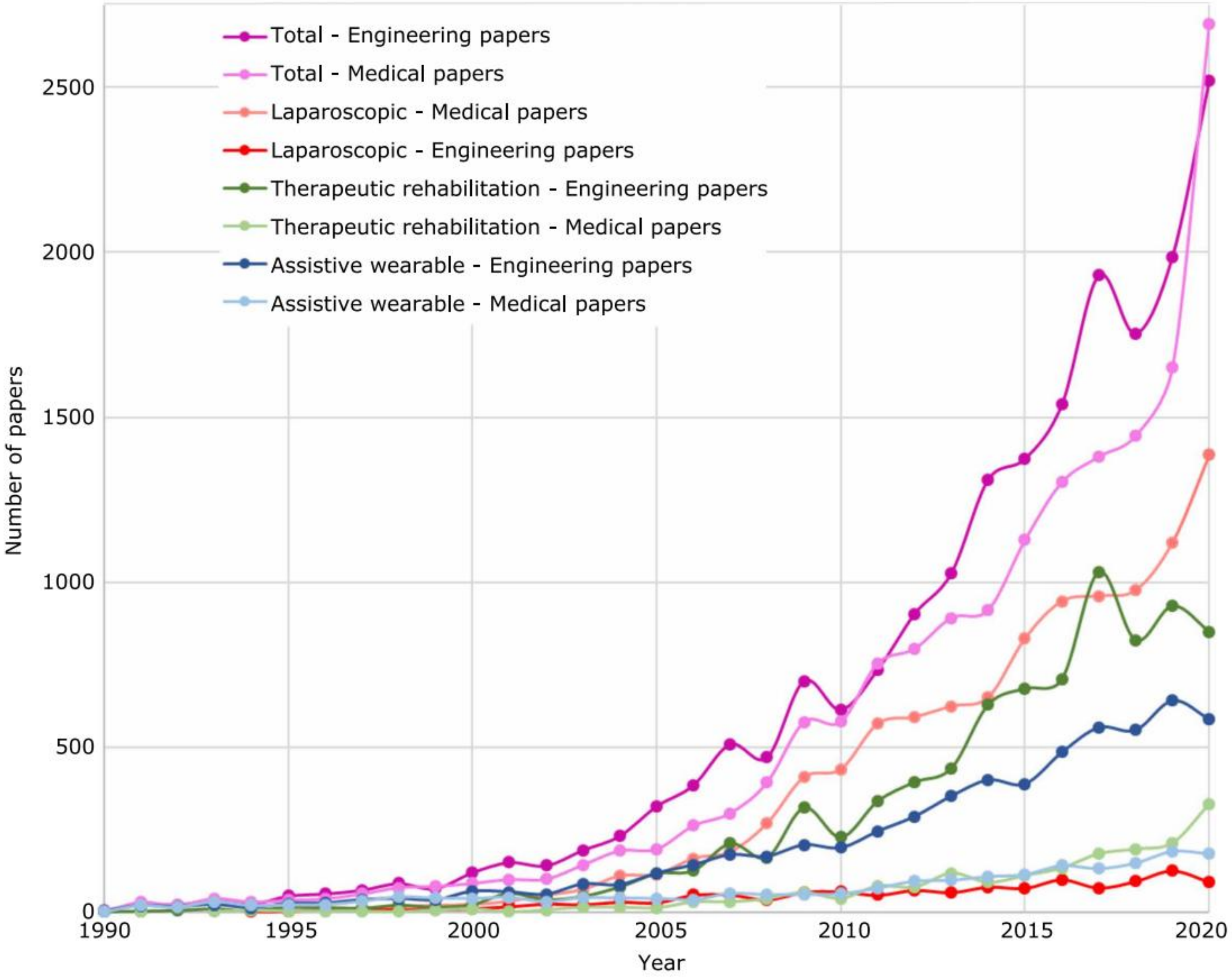


Fig. 2. Medical robotics papers published in engineering and medical journal papers from 1990 to 2020.

Introduction

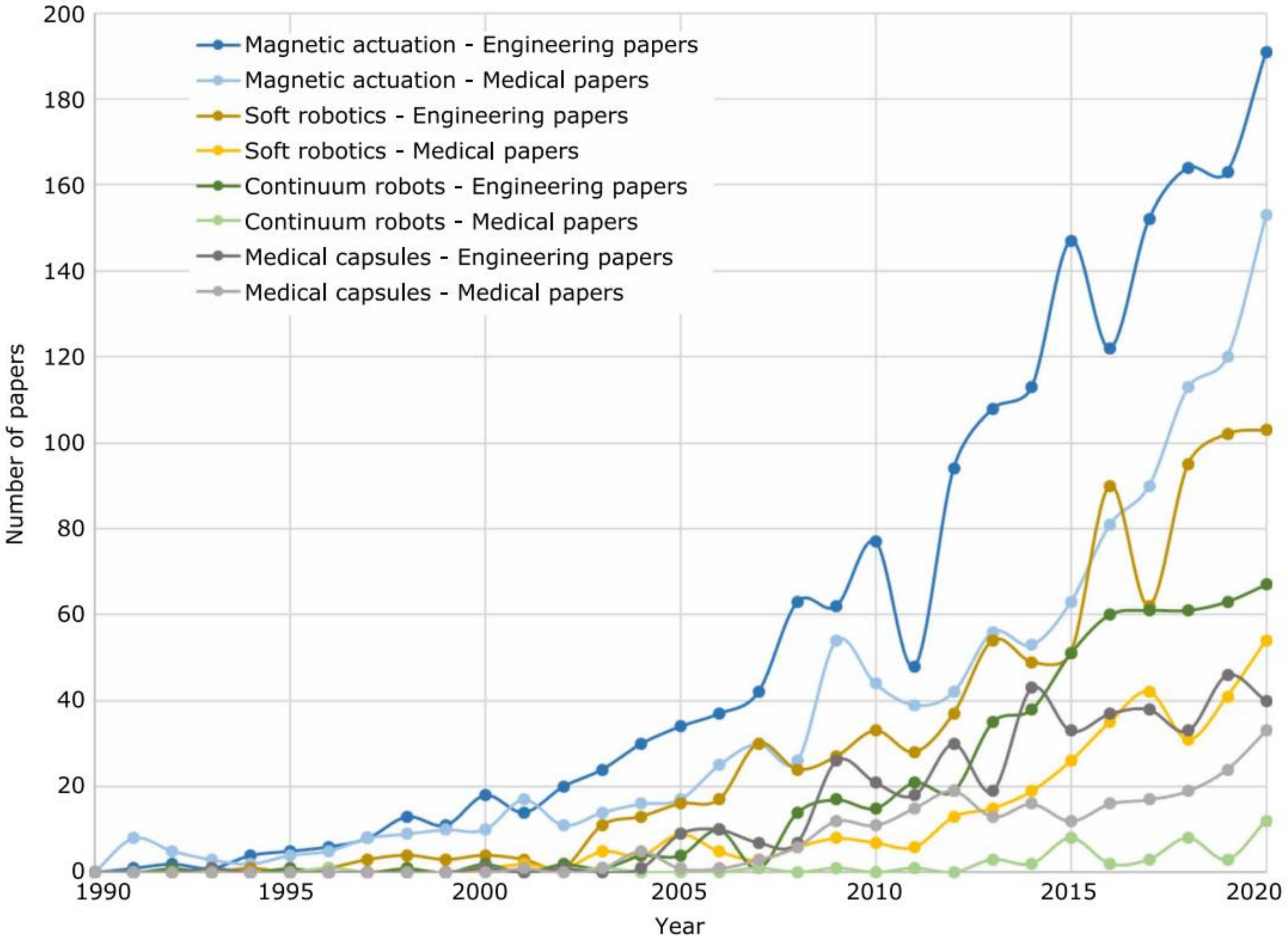
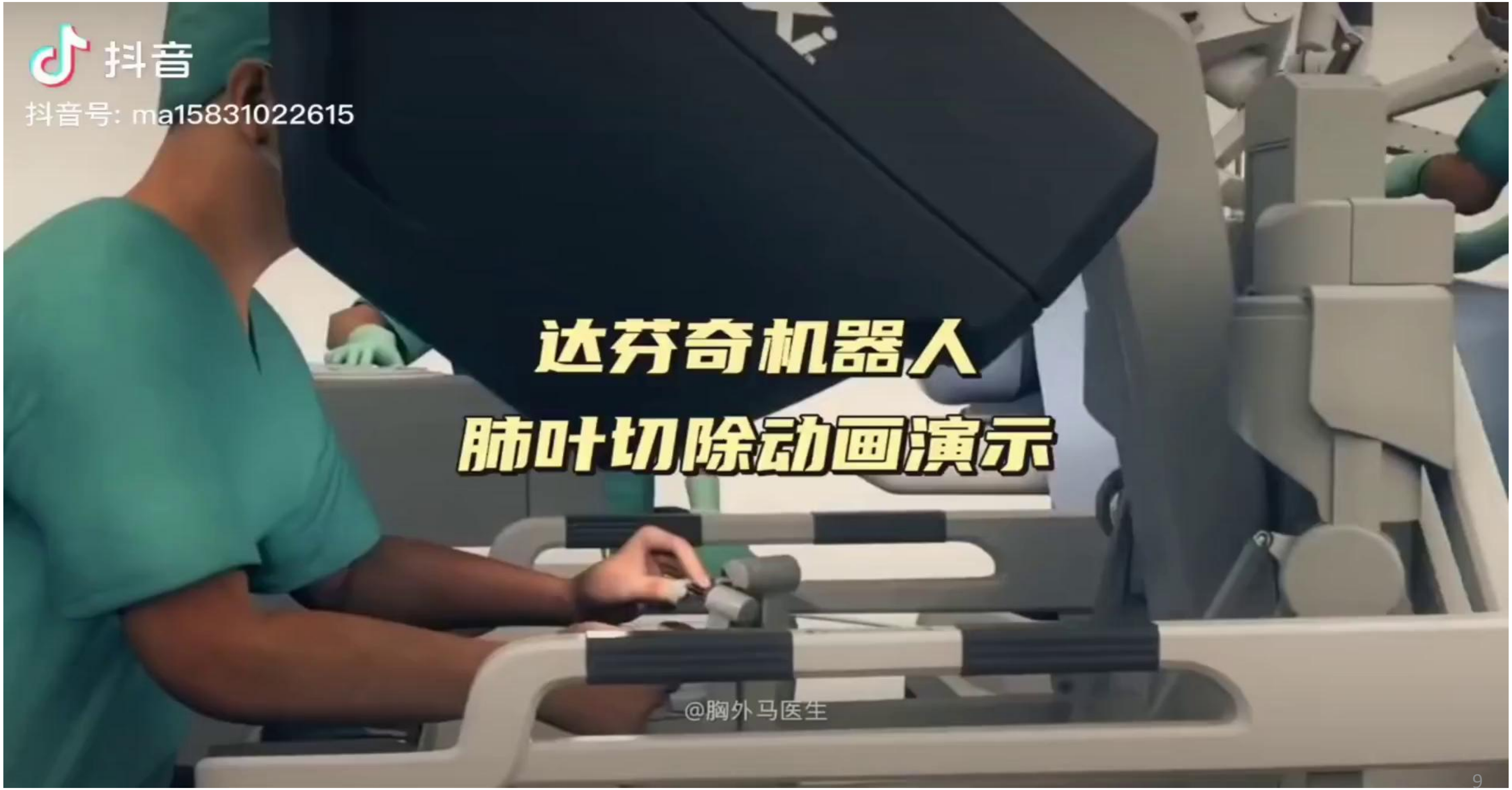


Fig. 3. Medical robotics papers published in engineering and medical journal papers from 1990 to 2020.

Robotic laparoscopy



Robotic laparoscopy

Perhaps the most mature and certainly the most commercially successful subfield of medical robotics. progress has been made on three fronts: clinical, commercial, and academic

Clinical

Many studies aim to compare the efficacy of the robot with standard (usually manual laparoscopic) techniques for different surgical procedures.
Examples include studies on radical prostatectomy, rectal cancer resection.
根治性前列腺切除术 直肠癌切除术

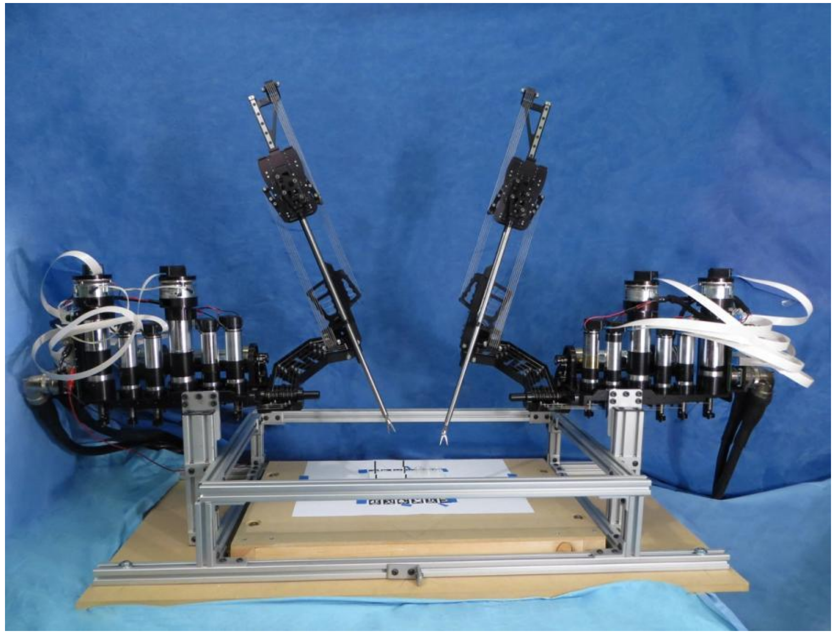
Commercial

Continuing evolutionary development of the da Vinci robot made by Intuitive Surgical. 50+ different instruments over the past decade and more than 1.2 million procedures completed in 2019.
Several large medical device companies also develop their own robots, since the initial patents of Intuitive Surgical began to expire.

Robotic laparoscopy

Academic research direction 1:
using laparoscopic robots as a platform for developing enhanced capabilities

Open platform laparoscopic robots



https://robotsguide.com/robots/ravensurgical

https://www.intuitive-foundation.org/dvrk/

Raven II
a nonclinical robotic surgery research platform that compactly supports two to four laparoscopic instruments

Da Vinci integration system
consisting of refurbished da Vinci Si patient and surgeon-side mechanisms, stereoscopic display hardware with a custom electronics, and a control package—the da Vinci Research Kit or dVRK

Robotic laparoscopy

Academic research direction 1:

using laparoscopic robots as a platform for developing enhanced capabilities

Surgical automation

Potential benefits：

① increased precision.

② fusion of non-visual or haptic sensor information.

③ adherence to precise preoperative plans.

④ amelioration of repetitive stress injury and other ergonomic hazards to surgeons.

Barriers：

① accurate three-dimensional (3D) reconstruction of the (changing) surgical field.

② repeatable and accurate control of elongated and flexible endoscopic mechanisms.

③ accurate situational awareness by the agent of the overall operation’s state.

④ robustness of task plans to sensor errors.

⑤ unusual tissue properties.

⑥ emergency events.

Robotic laparoscopy

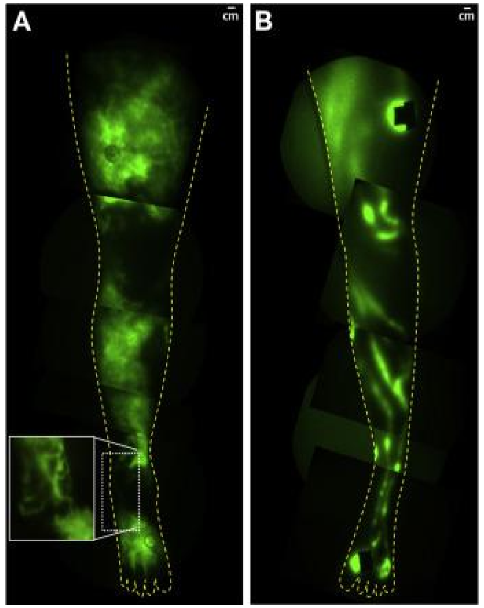
Academic research direction 1:

using laparoscopic robots as a platform for developing enhanced capabilities

Navigation, intraoperative imaging, and visualization

The incorporation of image guidance, using either intraoperative or preoperative data(术中和术前数据), enable assessment of tissue perfusion and visualization of anatomical details(组织灌溉和解剖细节可视化) below the tissue surface, minimizing the risks of damaging underlying vital structures such as nerves and blood vessels.

visualization example
integrating near-infrared imaging with indocyanine green (ICG)
近红外成像与吲哚菁绿,
allowing real-time assessment of microcirculation in vivo.



https://www.sciencedirect.com/science/article/pii/S2352667X15000831

Robotic laparoscopy

Academic research direction 1:

using laparoscopic robots as a platform for developing enhanced capabilities

Contact force sensing and control

The importance

- preserving safe handling of tissues in tasks such as retraction.
- allowing the recreation of tissue palpation at the manipulator during robotic surgery.

Technical barriers

- the small (5 to 10 mm in diameter) size of laparoscopic instruments.
- heat and corrosiveness of sterilization measures in reusable instruments.
- cost in single-use instruments.
- the mechanics imposed between sensing point and the tool-tissue contact point or area.

Progress

- the use of clever mechanical designs to separate pulling and grasping forces.
- the introduction of new sensing technologies, such as capacitive compliant polymer load cells.

电容式柔性聚合物测力传感器

Robotic laparoscopy

Academic research direction 2:
considering new robot architectures that might reduce procedural invasiveness.

Single-port laparoscopic robots

Reduce invasiveness, but combining multiple instrument controls, drives, and endoscopic visualization into a single-access port requires increased mechanical complexity and density.

Detached surgical robots

robots are inserted into the body and then detached mechanically, powered by tethers or external fields (magnetic forces).

Nonlaparoscopic robots for minimally invasive surgery

Endoluminal and natural orifice surgery 腔内和自然孔手术

Endoluminal and endoscopic robots seeking to further reduce morbidity by eliminating the need for skin incisions to access internal anatomy and by offering solutions allowing for deeper access along tortuous anatomical passages.

transnasal pituitary gland, transoral, transumbilical, transvaginal

https://www.intuitive.com/en-us/products-and-services/ion

Ion system (Intuitive Surgical)

https://springfieldbottomline.com/2020/10/riverbend-is-first-hospital-in-the-pacific-northwest-to-use-monarch-robotic-technology-to-diagnose-lung-cancer

Monarch system (Auris Healthcare)

The Ion and Monarch systems use dexterous catheter articulation to enable peripheral lung biopsy

Nonlaparoscopic robots for minimally invasive surgery

Microsurgery

Microsurgery requires high precision, and the surgical personnel inevitably tremble, microsurgery poses unique challenges that exceed the capabilities of existing manual surgical systems

Three approaches to addressing these challenges:

1. handheld robots with tremor filtering

the surgeon-produced tremor in the handheld tool is sensed, and a robot at the tip of the tool moves to oppose it.

2. Cooperative robots

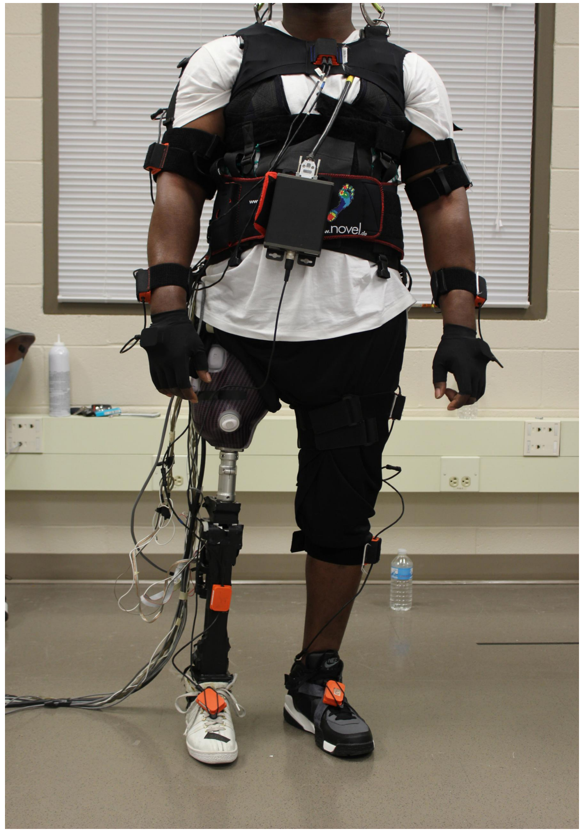
admittance control + assistive control laws

3. telemanipulated robots with a remote center of motion

control the robotic tool through an input device.

Assistive wearable robots

Assistive wearable robotics focuses on the design and control of wearable robotic devices intended to improve the mobility or functionality of individuals with musculoskeletal or neuromuscular impairment (肌肉骨骼或神经肌肉损伤).



https://phys.org/news/2014-11-impact-power-prosthetic-failures-amputees.html

https://cosmosmagazine.com/technology/forget-iron-man-skintight-suits-are-the-future-of-robotic-exoskeletons/

Areas of contribution

- the development of robotic limbs (also called powered prostheses 机械肢体/动力假肢) for individuals with upper and lower extremity amputation (上肢和下肢截肢).

- the development of exoskeletons (also called powered orthoses 外骨骼/动力矫形器) for individuals with neuromuscular impairment, such as those with spinal cord injury, stroke, multiple sclerosis, or cerebral palsy (脊髓损伤、中风、多发性硬化症或脑瘫患者).

lower limb prosthetics

energetically passive device → powered devices

control methods

- **piecewise passive impedance control 分段无源阻抗控制**
  provides assurances of locally passive behavior.
- **phase variable control 相位可变控制**
  supplants finite-state structures with a uniform control policy.
- **Pattern recognition aid 模式识别辅助**
  determine a current activity state and intent to change activity state.

upper limb prosthetics

single-DOF hands and sequential myoelectric control. → multi-DOF hand and arm control

control methods

electromyography (EMG 肌电图)
based pattern recognition approaches in which multichannel EMG is used as input to a pattern classifier, which, in turn, selects a corresponding desired grasp posture or arm movement and subsequently executes the corresponding coordinated hand or arm movement

implanted electrodes
were used for the efferent motor control of a multigrasp arm prosthesis and to provide meaningful neural sensory feedback corresponding to a hand prosthesis

Therapeutic rehabilitation robots

Rehabilitation robots are designed to deliver repetitive movement therapy to the limbs after neurological injuries, most commonly stroke and spinal cord injury (中风和脊髓损伤)

Therapeutic rehabilitation robots

Four areas of rehabilitation robotics research during 2010–2020

1. novel device design
increasingly of the exoskeleton form and focused on the distal joints of the upper limb, and incorporating compliance and soft materials for both actuation and structure.

2. the development of new control algorithms
modulate the interaction between human and robot to elicit maximum participation from the human.

3. the creation of methods of intent detection
infer and support the patient's desired movements, rather than prescribed or preprogrammed trajectories.

4. the expanded use of robotic devices
objective and quantitative assessment of neurorecovery, not just the delivery of therapy.

Therapeutic rehabilitation robots

Research cases

- on the design of rehabilitation robots for the hand and wrist, using tendon or cable-based actuation schemes to reduce device weight and inertia by remotely locating the actuators.

- detecting movement intent from patients using surface EMG to measure electrical activity of the muscles themselves or EEG to infer intent from changes in the electrical potentials recorded from the surface of the scalp could ultimately improve treatment efficiency.

- Robotic devices that outfitted with high-resolution sensors, can be used to assess range of motion, intra- and interlimb coordination, and movement smoothness, among other features. In addition, these devices can track recovery over higher-resolution time scales.

Therapeutic rehabilitation robots

Future research works

increasingly focus on gaining a better understanding of the mechanisms of neuroplasticity, including how it can be reliably induced and exploited to maximize therapeutic outcomes.

The foundation

- **neuroscience**

including new techniques for recording neuronal activity.

- **robotic technologies**

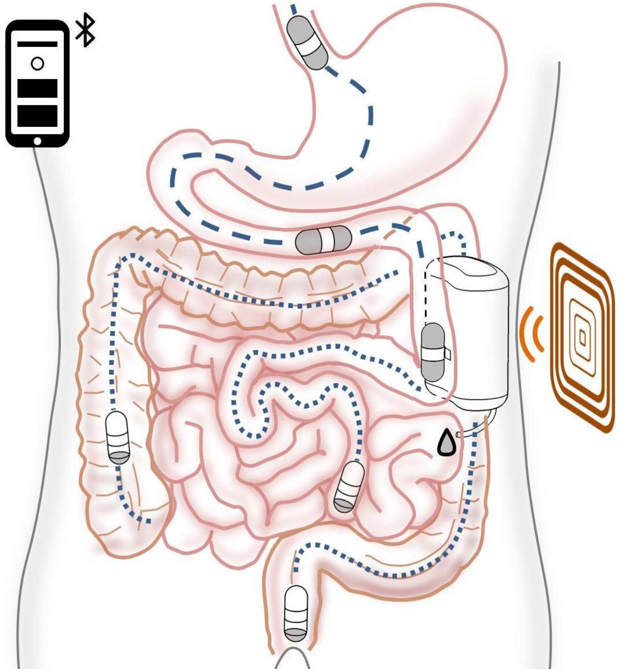
including the development of better-fitting devices and more precise sensing and actuation embedded in devices

- **control algorithms**

precisely characterize the patient's capabilities in real time, adjust the level of support needed to complete movements and impose appropriate resistance or challenge are needed

Capsule robots

At the dawn of 2000, Given Imaging (now Medtronic) introduced wireless capsule endoscopy as a minimally invasive method of inspecting the gastrointestinal tract.
The possibility of collecting images deep inside the bowel just by swallowing a "pill" revolutionized the field of gastrointestinal endoscopy.



Some changes Capsule robots have undergone

on-board actuation & internal, miniature locomotion mechanisms → magnetic actuation

handheld external permanent magnet → robotic control of the magnetic field

Capsule robots

Capsule robots control

The key factor affecting Capsule robots' motion control is the **real-time localization techniques**. Knowing the position and orientation of the capsule is crucial to plan the application of magnetic force and torque for the desired motion.

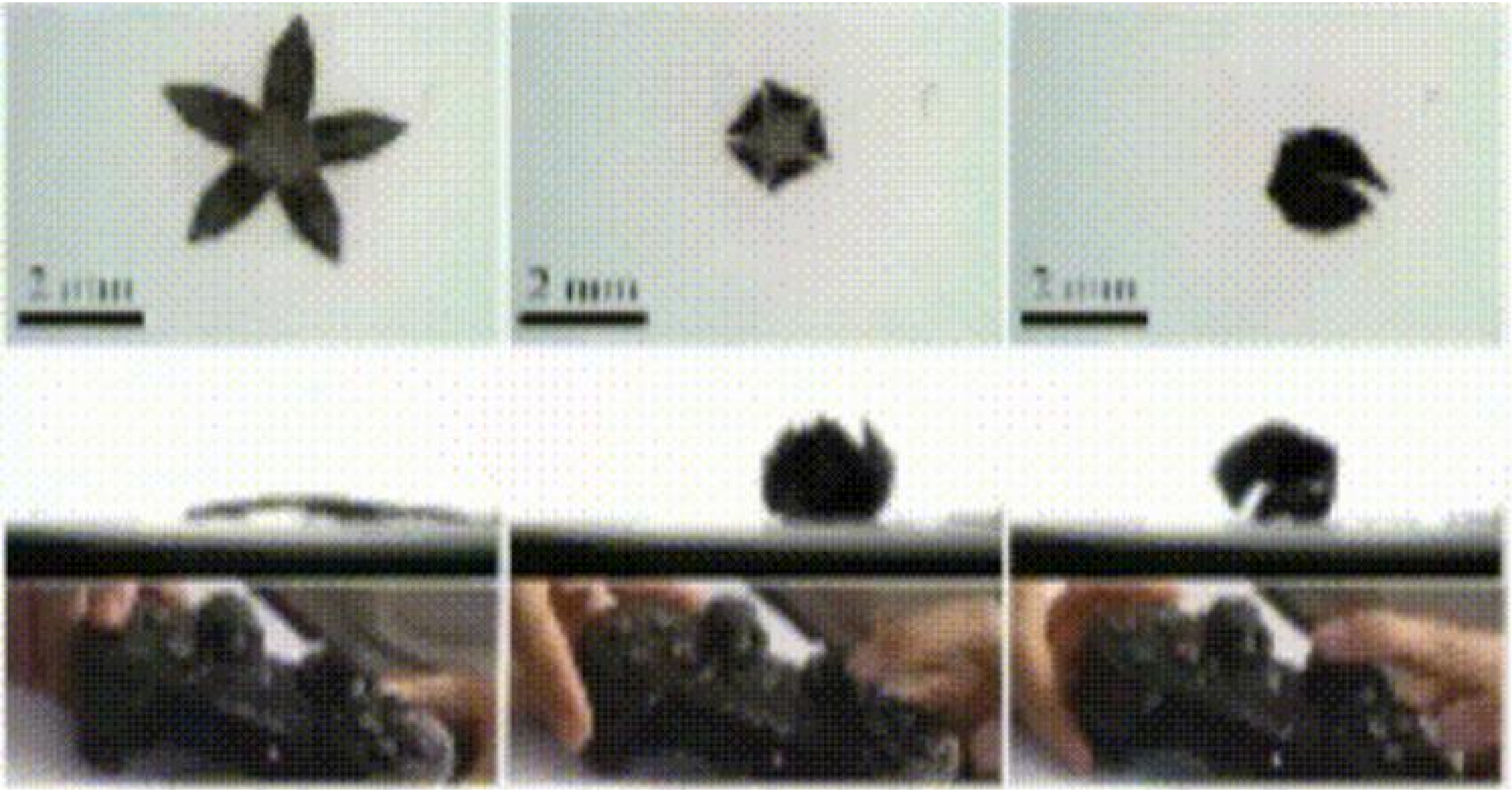
Clinically viable examples of localization are mainly based on **magnetic localization**.

Possible future developments

1. Combined the capsule robots with multimodal imaging and micro/nanorobotics.
Aside from the clinical uses, this could provide a research platform to reach deeper into the human body to address other scientific questions related to, for example, our microbiome

2. "on-board actuation" could be revived if there are significant advances in energy storage or wireless power transfer.

Magnetic actuation for medicine



opening/closing orienting/rotating grasping/jumping

Magnetic actuation for medicine

M. P. Kummer, J. J. Abbott, B. E. Kratochvil, R. Borer, A. Sengul, B. J. Nelson, **OctoMag: An electromagnetic system for 5-DOF wireless micromanipulation.** IEEE Trans. Robot. 26, 1006–1017 (2010).

This work generalized the physics and mathematics of an arbitrary number of geometrically arranged electromagnetics to exert a magnetic force and torque on a given magnetic body.

This led the way for the robotics community to bring more than 50 years of work in robotic manipulator control and design to bear onto the magnetic actuation problem.

Magnetic locomotion strategies

S. Tottori, L. Zhang, F. Qiu, K. K. Krawczyk, A. Franco-Obregón, B. J. Nelson,
Magnetic helical micromachines: Fabrication, controlled swimming, and cargo transport.
Adv. Mater. 24, 811–816 (2012).

Many of motion control techniques culminated in recent work from the work on a single device capable of multimodal locomotion enabled using a variety of dynamically varying magnetic fields.

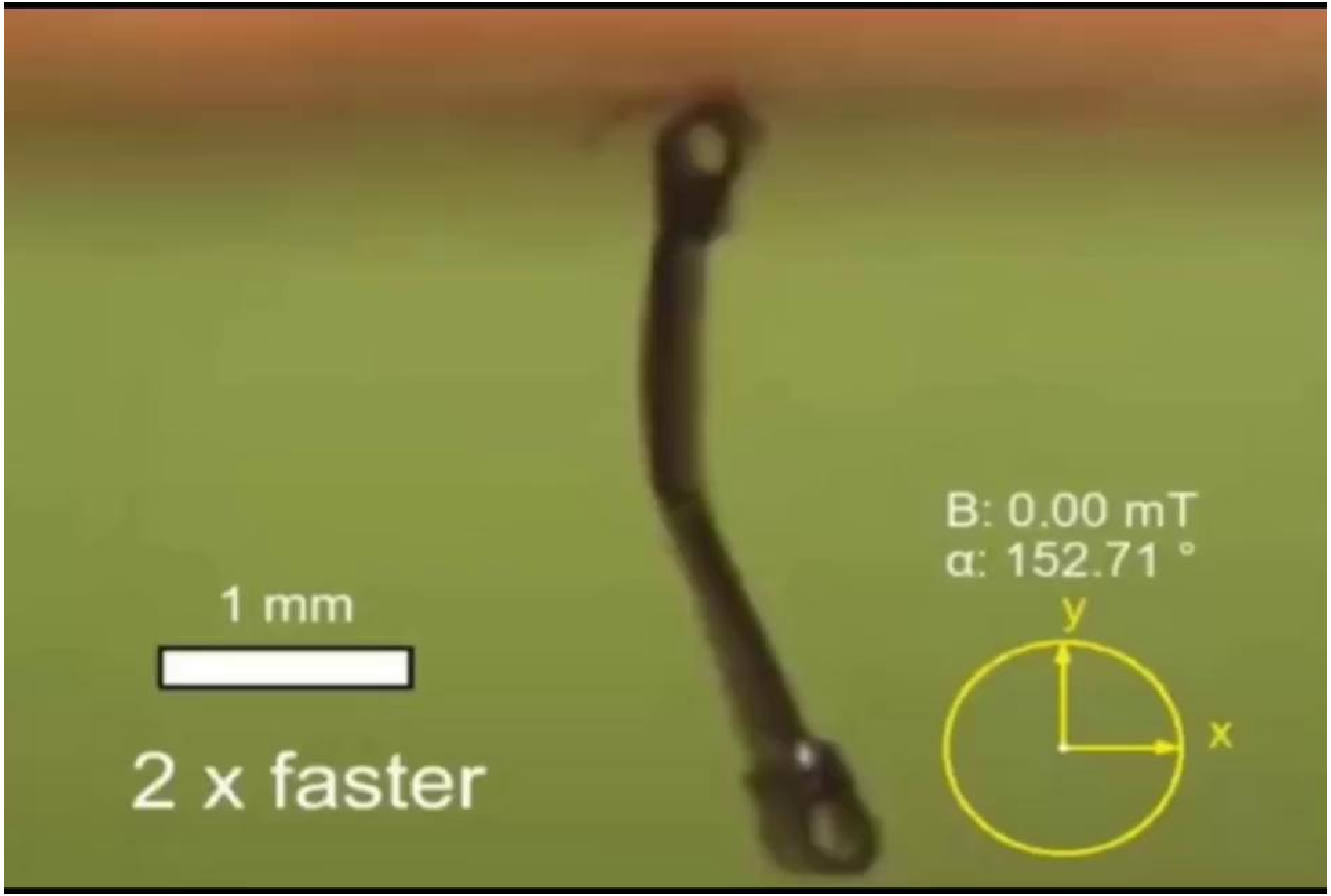
An impressive number of rolling, walking, jumping, and crawling motions were experimentally demonstrated in the paper.

Magnetic actuation for medicine

new impetus of research

- using materials that will eventually biodegrade in the body without harm to the patient
- developing magnetic tools for retrieving magnetic microrobots from the body after use.

Soft robotics for medicine



Soft robotics for medicine

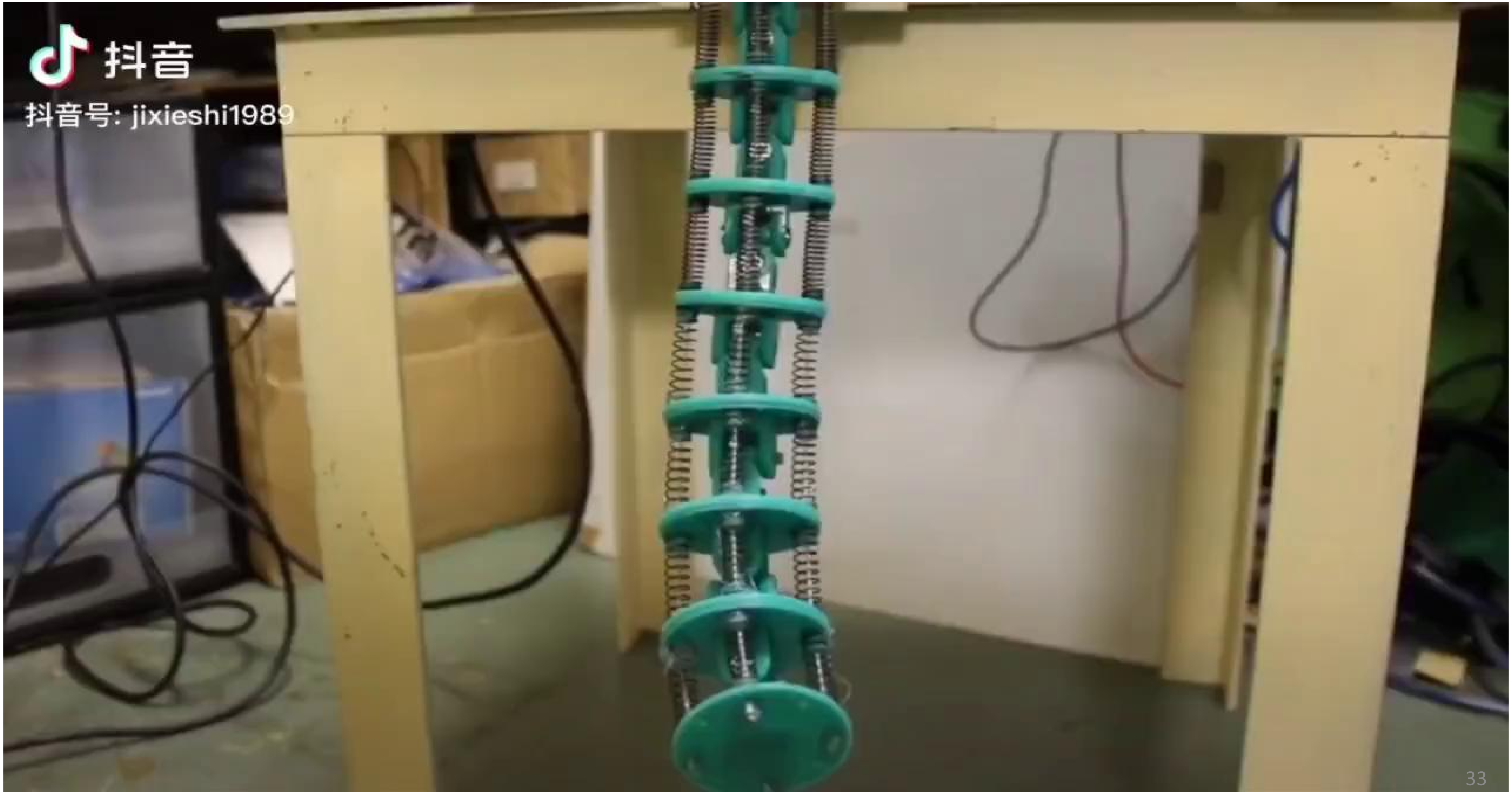
Robotics based on soft concepts, intrinsically compliant structures, and smart materials was strictly joined to biomimetics and bioinspiration from the beginning.

On the other hand, the growing interest for bioinspired robots with compliant bodies has promoted the research on smart materials that could be adopted for fabricating soft robots or for providing soft robots with sensing and actuation capabilities, from the macro-scale down to the nanoscale

Interesting design

transforming surgical manipulators into elephant trunks or octopus arms with the ability to do more tasks with the same arm, by simply changing the stiffness of the different segments.

Continuum robotics for medicine



Research area 1

Extending kinematic models to consider external contacts and loads

In many medical applications, a robot will contact tissue not only at its tip but also at many locations along its length. Unlike rigid robots, these contact forces can produce appreciable deformation of a continuum robot, leading to large errors in the kinematic map relating.

An important research thrust has been to include external loading in the kinematic model and to infer external loads from the kinematic input variables.

A model-free approach has been proposed in which the contact-constrained kinematic model is estimated during task execution

Research area 2

Stiffness control

The task-based force level together with limited volume available to maneuver the robot defines a minimum tip stiffness needed to perform the task.

Important work over the decade has developed mechanical design methods for enhancing and controlling continuum robot stiffness. For those situations when the inherent stiffness is sufficient, the kinematic inputs could be modified to achieve a desired tip stiffness.

Continuum robotics for medicine

Research area 3

Soft continuum robots

Continuum robots are often fabricated from compliant polymeric materials. With the explosive growth in soft robotics over the past decade, however, these actuation methods and the use of even more compliant materials are now being explored for medical applications

Research area 4

Application-specific continuum robot design

In addition to deepening the technological toolbox, researchers have also collaborated with clinicians to create robotic systems designed to perform specific procedures.

For example, Ding et al. produced a single-port system for abdominal surgery. Once inserted into the abdomen, two multibackbone continuum arms along with a conventionally jointed stereoendoscopic arm extend from a single sheath to create an anthropomorphic representation of the surgeon’s head and arms.

Continuum robotics for medicine

The past decade has provided a maturation of the fundamental techniques for designing and modeling the various continuum robot architectures.
Although this research is largely complete, the availability of new sensing technologies will likely spur the development of improved sensor-based control techniques.

There was a growing emphasis toward creating prototype systems such as those noted above that could perform actual medical procedures.
For continuum robots to reach the clinic, this line of research will be increasingly important in the years ahead.

Q & A