THE SECRET HISTORY OF ROBOTIC SURGERY

ROBOTIC SURGEON SERIES: RESEARCH FILES

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Prologue

Surgeons and healthcare professionals have been using robotic devices to assist in surgery and other clinical practices for twenty years. However, many in the general public have not noticed and consider the idea of "robotic surgery" to be future science fiction, and are often terrified by it. This research file shares some of the origins of robotic surgery and then goes on to illustrate how robotics are used in other parts of healthcare.

This research file is entirely true. I save the thrilling fiction and speculation for the novels. Read the novels, join the community at: www.rddsmith.com

Beginning

Given all of the potential entrees for robotic devices to enter the healthcare field, it is interesting that the first documented application was in surgery in 1983. The "Arthrobot", developed by Dr. James McEwen, Geof Auchinlek, Dr. Brian Day at the University of British Columbia, was used to assist in the positioning of a patient's leg during an orthopedic surgery. Arthrobot could manipulate and hold the leg in an exact position to support the incisions and bone cutting that would be performed by the surgeon. A second more interventional case of robotic surgery assistance was the 1985 conversion of the PUMA 560 industrial robot to assist with a brain biopsy. The PUMA used its mechanical accuracy to insert a biopsy needle at a precise angle, to a specific depth, and extract a brain tissue sample backward along the same path achieving a sample location accuracy of 0.05 mm. These early cases, opened the doors for an explosion of the technology that would expand to a multi-billion-dollar industry over the next three decades.

While the robotic surgery race has been very crowded and publicly visible, something similar has been occurring with equal fervor in multiple healthcare domains. Robotic systems can now be found in hundreds of different departments supporting all aspects of healthcare.

Technologies

Healthcare has always been a rich user of technology. Though it is often criticized for being slow to adopt a new technology when compared to manufacturing, defense, ecommerce, and social media industries, once it does embrace a technology like robots, it quickly becomes one of the largest users of that technology. Within any community the local healthcare systems are among the largest users of technologies like computers, networks, databases, energy devices, and robots. In most cities there are more robots in the healthcare system than there are in any other industry in town. Since healthcare is a local business at its core, these systems are duplicated from one city to the next.

If we examine the component technologies that make up the hundreds of robots that are currently servicing healthcare, we find essential pieces that have made significant advances in the last three decades. Robotic assistance in healthcare evolves by leveraging the following (Figure 1):

- Mechanical. Improving physical actions.
- Electronics. Extending human control of mechanical devices.
- Sensors. Extending, augmenting, and replacing human senses.
- Manipulators. Refining and regulating human movement.
- Connectivity. Global accessibility and control.
- Intelligence. Enhancing human thinking and communicating.
- Metaverse. Creating shared information spaces.

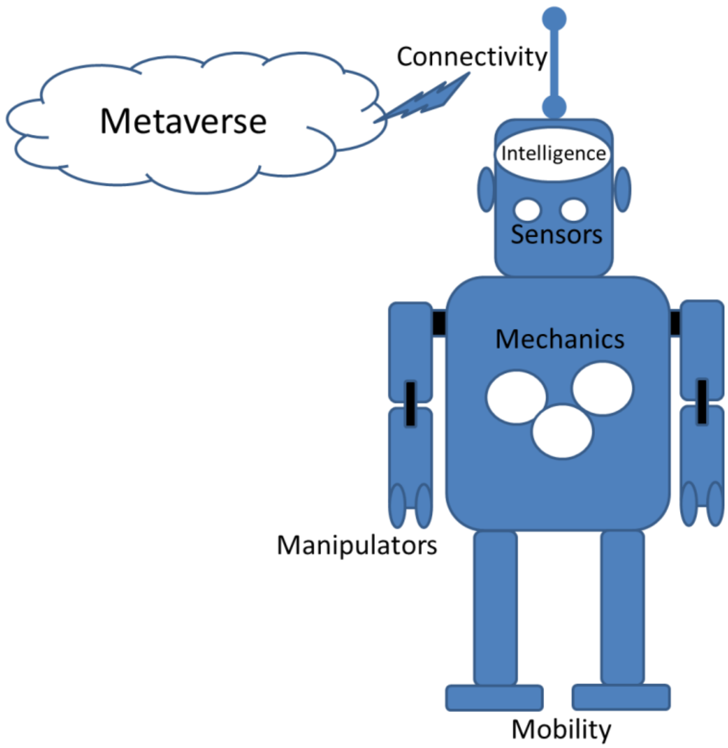

Figure 1. Technologies that contribute to healthcare robots.

Different combinations of these technologies form all of the robotic devices we are about to explore. Each application area has multiple competitors offering unique designs for devices that perform a specific service. This richness of solutions is a testament to the versatility of the technologies and the creativity of the designers and engineers who create them.

Applications

We have identified over twenty unique healthcare applications of robots that are currently in operation. These applications are aligned into a smaller number of categories based on the services that are rendered by the robots (Figure 2).

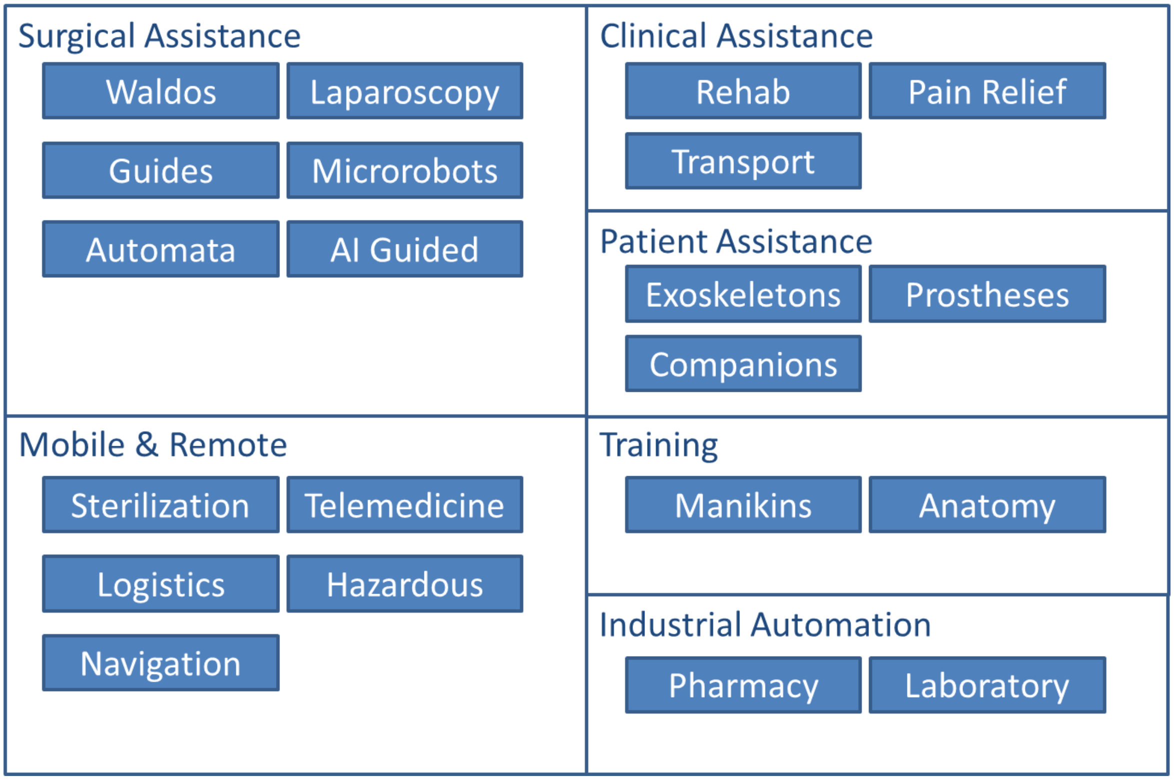

Figure 2. Six categories and over twenty unique applications of robotics in healthcare.

The use of robotics in all of these areas is much more prevalent that most healthcare administrators or clinicians realize because each is likely to encounter only one or two applications in the specific department where they work. Though robotics used to be a rare and unique in healthcare, it has quickly become an essential, embedded contributor and participant in the delivery of dozens of healthcare services and improvements to patient outcomes.

Surgical Assistance

It has been 35 years since robotics was introduced to healthcare through the Arthrobot - and the surgical domain remains the area where the devices are most well-known and where the highest levels of investment are made. In a previous work, I identified over 110 companies that are actively investing in robotic devices to assist with surgery (Figure 3). Intuitive Surgical has been so enormously successful in this area that it has encouraged dozens of other companies to invest in this space. These competitors address surgical procedures in almost every area of the body as shown in the figure. Each company represents several million dollars of investment, measure for the size of this market area.

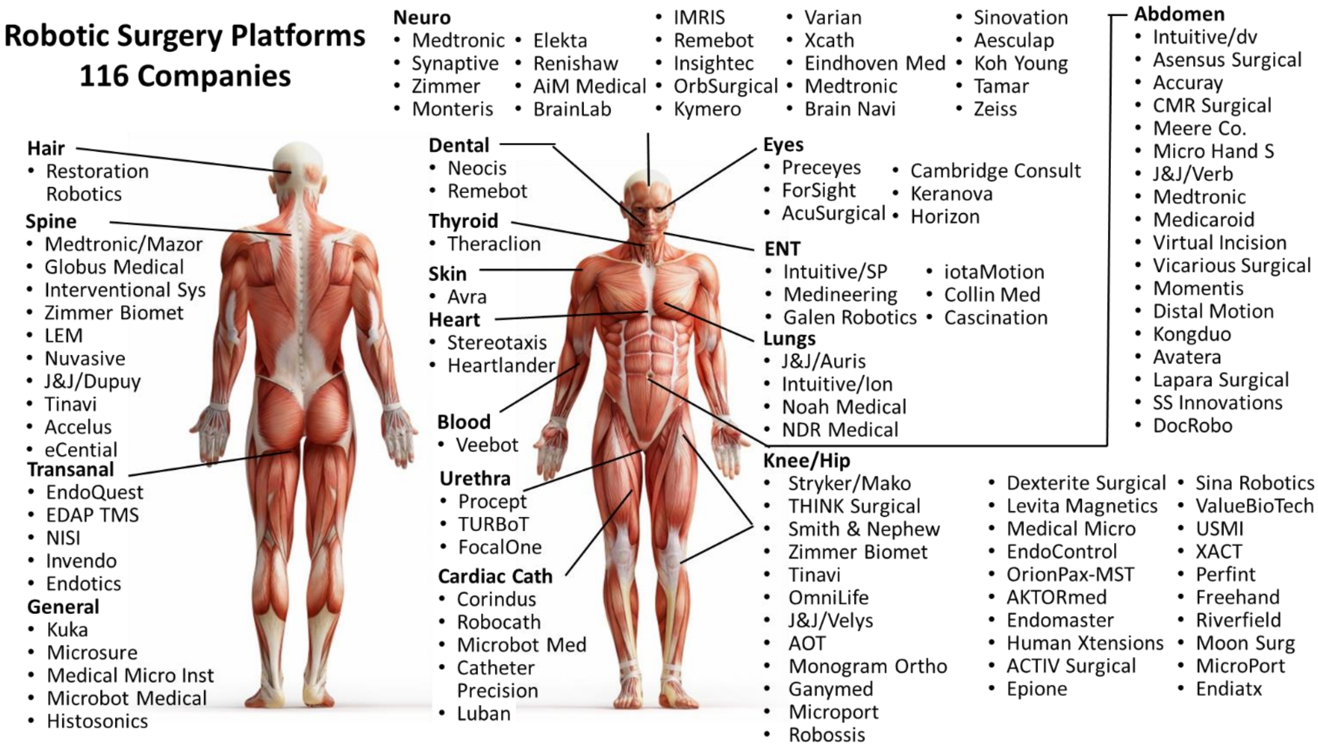

Figure 3. Companies creating a robotic surgical system.

Examining each of these surgical devices, we have grouped them into one of six types of assistance provided to a surgeon (Figure 4). Four of these are well established with multiple products in each. The other two, microrobots and AI driven robots, are just emerging from research laboratories with a few demonstrations of their capabilities.

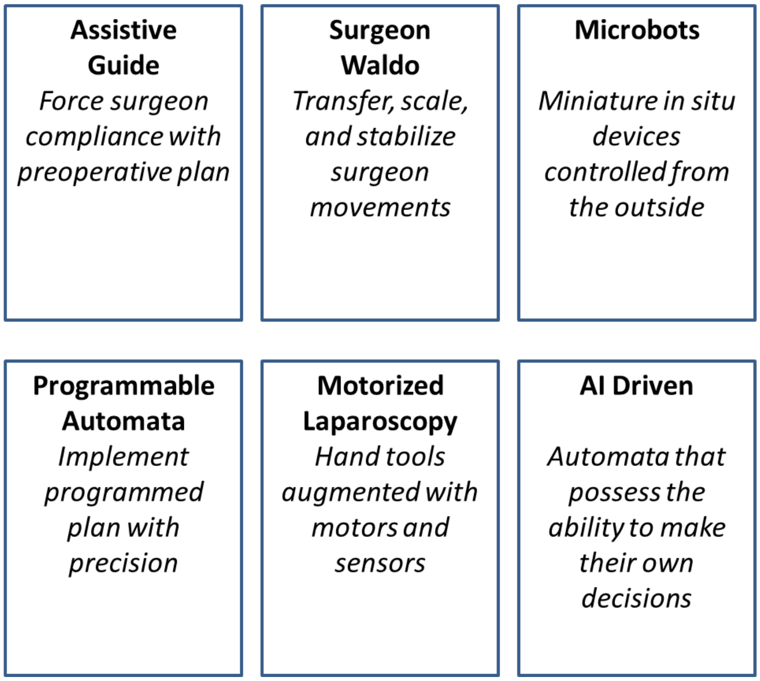

Figure 4. Six types of assistance for robotic surgery devices.

Assistive Guides

Several robots have been created with the specific objective of reducing variation in procedures that originate from the physical movements of the human surgeon. Inserting metal screws into the spine and shaving bone from a knee or hip is a physical activity that requires a strong and steady hand from the human surgeon. In spite of their experience and skills, these human movements are fraught with variations that are not always intended or beneficial. A robotic device can regulate the movement of that hand and the instrument it is using to reduce the unintended variation by several orders of magnitude.

Robots like the Medtronic Mazor spinal surgery robot precisely aligns a guide for a drill that will insert a pedicle screw into the spine. The human surgeon is still responsible for operating the drill and inserting the screw, but they are supported by the Mazor robot in improving the accuracy of the placement of the screw.

Surgeon Waldos

The Intuitive da Vinci robot which has been mentioned earlier is the most widely used form of a Surgeon Waldo robot. The term “Waldo” is derived from a 1952 science fiction story by Robert A. Heinlein of the same title. In that story, Heinlein introduced the concept of a family of robots that are controlled by the movement of human hands, arms, and feet. These robots scale up those movements to allow a single human to build a battleship or they scale down the movement to allow the human to create microelectronic components. For decades, a “Waldo” referred to a family of manufacturing tools that supported this kind of scaling.

The da Vinci robot is a perfect example of a “Waldo” from that original story. It is completely controlled by the actions of the human surgeon. It is not a guide for limiting the movement of the surgeon, rather it enhances and magnifies the actions of the surgeon. It allows them to operate on tissue that is more difficult to reach with manual surgical tools. It uses magnification of vision and scaling of hand to allow them to operate at a much smaller scale and with more precision than they could without the aid of the robot.

Programable Automata

Robotic radiotherapy offers improved precision in delivering energy at a specific location, in specific amounts, and for a specific time. These devices are programmed with the geometry of the patient, the tumor, and the physics of energy propagation. Using this information, they can function autonomously to precisely apply the right amount of energy to specific locations in the body. In fact, the human manual performance of these tasks is so fraught with errors and variation that it is often unsafe.

The CyberKnife system is a non-invasive treatment for cancerous and non-cancerous tumors and other conditions where radiation therapy is indicated. It is used to treat conditions throughout the body, including the prostate, lung, brain, spine, head and neck, liver, pancreas and kidney, and can be an alternative to surgery or an option when the patient’s condition is inoperable.

CyberKnife is an image-guided linear accelerator that was specifically designed to deliver stereotactic radiosurgery (SRS) and stereotactic body radiation therapy (SBRT). It is the precision of the system, delivered by its robotic arm, and real-time adaptive delivery of the radiation beam to the tumor throughout treatment, that makes a difference for patients. CyberKnife’s accuracy is at sub-millimeter levels, which can significantly reduce the risk of side effects from over exposure to healthy tissue or under exposure to cancerous tumor tissue.

The robot moves and bends around the patient, to deliver radiation doses from potentially thousands of unique beam angles, significantly expanding the possible positions to concentrate radiation on the tumor while minimizing dosage to surrounding healthy tissue.

Motorized Laparoscopy

Laparoscopic surgery was invented in the 1960s and became very widespread in the 1980s. It required the creation of a number of new instruments with long shafts, allowing the surgeon’s hands and instrument controls to remain outside the body, while the grasper, scissor, or energy tip entered the body through a small incision. As the mechanical and electronic components of the large robots in the above categories became smaller and cheaper, it enabled the addition of some of those robotic features to individual hand tools used in laparoscopy. Dozens of manufacturers created these enhanced, motorized laparoscopic tools for use in various procedures, generally in the abdomen.

Human Xtensions Ltd. has created the HandX robotic instrument. The motors in the handle and the unique design of the gripper allow the surgeon to control a grasper or energy hook at the end of the tool with six degrees of freedom (6 DOF). This full wristed motion at the end of the instrument is not possible with traditional laparoscopic tools and it is one of the most popular features of large robots like the da Vinci.

Microbots

Microrobots have shown significant potential to conduct microscale tasks such as drug delivery, cell manipulation, micro-assembly, and biosensing using manual control. The unique challenge with these miniature devices is achieving traction to enable mobility. The robots are so small that their own mass is not sufficient to leverage gravity and friction as the enablers of mobility. Multiple approaches have been taken to create a substitute, to include, applying external magnetic fields, equipping them with tiny grippers, attaching hooks on the tires and feet, and leveraging the flow of blood or digestive actions to move the robot.

In one case, the application of targeted delivery was accomplished using magneto-tactic bacteria under DC magnetic fields. Other research groups have also explored microrobots for transporting target objects such as cells and chemicals using magnetic fields. Microgrippers have been developed for microrobots using micro-electro-mechanical systems, a technology which can be used to improve functionality of microrobots. Researchers created tiny devices that can deliver drugs to the body by attaching themselves to a person’s intestines.

In a gastroenterology experiment at Johns Hopkins University, the scientists took inspiration from a hookworm creating shape-shifting microdevices called “thera-grippers” that can mimic the worm and latch on to the intestinal mucosa of a patient. The six-pointed devices, each as large as a dust speck, are made of metal and thin film that can allow them to change shapes. They are covered by a heat-sensitive paraffin wax and have the potential to release a drug gradually into the body. The scientists say that thousands of such devices can be let loose in a gastrointestinal tract. As the wax coating on the tiny robots matches the body’s temperature, thera-grippers automatically close and latch on to the wall of the colon. As they attach and dig into the mucosa, they start slowly releasing the stored medicine. In time, the devices lose their grip on the intestine tissue and leave the organ through normal gastrointestinal function.

AI Guided.

Each of the above devices is guided or programmed directly by a human surgeon, clinician, or multi-specialty team. As the understanding and encoding of each procedure becomes more complete it will be possible to provide instructions to AI software that can accurately perform the function and independently make decisions based on sensor data collected. AI-guided robots will remain under the supervision of a human clinician, but may be able to demonstrate that they can perform a routine procedure at a level equal to the human clinician. Once encoded, collecting data, and updating its model, an AI algorithm should be able to improve its performance more quickly than a human and share that knowledge with every other similar robot on the planet. This level of education and dissemination is impossible for globally distributed human practitioners who distribute their expertise via journal articles and conference presentations.

Clinical Assistance

Outside of the surgical suite, robotic devices are helping members of the clinical team deliver their services in hospitals and clinics. These devices usually allow a human to focus on activities that are at the top of their certifications, perform tasks with more precision, or deliver services more efficiently.

Rehabilitation robots

Rehabilitation from injuries has always posed unique challenges. Cerebral and motor stimulation are both required while using the limb under rehabilitation. Simple movement patterns and even passive exercise routines do not lead to maximum recovery of a limb's capabilities. Rehabilitation supported by robotic systems has numerous advantages: (1) it allows more intensive and tailored rehabilitation activities and services, thus increasing the amount and quality of therapy that can be administered; (2) it allows all the involved actors on the clinical team (e.g., physiotherapists, physicians, bioengineers and other figures) to set and manage work parameters to make the rehabilitation specific and optimal for the patient, this includes the type of exercise, the level of assistance from the robot, the force, and kinematics that the patient must exert; and (3) the computers can collect objective data on performance and use that to measure progress over time.

Robots, especially when coupled with imaginative and graphic computer exercise programs and games, have higher levels of flexibility and variability in creating engaging programs that encourage the therapist and the patient to be more involved with the program both cognitively and physically.

Devices like Barret Medical's BURT and TyroMotion's DIEGO robots have combined robotic supported exercises with engaging gaming environments that challenge the patient to achieve game objectives while performing the prescribed exercises. Engagement with the game can increase the time that a patient is willing to spend on rehabilitation and their level of cognitive engagement during the tasks. Both of these make significant contributions to the recovery of functionality. The self-guided play of the games also reduces the demands on the human physical therapist, allowing them to provide services to more patients simultaneously.

Pain Relief.

Service robots with human behavioral sensing for clinical or personal use in the home have attracted a lot of attention thanks to their advantages in relieving high labor costs of human assistance. One instance of this is the emergence of a robotic device that can provide custom programmed massage therapy. The hope is that the availability and anonymity of these devices will attract patients who are otherwise hesitant to engage in the more intimate traditional massage environment. Robotic devices also offer the advantage of programs that are customized for a specific patient, exactly repeatable, and with a potential for measurable progress toward physical and healthcare goals.

Capsix Robotics in Lyon France was founded with the aim of offering this type of robotic massage. Together with Kuka, the German robotic giant, and LBR Med, they have created the iYU robot, which can almost entirely replicate the work of a massage therapist. The core hardware components are provided by Kuka. LBR Med then customizes the system for massage applications, adhering to the necessary safety, sanitation, and compliance regulations of the healthcare field. Capsix then sells and services the devices for client locations.

Massage Robotics Inc. has launched a larger luxury robot that is equipped with multiple attachments, is controlled by neural networks created in collaboration with Google, and communicates what is learns with other installations of itself.

Pain management is also being addressed psychologically by Canadian researchers who have utilized a robotic device to effectively reduce pediatric cancer patients' distress during needle insertion. The humanoid MEDIport robot is placed next to the child at eye-level, and performs a pre-programmed series of behaviors, like as dancing, to distract the patient before, during, and after the needle insertion. The robot was found to significantly reduce distress.

Transport Patients.

Patient transport is one of the essential, but menial, entry-level positions in a hospital system. It requires no unique education so provides an employment entrée for almost anyone. Most hospitals require that a new employee in patient transport remain in the department of six to twelve months. But, at the completion of this period the transfer rate out of transportation and into other departments is 100%. Therefore, the department is constantly losing staff who know the hospital facility well enough to deliver patients reliably. An intelligent wheelchair that has been programmed to navigate the facility flawlessly would be an invaluable asset. It would be able to identify the fastest route, find alternatives when congestion or construction occur, navigate around people and equipment in hallways, and anticipate the queues that are forming at the destination.

Multiple universities have created prototype robotic wheelchairs with these capabilities. Northwestern University is developing a shared-autonomy wheelchair that is customized to the physical needs and personal preferences of the passenger. It also focuses on simple integration with existing chairs and control interfaces to mitigate the costs and leverage the insurance coverage for these existing wheelchairs. They have developed perception algorithms that can detect doorways, inclines, drop-offs, and docking locations.

Robotic wheelchairs could empower people with physical limitations in navigating their own homes without extreme physical exertion or the dexterity to operate the traditional controls of a motorized wheelchair. Large public spaces, to include malls, big box stores, and government facilities could empower guests to navigate their spaces with confidence. These devices would travel the best route to any store, product, or department without requiring guests to interpret "You Are Here" maps or wander uncertainly around the halls.

Patient Assistance

Robotic devices are not limited to clinical facilities, they can also accompany a patient home and assist them in living with conditions that previously would have severely limited their lifestyles.

Exoskeletons.

Every year, nearly 56 million people suffer from acquired brain injury, 15 million suffer from stroke, up to 500,000 people suffer from a spinal cord injury, and 2.8 million people live with multiple sclerosis. Many of these people are left with limited mobility or some form of paralysis. This can be a devastating diagnosis that is completely life-changing for both patients and their families. For those who are not confined to a wheelchair, an exoskeleton can provide the mobility and independence that they need to maintain a normal lifestyle. Exoskeletons have appeared in a number of science fiction movies, most notably assisting Sigourney Weaver in the 1979 "Alien" movie. But these devices are available in much less threatening and less industrial forms to assist people with healthcare needs.

The ReWalk exoskeleton is a battery-powered system composed of a light, wearable exoskeleton with motors at the hip and knee joints. It controls movement using subtle changes in the patient's center of gravity. A forward tilt of the upper body is sensed by the system, which initiates the first step. Repeated body shifting generates a sequence of steps which mimic the functional natural gait of the legs.

Ekso Bionics has applied their clinical and engineering expertise to develop exoskeleton robotics for rehabilitation centers. The device itself is an exoskeleton, but it is used in rehabilitation as described in a later section. Patients post stroke, brain injury, or spinal cord injury and those affected by MS can use exoskeletons in therapy to regain basic movements or even the ability to walk again. The patient may experience an increase in range of motion and the activation of muscles they had difficulty with before. Physical therapists remain a part of this treatment, leveraging the exoskeleton to improve their patients' gait and get them back to social and work functions.

Prostheses

More than one million annual limb amputations are carried out globally due to accidents, war casualties, cardiovascular disease, tumors, and congenital anomalies. Robotic prosthetic limbs integrate advanced mechatronics, intelligent sensing, and control for achieving higher order lost sensor-motor functions while maintaining the physical appearance of the amputated limb. Robotic prosthetic limbs are expected to replace the missing limbs of an amputee restoring the lost functions and providing a natural aesthetic appearance. These robotic prostheses contribute to enhanced social interaction, improved independent living, and productive work in society. Advances in electro-neural connectivity and miniaturization of mechanical motors will continue to make these limbs more effective and less expensive.

A Cleveland Clinic-led research team has engineered a first-of-kind neurorobotic prosthetic arm for patients with upper-limb amputations that allows wearers to think, behave and function more like a person without an amputation. Th robotic prosthetic combines intuitive motor control, a sense of touch, and grip kinesthesia (the intuitive feeling of opening and closing the hand).

Dr. Paul Marasco, Associate Professor in Cleveland Clinic Lerner Research Institute's Department of Biomedical Engineering said, "We modified a standard-of-care prosthetic with this complex bionic system that enables wearers to move their prosthetic arm more intuitively and feel sensations of touch and movement at the same time. These findings are an important step toward providing people with amputation a complete restoration of natural arm function."

Companions.

The PARO Therapeutic Robot looks like a baby harbor seal and is designed to provide the benefits of animal therapy without relying on live animals. Animal therapy is a common tool for easing patient stress, but there are not always trained animals available to satisfy current needs. The PARO robot is frequently used with elderly patients with dementia, and has been proven to reduce stress and provide comfort to anxious patients. The soft, fuzzy device can respond to its name, enjoys being stroked, and, over time, develops a customized, pleasing personality tailored by its memory of previous interactions. PARO also naps, blinks, wiggles its flippers and makes funny noises for its owner.

Devices like Connected Living's Temi robot also offer a window into the condition and safety of the elderly or patients needing home care. When equipped with visual, aural, and vocal sensors, these devices allow monitoring for alerts, consultations with clinicians, and reduce some of the fears of being entirely alone in a home. These companions combine the services of therapy animals, first alert buttons, and smart speakers to create a safer environment for independent living.

Mobile and Remote Services

Hospitals are very large and complex facilities in which mobility and a working knowledge of the locations of departments and services is required. Robots with mobility, intelligence, and independence can make significant contributions to the efficiency of these facilities.

Sterilization

Along with minimizing medical and surgical errors, hospital-acquired infections (HAIs) are a widespread problem in healthcare that could be improved with robots. The CDC reported that there were 722,000 HAIs in U.S. acute care hospitals in 2011. These often occur because hospitals can't always clean rooms to 100% sterility between patients, whether due to time constraints or the simple invisibility of germs. Patients who are already immunocompromised are more susceptible to bacterial infection. Several companies have created room sterilization robots that are being used to reduce HAIs.

The Xenex LightStrike robot was one of the first of these. It uses full-spectrum UV rays to kill a range of infectious bacteria in an entire room. Significantly, it is effective against Coronavirus and Methicillin-resistant Staphylococcus aureus (MRSA). The robot generates bursts of high intensity, short-wavelength ultraviolet (UV) light to kill disease-causing pathogens of all types. Light from the sun includes UVA and UVB rays, which can make it through the Earth’s ozone layer, as well as UVC rays, which cannot. Because viruses and bacteria were not previously exposed to UVC, they never developed defenses against it. As a result, UVC light deactivates these germs and prevents them from reproducing. One five-minute light treatment from the robot is enough to destroy all viruses and bacteria within a two-meter area. To protect the safety of staff, the robot operates behind closed doors, with no people in the room. After the UVC light turns off, it is safe for housekeeping staff to enter the room and clean it without the risk of exposure to coronavirus or any other infectious germs. UVC robots are also produced by Clorox, Philips, Adibot, and BlueBionics.

Logistics.

Hospitals are large and complex facilities. They require the delivery of supplies and medications throughout the day. This can be challenging for human staff who must learn the layout of the entire facility and spend the entire day looping through the hallways. A robot programmed with a map of the facility and equipped with appropriate sensors and decision logic is an attractive alternative to human delivery services.

MedStar Washington and other hospitals have employed the Aethon TUG robot to deliver food, supplies, medicines, and medical specimens. The device knows the layout of the hospital, is equipped with sensors to allow it to avoid people and obstacles, and has an electronic connection that allows it to call the elevator for a ride. MedStar Washington’s six TUGs traveled 1,554 miles and made 13,800 stops, delivering medications, linens, and other essentials in a single year.

Navigation Assistance

As described in previous sections, navigating a large, complex hospital is a challenge for the staff that work there, and even more so for the thousands of patients, family members, and visitors that flow through a facility every day. Hospitals address this with lobby help desks, facility maps, and the assistance of all of their employees. Many hospital systems inculcate a culture among all staff of stopping to help lost visitors. Recognizing the behaviors of these lost visitors and offering assistance is an expected service from everyone who works in the facility.

Navigation robots can make a contribution to this service. Using voice recognition, voice generation, onscreen displays, and a perfect map of the facility, these devices can be located anywhere in the hospital and roam to where visitor flow is the heaviest. They can show and explain a route to the visitor's destination or they can connect to a human assistant who can speak through the robot for more complicated problems. When showing the route on screen is not sufficient, the robot can physically escort the visitor all the way to their destination.

Telemedicine

Telemedicine robots enable clinicians to see, hear and speak with patients as if they were at their bedside, even when they are miles away at a different hospital or working from a home office. These devices provide a clear view of the patient, which is almost as good as being there. The cameras on the devices can be customized for the services to be provided. These may be high resolution with the ability to read monitors and charts in the room, possess magnification for examining small features like eye dilation and moles, or use infrared for viewing a patient's thermal profile.

During the covid pandemic, Liverpool Women's Hospital and Alder Hey Children's Hospital in the UK used two telemedicine robots to keep a full neonatal service running with limited staff and limited access. Other hospitals have used them to augment patient rounds by including physicians and specialists who would not otherwise be available during evening shifts.

Dr. Steve Jackson, chief medical information officer at University Hospitals of Leicester, has described the advantages that allow him to offer services at multiple locations during the same day, without the need to commute between them. Alternatively, physicians often dedicate whole days to a single facility and may not be able to serve patients at a facility until a later day. Jackson says, "I can consult with patients about whom my ward team are concerned or who might arrive on the ward between my ward round times and who might be able to go home outside of my designated ward round times. Such ad-hoc ward 'visits' would not otherwise be possible owing to my busy schedule and cross-site working."

He also believes that, "From the point of view of having patients who need super specialist opinions, which I've used the tech for, it's absolutely superb. It means that patients don't have to wait to be transferred across the city to go to a different hospital because the specialists can consult with them there and then and make a plan which everyone's happy with."

Devices like Teladoc's InTouch, Vecna Technologies' Vgo, and the Double Robot are examples of telemedicine robots in use today.

Hazardous Contact

Covid, SARS, Ebola, and similar outbreaks created situations in which it was actually life threatening for human clinicians to be in contact with patients. When new diseases break and the transmission pathways, effects, and lethality of the disease is not yet well known, it is a significant challenge to apply the necessary PPE, isolation, and contact procedures to keep clinicians safe while also meeting the needs of the patients. Some of the necessary interactions can be carried out through a robotic intermediary. Mobile, computerized devices can take patient history and some basic vital signs, thereby eliminating several of the pathways for disease transmission, making treatment centers safer for clinicians without withholding essential services from sick patients.

The InTouch, described earlier, was initially developed for patient-focused telemedicine applications, but was adapted for hazardous contact specifically to address Ebola treatment dangers.

Training

Clinician educators have relied on manikins and part-task trainers for decades. These very useful devices reduce the reliance on live human actors, cadaveric tissue, and animals as surrogates for patients. In recent years these devices have become much more active and intelligent at providing these services.

Smart Manikins

Simulation manikins first emerged as life-sized cloth dolls for nurse training in 1911. Since then, they have been through multiple evolutions such that the most advanced of these are now also classified as robots for training. These allow clinicians to practice their healthcare skills on the robot before attempting to assess or perform a treatment on a human patient. Using smart robotic manikins, learners can be better prepared to manage their immediate reactions to critical situations. These devices also reduce the need for supervision or direct oversight during many clinical patient encounters. Robotic manikins allow clinicians to rehearse repeatedly under identical conditions, and support the collection of objective data that measures improved performance.

Laerdal, founded in 1940 and headquartered in Stavanger, Norway, produces a number of manikin products that vary in age, gender and clinical treatment applications. Devices that would be considered robots include SimMan, SimMom, SimJunior, SimNewB, and Premature Anne.

These devices can display neurological and physiological symptoms that clinicians must diagnose and treat. Laerdal's robot manikins have a pulse, blood pressure, breath, lung sounds, heart sounds, pulse oximetry and a monitor that can display EKG, arterial waveforms, and pulmonary artery waveforms. These manikins can be used to train tasks like CPR, bag-mask ventilation, intubation, defibrillation, chest tube placement and others. Similar devices are available from Gaumard, CAE Health, and others.

Anatomical Replicas

Just as simple full-body manikins evolved into robotic devices, partial body replicas are following the same path. Most part-task trainers are simple latex covered frames that present a passive piece of anatomy for learning and rehearsing a specific procedure. But a few devices like the Gaumard Advanced CPR and Airway Trainer are adding smart dynamic actions to these replicas. As computers and sensors become smaller and cheaper this opens the door for incorporating them into lower-cost and more focused training devices. Like the full body manikins, the objective is to replicate the functions of the human body and the responses that occur during a medical procedure. The device is no longer an inanimate piece of latex, but a robotic replica of the anatomy and its dynamic functionality.

Industrial Automation

All manufacturing and warehouse industries have been using robots for decades. These devices perform well defined and repetitive tasks much more quickly, accurately, and economically than their human counterparts. In the healthcare space, similar manifestations of these robots are found in pharmacies and laboratories.

Pharmacy

Robotic picking arms can be used in both large pharmacy warehouses and in smaller dispensaries at individual hospitals. The principles of operation are very similar to the plethora of warehouse robots that are used for every other type of order fulfillment. The devices are programmed with the location of the drug that has been requested and then read barcodes when they arrive at the destination to ensure that they are retrieving the right product.

These machines tend to employ either chaotic or channel-fed dispensing systems. Omnicell's Cyrus Hodivala says, "In chaotic storage, the robot takes a pack and puts it on the shelves, and only the robot knows where that pack has gone. It does this for space efficiency, tessellating packs together on a shelf to fit the most packs inside that it possibly can. That's great if you've got a very big formulary, which is why hospitals love it, because you've got thousands of drugs on register."

The main problem with chaotic storage is that the picking speed can be quite slow because the robot will often need to move packs around to find the one it needs. The time between making a dispensing request to receiving the pack in a chaotic storage system is around 14 seconds.

The alternative method of channel-fed dispensing involves storing drugs in individual metal or plastic channels, each of which is dedicated to just one drug type. Channel-fed dispensing allows for much faster picking speeds compared to chaotic storage, taking around four seconds to dispense a single pack.

Hodivala says: "The downside for channel-fed is your channels need to be sized for your packs. If you've got lots of varying pack sizes, you have to continually keep reallocating channels. Also, if you're only holding one pack of a particular drug type an entire channel needs to be dedicated to it, so it's not very space efficient."

The University of California, San Francisco (UCSF) hospital, also use robots to process daily medication orders for individual patients. Using mechanical arms, they select and sort multiple medications into barcoded packets that are customized to the patient.

Laboratory

Clinical laboratories use small, nimble robots to perform the most repetitive laboratory tasks, relieving humans from this inhuman work. ABB Robotics, which runs a research center at the Texas Medical Center (TMC) Innovation Institute in Houston, estimates that the market for laboratory robots in healthcare will reach 5,000 by 2025.

This influx of robot assistants doesn't mean humans will be banished from the laboratory, rather the robots will be supporting humans with dangerous or dull activities. Currently robots are used to organize the most routine and repetitive part of the laboratory, like centrifuging, aliquoting, and automating routine chemistry, immunoassay, hematology, and urinalysis. The systems are guided by bar codes that tell the robots in various instruments what to do. This is most common for routine high volume tasks that can justify the purchase of a robotic device. But, once the robots are on premises, there is the potential to add end effectors and software to allow them to perform lower volume, more specialized tasks as well. As these robots become more sophisticated, more accurate, more intelligent, and cheaper they become a more attractive alternative to human laboratory technicians.

Future Direction

It is no surprise that visions of the near future suggest that robotic devices will continue to proliferate in healthcare. This is being driven by a number of complimentary forces shown in Figure 5.

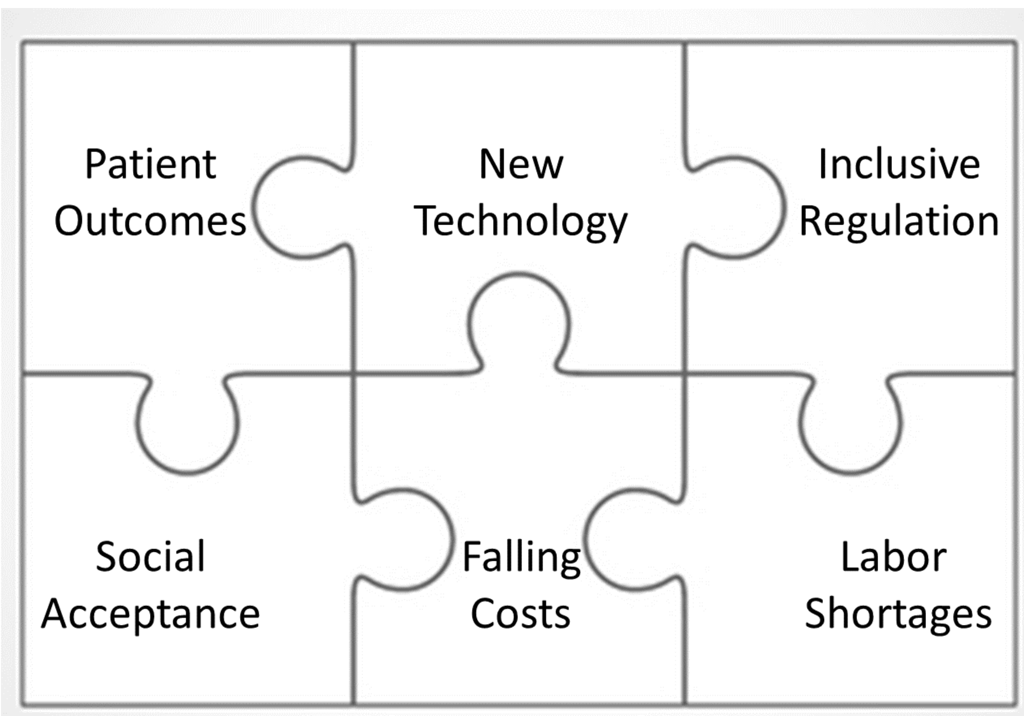

Figure 5. Six future forces that create a healthcare environment that is inclusive to robotic assistance.

Patient Outcomes. Since many robots are introduced as part of a controlled experiment, there is growing evidence published in the medical literature that quantify the impacts that these devices have had. Many of these studies present a very positive picture of the contribution of a robotic device, which encourages their adoption and use in healthcare systems.

New Technology. Improvements is every technology that is used to create a robot is resulting in devices that are smaller, smarter, more mobile, more dexterous, more connected, and consume less power. The next generation of devices will be more helpful, less intrusive, and less expensive than those on the market today.

Inclusive Regulations. The healthcare field has been limited by regulations on the use of telemedicine and assistive devices for decades. One impact of the COVID crisis has been the necessity to connect patients with healthcare providers in new ways. This has opened the door on regulation and insurance reimbursement such that robots and similar technologies can be billed to these payors, reducing the burden on patients and end-users.

Social Acceptance. The term “robot” has historically conjured threatening images of the Terminator. But, with exposure to the many forms of robots and media stories about their benefits, the general public is becoming less fearful and more accepting of the devices. Contributing to this acceptance is the maturation of a generation of children who grew up with these technologies, are comfortable using them, and have aged into positions of leadership in healthcare, government and medical device companies.

Labor Shortages. The demand of healthcare services is exceeding the ability of an all-human workforce to deliver these in the traditional manner. Meeting the needs of an aging population requires the recruitment of a new set of hands to assist the limited supply of healthcare providers. Some of these hands can come from smart robotic devices.

Falling Costs. Improved technologies and loosened regulations create an environment in which robotic devices can be produced in larger numbers, reducing the per unit price. Robotic assistance in healthcare will become less costly as it becomes more prevalent and better integrated into the larger healthcare delivery system.

The advantages of adding robotic devices to the healthcare system are overcoming the resistance to the devices that was a natural part of a new technology in its early stages and which was poorly understood by both clinicians and patients. These devices are no longer relegated to science fiction stories, but have become a common component of a modern, integrated healthcare system that delivers the best outcomes for patients.

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