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Healthcare robotics can provide health and wellness support to billions of people.

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Healthcare Robotics

THE USE OF robots in healthcare represents an exciting opportunity to help a large number of people. Robots can be used to enable people with cognitive, sensory, and motor impairments, help people who are ill or injured, support caregivers, and aid the clinical workforce. This article highlights several recent advancements on these fronts, and discusses their impact on stakeholders. It also outlines several key technological, logistical, and design challenges faced in healthcare robot adoption, and suggests possible avenues for overcoming them.

Robots are "physically embodied systems capable of enacting physical change in the world." They enact this change with effectors, which can move the robot (locomotion), or objects in the environment (manipulation). Robots typically use sensor data to make decisions. They can vary in their degree of autonomy, from fully autonomous to fully teleoperated, though most modern system have mixed initiative, or shared autonomy. More broadly, robotics technology includes affiliated systems, such as related sensors, algorithms for processing data, and so on.[28]

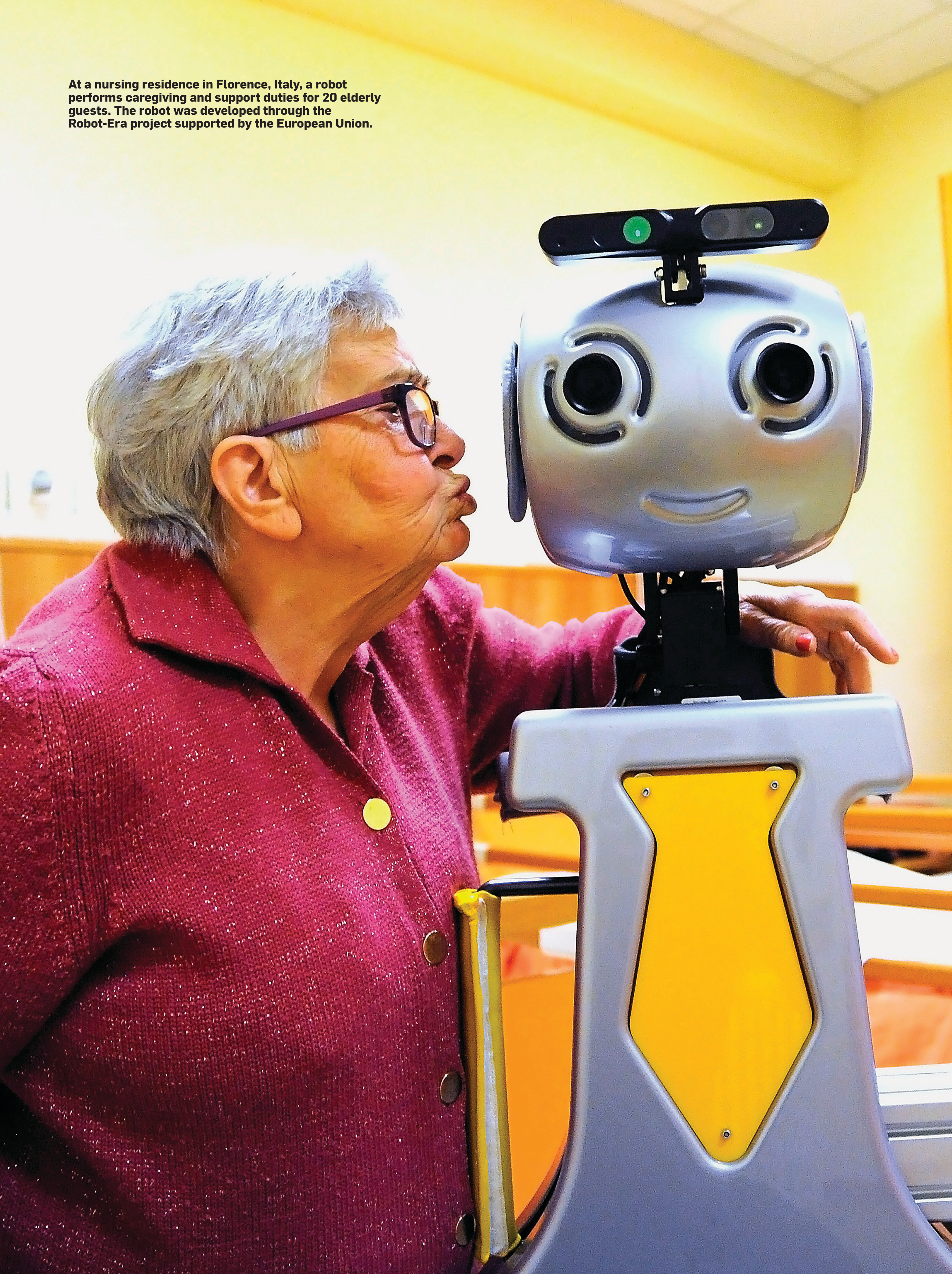
There have been many recent exciting examples of robotics technology, such as autonomous vehicles, package delivery drones, and robots that work side-by-side with skilled human workers in factories. One of the most exciting areas where robotics has a tremendous potential to make an impact in our daily lives is in healthcare.

An estimated 20% of the world's population experience difficulties with physical, cognitive, or sensory functioning, mental health, or behavioral health. These experiences may be temporary or permanent, acute or chronic, and may change throughout one's lifespan. Of these individuals, 190 million experience severe difficulties with activities of daily living tasks (ADL).[a] These include physical tasks (basic ADLs), such as grooming, feeding, and mobility, to cognitive functioning tasks (instrumental ADLs), which include goal-directed tasks such as problem solving, finance management, and housekeeping.[14] The world also has a rapidly aging population, who will only add to this large number of people who may need ADL help. Of all of these individuals, few want to live in a long-term care facility. Instead,

a World Bank; http://documents.worldbank.org/curated/en/2011/01/14440066/world-report-disability

» key insights

- **Over 20% of the world's population experience physical, cognitive, or sensory impairments. Robots can fill care gaps and support independence.**
- **Robots can help caregivers and the clinical workforce, who are overloaded and experience high rates of injury themselves.**
- **In health, most problems are open-ended, and there is no "one-size-fits-all" solution. Every person, task, and care setting are different, and require robots to be able to robustly learn and adapt on the fly.**
- **Technologists, researchers, providers, and end users must closely collaborate to ensure successful adoption.**



At a nursing residence in Florence, Italy, a robot performs caregiving and support duties for 20 elderly guests. The robot was developed through the Robot-Era project supported by the European Union.

Figure 1. The main stakeholders for healthcare robotics, and exemplar contextualizations of their relationship to the technology.

Stakeholder	Context for Robotics	Examples of Robotics Use
Primary Stakeholders:		
Direct Robot Users (DRU): People who directly use robots to aid them with daily living or wellness activities. This may include people who experience difficulties with physical, cognitive, or sensory functions, mental health, or behavioral health. These experiences may be temporary or permanent, acute or chronic, and may change throughout one's lifespan.	A DRU may directly use robotics technology to help them accomplish daily living activities, with physical, cognitive, or social tasks.	► A person with a lower limb amputation uses a robotic arm to grasp objects ► A person with autism works with a robot to learn to read facial expressions ► A person who has low vision uses a smart cane to sense obstacles
Clinicians (CL): Persons who may provide healthcare or work with DRU. These individuals may be: nurses, physicians, mental healthcare providers, rehabilitation professionals, pharmacists, EMTs, among others.	A CL may use robotics technology while providing care, in the course of their training, or to help them with day-to-day administrative tasks.	► A therapist employs a therapeutic robotic pet in a treatment regiment ► A nurse uses a robot to help lift a DRU from their wheelchair to a bed ► A surgeon uses a robot to aid with a minimally invasive procedure ► A medical student uses a robotic patient simulator to learn how to treat a stroke
Care Givers (CG): Family members, neighbors, volunteers, or other unpaid persons who may support DRU.	A CG may use robotics technology to directly or indirectly support a DRU	► An adult child uses a telepresence robot to communicate with an older parent ► A friend may use a robot to perform household tasks in the DRU's home
Secondary Stakeholders:		
Robot Makers (RM): Individuals who design, build, program, instrument, or research robotics technology.	A RM may work with DRU, CL, CG, PM, and ESW to perform their work.	► A company builds a hospital discharge robot ► A student writes sensing algorithms for a robot to lift people out of a wheelchair ► A Maker club adapts toys to be accessible by children with motor impairments
Environmental Service Workers (ESW): Persons who provide secondary care to DRUs by helping prevent the spread of infection through cleaning services. These can include environmental service workers in hospitals, housekeeping staff in nursing homes, and so on.	An ESW may use robotics technology to ensure care environments are safe and sanitary to help prevent the spread of infection. Their use of robotics directly affects DRU's quality of care, and CL's workplace safety.	► An ESW teleoperates a disinfecting robot which emits UV light to kill superbugs in a hospital room ► An ESW uses a waste removal robot to safely transport medical waste
Health Administrators (HA): Individuals who provide leadership to a care setting by planning, coordinating, and directing care delivery.	An HA may purchase robots to support staff, patients, or visitors, or set policy on their usage.	► A chief medical officer reviews clinical effectiveness data of a rehabilitation robot ► A HA preforms a cost effectiveness study of acquiring robots for their institution
Tertiary Stakeholders:		
Policy Makers (PM): People who work for or with federal, state, and local governments to design policy regarding: how robots will be used, which robots will be used, and how their costs will be managed.	A PM may work with DRU, CL, CG, ESW, RM, and AG to understand how to best craft policy for the use of robots.	► A Federal Food and Drug Administration (FDA) worker establishes new policy for Home Use Devices ► A Federal Trade Commission (FTC) worker sets privacy policies for robot sensors
Insurers (IC): Public or private organizations who makes decisions about benefits to DRU and CG, including service payments to CL and RM.	ICs may work with PM, AG, HA, RM, and CL to establish guidelines for reimbursable robot-related services.	► An IC worker explores the robotic exoskeletons evidencee base to establish reimbursement policy ► An IC worker consults with a company to understand a robot's control system
Advocacy Groups (AG): Organizations who work on behalf of DRU populations	AGs may work with with DRU, CL, CG, RM, PM, and others to ensure robots are employed in ways that are of the best interest of their DRU population.	► An muscular dystrophy AG supports new research on exoskeletons ► An MS advocacy group lobbies congress to fund new robotic therapies

many people would prefer to live and age gracefully in their homes for as long as possible, independently and with dignity.[22] However, for people requiring help with ADL tasks, this goal is challenging to meet for a few reasons. First, this level of care is quite expensive; in the U.S. it costs between $30,000 and $85,000 per year in provider wages alone.[b]

Second, there is a substantial healthcare labor shortage—there are far more people who need care than healthcare workers available to provide it.[33] While family members and friends attempt to fill these care gaps, they too have full-time jobs and other familial obligations, and thus cannot meet the need. Healthcare workers are not only overburdened by this labor shortage, but face increas-

b U.S. Department of Health and Human Services; http://longtermcare.gov/costs-how-to-pay/costs-of-care/

ingly hazardous work environments, and are themselves at great risk of debilitating injury and disability. According to the National Institute for Occupational Health and Safety (NIOSH), health care workers have the most hazardous industrial jobs in America, with the greatest number of nonfatal occupational injuries and illness.[c]

Thus, there is an incredible opportunity for robotics technology to help fill care gaps and help aid healthcare workers. In both the research and commercial space, robotics technology has been used for physical and cognitive rehabilitation, surgery, telemedicine, drug delivery, and patient management. Robots have been used across a range of environments, including hospitals, clinics, homes, schools, and nursing homes; and in both urban and rural areas.

Before discussing these applications, it is important to first contextualize the use of robots within healthcare. This article begins by identifying who will be providing, receiving, and supporting care, where this care will take place, and key tasks for robots within these settings. Examples of new technologies aimed at supporting these stakeholders will be introduced, and key challenges and opportunities to realizing the potential use of robots in healthcare that research and industry are encouraged to consider, will be addressed. These adoption issues include a robot's capability and function (Does a robot have the required capabilities to perform its function?), cost effectiveness (What is the robot's value to stakeholders relative to its cost?), clinical effectiveness (Has the robot been shown to have a benefit to stakeholders?), usability and acceptability (How easy is the robot to use, modify, and maintain? Is the robot's form and function acceptable?), and safety and reliability (How safe and reliable is the robot?)

Stakeholders, Care Settings, and Robot Tasks

Stakeholders. For this article, stakeholders are defined as people who have a vested interest in the use of robotics technology in healthcare. Stakeholders can be: people who directly use robots to provide assistance with daily living or wellness activities (direct robot users (DRU)), health professionals who use robots to provide care (clinicians (CL)), non-CL individuals who support DRUs (care givers (CG)), technologists and researchers (robot makers (RM)), health administrators (HAs), policymakers (PMs), advocacy groups (AGs), and insurers (IC). Figure 1 introduces these stakeholders.

These stakeholders can be grouped into three beneficiary groups: *Primary beneficiaries:* direct robot users, clinicians, and caregivers, all of whom are likely to use robotics technology on a regular basis; *Secondary beneficiaries:* health administrators, robot makers, and environmental service workers, all of whom are involved in the use of robotics technology in healthcare settings but do not directly use the robots to use robots to support the health and wellness of DRUs; and *tertiary beneficiaries:* policymakers and advocacy groups, who have interest in the use of robots to provide care to their constituents, but are unlikely to use them directly.

c National Institute for Occupational Safety and Health, http://www.cdc.gov/niosh/topics/healthcare/

Selected care settings where robots may be used.

Care Setting	Definition
Longer-Term	
Assistive Living Facility	"Congregate residential facility with self-contained living units providing assessment of each resident's needs and on-site support 24 hours a day, 7 days a week, with the capacity to deliver or arrange for services including some health care and other services."
Group Home	"A residence, with shared living areas, where clients receive supervision and other services such as social and/or behavioral services, custodial service, and minimal services (e.g., medication administration).
Custodial Care Facility	"A facility which provides room, board and other personal assistance services, generally on a long- term basis, and which does not include a medical component"
Nursing Facility	"A facility which primarily provides to residents skilled nursing care and related services for the rehabilitation of injured, disabled, or sick persons, or, on a regular basis, health-related care services above the level of custodial care to other than [people with intellectual disabilities]"
Home Care	"Location, other than a hospital or other facility, where [a person] receives care in a private residence."
Shorter-Term	
Inpatient Hospital	"A facility, other than psychiatric, which primarily provides diagnostic, therapeutic (both surgical and nonsurgical), and rehabilitation services by, or under, the supervision of physicians to patients admitted for a variety of medical conditions."
On/Off Campus Outpatient Hospital	"A portion of a… hospital provider based department which provides diagnostic, therapeutic (both surgical and nonsurgical), and rehabilitation services to sick or injured persons who do not require hospitalization or institutionalization."
Urgent Care Facility	"Location, distinct from a hospital emergency room, an office, or a clinic, whose purpose is to diagnose and treat illness or injury for unscheduled, ambulatory patients seeking immediate medical attention."
Inpatient Psychiatric Facility	"A facility that provides inpatient psychiatric services for the diagnosis and treatment of mental [health disorders] on a 24-hour basis, by or under the supervision of a physician."
Hospice	"A facility, other than a patient's home, in which palliative and supportive care for terminally ill patients and their families are provided."
Substance Abuse Treatment Facility	"A location which provides treatment for substance (alcohol and drug) abuse on an ambulatory basis. Services include individual and group therapy and counseling, family counseling, laboratory tests, drugs and supplies, and psychological testing." Residential facilities also provide room and board.

Source: http://www.cms.gov/Medicare/Coding/ place-of-service-codes/Place_of_Service_Code_Set.html

This article will focus on primary beneficiaries; however, it is important to note that all other stakeholder groups are critical to the successful end-deployment of robotics in healthcare, and should be included when possible in decision-making.

Care settings. Another critical dimension to contextualizing the use of robotics in healthcare is to consider the location of use. This can significantly impact on how suitable different technologies are for a given setting,[12] and can affect the design of a robot and its required capabilities. For example, while a 400-lb, 5'4" dual-arm mobile manipulator may work well in a lab, it is ill-suited to an 80-sq. ft. room in an assisted living facility. While it is understandable robot makers may immediately be more concerned with achieving platform functionality than the particulars of care settings, to successfully deploy healthcare robots, setting must be considered.

The accompanying table defines different kinds of care settings, and includes longer-term care facilities in the community, as well as shorter-term care facilities, such as hospitals. For longer-term care in the U.S., the Fair Housing Act, and Americans with Disabilities Act set some general guidelines for living space accessibility; however, the majority of space guidelines is state-dependent, and can have a large degree of variation. For example, an assisted living facility in Florida must provide 35-sq. ft. per resident for living and dining, whereas in Utah it is 100-sq. ft. An in-patient psychiatric facility in Kentucky must provide 30-sq. ft. per patient in social common areas, Oregon requires 120-sq. ft. in total and 40-sq. ft. per patient.

Robots in healthcare can also affect the well-being, health, and safety of both direct robot users and clinicians. The field of evidence based healthcare design[40] has produced hundreds of studies showing a relationship between the built environment and health and wellness, in areas including patient safety, patient outcomes, and staff outcomes. When new technology such as a robot becomes part of a care setting, it is now a possible disruptor to health. HAs must balance the risks and benefits for adopting new technology, and robot makers should be aware of these tradeoffs in how they design and test their systems.

Care tasks. Robots may be helpful for many health tasks. Robots can provide both physical and cognitive task support for both DRUs and clinicians/caregivers, and may be effective and helping reduce cognitive load. Task assistance is particularly critical as the demand for healthcare services is far outpacing available resources, which places great strain on clinicians and caregivers.[33]

Physical tasks. *Clinicians.* Tasks involving the "3Ds" of robotics—dirty, dangerous, and dull—can be of particular value for clinical staff. Clinicians spend an inordinate amount of time on "non-value added" tasks, for example, time away from treating patients. The overburden of these tasks creates a climate for error; so robots, which can help clinicians effectively, surmount these challenges would be a boon. Some of these non-value added tasks include: Transportation, such as moving materials or people from one place to another, Inventory, such as patients waiting to be discharged, Search Time, such as looking for equipment or paperwork, Waiting, for patients, materials, staff, medications, and Overburdening of Staff and Equipment, such as during peak surge times in hospitals.[42]

Two of the best tasks for robots in this task space are material transportation and scheduling, which robots can be exceptionally skilled at given the right parameters. For example, robots that can fetch supplies, remove waste, and clean rooms. Another task robots can do that will help greatly improve the workplace for clinicians is moving patients. This is a very hazardous task—hospital workers, home health workers, and ambulance workers experience musculoskeletal injuries between three and five times the national average when moving patients according to NIOSH.

Robots can also help clinicians with other dangerous tasks, such as helping treat patients with highly infectious diseases. Robot mediated treatment has become particularly pertinent after the recent Ebola outbreak, where clinicians and caregivers can perform treatment tasks via telepresence robots.[17]

Finally, robots may help extend the physical capabilities of clinicians. For example, in surgical procedures, robots may provide clinicians with the ability to perform less invasive procedures to areas of the body inaccessible with existing instrumentation due to issue or distance constraints. These can include types of neurological, gastric, and fetal surgical procedures.[41]

Direct robot users. When designing robots for DRUs, there is great value in designing straightforward solutions to problems. At a recent workshop discussing healthcare robotics, people with Amyotrophic Lateral Sclerosis (ALS) and other conditions reported that most of all they just wanted "a robot to change the oil."[30] In other words: help is most needed with basic, physical ADL tasks, such as dressing, eating, ambulating, toileting, and housework. Robots that can help people avoid falling could also be incredibly beneficial, as falls cause thousands of fatal and debilitating injuries per year.

Currently, standalone robots that can successfully perform the majority of these key physical ADL tasks are a long way from reaching the consumer market. There are several reasons for this. First, the majority of these tasks remain challenging for today's robots, as they require a high degree of manual dexterity, sensing capability, prior task knowledge, and learning capability. Furthermore, most autonomous, proximate robots move extremely slowly due to safety and computational purposes, which will undoubtedly be frustrating for end users. Finally, even if robots could perform some of these more complex ADL tasks, their power budgets may make them impractical for deployment in most care settings.

However, there have been substantial gains in recent years for other tasks. For example, robots that provide DRUs with additional physical reach (for example, smart on-body prostheses, wheelchair mounted robot arms) and robots which provide multi-setting mobility capability (for example, exoskeletons, accessible personal transportation devices).[26] These are likely to continue to be the types of systems that reach end users first for the foreseeable future.

Cognitive tasks. *Clinicians.* Any technology that can effectively reduce clinical workload is likely to be warmly embraced in healthcare. Many of these systems exist in a non-embodied fashion, for example, decision support tools to aid in emergency medicine,[12] patient logistical management, or charting. However, robotic systems may have a place within this domain, particularly if a robot is well integrated into existing workflow and able to access EHR data. For example, perhaps a medication management robot could anticipate a clinician's "next move" in treatment by prefetching a likely medicine from the pharmacy. Or perhaps a robot could deliver personalized messages to family members in waiting rooms to update them on the status of their relative while clinicians are occupied with other tasks.

Another area where robotics has been extensively used to aid clinicians with cognitive tasks is in clinical simulation and training. Robotic patient simulators are life-sized, humanoid robots that can breathe, bleed, speak, expel fluids, and respond to medications. They are the most commonly used humanoid robot worldwide, and provide learners with the ability to simultaneously practice both procedural and communication skills.[22,23] These robots are used by inter-professional clinicians across a wide range of specialties, including acute care, perioperative care, trauma, and mental healthcare. The author and her students have been designing the next generation of these simulators, which can convey realistic facial patient pathologies, such as pain, stroke, and cerebral palsy, and are integrated with on-board physiological models.[23,29]

Direct robot users and care givers. The ways in which robots may be able to provide cognitive task support to CGs has yet to be fully realized. However, similar to clinicians, the ability to reduce cognitive load would be greatly welcomed. CGs in particular are often overburdened when providing care; they frequently have other family members to care for, other jobs, and their own lives (and health) to manage.[3] Robots might be able to cognitively support CGs by learning and anticipating their needs, prefetching items, attending to time-intensive tasks which detract from care, and so on.

For DRUs, robotics technology might be able to help facilitate independence by providing sensory augmentation or substitution. For example, DRUs who are blind or low vision may benefit from a robotic way finding tool, or DRUs using robotic prostheses might receive sensory feedback from a robotic finger in their shoulder.

Robots also may be able to help DRUs with regaining (or supplementing) cognitive function in neurorehabilitative settings, such as in cases of stroke, post-traumatic stress disorder, or traumatic brain injury. Robots also may provide socio-emotional support to DRUs: to provide companionship, teach people with autism to learn to read emotions, or to help reduce symptoms of dementia. However, there is a paucity of clinical effectiveness trials showing DRU benefit compared to standard treatment, so it is unclear what the future for these robots may be.[29]

There is incredible opportunity for robotics technology to help fill care gaps and aid healthcare workers. Robotics have been used for physical and cognitive rehabilitation, surgery, telemedicine, drug delivery, and patient management.

Recent Advances in Healthcare Robotics

The 2016 U.S. Robotics Roadmap was recently released,[1] which frames the state of the art in robotics and future research directions in the field. Over 150 robotics researchers contributed, including the author of this article. The roadmap includes a detailed summary of advancements in robotics relating to health and wellness. Some key focus areas include: aging and quality of life improvement, surgical and interventional robotics, rehabilitative robotics, and clinical workforce support.

In general, robots used in these areas can be divided into three categories: inside the body, on the body, and outside the body. Those inside and on the body are primarily intended for direct robot users, and those outside the body for direct robot users, care givers, and clinicians. These robots have the potential to be used across a range of care settings and clinical foci, and can provide both physical and cognitive support.

Inside the body. Recent advances for internal robots have occurred in the fields of microrobotics, surgical robotics, and interventional robotics. Microrobotics are micro-scale, untethered devices that can move through the body and can perform a range of functions, such as targeted therapy (that is, localized delivery of medicine or energy), material removal (for exam-

Figure 2. Key examples of recent advances in healthcare robotics. Those inside and on the body are primarily intended for direct robot users, and those outside the body for direct robot users, caregivers, and clinicians. These robots have the potential to be used across a range of care settings and clinical foci, and can provide both physical and cognitive support. Image credits (clockwise from upper left): B. Nelson, R. Alterovitz, Mobius, TED, Ekso Bionics, B. Smart, L. Riek, S. Sabanovic, C. Kemp.

In the body | **On the body**

Microrobots are micro-scale, untethered robots that can move through the body and can per form targeted therapy, material removal, structural control, and sensing.

Concentric tube robots (active cannulas) can be used as small, teleoperated manipulators or as steerable needles, and enable procedures in areas inaccessible with traditional instruments.

Robotic prostheses and exoskeletons. People with forearm-to-shoulder amputations can use wearable robot prostheses, which can provide fine-grained dexterity, reach, and strength. People with lower-limb amputations or lower-body muscle weakness can use powered-knee and ankle prostheses to do everything from running marathons to dancing. Exoskeletons have helped people with muscle weakness, movement disorders, or paralysis locomote.

Outside the body

Mobile manipulators. Clinicians can safely tele-operate mobile robots to treat patients with highly infectious diseases such as Ebola Virus Disease.

Patient simulators. Over 180,000 clinicians annually train on high fidelity robotic patient simulators, which can simulate physiological cues, and sense and respond to learners.

Mental and Behavioral Healthcare. Robots can support people with cognitive impairments, facilitate neurorehabilitation, support wellness, or provide companionship.

Physical task support. Robots can support people with motor impairments, movement disorders, and brain injuries to provide external manipulation capabilities.

ple, biopsy, ablation), structural control (for example, stent placement), and sensing (for example, determining oxygen concentrations, sensing the presence of cancer).[25] Recent advances in the field have enabled actuating, powering, and controlling these robots (see Nelson et al.[25] for a review.)

In surgical and interventional robotics, a range of advances have been made that enable clinicians to have improved dexterity and visualization inside the body and reduce the degree of movement during operations.[1] Furthermore, promising advances have been made in concentric tube (active cannula) robots. These robots are comprised of precurved, concentrically nested tubes that can bend and twist throughout the body. The robots can be used as small, teleoperated manipulators or as steerable needles. The robots can enter the body directly, such as through the skin or via a body opening, or could be used via an endoscope.[11]

Some future research directions for in-the-body robots include new means for intuitive physical and cognitive interaction between the user and robot, new methods for managing uncertainty, and providing 3D registration in real time while traversing both deformable and non-deformable tissue.[1]

On the body. In terms of wearable robots for DRUs, there have been recent advances in the areas of actuated robot prostheses, orthoses, and exoskeletons. A prothesis supplants a person's missing limb, and acts in series with a residual limb. An orthosis is a device that helps someone who has an intact limb but an impairment, and an exoskeleton provides either a person with intact limbs (DRU or otherwise) assistance or enhancement of existing physical capability. Orthoses and exoskeletons act in parallel to an existing limb.[39]

All of these robots can be used to enable DRUs to perform tasks. For example, people with forearm-to-shoulder amputations can use wearable robot prostheses, which can provide dexterity, reach, and strength. People with lower-limb amputations or lower-body muscle weakness can use powered-knee and ankle prostheses to engage in a range of activities, including everyday locomotion to running marathons and dancing. Exoskeletons have helped people with muscle weakness, movement disorders, and paralysis locomote.

Several advances have been made recently in how people interface with these robots. For example, some robot prostheses offer neural integration to provide tactile feedback and increasingly more intuitive control of the limb.[1] Other advances include an increase in the workspace and range of motion of wearable robots, as well as improvements in user comfort.

Outside the body. Robots outside the body are being used across many clinical application spaces. For clinicians, mobile manipulators are being used to help treat patients with highly infectious diseases,[17] aid in remote surgical procedures,[26] and help provide physical assistance to CLs when moving patients.[24] They are also used extensively in clinical training, as discussed earlier.

Robots are also being explored in mental and behavioral healthcare applications. Robots are being used to support people with autism spectrum disorder and cognitive impairments, to encourage wellness, and to provide companionship.

(See Riek[29] for a detailed review of these applications).

For physical task support, robots can provide external manipulation and sensing capabilities to DRUs. For example, wheelchair mounted robot arms can provide reach, smart wheelchairs can help facilitate safe navigation and control, and telepresence robot surrogates can enable people with severe motor impairments the ability to fly, give TED talks, and make coffee.[6,7,38]

There are other examples of external robots that are outside the scope of this paper, but could prove highly pertinent in healthcare. For example, autonomous vehicles may provide new opportunities for DRUs to locomote, or may enable EMTs to focus on treating patients rather than driving ambulances. Telepresence may also have unforeseen applications in healthcare, such as through aerial manipulation, drone delivery of medical supplies, among others.

Healthcare Robotics Adoption: Challenges and Opportunities

While there are exciting advances in healthcare robotics, it is important to carefully consider some of the challenges inherent in healthcare robotics, and discuss ways to overcome them. Robots have the ability to enact physical change in the world, but in healthcare that world is inherently safety critical, populated by people who may be particularly vulnerable to harm due to their disability, disorder, injury, or illness. Stakeholders face five major considerations when considering deploying robots in healthcare: Usability and acceptability, safety and reliability, capability and function, clinical effectiveness, and cost effectiveness. Each is explored here.

Usability and acceptability. Robots that are difficult for primary stakeholders to use have a high likelihood of being abandoned. This phenomenon has been well documented in the Assistive Technology Community.[5,9,20] For example, a 2010 study reported that as many as 75% of hand rehabilitation robots were never actually tested with end users, rendering them completely unusable in practice and abandoned.[2]

One the major challenges is that clinicians, even those who are well-educated and accomplished in their disciplines, often have low technology literacy levels.[19] Thus, if they themselves find a robot unusable, the likelihood of them successfully training a direct robot user or caregiver to use the robot is greatly diminished.

Another challenge is that DRUs are often excluded from the robot design process, which leads to unusable and unsuitable technology. Robots with multiple degrees of freedom, such as wearable prostheses or wheelchair-mounted arms, require a high level of cognitive function to control.[38] However, many people needing such robots often have co-morbidities (that is, other conditions), which can make control a further exhausting process.

There are several ways to address this issue. One approach is for robot makers to reduce robot complexity. Balasubramanian et al.[2] argue for functional simplicity in therapeutic robot design, which will lead to robots that are easier for all primary stakeholders to use, control, and maintain. This concept is echoed in much of the reliability and fault tolerance literature; lower-complexity robots are more likely to be longitudinally reliable and fault tolerant.

Forlizzi and Zimmerman propose the idea of a service-centered design process, wherein rather than only think about a single user and a system, designers consider including the broader ecosystem surrounding a technology.[10] This is a particularly beneficial idea in healthcare robotics. Rarely will there be one DRU and one robot; rather, there is a complex social structure surrounding caregiving that should be considered carefully in robot design.

Another important barrier to healthcare robot adoption is its acceptability. The morphology, behavior, and functionality of a robot play a major role in its adoption and use. When a DRU uses a robot in public, they are immediately calling attention to their disability, disorder, or illness. DRUs already face significant societal stigma, so frequently avoid using anything which further advertises their differences, even if it provides a health benefit.[27,32,33]

Shinohara and Wobbrock argue that in addition to designers considering the functional accessibility of system, they also consider its social accessibility, and employ a "Design for Social Acceptance" (DSA) approach.[35] This means going beyond purely functional designs, which may be "awkward and clunky."[34] Robot makers are usually primarily concerned about a robot's functional capabilities; for example, can the robot perform its task safely and reliably given workspace, environmental, and platform constraints. However, the aforementioned literature suggests that there may be great value in also considering a robot's appearance and behavior to help enable technology adoption.

Safety and reliability. When robots and people are proximately located, safety and reliability are incredibly important. This is even more critical for DRUs who may rely extensively on robots to help them accomplish physical or cognitive tasks, and who may not have the same ability to recover from robot failures as easily as non-DRUs.

There has been a fair bit of work on safe physical human-robot interaction, particularly with regard to improving collision avoidance, passive compliance control methods, and new advances in soft robotics to facilitate gentle interaction.[37] There also have been recent advances on algorithmic verifiability for robots operating in partially unknown workspaces,[18] which may prove fruitful in the future.

However, there has been little work to date on safe cognitive human-robot interaction. People with cognitive disabilities and children are particularly prone to being deceived by robots.[29] This is an important and under-explored question in the robotics community, though a few efforts have been made recently with regard to encouraging robot makers to employ value-centered design principles. For example, ensuring the appearance of the robot is well-aligned with its function (for example, avoiding false-advertising), enabling transparency into how a robot makes decisions, and maintaining the privacy and dignity of DRUs.[15,31]

Another way to help bridge the

safety gap is for robot makers to employ in-depth testing and training regimens that enable direct robot users, care givers, and clinicians to fully explore the capabilities of a platform. This can help prevent people from either over-relying or under-relying on the robot, and help facilitate trust.

Capability and function. The field of robotics has seen amazing capability gains in recent years, some of which have been instrumental in healthcare. However, despite these advances, robotics is still an exceptionally difficult problem. For example, many demonstrations in robotics technology remain demos, and fail outside of highly constrained situations.[8] This is particularly problematic when designing technology for healthcare: most problems are open-ended, and there is no "one-size-fits-all" solution.[12,28] Every person, task, and care setting are different, and require robots to be able to robustly learn and adapt on the fly.

As discussed previously, care settings differ substantially. Even the same type of care setting, such as an emergency department or assisted living facility, have substantial differences in their environment, practices, and culture. In our prior work designing health information technology, we have demonstrated that these differences can be surmounted by conducting multi-institutional trials, and by building solutions that are adaptable to different care settings.[13] The same approach can be taken in robotics.

Real-world, real-time, robust perception in human environments is a another major challenge in robotics. While the field of computer vision has seen advances in solving still-image, fixed-camera recognition problems, those same algorithms perform poorly when both the cameras and people are moving, data is lost, sensors are occluded, and there is clutter in the environment. However, these situations are highly likely in human social settings, and it is an open challenge to sense, respond to, and learn from end users in these settings.[28] There have been some recent advances, however: the fields of social signal processing and human-robot interaction have moved toward multimodal sensing approaches, which help enable more robust algorithms. Furthermore, lifelong learning and longitudinal experimental approaches have also enabled researchers to surmount some of these perceptual challenges. Modeling situational context and object and environmental affordances within them can also be a useful tool in surmounting these issues.[1,28]

Robotic patient simulators are life-sized, humanoid robots that can breathe, bleed, speak, expel fluids, and respond to medications.

Learning, too, is a challenge. It is critical that primary stakeholders, who have a wide range of physical abilities, cognitive abilities, and technology literacy levels, are able to easily repurpose or reprogram a robot without a RM present. This level of adaptability and accessibility presents robot makers with a complex technical and socio-technical challenge. As mentioned previously, simple is undoubtedly better; it helps constrains the problem space and lowers the complexity of the system. Another major aid will be the research community continuing to develop new datasets, evaluation metrics, and common platforms;[8] these have shown to be useful in other computing domains, so are likely to be helpful here.

Cost effectiveness. When robots are being acquired in healthcare, it is important that their cost effectiveness is considered beyond the purchase, maintenance, and training costs for the system. For example, when electronic health records (EHRs) were first employed in hospitals, they were touted as a means to save clinicians and patients' time. However, because EHR systems were so poorly designed, difficult to use, and poorly integrated into existing they ended up creating substantially more non-value added work. This resulted in "unintended consequences," including increasing costs and patient harm.[16] It is critical these same pitfalls are avoided for robots.

The Agency for Healthcare Research and Quality (AHRQ) created a guide for reducing these unintended consequences for EHRs;[16] the same methodological approach can be employed for robots. For example, when assessing the acquisition and deployment of a robot in a first place:

- *Are you ready for a robot (and is a robot ready for you)?* HAs must carefully consider their institution's robot readiness. Robots may solve some problems, but may make others worse. For example, suppose a supply-fetching robot that is purchased help nurses save time. However, it has difficulties functioning at high volume times of day due to sensor occlusion, so supply deliveries end up being delayed. This causes a cascade effect, increasing the workload of nurses. Situations like these can be remedied through a careful exploration of existing workflow in a unit, and by fully understanding a robot's existing capabilities and limitations. See Gonzales et al.[12,13] for examples on engaging in this process with clinicians in safety critical settings.

▸ *Why do you want a robot?* It is important stakeholders define exactly why a robot is necessary for a given task in the first place. What are the goals of the stakeholders? What is the plan for deploying the robot, and how will success be measured? These questions can also be explored through design activities while assessing workflow and institutional readiness.

▸ *How do you select a robot?* As mentioned previously, functionality is only one aspect to a robot; there is also: usability, acceptability, safety, reliability, and clinical effectiveness. While there are not yet definitive guidelines to aid HAs in this process, science policy is starting to be shaped within this space. The CCC recently held an event entitled "Discovery and Innovation in Smart and Pervasive Health,"[d] which brought together over 60 researchers from across academia, industry, and government, many of whom are roboticists who work in health. These efforts will hopefully begin to provide guidelines in the future.

▸ What are the recommended practices for avoiding unintended consequences of robot deployment? Successfully deploying robots is a difficult process that may result in a disruptive care setting, and upset key stakeholders. To avoid unintended consequences, it is important that:

▸ The robot's scope is well-defined with clear goals;

▸ Key stakeholders are included and engaged in the deployment from the onset;

▸ Detailed deployment plans are provided but are not overly complicated;

▸ There are multiple ways to collect, analyze, and act on feedback from users;

▸ Success metrics should be determined in advance and evaluated continually; and,

▸ Quality improvement should be supported on an ongoing basis.

Recently, the IEEE released a document on "Ethically Aligned Design" which contains detailed suggestions for how to engage in this value-centered practice in engineering, which could be helpful for all stakeholders moving forward.[e]

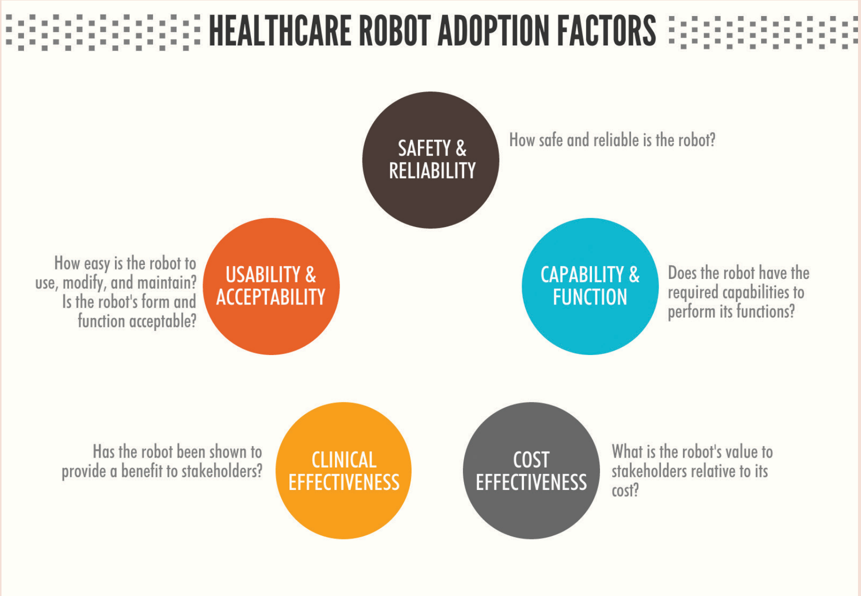
Clinical effectiveness. Clinical effectiveness answers the question: "Does it work?" In particular, does a given intervention provide benefit to a primary stakeholder? This question is answered by conducting thorough, evidence-based science. For robots directly affecting DRUs, this evidence comes from comparative effectiveness research (CER), which is "generated from research studies that compare drugs, medical devices, tests, surgeries, or ways to deliver healthcare."[f]

CER can include both new clinical studies on effectiveness, or can synthesize the existing literature in a systematic review.

All consumer in-the-body robots and many on-the-body robots must undergo regulatory approval before they can be marketed and sold. In the United States, this approval is through the FDA, which typically requires a strong level of evidence showing the effectiveness and safety of a medical device. Outside-the-body robots typically do not need to undergo a device review process provided they fall within existing classifications; for example, Paro the robot seal (see Figure 2, bottom right) is classified by the FDA a neurological therapeutic device, and thus is exempt from premarket review. Shimshaw et al.[36] argue this lack of regulation of healthcare robots may be harmful to stakeholders both physically and informationally, and should be subject to premarket review on dimensions including privacy, safety, reliability, and usability.

In the meanwhile, while the policy community races to catch up with technology, the robotics community can and should engage in research that tests the clinical effectiveness of robots across care settings. Begum et al.[4] suggest robot makers follow existing clinical effectiveness benchmarks within their intended care space and adopt them for use with robots. Furthermore, Riek[29] suggests that when

Figure 3. Factors that will affect the widespread adoption of robotics in healthcare.



d http://cra.org/ccc/events/discovery-innovation-smart-health/

e http://standards.ieee.org/develop/indconn/ec/ead_v1.pdf

f Agency for Health and Research Quality, effectivehealthcare.ahrq.gov/index.cfm/what-is-comparative-effectiveness-research1/

conducting CER with robots, particularly in cognitive support settings, it is not sufficient to simply test robot vs.no-robot, as the morphology can affect outcomes, but to instead to test actuated vs. non-actuated.

Discussion

Healthcare robotics is an exciting, emerging area that can benefit all stakeholders across a range of settings. There have been a number of exciting advances in robotics in recent years, which point to a fruitful future. How these robots ultimately will be integrated into the lives of primary beneficiaries remains unknown, but there is no doubt that robots will be a major enabler (and disruptor) to health.

It is critical that both the research and industrial communities work together to establish a strong evidence-base for healthcare robotics. As we have learned from the large-scale deployment of EHRs, technology development and deployment cannot happen in a vacuum, or it is likely to cause grave harm to DRUs, overwhelming stress to clinicians, and astronomical unseen costs. It is wise for all stakeholders to proceed cautiously and deliberately, and consider the full context of care as much as possible.

It is also critical that direct robot users remain directly involved in the research, development, and deployment of future robots in health and wellness across the entire lifecycle of a project, as ultimately they are the ones who will be using these robots. As discussed earlier, ignoring DRU input leads to unusable, unsuitable, and abandoned robots, which benefits no one. Secondary and Tertiary stakeholders should look to the Patient Centered Outcomes Research Institute (PCORI)[g] as a highly successful model for how-to engage with primary stakeholders in clinical research and development.

Finally, it is important that robot makers work with DRUs to help bridge technology literacy gaps and appropriately set expectations. Most people's experience with robotics comes from movies or media, which rarely reflects the true state of affairs. Robots are quite fallible in the real world, and will remain so for the foreseeable future; however, they still have the potential to be a remarkable game changer in health.

g http://pcori.org

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