



Rehabilitation Engineering: A perspective on the past 40-years and thoughts for the future

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ABSTRACT

Over the past four decades, there have been breakthroughs in communication, mobility and tools to manipulate objects. Probably the most important transformation has been the growing inclusion of people with disabilities into the prioritization, conceptualization, and design of new assistive devices. Advances in technology, demands from people with disabilities, and changes in cultural perceptions have made noteworthy changes in the technologies that have improved lives, and affected transformations that benefit both individuals and society. People with disabilities lives have been improved but there is still much to be done. Unfortunately, people with disabilities in low income countries have lagged people in higher income countries in benefitting from technical and social changes. Assistive devices have benefitted from the availability of powerful, portable computing power, from small low-power sensors, from new materials, from rapid prototyping and flexible manufacturing. There are exciting emerging technologies that show promise for future advances.

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1. Introduction

Technology plays a central role in facilitating the health, integration, and quality of life of people with disabilities and older adults [1,2]. Engineers have contributed to the advancement of assistive technologies for decades and have made significant contributions; however, there remains substantial work to be done [3,4]. Over the past four decades, there have been breakthroughs in communication, mobility and tools to manipulate objects [5,6]. Probably the most important transformation has been the growing inclusion of people with disabilities into the prioritization, conceptualization, and design of new assistive devices [7,8]. As science, technology, engineering and mathematics fields become more accessible to people with disabilities and more people pursue careers in these areas, a more inclusive and representative working environment and communities should result [9,10]. Technology will no doubt contribute to this ideal.

To help picture the world of people with disabilities 40 years ago, let us outline a few of the changes that have taken place. All the professional organizations focused on rehabilitation engineering and assistive technology were formed during this time period.

Conferences, continuing education, formal coursework, and even some college degrees were created within this time framework [4,11]. There were no standards to assure people that the products that people with disabilities rely on were safe and effective. Today, we have established International Standards Organization test methods and minimal performance criteria; with work ongoing by several active committees [12]. The disability rights movement had only just begun in a few countries, and while it continues to this day, the United Nations has passed a convention for the Human Rights of the People with Disabilities [13]. Several countries have also passed landmark legislation protecting people with disabilities and promoting greater inclusion. While the world has become friendlier towards people with disabilities, it remains a difficult place to live and technology and social change are needed to ensure further progress.

2. Life changing advances

Advances in technology, demands from people with disabilities, and changes in cultural perceptions have made noteworthy changes in the technologies that have improved the lives of people with disabilities, and affected transformations that benefit both the individual and society.

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2.1. Mobility and manipulation

The ability to move freely within one's home and community is important to participating in life's activities to include work, school, healthcare, and community [14]. Similarly, manipulating objects in space is essential to eat, work, and perform a whole host of activities. Technology is key to making this possible, and to free family, friends and non-medical assistants to assist with other tasks or to simply share quality time [15].

2.2. Wheeled mobility devices

It may be hard to believe that 40 years ago the manual wheelchair had remained little changed for nearly 50 years [16]. In addition, powered wheelchairs were essentially motorized versions of manual wheelchairs that could only accommodate few people in need of independent mobility [17]. There was little understood about seating and clinicians would frequently make custom devices from simple materials such as foam, plywood, and vinyl [18]. Several advances in wheeled mobility devices have transformed lives and expanded opportunities for people with disabilities.

2.2.1. Digital controls and pulse-width modulation amplifiers

Decades ago powered wheelchairs used either analog linear amplifiers or relays to controls speed and direction [19]. While this created independent mobility for some, it excluded most people with complex disabilities from independent mobility. With the introduction of digital controls that allows for digital signal processing and pulse-width-modulated amplifiers the gates were opened for independent powered mobility [20]. This was accomplished by adding the ability to adjust gains, implement complex feedback algorithms, controls with disturbance rejections, and input signal conditioning [21,22].

2.2.2. Power bases and drive wheel options

Early powered wheelchairs used fixed or folding tubular frames with large drive wheels in a rear wheel drive configuration [23]. The concept of creating a power base, which is essentially a chassis without a seat, allowed optimization of driving performance and seating needs [24,25]. This led to power bases with front, mid, and rear wheel configurations to provide users with options based on their performance characteristics that best meet their needs.

2.2.3. Pushrim activated power assist wheelchairs (PAPAW)

The PAPAW represented an entirely new wheelchair that is a hybrid of manual wheelchairs and powered wheelchairs [26,27]. PAPAW's operate by using a motor to assist the powered applied the pushrims by the user. The amount of power can be tuned to the strength and coordination of the user, which helped to reduce strain in the arms and still provide some exercise with a lightweight wheelchair [28,29].

2.2.4. Ultralight manual wheelchairs

The weight of the wheelchairs plays an essential role in the mobility of the user. It effects that ability to propel, the effort required to load into a vehicle, and the maneuverability [30–32]. Lower weight manual wheelchairs made it possible for more people to achieve independent mobility and to participate in life's activities [33,34]. Emerging from the desire of athletes to improve their sports performance; the ultralight manual wheelchair has transformed lives and the health of users [35–37].

2.2.5. Suspension

Once the quality of manual and powered wheelchairs made it practical for people to travel distances outdoors like people who walk, it started to become clear that the roughness of the surface

could be jarring for the user and effective both comfort and safety [38,39]. Suspension has made it practical for people to drive practical distance over pedestrian walkways and to negotiate thresholds [40,41].

2.2.6. Ergonomic pushrims

For decades manual wheelchairs used small round tubular pushrims for the user to propel. There was little or no science to support this decision, and only after evidence that the risk of developing rotator cuff injuries and carpal tunnel syndrome was related to manual wheelchair ergonomics did new designs start to emerge [34,42]. The ergonomic pushrim transitions people from using a harmful pinch grip to a more effective tool grip resulting in a nearly 50% reduction in repetitive strain injuries [43].

2.2.7. Seating systems

Discomfort, pressure injuries, and postural deformities were the norm until research and development led to creation of medically sound new products [44]. There has been a virtual explosion of powered seating functions that help to address lymph and blood flow reducing risk of pressure injuries [45,46]. Pressure management cushions that distribute pressure or control the shape of the seated tissue have helped to reduce postural deformities, back/neck pain, and pressure injuries [47]. Rigid backrests, especially using composite materials, help to support the pelvis and lower back reducing pain and improving propulsion efficiency [48,49].

2.3. Prosthetics and orthotics

Devices to replace the function of missing limbs or to augment the function of limbs that are impaired have made tremendous strides in the past four decades [50,51]. Technology moved from being hand-crafted by artisans to engineered devices [52,53].

2.3.1. Energy storing devices

It is difficult for many people to walk, run or perform other mobility related activities when using a prosthetic limb or orthotic brace [54]. Energy storing prosthetic feet and energy storing lower leg orthoses have transformed people's lives [55,56]. Patellar tendon energy storing lower leg orthoses have allowed individuals who have had severe neurological impairment or life altering limb salvage surgeries to run again, play basketball, and return to various work activities [57]. Energy storing prosthetic pylons have provided more comfort, reduced risk of injury, and increased mobility [58].

2.3.2. Prosthetic to body interfaces

The performance, comfort, and safety of prosthetic limbs depends in large part on the interface to the body [59]. The most common interface is the prosthetic socket, which has been the norm for over a century. However, significant advances have been made in prosthetic sockets because of the availability of composite materials used to fabricate sockets, and silicone to make liners [60]. The lighter weight and higher strength have allowed sockets to be more form fitting and to withstand more strenuous activities. Following the science of dental implants that made people with missing teeth regain much of their function, and they are a significant improvement over alternatives in many cases. Directly implanting a device in the bone of a leg or arm that crosses through the skin to serve as an alternative to a socket [61–63]. Although there are potential issues with infection or fractures, studies have shown that users report satisfaction with greater sensation, no skin breakdowns, and more tolerance for using a prosthetic limb.

2.3.3. Microcontroller variable compliance knees

An amputation above the knee can demand more energy to perform mobility related activities of daily living while also increasing the risk of falling [64,65]. Mechanical knees have been the standard for decades although improvements continue to be made. Electromechanical knees that use microprocessor control to regulate the stiffness of the knee joint during the gait cycle or in response to a trip have dramatically improved the mobility and safety of prosthetic limbs for individuals with transfemoral amputations [66,67].

2.4. Manipulation devices

The ability to manipulate objects in space is essential to being able to live independently as well as to perform many activities of daily living. [Robotic devices to assist people with disabilities were only material for science fiction novels 40 years ago. Body powered upper extremity prosthetic devices existed that were in large part inspired by the cable systems used on airplanes during World War II [68]. For individuals with trans-radial amputations, they worked well and they are still commonly in use. However, in the past two decades largely due to the wounds experienced in recent military conflicts there have been significant advances in robotic devices [69,70].

2.5. Telemanipulation robotic arms

For individuals without their arms or with limited or no use of their arms, robotic arms may offer substantial improvements in quality of life. The first attempts at wheelchair and workstation mounted robotic arms emerged in the 1990s, but practical devices did not come into being until after 2010 [71–73]. There are a few devices that have made it to the marketplace, and their companies are working to prove commercial viability [74,75]. Many more devices are under development. Nearly all are based on telemanipulation using a variety of user interfaces – joysticks, keypads, touch screens, eye-gaze, voice control, and brain computer interfaces [76,77]. Some of the challenges that require further research and development are improving human–robot interaction to make the performance of tasks intuitive, natural, and of comparable speed to people using fully functional arms [78]. Safety of robotic arms working in close proximity too or even intimately with people is paramount. Safety has largely been addressed by making the robotic arms incapable of causing significant harm by making them either weak (e.g., low payload, low power) or very slow [79]. However, this also limits performance by making it impossible to lift or manipulate many common objects or making it painfully slow [80]. Stronger and faster robotic arms that are safe when used to touch and assist humans are required.

2.6. Powered prosthetic arms

Powered prosthetic arms (PPA) were developed as an alternative to body powered prosthetic arms in attempts to improve function and versatility. PPA share much in common with robotic manipulators except that they are physically interface with the arm at the level of amputation. Due to investment by the US Department of Defense and other advanced research agencies, there have been advances in practical PPA to include multi-fingered hands [81,82]. The cost and reliability of PPA need to continue to be improved before they can gain wider acceptance. Another challenge is the need for natural interfaces, and greater coordination for bi-manual manipulation [83].

2.7. Myoelectric control

The use of the electrical signal produced by muscle when activated has long fascinated scientists and engineers as a source to control devices and to understand human movement intent [84]. Advances in electrode technology and digital signal processing have made tremendous improvements in surface mounted myoelectric control [85]. There are still some issues with noise, and variations in electrode placement and signal quality from day-to-day or within a day, but with machine learning a set of grasps can be reliably classified and implemented [86]. There have been some attempts at improving control using implanted electrodes, and even injectable electrodes [87]. Besides the advances in digital signal processing and control algorithms, one of the most exciting advances has been targeted nerve re-innervation [88]. This is a process of reattaching the nerves from an amputated or severed limb to intact muscle more proximal to the body. If successful, these nerves than activated the muscle at their new host site producing an electrical signal in response to the purposeful initiation of the movement of a portion of the missing limb. When successful, this produces an intuitive control signal related to the desired motion.

2.8. Adaptive sports and recreation technology

There is a long history of sports and recreation for people with disabilities. The early origins date back to soldiers recovering from wounds received during World War I; who participated in sports, recreation and exercise as part of their rehabilitation and convalescence [89]. Organized sports competition emerged from World War II when there were numerous wounded, injured and ill who had survived the ravages of war and the dangers of military service, and who developed a high interest in returning to being productive in their homes and communities [90]. This movement has continued and has garnered wider attention as societies around the world become more understanding of the needs for being more inclusive. Technology has enabled participation in many sports and recreation activities such as mountain biking, skydiving, scuba diving, rock climbing, and a whole host of other activities [91].

2.9. Wheeled sports

Looking back, it is difficult to believe that 40 years ago many of today's wheeled sports did not exist and those that did would be incomprehensible to current participants. In those years prior to 1980, people participated in wheelchair sports using essentially the types of wheelchair use to transport patients in hospitals today [92]. Some athletes made modifications to improve performance, but they were simple and few. Despite the poor equipment and lack of scientific and engineering knowledge, there were some tremendous accomplishments such as Bobby Hall's completion of the Boston Marathon in 1976 [93].

Over the course of the past four decades, the sports of wheelchair tennis, wheelchair rugby, powered wheelchair soccer, powered wheelchair field hockey, and hand-cycle racing have emerged [94]. Wheelchair racing has been totally transformed to where the technology bears little resemblance to a wheelchair used for daily mobility. The combination of hand-cycling and wheelchair racing have also spawned the sport of para-triathlon [95].

2.10. Adaptive sports on snow and ice

Many people enjoy winter sports, but until quite recently people with disabilities had very limited options available to them [96]. Through the efforts of athletes with disabilities who were

creative inventors collaborating with engineers developed technologies that have opened up a wide array of winter sports [97]. Mono-skis, bi-skis, for example, allow people with diverse disabilities to participate in downhill skiing and even for some people to achieve performances similar to or better than people without impairments [98].

Hockey is a popular sport in some regions of the world. The desire for people with disabilities to participate in hockey led to the creation of sled hockey, which is a very popular in the Paralympic Games [99]. People use a seated sled that with two hockey blades under the seat that is propelled by using shortened hockey sticks with small teeth to grip the ice on the handle opposite the blade [100].

2.11. Computer access and communication

The ability to communicate with other people both face-to-face and at a distance is essential for people to be connected to one another [101]. Connection is essential for well-being, employment, education, and participation in society [102]. Advances in software, machine learning, computing power, wireless connectivity, and signal processing have all had tremendous impact on computer access and communication [103].

For people who are non-verbal or have great difficulty generating speech have benefitted from advances in augmentative communication. Advances in technology have improved speech to text in many ways to include word prediction, auto correction, and syntax construction [104]. Means of communication with computing devices (e.g., smart phones, wearables, tablets, computers, etc.) have improved tremendously and now include feature capture interfaces such as eye-gaze, and facial feature tracking [105]. Text or icon to speech has also given voice to many people and continues to improve to include intonation, inflection, and personalization of speech [106].

Portable digital devices have transformed the lives of people with disabilities [107]. They are used as aides to communication, executive functioning, and coaching positive behaviors [108]. Coupled with wireless and cellular connectivity they provide powerful tools for enhancing function and improving inclusion. Portable devices allow people vastly improved way finding and navigation and transportation – whether to communicate with public transportation or to schedule on-demand transportation services [109].

Digital signal processing chips have revolutionized hearing aides and assistive living devices to include complex and sometimes controversial technologies such as cochlear implants [110]. Through wireless microphone technology a person who is hearing impaired can have a speaker's voice transmitted directly to their hearing aids. Digital signal processing on a portable device with a camera can be tremendously powerful in helping people with visual impairments to read, navigate their environment, to orient themselves, and to participate in activities previously impossible [111]. For example although in its nascent stage, there are services that allow a person to remotely access a visually or cognitively impaired individual's mobile device and camera and to describe what is being viewed to for example locate an item or to provide instruction on how to proceed with a task [112]. Digital cameras with object identification can be used by blind individuals to identify denominations of money or to use optical character recognition to read labels or warnings [113].

2.12. Personal transportation

One of the biggest barriers to employment, participation and health for people with disabilities and older adults is the ability to access transportation [114]. For some people adaptations can be made to personal vehicle to allow them to drive or to at least ride

as a passenger. Advances have been made to afford more people the ability drive independently. This has in large part been the result of advances in electronics and sensors, and the changes to motor vehicles to incorporate fly-by-wire and micro-controller control [115]. For many years, alternative vehicle controls were limited to levers attached to brake and accelerator pedals for hand-control, moving the location of the pedals, or altering the pedals themselves [116]. Currently, motor vehicles can be controlled a host of interfaces traditional hand or foot pedal controls to head-tracking and smart car technologies. Other advances in autonomous vehicle technology have benefitted people with disabilities and older adults as well. For example, lane following, automated parking, and safe following distance all enable people with disabilities and older adults to drive safely [117].

3. NEW foundations

Advances in the assistive technologies that are available and they are emerging in large part due to foundational changes that have taken place in the past decades. Some of these changes are a result of integration of tools driven by other fields or disciplines, and others are a direct result for the need to find solutions for people with disabilities and older adults. Transfer of knowledge has come from other fields of engineering and science to help advance rehabilitation engineering as well as come from rehabilitation engineering to further knowledge in other disciplines. For example, speech to text has long been an area of research to provide computer access for people with disabilities, and so has icon to speech or icon to text. This foundational work in rehabilitation engineering has led to such things as emoji's, tiles, and other common features used on hand-held devices.

3.1. Design tools

The tools used to design, and manufacturer assistive technologies has totally transformed research, development, and manufacturing. Gone are the days of pen and paper to create drawings and the difficulty in making changes or creating models for visualization. Forty years ago, it was not uncommon to face challenges of getting repair parts for wheelchairs because of the rapid pace of revision and the cost and difficulty of maintaining stock of repair components. Today, designs are created and stored as three-dimensional solid model assemblies that are linked to original equipment manufacturer data [118].

3.2. Participatory action design and engineering

The ultralight wheelchair design and adaptive sports revolutions of the 1980s laid the groundwork for participatory action design and engineering (PADE) that is gaining momentum [119,120]. The basic premise follows from the global disability rights movement that led to such fundamental declarations as the United Nations Convention of the Human Rights of People with Disabilities [13]. Essentially, PADE embraces the cry by disability rights advocates of “nothing about us without us” and incorporates inclusion and engagement of end-users through the design and engineering process from conceptualization through the commercialization and standard of practice. PADE is also conducted in the context of the Policy, Human, Activity, Assistance, Technology, and Environment (PHAATE) model [119]. The PHAATE model provides a framework that a person is doing something, somewhere, with assistance from technology and or another person, and all of this is done within a legal and regulatory framework. Both PADE and the PHAATE model have changed the mindset of a generation of rehabilitation engineers and provided greater opportunities for people with disabilities [120].

3.3. Parametric design tools

It may be difficult to believe but it was not that long ago when there were just a few sizes and types of manual wheelchairs. A person could nearly be an expert by memorizing the catalog of a few manufacturers. Thankfully those time have changed. Parametric design based upon the anatomy and functional mobility of the user has become a driving force [121]. Two basic approaches are used. For manual wheelchairs the process includes taking measurements of the user, determining their functional abilities, and noting user preferences. The results are then provided to a manufacturer who includes this data into their design models for basic frame geometry styles to create a personalized wheelchair that is produced for that specific individual. This helps to reduce weight and improve the function of the user. For powered wheelchairs a universal design approach is used where the anatomy and function of potential users are accounted for primarily through historical data to produce designs that fit most people through adjustable features and matching appropriate hardware options such as postural supports and controls.

3.4. Computer aided design – computer aided manufacturing

Advances in flexible manufacturing and design tools generated to improve productivity and increase quality of products across broad industry sectors have also benefitted people who use assistive technologies. Because people with disabilities have such diverse needs, the ability to personalize solutions has been critical to improving the quality of products, but also to improving function and health. Flexible manufacturing and rapid prototyping have made it feasible to design and create products in small quantities and have a viable business [122]. Additive manufacturing has recently facilitated the return of rehabilitation engineers to clinical settings, primarily in partnerships with occupational therapy departments, to make custom devices for individual clients. Numerous devices can be used in both clinical and home settings that can be manufactured in plastic with a good quality three-dimensional printer using common materials such as ABS or nylon [123]. An additional benefit is that computer aided design files aid in making modifications or changes as needed, and to creating replacement devices. This approach has the added benefit of replacing a closet or room full of replacement components with simple plastic spools, powders or resins, and the corresponding solid model computer files.

Computer aided design and manufacturing has begun to transform prosthetic and orthotic device fabrication. Componentry used to assemble artificial limbs or functional braces have long been using computer aided design and manufacturing increasing both quality and options. Recently, central fabrication has offered an alternative to have an individual prosthetist or orthotist fabricate a molded socket or brace, instead sending a computer file or a casting to a central fabrication facility [124]. This has the potential to lower costs and raise quality across the industry while still providing personalized devices.

3.5. Standards and test methods

A sign that a device market is becoming mature and has reached a global market scale is when international standards become available. The International Standards Organization (ISO) has been working on standards for assistive devices for 40 years. The impact of these standards has been improvement in clinical services primarily by standardizing terminology, definitions, and measurement, and high minimum quality of products through test methods and normative values [125–127]. Interoperability has in

some cases also improved, although there is still a tendency to retain proprietary communication protocols. The ISO standards are voluntary but form the basis for many national standards that are frequently used by regulatory bodies and insurance providers. Work on standards is constantly evolving to keep pace with new products, manufacturing techniques, and markets.

3.6. Electronic medical records and databases

The ability for a clinician and an engineer working with them to review a person's medical, functional and device history has and shall continue to transform the quality of design and services. Moreover, the capability exists to place notes or links to custom devices that have been made for an individual over time, and to share the designs with others to learn from a collective clinical knowledge set [128]. Engineers and clinicians are beginning to use electronic medical records to identify changes in people's abilities and conditions over time, which could provide the ability to predict and accommodate future needs before they arise [129]. These tools also provide a clearer picture of the individual's health and function and can provide opportunities for recommending lifestyle changes or for experts to provide on-site or remote consultations expanding access to information and expertise.

3.7. Measurement

Measurement has transformed rehabilitation, especially the ability to record measurements outside of a clinic. Until recently, accurately recording clinically or scientifically relevant data outside of a treatment facility or laboratory was at best difficult and often impossible. The ability to collect and even analyze data nearly anywhere and nearly all the time grows each year.

3.8. Wearable technologies

Portable and connected computing technologies have enabled numerous new technologies or improvements to traditional technologies [130]. The growing variety of low-power and millimeter size sensors enable collection of a wide variety of data to include motion, location, force, blood-flow, heart rate, etc. Because of the availability of compact computing and connected technologies, engineers can create a variety of body worn and technology born packages [131–133]. Consequently, there is a much better understanding of how far, fast and often wheelchairs and prosthetic limbs are used [134–136]. Wearable technologies provide tools to understand the causes and courses of pressure injuries and lymphedema [47,137].

3.9. Digital motion capture

The ability to capture high quality digital images and then automatically analyze and track motion has nearly unlimited potential. In decades past, scientists would use motion picture cameras, sometimes with high frame rates, to collect motion data and then painstakingly analyze each frame by hand with a marker and rule. That was replaced by the video camera, but they were originally slow and had low resolution. Engineers interfaced them to a computer with a frame grabber board and road early software to identify high contrast markers [138]. The basic techniques remain the same, but the quality of the images, the cost of the cameras, and the accuracy of the image processing algorithms are much better. In addition, motion capture has evolved away from solely using cameras to a sensor fusion approach with inertial tracking, laser and/or sonar ranging, and camera images. By taking a sensor fusion approach motion capture has become faster, cheaper, and more accurate [139].

3.10. Home and community health technologies

Once it became clear that data could be collected from an individual and our environment remotely and analyzed at a distance, it did not take people long to realize that they could extend their reach for providing remote consults among clinicians or make virtual house calls [140]. Early systems experimented with augmenting Plain Old Telephone System (POTS) [141]. POTS could transmit voice and data at low speeds using a modem. While the early approaches were clunky, they demonstrated that the concept of telehabilitation had potential. Currently, people routinely use video conferencing and send images through their portable connected devices, and with secure software clinicians do so too communicating amongst themselves and their healthcare clients [142]. A challenging that we must face is how to manage the large volume of data that is available and determining the clinical obligation to review this data for clinical decision making [143]. There are a growing number of studies that various synchronous, asynchronous, and even autonomous approaches have the potential to improve outcomes and health.

4. Emerging areas

Despite the tremendous life altering progress that has been made in the past 40-years, there remains nearly limitless possibilities for continued advances to improve the health, quality of life and participation of older adults and people with disabilities. It is impossible to predict with any accuracy what the next 40 years will bring; however, there are emerging areas that show promise to make contributions of note and those that could form the foundation for future advances. An overarching need is for naturalistic and intuitive interfaces to improve the control of and interaction with assistive devices [120].

4.1. Machine learning and artificial intelligence

Computing power provided a foundation for numerous advances in the past and will likely continue to be a key element for future technologies. As computing power grows and becomes more widely available, it will enable further advances. Those advances are likely to be in the domains of machine learning and artificial intelligence. There are already some hints as to applications to assistive technologies.

4.2. Activity identification

Rehabilitation and independent living are highly dependent on human intervention and support. This essentially limits services to clinical settings and periodic interactions with a professional within a person's home or community. As technology advances to be able to recognize the types and quality of activities than machines could extend therapy from just a few weeks with periodic follow-up to be almost continuous over a lifetime [144]. Wearable, home-based, and other devices could monitor a person's vitals, activities or daily living, and compliance with clinical guidance to help avoid life-style related diseases and to optimize health and function [145]. Much of this monitoring and even the intervention could be done autonomously, only calling for human intervention when needed.

4.3. Virtual coaches

For devices to assist people to be compliant with performing activities or in taking medications to promote health or quality of life; there needs to be virtual coaches [129]. Virtual coaches combine monitoring, activity identification, and intervention with contextual awareness, and knowledge of a person's preferences [146].

To be effective, a coach must provide the appropriate guidance at the opportune time in the proper environment with a means amenable to the person being coached. Human coaches are available for a wide array of activities from sports to personal finances to health, and a whole host of other aspects of life. Coaches are often highly skilled and trained. Hence replacing them effectively with a machine is a daunting challenge, but one worthy of pursuit.

There are some examples of virtual coaches. The most common are software programs that work as smart user manuals. There are a few examples in the domain of assistive technology as well; most notably executive function coaching devices and pressure injury risk reduction devices [147,148].

4.4. Collective learning

Connected devices provide the ability to have the data from multiple people shared to a common source and for the devices to learn from the collective experiences of all the users. This could accelerate advances and learning. For example, if a virtual coach learns a technique to reduce risk of developing a pressure injury among a subset of users, the technique can be shared with all other users with similar traits. Even in simpler form, collective learning could help to collect and analyze the large data sets needed to better understand low-incident events or rare conditions [149]. For example, little is understood about the progression of amyotrophic lateral sclerosis and how technological interventions could provide assistance. Social media suggests that sharing experiences is beneficial, but the impact could be greatly amplified by sharing data as well.

4.5. Sliding autonomy

People with disabilities desire and deserve as much control and autonomy over their lives as possible. Technology provides both an opportunity and poses a threat to achieving the goals of people with disabilities. Sliding autonomy is the concept that the control of a device can be operate along a continuum from complete control by the user to autonomous operation by the device [78]. The idea sharing of user control to machine control is dependent on the type of device, the specific activity and the ability and preferences of the user. Current research indicates that the most likely scenario is human and machine control working simultaneously in harmony [150].

4.6. Personal natural language generation

Individuals with the inability to speak or who have difficulty speaking currently use a variety of devices that generate speech from text or icons [1]. This method has had a tremendous positive impact, but it is slow and unnatural. Moreover, the speech is robotic and has limited ability to convey individual personality. There is the need to create means of generating natural speech at rates like people without impairments, and that is indistinguishable from another person.

The inverse problem of taking video or streaming images and converting them to text and text descriptions is also currently unavailable and much needed. This is a significant limitation for individuals with visual impairments.

4.7. Robotics

There is simply not enough trained human professionals and non-medical assistants to meet the needs of people with disabilities and older adults. This challenge has been recognized and initiated research into assistive robotics. Even after nearly three decades, assistive robotics are still in the nascent stage. There are several challenges yet to be overcome.

4.8. Obstacle negotiating mobile robots

The ability to be mobile in a world that is hostile for people who have severe mobility impairments such as wheelchairs presents a significant technical and social integration challenge. There has been substantial investigation into obstacle detection and avoidance based largely on industrial mobile robot technology [151,152]. However, the greatest need is for mobile robotic devices that can negotiate obstacles both in the built environment and the natural environment, while still being fully functional in indoor environments, especially homes. Some early work shows promise in this area [153–155].

4.9. Bi-manual manipulation

Assistive robotic manipulators (ARM) have largely focused on using a single device to perform various activities [76]. The progress in this area shows promise but is inherently limited by using a single manipulator [156,157]. Many common tasks require or are often performed bi-manually. Besides the expense of current ARM, the complexity of programming, control, user interface, and coordination of bi-manual manipulation in close contact with people is an inherently difficult challenge [158,159].

4.10. Collaborative robots

Robotic prosthetic limbs and robotic exoskeletons have recently emerged and provide in inkling of what may come [160–162]. These devices, as well as powered orthoses or hybrid orthoses (combined human and alternative power), must work concert with the wearer in a natural and seamless fashion as has been illustrated in motion pictures for decades [163,164]. There are also more immediate challenges of power sources, actuators, controls, sensors, and form-factor [165].

4.11. Powerful robots and assistants

Engineers have attempted to avoid the problem of powerful robots working intimately with people because of the inherent risk [150,166]. However, to provide much needed assistance to people with disabilities and to reduce the strain on caregivers it is necessary to create safe, effective, and powerful assistive robots with the ability to lift people and realistic common objects [80,167]. This requires clever engineering, and new approaches to safety. In addition, studies need to be conducted to determine people preferences, and tolerances for technology and the associated risks.

4.12. Powered sports and recreation

Sports and recreation are key elements of successful rehabilitation programs and afford people the opportunity to participate in healthy activities with friends and family in their communities [168,169]. Adaptive sports have revolutionized the lives of people with disabilities and have played a pivotal role in altering the attitudes of many people. It was not that long ago that many people with disabilities lived in institutions or were sheltered by their families. Through the disability rights and adaptive sports movement people with disabilities mostly live in homes and communities, attend school, and have the opportunity to participate in society.

Adaptive sports continue to grow and at the same time are receiving more attention from the public. The Paralympic Games are televised in many countries, are popular on the internet, and a viewed in person by sell-out crowds [170,171]. Despite the advances made, people who use motorized or power assist devices have few sports and recreation opportunities. There is a large and

growing need for powered sports and recreation devices to expand participation beyond power soccer, power field hockey, and a few other sports. For example, power steering for downhill skiing, powered sled hockey, and powered boating need technologies to be created and tested [172].

5. Summary

Engineering has changed medical rehabilitation and assistive devices through original research and development and integration of knowledge and technologies generated by other fields. As a result, people with disabilities lives have been improved but there is still much to be done. Unfortunately, people with disabilities in low income countries have lagged people in higher income countries in benefitting from technical and social changes. Assistive devices have benefitted from the availability of powerful, portable computing power, from small low-power sensors, from new materials, from rapid prototyping and flexible manufacturing. There are exciting emerging technologies that show promise for future advances.

Engineering technical aids for people with disabilities, like many other technologies, is in many cases dependent upon the availability reliable portable power sources. Batteries are used extensively, but other sources have been explored such as compressed gases, and fuels. Research and development is needed to study the applicability of advanced batteries, and non-electric energy sources. Power sources will provide the foundation for new technical aids.

Further progress in technologies for people with disabilities needs to include them throughout the process from conceptualization to wide-spread implementation. Rehabilitation engineering needs to move from design for people with disabilities to design with people with disabilities. Barriers to receiving a scientific, technical, and engineering education need to be lowered or removed for people with disabilities. There are too few people with disabilities educated, trained, and working to develop new or improved assistive devices. This limits advances and employment opportunities. For those people with disabilities in technical and engineering education programs, too many are not actively engaged in hands-on learning experiences rather they are relegated to being observers or notetakers [9,173]. This needs to change by taking an inclusive approach to designing classrooms, laboratories, and scientific machines and instruments [173–175], here is a trend towards on-line open source materials for education; however, little attention has been given to making these resources accessible.

Technology is essential for health and quality of life for many people with disabilities. The ability to live in the least restrictive environment, to work, and to participate in society are all enhanced through technical aides. Although tremendous progress has been made, the journey has really only just begun, and many astonishing changes are likely to occur in the future.

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