Technology for Mobility in SCI Ten Years From Now

Michael Boninger[1,2, 3], Jennifer French[4], James Abbas[5], Laszlo Nagy[6], Martin Ferguson-Pell[7], Susan Johnson Taylor[8], Mary Rodgers[9], Norman Saunders[10], Hunter Peckham[11,12], Ruth Marshall[13], Art Sherwood[14]

[1] Department of Physical Medicine & Rehabilitation, Pittsburgh, PA

[2] UPMC Rehabilitation Institute, Pittsburgh, PA

[3] Human Engineering Research Laboratories, VA Pittsburgh Healthcare System, Pittsburgh, PA

[4] Neurotech Network, Tampa, FL

[5] Center for Adaptive Neural Systems, School of Biological and Health Systems Engineering, Arizona State University, Tempe, AZ

[6] Community Advisory Board, MetroHealth Rehabilitation Institute of Ohio, Cleveland, OH

[7] Faculty of Rehabilitation Medicine, University of Alberta, Edmonton, AB

[8] Rehabilitation Institute of Chicago, Chicago, IL

[9] Department of Physical Therapy & Rehabilitation Science, University of Maryland School of Medicine, Baltimore, MD

[10] Department of Pharmacology, University of Melbourne, Parkville, Australia

[11] Department of Biomedical Engineering, School of Medicine, Case Western Reserve University, Cleveland, OH

[12] Louis Stokes Cleveland VA Medical Center, Cleveland, OH

[13] School of Medicine, Faculty of Health Sciences, University of Adelaide, Adelaide, Australia

[14] National Institute on Disability and Rehabilitation Research, U.S. Department of Education, Washington, DC

Address all correspondence to:
Michael Boninger, M.D.
3471 5th Ave. Suite 201
Pittsburgh, PA 15213
boninger@pitt.edu
Ph: 412-648-6654 Fax: 412-692-4354

1

Abstract

Objectives: To identify technological advances that are likely to have a great impact on the quality of life and participation in individuals with spinal cord injury (SCI).

Methods: In this paper we use the International Classification of Function to frame a discussion on how technology is likely to impact SCI in ten years.

Results/Conclusion: While technology advances are exciting, a large challenge for the research community will be how to effectively apply and deploy this technology. Advances occurring in the next 10 years that reduce cost of technology may be more important to the population with SCI than brand new technologies. Social context is everything. As a research community we must advocate for better systems of care. Advocating now for better care will lead to a world in 2020 that is ready to adopt new technologies that are truly transformative.

Keywords: Spinal cord injury; mobility, assistive technology; International Classification of Function

Introduction

The International Classification of Function defines mobility as “moving by changing body position or location or by transferring from one place to another, by carrying, moving or manipulating objects, by walking, running or climbing, and by using various forms of transportation.”(1) Clearly this broad definition highlights the areas that can be affected by paralysis and loss of sensation in individual with spinal cord injury (SCI). Individuals with SCI and significant neurologic impairment are able to move through use of technology such as wheelchairs, orthoses such as leg braces, and neuroprosthetic functional electrical stimulation (FES) systems. Recovery of function is likely to be impacted by technology such as robotic therapy devices. Thus current technologies enable significant independence and participations. However there is also substantial room for improvement. In this paper we discuss where we believe technology for movement will be in approximately ten years, thus informing directions for future research.

Framework

According to the International Classification of Function (ICF) framework a patient’s level of disability is an interaction between their impairment and the environment.(1) Technology impacts this in a number of ways. A robotic gait trainer can reduce impairment and thus disability. A wheelchair makes it possible for an individual with paralysis to traverse a sidewalk. FES can reanimate an arm to allow for object manipulation. In this framework, technology has the potential to fully eliminate disability (see figure 1). However, technology has not achieved that end goal.

Wheelchairs available on the market cannot traverse steps, FES devices do not allow an individual to play a piano, and robotics do not result in full recovery.

Will technology allow complete independence someday? The answer is likely yes. How will this come about? While research directly in the field of rehabilitation is essential, in the technology realm, it is likely that breakthroughs in general technology will drive improvement in technology for mobility. In ten years computers will be faster, power supplies will last longer and deliver more power, all components will be smaller, and the software that controls devices will be smarter. In addition the ability for machines to interact directly with the body will improve through better sensing, biocompatibility and integration with the nervous system.

All of these advances have the potential to greatly impact individuals with SCI, but individuals with SCI frequently don't fully benefit from the technologic advances. Economic reality often stifles research for products that would only benefit a relatively small population. Even when large populations exist, such as all wheelchair users or all individuals with upper limb impairment, the reimbursement of medical services or the complexity of health systems across the world can prevent progress. Thus, when discussing future technology, it is essential to look at social context. In this paper we will review expected advances in specific areas of technology. We will then look at the device level to project how these advances will impact rehabilitation and assistive technology. Finally we will look at the social context of technology for mobility and how the political, social and economic environment is likely to impact advances.

Advances in Technologies

Power sources

Power sources have advanced with higher capacity and lighter weight cells that are more resilient to “abuse”. This has been driven largely by the demands of cell phones and laptop computers. New technologies demand even greater capabilities including greater capacity, extended periods between charges, longer life, and greater tolerance of over-discharge. Even greater demands are created when the device is implanted in the body with the consequences of failure amplified by replacement that requires surgical intervention. Several approaches have been developed to address these challenges including power supplied by inductive radio frequency (RF) coupling of power to the implanted (and moisture protected) circuitry. This can be used as the direct power source, eliminating the need for implanted batteries, or as the source to recharge an implanted battery.

One may expect new technologies to provide a larger number of alternatives for power sources. Already, lithium ion and similar chemistries have advanced to allow greater capacity, an enhanced number of charge/discharge cycles, and discharging to zero charge without damage to the cell. Looking further into the future, one can envision cells that not only include new chemistries, but also entirely new concepts. Are implanted fuel cells in our future? As our consumer demands on large power systems for automobile propulsion enable clean power solutions, one can expect that some of these will be applicable to power sources for SCI. What about cells recharged by the movement of the body—a physiological recharging mechanism(2) or cells that can utilize the body’s own chemistry to provide the power source to the cell. With the demands of a greater number of portable consumer devices to drive them to smaller dimensions and lighter weight, and the broader acceptance of implantable medical devices, clearly some of these technologies will be realized in practical forms.

Processing

Moore’s law predicts that the number of transistors that can be economically placed in a processor will double every two years.(3) For the last 45 years, the semiconductor industry has met this prediction. Advances in processor technology have provided us with affordable laptops, mobile phones, digital cameras, HD TV’s, internet communication, and wireless routers. Perhaps more importantly, these advances have enabled much of the progress in medical care that has occurred over the past several decades. For individuals with disabilities, the independence provided by mainstream technologies such as mobile phones, laptops and internet access is substantial. So, what can we expect as an encore? First, we should ask: does it matter? Many of the advances in rehabilitation technology that we can expect to see over the next decade may be possible with microprocessors available today. Our primary challenge is to utilize these fast, cheap and powerful processors to restore mobility with the next generation of technology.

Some experts predict that Moore’s law may hold only for another 5 years, so we will have to look beyond the mainstream of the semiconductor industry for the next round of advances in processors. We see at least three trends in processors that may enable improved mobility for people with SCI. First, we will move beyond the binary realm of the digital transistor. ‘Neuromorphic’ technology(4-6) uses paradigms that mimic biological neurons in an attempt to gain some of the computational capabilities and computational efficiencies of neurobiological systems. Second, we will have processors that adapt to needs of the user. These adaptations may come about through neuromorphic design or entirely different approaches, but they will enable autonomous reconfiguration of the processor itself to improve processing speed, enhance processing capability and/or reduce power consumption. Finally, we will have tools that will reduce costs and improve the functionality of custom-designed processors. Engineering design tools that enable rapid and cost-effective development of specialized microchips will enable their utilization in small market technologies such as those for people with SCI.

Sensors

Sensors technology can be critical to movement in SCI. As an example position sensors can provide a feedback loop necessary for high level control of a FES-power neuroprosthesis.(7) Additionally sensors that can detect tissue hypoxia can alert an individual with SCI to move as a means of preventing pressure sores.(8) Advances in sensors over the next ten years will likely include an increased capacity to sense various body stasis parameters noninvasively. There will also likely be an increased ability to transfer this data in real time to widely distributed networks. GPS and ubiquitous camera systems are likely to be able to provide additional information related to location and position in the environment. Thus one could envision that in ten years wheelchairs will incorporate GPS and sensor ability. The sensors will automatically trigger movement for pressure sore prevention. Cameras could allow for collision avoidance so that individuals who have limited motor function are safer while driving.(9;10) In addition smart clothing based sensors will provide the feedback needed for high level closed loop control, including temperature sensors, to avoid burning an insensate hand.

Manipulators

Manipulators or robotic arms represent a range of devices that have the potential to be used by people with high level SCI to perform tasks. They can be attached to work-surfaces or wheelchairs and have been produced commercially for nearly two decades. (11;12)The limitation of most of these devices has been the need for extensive inputs from the user, through devices such a ‘sip and puff’, and head or eye-tracking. This limited input coupled with the multiple degrees of freedom of the manipulators makes task performance very slow compared to typical function. Therefore manipulator or robotic arm technology is more limited by the ability of a user to control the arm than the technology to build the arm. Advanced machine vision systems, brain computer interfaces, and shared control with a remote user, maybe the most important advances that can be achieved. The advances that are likely to occur in manipulators will involve greater dexterity of the “hand”, the inclusion of sensory feedback, and greater speed and strength through miniaturized motors. It is likely that some of the DARPA-supported advances related to the ongoing emphasis of prosthetic limb control will be applicable to people with SCI. In the end, additional improvements are likely to be driven by commercialization strategies that increase access to manipulator technologies. Advances in many of the areas covered in this paper will be needed to drive complex manipulators. For example, machine vision and “function-prediction” features involving artificial intelligence will reduce the level of control required from the user.

Algorithms – software

‘Graceful’ is a term that has rarely been used to describe the movements produced by a neural prosthesis, an exoskeleton, or a semi-autonomous wheelchair; ‘robotic’ is a term that has rarely been used to describe the movements of a cat. The cat has arrays of high quality sensors for multiple modalities of information and has a set of strong and well-controlled muscles. Most importantly, however, the cat utilizes highly evolved and specialized algorithms to integrate information, plan movement and execute a coordinated strategy. Over the next decade, we envision technology for mobility that is safer, more highly functional, more energy efficient and more graceful. The pattern of light that falls on a camera lens can be used to gather information about obstacles, the pattern of forces on an insole sensor array can be used to monitor the progression of the center-of-pressure during gait, and the pattern of torques generated by motors can provide information about the actions of the exoskeleton. Integrating sensor information across multiple modalities to plan a movement path or strategy provides an even greater challenge. Advances in these areas will primarily be achieved through the development of algorithms that are akin to those used by the cat and other biological systems. ‘Biomimicry’ is an expanding branch of engineering that seeks to develop technology that mimics biological systems.(13) Biomimetic sensors and biomimetic actuators will play a role in improved systems for mobility, but perhaps the greatest advances will come from the development of biomimetic algorithms – computations that mimic those of the sensorimotor regions of the brain and spinal cord.(14) The combination of multi-modal sensor fusion tactics and motor coordination strategies may ultimately produce systems for mobility that deserve to be described as ‘graceful’.

Impact on specific devices

Robotics

For the purpose of this paper, rehabilitation robotics for mobility can take two roles. Rehabilitative robotics can help the individual with SCI regain function. Two current examples include robotic treadmill ambulation devices and robotic upper limb retraining devices.(15) Research has found that repetitive movement can enhance the return of motor function. These exoskeletally applied rehabilitative robotics are ideally suited to this role and have the added benefit of measurable outcomes, a critical issue in healthcare. Most rehabilitation robotics use computer feedback or a virtual reality type environment to give the user feedback in a gaming environment. In the future, these relatively simple exoskeletally applied devices are likely to become more complex, allowing for greater freedom to received assistance during an actual task. At the same time they will likely be able to measure the amount of assistance provided and adjust their rehabilitation regimen in subtle ways. As these tools become more widespread, the cost is likely to decrease and the proliferation of these devices is likely to occur.

In addition, assistive robotics can theoretically provide direct assistance with activities of daily living. Assistive robotics have significantly more technical hurdles to overcome to become truly functional. Technical hurdles include the ability to move around in a changing environment autonomously. This is an intense challenge in the robotic realm. Simply picking up objects and being able to adequately manipulate them for functional uses is challenging. Above all else safety must be maintained, which requires that the robots operate with extreme precision not needed in other applications. Advances in the technical areas listed above are likely to hasten progress in assistive robotics and in the meantime simple robotics as part of other devices (smart wheelchairs – see below) are likely to predominate in rehabilitation.

Exoskeletons

Born out of military and space applications to enhance performance on the battlefield and in space, respectively, exoskeletons have a place in the rehabilitation market for SCI. In general, the term 'exoskeleton' is used to describe a device that is external to the body, like a brace. But unlike a brace, augments the performance(16) through actuators. Many exoskeletal systems have been developed to augment function, but have yet to gain wide spread use. This is largely due to the size and weight of current systems and to difficulties with performance in the natural environment. Exoskeletons as devices to improve rehabilitation, like the robotic treadmills have gained some acceptance. New developments in hydraulic actuators, battery power, sensory circuitry and materials are likely to turn the exoskeleton of the future into more of a ‘Second Skin Space Suit’, as military focus on such developments will have spinoffs to people with disabilities. The devices will be customizable to the needs and anatomy of the user, sensing and compensating for fatigue and worn inconspicuously under common clothing. By 2024, people will walk down streets, in malls and home bearing exoskeletons. Rehabilitation will have an assortment of them available to aid people with SCI, some as assistive technology to wear for walking and some for rehabilitation in the clinic.(17)

Wheelchairs

At present, wheelchairs are the most important mobility technology for individuals with SCI and are likely to remain so for at least the next decade. The evidence that wheelchairs impact quality of life is overwhelming.(18) Yet in the last decade design improvements in wheelchairs can be described as "incremental". Changes in the next decade in manual wheelchairs will likely be dictated by improvements in materials and manufacturing that will drive down the weight and increase the ease of mobility and customizability of chairs. Mobility control will be greatly impacted by advances in machine vision that will allow autonomous navigation. Advances in virtual reality will allow better training. Software and microprocessor advances will allow for smarter joysticks that will enable even those with the most severe motor impairments to use this control and in the absence of any motor input brain computer interface (BCI) will allow a user to think and control the wheels. The power wheelchair itself will involve greater sensing and flexibility allowing it to traverse significant environmental barriers and very rough terrain. In addition, the wheelchairs will be able to sense aspects of the driver's well being and automatically call for help, or shift seat configuration to prevent pressure sores. Although it is possible that advance in other areas, like exoskeletons, will eventually render the wheelchair as we know it obsolete, this is unlikely to happen in the next ten years making continued research essential. Furthermore, there is a significant challenge in seeing these advances adopted by manufacturers who are challenged with decreasing reimbursement and manufacturing facilities that are not setup to incorporate new high tech materials.

Direct Brain Interfaces

Direct Brain Interfaces (DBI or Brain Machine Interfaces) refer to a direct access to brain signals for the purpose of controlling a device or receiving sensory feedback.(19) At present there is significant study in this area as it relates to SCI. DBI have the theoretical benefit of offering virtually unlimited control signals using thought to operate a device. Current major hurdles for DBI are related to biocompatibility and stability of electrodes that penetrate the brain, achieving maximal degrees of freedom from the implanted device, and providing sensory input that is needed for higher levels of control. Even with these barriers investigators have achieved multiple degree of freedom control in non-human primate studies and in human studies.(20;21)

It seems likely that higher degrees of motor control will be achieved in humans in the next 10 years and that a clinically viable product will be available. Creating a stable interface will likely still be the subject of investigation for electrodes that penetrate the brain. However, non-penetrating electrodes (known as ECoG) may achieve high degree of freedom control and be a stable long term solution. Providing the high level sensory feedback needed for closed loop control will likely still be the subject of much research and the interaction of the brain and the interface to achieve maximal neuroplasticity will likely be studied for decades.

Neural Prostheses

Neural prostheses (NP) can increase the function of people with SCI providing the ability to use paralyzed hands, breath independently, improving bowel and bladder function and trunk control.(22;23) Currently, these functional enhancements are each provided with individual devices. In the near future a multifunctional networked device will enable a network of sensing and actuation (stimulation) power and control modules to be distributed throughout the body in the regions of the target organs. This will allow scalability and has the potential of enabling a user to have many body functions restored with a single device. NP function also will be impacted by other advances in electrodes, sensors, power supplies, cellular therapies as well as techniques to modify the function of neural circuitry. Despite strong performance, NP technology is not widely available. This demonstrates the challenges of bringing class III technologies onto the commercial market in small populations such as SCI.

Neuromodulation and drug delivery

Although biologically driven neuro-repair is not the focus of this paper, advances in technology are likely to drive this area and warrant discussion. A critical aspect of recovery of movement after SCI is central nervous system neuroplasticity. Neuroplastic changes can be influenced both by the environment and activity which can be manipulated through interventions ranging from activity-based therapy(24;25) to electrical stimulation(26) to cellular implants, to local or systemic application of various substances. Here we focus on neuromodulation via electrical stimulation and via chemical agents. By 2020, delivery systems will be available at a scale appropriate to the job, from macro down to nanoscale.(27;28) Indeed, there are already movements from macro to micro in electrodes.(29) Similarly, progress is being made in developing new drug delivery systems, from the current macro system implantable pumps, to drug infusion patches, to encapsulation of drugs in nano-sized carbon buckyballs and nanotubes permitting delivery even across the blood-brain barrier.(30)

Technical challenges in creating such technologies can be confidently predicted to be overcome; however, knowing where and how to stimulate (electrical) or what substances to deliver at what rates, and the means of directing these devices to those targets, pose the rate limiting factors in employment of this new technology. Neuromodulation is likely to be used to augment gait therapy for example, where it could facilitate the lumbar pattern generator, thus promoting ambulation. In terms of impact on rehabilitation, it can be anticipated that deployment of these approaches will not be in the nature of the Fantastic Voyage (1966), but rather will be commonly utilized in a rehabilitation setting in coordination with targets autonomously acquired using chemoattractors and magnetic field manipulation.

Virtual Reality

Simulation and virtual reality (VR) hold the promise to assist in achieving greater mobility in a wide range of activities such as walking(31) and driving.(32) In addition, VR can be used to improve social integration, state of health, morale and self esteem through virtual sport.(33;34) There is a critical difference between systems that use VR only and those that link VR to physical simulation of a real-life activity such as walking, driving or sailing. VR that uses bodily responses can be fun and motivating, and can be structured to provide progressive challenges thus increasing motor skills as rehabilitation progresses.(35) In 10 years VR will likely be less expensive, more immersive, and better able to respond to any biologic signal such as BCI.(36) VR in one form or another will likely be a normal part of rehabilitation, increasing the fun of repetitive movement and motivating patients. Research in 2020 is likely to involve the best way to use this potentially potent tool from a neuroplasticity, motivation and motor recovery perspective.

Potential impact on individuals with SCI

Impact on movement in ICF framework

The International Classification of Functioning, Disability and Health (ICF) was developed by the World Health Organization with the overall aim of providing a unified and standard language and framework for the description of health and health-related states.(1) It uses detailed accounts of a variety of impacts on daily living and quality of life, for example, which can thoroughly classify an individual with more than one condition. The model also accounts for a treatment shift from simple diagnosis by observation to a diagnosis not only of the condition but also the impact on body structure. As related to SCI, the ICF model defines mobility very specifically, not leaving this to interpretation by regulators, third party payers or policymakers.

Since its creation, the implementation of the ICF model has been limited. The model uses a matrix to compare domains versus qualifiers of performance and capacity. This classifies an individual in great detail making it difficult to adopt in the clinical environment. In the future, a training module or computer algorithm may be developed to create a deployment tool for practicing clinicians and third party payers to quickly and simply apply the model. As the ICF model relates to the application of technology to overcome a disability, the classification may demonstrate the user’s improved performance even though limitations in capacity still exist. More widespread use of the ICF model will improve our ability to assess the effectiveness of technology as it relates to daily functioning and allow for a common language across world health systems.

Barriers to deployment

It is paramount that the scientific process leads to an influential end result for the user. Perpetual research that yields nothing to benefit the consumer can be considered by many to be a waste of money and time. There are three main barriers to deployment of technologies for mobility; 1) market availability, 2) awareness and 3) financial access or cost. Market availability has several components including technology transfer, commercial intent early in the development process and technology evolution for commercialization. Awareness includes not only the person with an SCI, but caregivers and clinicians. In clinical practice the integration of technology should be part of the standard of care. These barriers must be considered early when designing new technology. Inclusion of end users with SCI throughout the process can help reduce barriers. While these issues are current, they are unlikely to change and may become more challenging over the next 10 years.

Financial access or cost relates to the design of useable technologies that are affordable to the diverse world health systems including third party payers, government programs and out of pocket purchases. Inevitably, prototypes cost more than marketable technology; however innovation must lead to affordable end products. If researchers are overly concerned about cost engineering, many of the developments discussed above will not come to fruition and great advances will not occur. But researchers must not ignore cost decisions when developing products. Although the costs may be high for many technologies, the impact is substantial and can be available over the full life of the individual. Thus, the Quality of Life Years that are provided by technologies for people with SCI will be a significant argument to be promoted to gain acceptance by payers. A major challenge will be to develop delivery models that ensure that when regulatory approvals are received, that it is sustainable both clinically and financially.

If third party payers do not approve a device it will only be available to the wealthy and will likely fail for lack of a market. Companies with great ideas have gone out of business, because their products could not be coded and reimbursed. Independence Technology, a J&J company, was founded to market and sell the innovative wheelchair known as the IBOT™.(37) The IBOT™ incorporated gyroscopes that allowed it to balance on two wheels, go over rough terrain and up stairs. These features are listed above as futuristic. However, the device was deemed not medically necessary and the absence of a successful reimbursement model led to a failed product.

Fortunately the cost of technology is decreasing. This trend is likely to continue through 2020 opening new possibilities. While research progresses in new technologies it is essential that cost benefit models be explored that document the added medical and functional impact of products. At the same time research must advocate for the broader ICF view of participation instead of a narrow focus of “medical necessity”. What needs to be elucidated is the cost for an individual and society if the enabling technology is not provided. In 2020, it may not be justifiable to deny technology on the basis of affordability, particularly if the provision of an item allows an individual to become a valued member of society.

Conclusion

Technology holds great promise to ameliorate disability and allow for full participation for individuals with SCI. However a few themes emerge as one follows where technology for mobility research is likely to be in 2020. While technology advances are exciting, a large challenge for the research community will be how to effectively apply and deploy this technology. It is not how we design the latest rehabilitation robot, but how we use it to enhance the lives of people with SCI. Technology is likely to put amazing tools at the fingertips of clinicians, but if it is not properly implemented, they may be discarded. In addition, if during technology development, research has not effectively shown the value of the product, it will not be accepted by third party payers. These issues require imaginative approaches, not just to the development of technologies, but to the proof of their efficacy. Given the size of the population with SCI, greater national and international collaborations will be needed than ever before to develop the studies needed to prove efficacy.

A second theme is cost. Advances occurring in the next 10 years that reduce cost of technology will likely be more important to the population with SCI than brand new technologies. The affordability of mobile communication has arguably done more for the safety of this population than any device research has developed. Advances that have commercial appeal and can sell to mass market will lower prices and open the technology up to the community with SCI. The assistive technology researchers of 2020 will need to take advantage of reduced costs and address the commercial viability of their inventions, not just for an initial target population of SCI, but for a broader marketplace.

Finally, social context is everything. If the 2020 researcher develops a great product but health care systems do not support its use, a life’s work could be wasted. In addition, advances in genetics and stem cells could be legislated against if not politically acceptable. As a research community we must advocate for better systems of care now. In addition we must pay attention to the social and political climate in which we work. If we wait for 2020 it is unlikely that the products developed at that time will ever sell. This advocacy cannot just stop in our own country. It must extend beyond individual borders and determine how we impact the world population with SCI. Advocating now for better care will lead to a world in 2020 that is ready to adopt a new technology that is truly transformative.

Conflict of Interest Statement

The authors declare no conflict of interest.

The contents of this paper do not represent the views of the Department of Veterans Affairs or the United States Government.

Reference List

(1) International Classification of Functioning. World Health Organization . 1-1-2007. World Health Organization. 1-3-2011.
Ref Type: Electronic Citation

(2) Donelan JM, Li Q, Naing V, Hoffer JA, Weber DJ, Kuo AD. Biomechanical energy harvesting: generating electricity during walking with minimal user effort. *Science* 2008; **319**: 807-810.

(3) Moore G. Cramming more components onto integrated circuits. *Electronics* 1965; **38**: 114-117.

(4) Mead C. Neuromorphic Electronic Systems. *Proceedings of the IEEE* 1990; **78**: 1629-1636.

(5) Jung R, Brauer EJ, Abbas JJ. Real-time interaction between a neuromorphic electronic circuit and the spinal cord. *IEEE Trans Neural Syst Rehabil Eng* 2001; **9**: 319-326.

(6) Sarpeshkar R. Ultra Low Power Bioelectronics: Fundamentals, Biomedical Applications, and Bio-inspired Systems. New York: Cambridge University Press, 2010.

(7) Strange KD, Hoffer JA. Restoration of use of paralyzed limb muscles using sensory nerve signals for state control of FES-assisted walking. *IEEE Trans Rehabil Eng* 1999; **7**: 289-300.

(8) Jan YK, Brienza DM, Boninger ML, Brenes G. Comparison of skin perfusion response with alternating and constant pressures in people with spinal cord injury. *Spinal Cord* 2011; **49**: 136-141.

(9) Rentschler AJ, Simpson R, Cooper RA, Boninger ML. Clinical evaluation of Guido robotic walker. *J Rehabil Res Dev* 2008; **45**: 1281-1293.

(10) Fioretti S, Leo T, Longhi S. A navigation system for increasing the autonomy and the security of powered wheelchairs. *IEEE Trans Rehabil Eng* 2000; **8**: 490-498.

(11) Laffont I, Biard N, Chalubert G, Delahoche L, Marhic B, Boyer FC et al. Evaluation of a graphic interface to control a robotic grasping arm: a multicenter study. *Arch Phys Med Rehabil* 2009; **90**: 1740-1748.

(12) Bach JR, Zeelenberg AP, Winter C. Wheelchair-mounted robot manipulators. Long term use by patients with Duchenne muscular dystrophy. *Am J Phys Med Rehabil* 1990; **69**: 55-59.

(13) Bar-Cohen Y. Biomimetics: Biologically-Inspired Technologies. Boca Raton, FL: CRC Press, 2006.

(14) Abbas JJ, Abraham A. Biomimetic Approaches to Physiological Control. In: Bronzino JD, editor. The Biomedical Engineering Handbook. Boca Raton, FL: CRC Press, 2011.

(15) Hesse S, Schmidt H, Werner C, Bardeleben A. Upper and lower extremity robotic devices for rehabilitation and for studying motor control. *Curr Opin Neurol* 2003; **16**: 705-710.

(16) Herr H. Exoskeletons and orthoses: classification, design challenges and future directions. *J Neuroeng Rehabil* 2009; **6**: 21.

(17) Ferris DP. The exoskeletons are here. *J Neuroeng Rehabil* 2009; **6**: 17.

(18) Chaves ES, Boninger ML, Cooper R, Fitzgerald SG, Gray DB, Cooper RA. Assessing the influence of wheelchair technology on perception of participation in spinal cord injury. *Arch Phys Med Rehabil* 2004; **85**: 1854-1858.

(19) Berger S, King EC. Designing services for the elderly. *AORN J* 1990; **51**: 448, 450, 452-448, 450, 454.

(20) Allen JB. Sports medicine and sailing. *Phys Med Rehabil Clin N Am* 1999; **10**: 49-65.

(21) Velliste M, Perel S, Spalding MC, Whitford AS, Schwartz AB. Cortical control of a prosthetic arm for self-feeding. *Nature* 2008; **453**: 1098-1101.

(22) Peckham PH. Restoration of function: current challenges and future opportunities through electrical stimulation. *J Rehabil Res Dev* 2001; **38**: xiii-xxvi.

(23) Peckham PH, Knutson JS. Functional electrical stimulation for neuromuscular applications. *Annu Rev Biomed Eng* 2005; **7**: 327-360.

(24) Sadowsky CL, McDonald JW. Activity-based restorative therapies: concepts and applications in spinal cord injury-related neurorehabilitation. *Dev Disabil Res Rev* 2009; **15**: 112-116.

(25) Dobkin B, Barbeau H, Deforge D, Ditunno J, Elashoff R, Apple D et al. The evolution of walking-related outcomes over the first 12 weeks of rehabilitation for incomplete traumatic spinal cord injury: the multicenter randomized Spinal Cord Injury Locomotor Trial. *Neurorehabil Neural Repair* 2007; **21**: 25-35.

(26) Kaplan HM, Loeb GE. Design and fabrication of an injection tool for neuromuscular microstimulators. *Ann Biomed Eng* 2009; **37**: 1858-1870.

(27) Allen JB, De Jong MR. Sailing and sports medicine: a literature review. *Br J Sports Med* 2006; **40**: 587-593.

(28) Andrews RJ. Neuroprotection at the nanolevel--Part I: Introduction to nanoneurosurgery. *Ann N Y Acad Sci* 2007; **1122**: 169-184.

(29) Perlin GE, Wise KD. A compact architecture for three-dimensional neural microelectrode arrays. *Conf Proc IEEE Eng Med Biol Soc* 2008; **2008**: 5806-5809.

(30) Allen JB, De Jong MR. Sailing and sports medicine: a literature review. *Br J Sports Med* 2006; **40**: 587-593.

(31) Riva G. Virtual reality in paraplegia: a VR-enhanced orthopaedic appliance for walking and rehabilitation. *Stud Health Technol Inform* 1998; **58**: 209-218.

(32) Ku J, Jang D, Ahn H, Lee J, Kim JA, Lee B et al. The development and clinical trial of a Driving Simulator for the handicapped. *Stud Health Technol Inform* 2002; **85**: 240-246.

(33) Allen JB, De Jong MR. Sailing and sports medicine: a literature review. *Br J Sports Med* 2006; **40**: 587-593.

(34) Chen CH, Jeng MC, Fung CP, Doong JL, Chuang TY. Psychological benefits of virtual reality for patients in rehabilitation therapy. *J Sport Rehabil* 2009; **18**: 258-268.

(35) Steffin M. Virtual reality therapy of multiple sclerosis and spinal cord injury: design consideration for a haptic-visual interface. *Stud Health Technol Inform* 1997; **44**: 185-208.

(36) Marathe AR, Carey HL, Taylor DM. Virtual reality hardware and graphic display options for brain-machine interfaces. *J Neurosci Methods* 2008; **167**: 2-14.

(37) Cooper RA, Boninger ML, Cooper R, Dobson AR, Kessler J, Schmeler M et al. Use of the Independence 3000 IBOT Transporter at home and in the community. *J Spinal Cord Med* 2003; **26**: 79-85.

Figure Legend

Figure 1: International Classification of Function (ICF) based model for the paper. The frame of the picture represents the social context that will impact utilization and development of new technology. Along the top are the ICF related functions likely to be impacted by technology advances. Beneath ICF functions are the specific technologies that will impact devices, which are listed down the right side. At the center of it all is the person with a SCI.

Figure 1