WTEC Panel Report on

EUROPEAN RESEARCH AND DEVELOPMENT IN MOBILITY TECHNOLOGY FOR PEOPLE WITH DISABILITIES

FINAL REPORT

August 2011

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WTEC PANEL ON EUROPEAN RESEARCH AND DEVELOPMENT IN MOBILITY TECHNOLOGY FOR PEOPLE WITH DISABILITIES

Sponsored by the National Science Foundation (NSF), the National Institutes of Health (NIH), and the Department of Veterans Affairs.

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ABSTRACT

Mobility technologies, including wheelchairs, prostheses, joint replacements, assistive devices, and therapeutic exercise equipment help millions of people participate in desired life activities. Yet, these technologies are not yet fully transformative because many desired activities cannot be pursued or are difficult to pursue for the millions of individuals with mobility related impairments. This WTEC study, initiated and funded by the National Science Foundation, was designed to gather information on European innovations and trends in technology that might lead to greater mobility for a wider range of people. What might these transformative technologies be and how might they arise?

Based on visits to leading mobility technology research labs in western Europe, the WTEC panel identified eight major trends in mobility technology research. First, assistive technologies are being designed to integrate more closely with the user, decreasing user burden while increasing capability. Second, research on technologies for rehabilitation therapy is growing rapidly and is beginning to transform clinical practice. However, the need for therapeutic technology that can be used outside a clinical setting is largely unmet. Third, there is a fundamental need for better neuromusculoskeletal models that can be personalized to predict on a case-by-case basis optimal treatments for individuals. Engineers recognize the immense influence that an experimentally verified model of human motor control and use-dependent neural recovery would exert over the design process of mobility medical interventions and technology. Fourth, wearable sensors and pervasive systems will improve health and wellness monitoring, safety monitoring, home rehabilitation, assessment of treatment efficacy, and early detection of disorders for people with mobility impairment. Fifth, actuators used in mobility technology have not improved as quickly as sensors; the invention of a stronger, lighter, and more efficient actuator and a more compact power source would accelerate assistive and therapeutic technology advances as well as spawn many new applications for mobility technology. Sixth, eliminating physical impairment will ultimately require combinations of physical training and regenerative/plasticity therapies, possibly including molecular and cellular approaches. The science of combination therapies will be rich and is just beginning. Seventh, multidisciplinary teams, embedded with scientists with a disability and which work closely with consumers, are best positioned to produce transformative mobility technology. Finally, government support for research in mobility technology has led to substantial gains. Continued, growing support will be essential to achieve the full potential of mobility technology.

The WTEC panel concludes that research development and application of mobility technology will grow dramatically in future years. As evidenced by the trends listed above, researchers in the field have identified and are solving key problems that have limited progress in mobility technology. It is expected that advances in mobility technology will substantially expand participation in desired life activities for a wider range of people in future years.

ACKNOWLEDGMENTS

We at WTEC wish to acknowledge and thank all the panelists for their valuable insights and their dedicated work in conducting this international benchmarking study, and also to thank all the site visit hosts for so generously sharing their time, expertise, and facilities with us. For their sponsorship of this important study, our sincere thanks go to National Science Foundation, the National Institutes of Health, and the Department of Veterans Affairs. We particularly appreciate the support provided by Cheryl Albus, Semahat Demir, and Ted Conway of the NSF. We received support from the Grace Peng at the National Institute for Biomedical Imaging and Bioengineering, and in-kind support from the NIH intramural research program in the form of the much valued participation of Leighton Chan. We also benefited from the insights and support of Bob Jaeger at the Department of Veterans Affairs.

R.D. Shelton
President, WTEC
FOREWORD

We have come to know that our ability to survive and grow as a nation to a very large degree depends upon our scientific progress. Moreover, it is not enough simply to keep abreast of the rest of the world in scientific matters. We must maintain our leadership.¹

President Harry Truman spoke those words in 1950, in the aftermath of World War II and in the midst of the Cold War. Indeed, the scientific and engineering leadership of the United States and its allies in the twentieth century played key roles in the successful outcomes of both World War II and the Cold War, sparing the world the twin horrors of fascism and totalitarian communism, and fueling the economic prosperity that followed. Today, as the United States and its allies once again find themselves at war, President Truman’s words ring as true as they did a half-century ago. The goal set out in the Truman Administration of maintaining leadership in science has remained the policy of the U.S. Government to this day: the current NSF strategic plan lists as its first goal, “Foster research that will advance the frontiers of knowledge, emphasizing areas of greatest opportunity and potential benefit and establishing the nation as a global leader in fundamental and transformational science and engineering.”²

The United States needs metrics for measuring its success in meeting this goal of maintaining leadership in science and technology. That is one of the reasons that the National Science Foundation (NSF) and many other agencies of the U.S. Government have supported the World Technology Evaluation Center (WTEC) and its predecessor programs for the past 20 years. While other programs have attempted to measure the international competitiveness of U.S. research by comparing funding amounts, publication statistics, or patent activity, WTEC has been the most significant public domain effort in the U.S. Government to use peer review to evaluate the status of U.S. efforts in comparison to those abroad. Since 1983, WTEC has conducted over 60 such assessments in a wide variety of fields, from advanced computing, to nanoscience and technology, to biotechnology.

The results have been extremely useful to NSF and other agencies in evaluating ongoing research programs, and in setting objectives for the future. WTEC studies also have been important in establishing new lines of communication and identifying opportunities for cooperation between U.S. researchers and their colleagues abroad, thus helping to accelerate the progress of science and technology generally within the international community. WTEC is an excellent example of cooperation and coordination among the many agencies of the U.S. Government that are involved in funding research and development: almost every WTEC study has been supported by a coalition of agencies with interests related to the particular subject at hand.

As President Truman said over 50 years ago, our very survival depends upon continued leadership in science and technology. WTEC plays a key role in determining whether the United States is meeting that challenge, and in promoting that leadership.

Michael Reischman
Deputy Assistant Director for Engineering
National Science Foundation

¹ Remarks by the President on May 10, 1950, on the occasion of the signing of the law that created the National Science Foundation. Public Papers of the Presidents 120:338.

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EXECUTIVE SUMMARY

David J. Reinkensmeyer, Paolo Bonato, Michael L. Boninger, Leighton Chan, Rachel E. Cowan, Benjamin J. Fregly, Mary M. Rodgers

Mobility technology plays a critical role in millions of people's lives: consider the impact of a wheelchair on an individual who cannot walk, or of a prosthetic leg on a person with an above-knee amputation, or of a hip replacement on a person who has become sedentary because of the pain associated with joint degeneration. In each case, the technology transforms the person's life because it allows him or her to participate much more fully in desired life activities. Yet, even state-of-the-art mobility technology is not yet fully transformative. As illustrated in Chapter 2 by Boninger and Cowan, there are still routine activities that cannot be pursued, or are difficult to pursue, by individuals who use wheelchairs, prostheses, or joint implants. In addition, there are people with other physical disabilities, including those caused by age-related impairments, for which the enablement provided by technology is still too limited. This study is about identifying status and trends in technology that will lead to a fuller restoration of movement ability for a wider range of people. What might these transformative technologies be and how might they arise?

The National Science Foundation, working with the World Technology Evaluation Center and the Department of Veterans Affairs, selected a panel of American experts in mobility technology to help answer this question. The assembled team included engineers and clinicians with expertise in a broad range of mobility technologies and included an engineer and a scientist with a physical disability. The team worked with WTEC to arrange a brief (5 days) but intense (33 site visits split between two groups) tour of leading laboratories in mobility technology in western Europe. Western Europe was chosen because of its rich and broad research activity in mobility technology. The premise of this methodology was that visiting cutting-edge research sites in Europe in person in rapid succession would afford the team an opportunity to identify trends in mobility technology research while also allowing us to think outside the box of what is currently being done in the United States in this field. We are deeply appreciative of the hospitality, openness, and thoughtful input from our European hosts, which made this study possible.

We first characterized the trends we observed during the October 18-22, 2010 European tour at a workshop held at NSF on November 16, 2010 (video available at http://www.wtec.org). This executive summary briefly summarizes the major trends we observed, while the technical reports that follow provide greater detail.

Major Trends in Mobility Technology Research

The panel identified eight major trends in mobility technology research.

1. Assistive technologies are being designed to integrate more closely with the user, decreasing user burden while increasing user capability.

Although the panel saw no fundamentally new assistive technologies, there was much innovation aimed at making existing assistive technologies, including powered wheelchairs, prostheses, functional electrical stimulation systems, and exoskeletons, more seamlessly integrate with the capabilities of the user. While each solution we observed was uniquely conceived for a specific application, in general, seamless integration was often being facilitated by smaller, better movement sensors and embedded computation that took advantage of this sensor data, along with a careful consideration of the fundamental physiology, mechanics, available capacities, and needs of the user. Examples are a prosthetic
hand that incorporates a small camera and automatically shapes itself to the object being
grasped, a wheelchair that seamlessly shares control with the user, and a functional electrical
stimulation system that identifies and cancels tremor in real-time. Better integration
decreases user burden while also expanding user capability and, as discussed by Cowan and
others in Chapter 3, thereby provides a possible route to transformative impact by assisting
in the desired life activities of the user.

2. Research on technologies for rehabilitation therapy is growing rapidly and beginning to
transform clinical practice. At the same time, the need for therapy technology that can be used
at home is largely unmet.

Research into new therapeutic technologies, including robotics, virtual reality, and motion-
based gaming, has risen rapidly over the past twenty years and continues to evolve rapidly.
Such technologies have proven effective at reducing physical impairment, and they make
rehabilitation exercise more engaging and less labor intensive. Most sites we visited had
major efforts aimed at developing improved therapeutic technologies, and we visited an
impressive new rehabilitation hospital in Berlin that was designed explicitly to integrate
these technologies closely into clinical practice. Thus, technologies for rehabilitation therapy
are a large, if not the largest, thrust area currently in mobility technology research.
Nevertheless, these technologies as yet have only limited therapeutic benefit, and the
technological transformation of at-home therapy is yet to happen.

As discussed in the Chapter 4 by Reinkensmeyer and Boninger, next generation approaches
to improving therapeutic technology include designing technology for early application after
injury, designing lower cost devices, developing technology with more degrees of freedom to
allow training of more naturalistic movements, and improving control and feedback to
enhance movement recovery and motor learning. Wearable systems are being developed to
be used while performing daily activities, thereby blurring the traditional distinction between
assistive and therapeutic technologies. In the future, people will use assistive technologies
both to perform activities of daily living and to assist in recovery, transforming the nature of
rehabilitation therapy and meeting the need for therapy outside of the clinic at the same time.

3. There is a fundamental need in mobility technology research for better neuromusculoskeletal
models that can be personalized to predict on a case-by-case basis optimal treatments for
individuals.

As discussed in Chapter 5 by Fregly and others, current clinical treatment plans are often
generic rather than customized to each patient, and this situation likely limits the
effectiveness of these plans. The panel observed a significant amount of work aimed at
developing personalized neuromusculoskeletal models that can predict outcomes of different
treatments, or the effect of different parameters within a treatment, on a patient-by-patient
basis. These models are based on the premise that each patient possesses unique anatomical,
neurological, and functional characteristics that significantly impact his or her optimal
treatment.

There is a particularly large gap in the development of verified, customizable models of
neural control, learning, and plasticity; that is, more progress has been made in personalizing
muscle and skeletal models, although these too still need development. Thus, the design of
many mobility technologies is still largely based on trial-and-error clinical testing because
there is a lack of fundamental scientific insight into how different technologies will interact
with the human movement control system. Engineers worldwide recognize the immense
impact that a detailed, customizable, computational model of human movement control and
use-dependent neural recovery, for example, could exert over the design process for mobility medical interventions and technology.

4. **Wearable sensors and pervasive systems will improve health and wellness monitoring, safety monitoring, home rehabilitation, assessment of treatment efficacy, and early detection of disorders for people with mobility impairment.**

Improvements in health care are resulting in increased survival rates from acute trauma as well as in people living longer but with more complex health conditions, including the large population of baby boomers. Thus, many societies have a need to provide complex health care for an increasing number of individuals, many with physical disabilities, and many with reduced access to providers. As discussed by Patel and others in Chapter 6, wearable sensors and pervasive sensing systems will improve monitoring of health and safety and will help automate and quantify home rehabilitation. They will also assist in early detection of disorders for people with mobility impairment. Several new technologies are enabling this revolution. Miniaturized inertial sensors are been used in motor activity and other health status monitoring systems, and in smart prostheses and orthoses. Advances in material science have enabled the development of e-textile based systems that integrate sensing capability into garments. Mobile phone technology provides a widespread platform for remote monitoring systems based on wearable sensors. Continued development and integration is needed to provide the usability, safety, reliability, and security needed for home health care.

5. **Improvements in actuators and power supplies have not progressed as quickly as those in sensors; the invention of a stronger, lighter, and more efficient actuator and more compact power supply would accelerate assistive and therapeutic technology advances as well as spawn many new applications of mobility technology.**

A striking trend observed during our visit was that, while new forms of sensors were being routinely applied to improve mobility technology, the actuator technology we observed being used in mobility technology was relatively static. There is a fundamental need for a stronger, lighter, more efficient actuator and a more compact power supply. Mobility at its core is about applying forces, and our current methods for applying forces are relatively bulky and inelegant, and thus limit the environments and situations in which mobility technology can be applied.

6. **Eliminating physical impairment will ultimately require combinations of physical training and plasticity/regenerative therapies.**

There is an increasing recognition that the ability of therapeutic technologies to substantially resolve impairment will ultimately lie in combining these technologies with plasticity-enhancing and regenerative therapies, such as cellular, molecular, or electrical stimulation approaches. As discussed by Reinkensmeyer and Boninger in Chapter 4, there is a “science of combination therapies” emerging, which seeks to characterize the complex interactions between training, plasticity, and regeneration. This science will define the conditions under which combined treatments cancel each other, add their effects, or synergize with each other. An important concept that will influence mobility technology design is that the experience of different physical training activities may compete for the new neural resources made available by plasticity or regenerative therapies. In general, future physical therapeutic technologies that are based on the science of combination therapies will stand the best chance of eliminating many forms of physical impairment.
7. Multidisciplinary teams that work closely with consumers and are embedded with scientists with an intimate knowledge of disability are best positioned to produce transformative mobility technology.

As observed by Boninger and others in Chapter 7, an overwhelming theme that emerged from the trip was that multidisciplinary teams that included, at a minimum, engineers, clinicians, industrial partners, and consumers, were by far the most successful in promoting education, research, and technology transfer in mobility technology. Multiple, multi-disciplinary teams at one site appeared to generate a critical mass, which increased productivity. In addition, collaborations across counties, which are required by many European Union funding mechanisms, brought unique expertise and knowledge of different cultures while helping with recruitment. Experiential learning programs that incorporated the multidisciplinary approach appeared to prepare students best for mobility technology research and development. The panel observed that funding agencies have the ability to force change, as exemplified by the presence of multi-country collaboration in Europe, and assist in commercialization. An important target for funding agencies is to devise strategies for recruiting and training people with mobility impairment to participate in and lead mobility technology research teams.

8. Finally, government support for research in mobility technology has led to substantial gains. Future and growing support is essential to continued advancement.

The vast majority of the research we observed was government funded. This funding has spurred technology that has already transformed the lives of individuals with mobility related impairments. In Europe, there were a number of programs that promote technology transfer and greater ties between industry and researchers. It is clear that continued and increased funding in this growing area of need is essential to continued progress. The support should encourage industry and university collaboration for commercialization of products

Conclusions

The WTEC panel concludes that research and application of mobility technology will grow dramatically in future years. As evidenced by the trends listed above, researchers in the field have identified and are solving key problems that have limited progress in mobility technology. It is expected that advances in mobility technology will substantially expand participation in desired life activities for a wider range of people in future years.
1. INTRODUCTION

David J. Reinkensmeyer

BACKGROUND

There is a wide variety of disability, rehabilitation, and other enabling research being conducted in the United States, Europe, and Asia to develop technologies for independent living. As populations age, more people need assistance, and there are substantial national initiatives abroad; for example, Japan and Korea have sophisticated programs in personal and service robots for seniors.

There are also many similar activities in the United States, some inspired by the Americans with Disabilities Act (ADA), and more recently by the New Freedom Initiative. Research by the U.S. Government in this area is coordinated by the Interagency Committee on Disability Research (ICDR). Active projects include technologies to support aging in place and research into the more general issue of how to enable independent living. These projects could profit from more detailed knowledge of similar efforts abroad. One problem is that commercial activity in the United States can best be described as a "cottage industry" where small companies build custom equipment for particular individuals, without fully exploiting opportunities to build larger markets by finding the requirements of other individuals around the world who might benefit from the same type of equipment. Thus, there are relatively few economies of scale realized in the production of devices for independent living. Knowledge from abroad can assist in matching requirements for larger numbers of individuals, and provide ideas for improving commercial success of U.S. companies. However, the main thrust of the study was to find good research and development themes being conducted abroad to better inform program officers and managers in Federal agencies of the opportunities that could be pursued here.

WTEC BACKGROUND

The study was organized on behalf of the sponsors by WTEC, which is a nonprofit research institute. With core funding and management from the NSF Directorate for Engineering, WTEC has conducted over 60 international technology assessments. Additional support from the NIH, DOE, NIST, NASA, and several research agencies of DOD has been made available via NSF and ONR. Panels of experts using the WTEC peer review methodology have assessed international R&D in many technologies including: nanotechnology, tissue engineering, rapid vaccine manufacturing, simulation-based engineering and science, and many others. Final reports are posted at http://www.wtec.org/.

This study builds on recent WTEC international studies of R&D on brain-computer interfaces (BCI) and robotics. The BCI study included some facets of this field, such as the use of internal and external sensors of brain waves to control prosthetic limbs and computers. Another recent WTEC report covered the broad field of robotics, including some coverage of the extensive national programs for personal and service robots to assist aging populations.
1. Introduction

SCOPE OF THE STUDY

The purpose of the study was to compare research on disability, rehabilitation, and related research on the development of technologies for independent living ongoing in the United States with that being conducted abroad.

The main objectives of the international assessment were to:

- Guide and justify U.S. research investments
- Look for good ideas abroad (technology transfer)
- Look for opportunities for cooperation and collaboration
- Compare U.S. R&D programs and status with those abroad

To achieve the above goals, data were gathered in international activities in areas including:

- Funding sources
- Customer bases – requirements of the communities served
- Goals and methodologies of research projects
- Findings from research and development
- Industry and market development

The results are expected to contribute to future research planning efforts by the NSF, and the U.S. Government generally, and its partners overseas, and to enhance technology transfer.

Some of the subjects investigated can be termed “technologies for independent living,” which is intended to encompass a wide variety of potential solutions for many issues that impede the independence of individuals in modern society. Issues impeding independence that might have been covered in the international study include the following:

- Limited or no vision or hearing
- Mobility impairments
- Motor function impairments
- Cognitive impairments
- Diseases of aging, which may involve some of the above

In this initial study the focus was on technologies for enhancing mobility and independent living. The subtopics were presented at the kickoff meeting as follows:

- Overview of the Need/Disabling Conditions: MS, CP, stroke, SCI, arthritis, amputation, orthopedic injury, TBI, balance impairments, aging, cognitive impairment
- Prostheses
- Exoskeletons
- Robot- and computer-based movement training
- Wheelchair technologies
- Joint injury prevention and orthopedic implants
- Functional electrical stimulation
- Control
- Assistive robotics/smart homes
Fall prevention technology

METHODOLOGY OF THE STUDY

A panel of U.S. experts (Table 1.1), nominated by sponsoring agencies and recruited by WTEC, conducted this study, using the WTEC methodology of peer reviews of research abroad, visiting the sites of the research institutions and researchers who are noted for the most advanced work in Europe.

Table 1.1. Panelists and Their Affiliations

<table>
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<tr>
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<th>Affiliation</th>
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<tr>
<td>Mary M. Rodgers, PhD</td>
<td>University of Maryland</td>
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The site visits (Table 1.2 and Figure 1.1) took place during October 16-23, 2010.

The results were presented in a full-day public workshop in Arlington, Virginia on November 16, 2010. The workshop was webcast and placed in an archive, which will be posted at wtec.org. The webcast can also be accessed at:

http://www.tvworldwide.com/events/nsf/disability/101116/

An academic quality final report will serve to disseminate the results widely, and a special issue of a research journal is also planned.

OVERVIEW OF THE REPORT

In Chapter 2, Michael Boninger and Rachel Cowan motivate the study by relating the difficulties of a person with a disability navigating the study tour in Europe—a sort of report within a report. Chapter 3 by Rachel Cowan, B.J. Fregly, Michael Boninger, Leighton Chan, Mary Rodgers, and David Reinkensmeyer discusses assistive technologies for mobility. In Chapter 4, David Reinkensmeyer and Michael Boninger cover technologies for movement therapy and combination therapies. Chapter 5 by B.J. Fregly, Michael Boninger, and David Reinkensmeyer, discusses personalized models to improve treatment of mobility impairments, and Chapter 6 by Shyamal Patel, Hyung Park, Paolo Bonato, Leighton Chan, and Mary Rodgers covers sensing technologies for mobility. In Chapter 7, Michael Boninger, Rachel Cowan, and B.J. Fregly address broader issues, such as structures promoting research in the field, training, and technology transfer. (Note: The Executive Summary and Chapters 2-7 in this volume also will be published in a forthcoming issue of the Journal of Neuroengineering and Rehabilitation.)

Appendix A contains short bios of the panelists, and Appendix B has the detailed trip reports from the 33 sites studied. A glossary of technical terms is given in Appendix C.
Table 1.2. Sites Visited in Europe

<table>
<thead>
<tr>
<th>Country</th>
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<tr>
<td>Belgium</td>
<td>European Commission</td>
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<td>France</td>
<td>Arts et Metiers Paris (Technical University of Paris)</td>
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<td>France</td>
<td>Assistance Publique, Hopitaux De Paris, Raymond Poincare</td>
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<tr>
<td>France</td>
<td>Institut Telecom SudParis</td>
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<td>France</td>
<td>Institute of Intelligent Systems and Robotics (ISIR), Université Pierre et Marie</td>
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<td>France</td>
<td>U. Paris Descartes, Garches Hospital</td>
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<tr>
<td>Germany</td>
<td>Fraunhofer IPK (Institute for Production Systems and Design Technology)</td>
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<td>Germany</td>
<td>University Hospital Charité</td>
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<td>Denmark</td>
<td>University of Aalborg</td>
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<td>Ireland</td>
<td>*TRIL Centre, University College Dublin</td>
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<td>Italy</td>
<td>University of Bologna</td>
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<td>Italy</td>
<td>Scuola Superiore Sant’Anna</td>
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<tr>
<td>Italy</td>
<td>* Neurological Rehabilitation Unit, Auxilium Vitae Rehabilitation Center</td>
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<tr>
<td>Italy</td>
<td>Instituto Ortopedico Rizzoli</td>
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<td>Italy</td>
<td>Cisanello Hospital, University of Pisa</td>
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<td>Italy</td>
<td>*Motor Learning and Rehabilitation Lab (MLRlab) at the Italian Institute of Technology, Dept. Robotics, Brain and Cognitive Sciences</td>
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<td>* NeuroLab, University of Genoa</td>
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<td>Smartex and University of Pisa</td>
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<td>*University of Padua</td>
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<td>Baat Medical BV</td>
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<td>Netherlands</td>
<td>*Robotics in the East Netherlands - “RoboNED”; and LEO Center for Service Robotics</td>
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<td>Netherlands</td>
<td>Xsens Technologies B.V.</td>
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<td>Netherlands</td>
<td>* Delft University of Technology</td>
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<td>Netherlands</td>
<td>Demcon Advanced Mechatronics</td>
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<tr>
<td>Netherlands</td>
<td>*Robotics in the East Netherlands - “RoboNED”</td>
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<tr>
<td>Spain</td>
<td>* Center for Automation and Robotics, Consejo Superior de Investigaciones Científicas, Spanish National Research Council</td>
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<tr>
<td>Switzerland</td>
<td>Zentrum für Ambulante Reha (ZAR); and Institut für Automatik</td>
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<td>Switzerland</td>
<td>Hocoma AG</td>
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<tr>
<td>United Kingdom</td>
<td>Sensory-Motor Systems Lab, Institute of Robotics and Intelligent Systems, ETH Zurich &amp; Spinal Cord Injury Center; and University Clinic Balgrist</td>
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<tr>
<td>United Kingdom</td>
<td>Imperial College</td>
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<tr>
<td>United Kingdom</td>
<td>* Cambridge Centre for Brain Repair, Cambridge University</td>
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* Not visited: Reps from the site gave presentation to panelists at another location
Figure 1.1. Locations of the sites visited in Europe.

ACKNOWLEDGMENTS

This study would not have been possible without the sustained support from several U.S. Government program officers: Ted Conway, Semahat Demir, Cheryl Albus, and Michael Reischman of NSF, Bob Jaeger of the Veterans Administration, and Grace Peng of the National Institute of Biomedical Imaging and Bioengineering (NBIB) of the National Institutes of Health. We also wish to extend our thanks to the foreign hosts for their hospitality and generosity in sharing with us their research results, their facilities, and their insights. And most of all, WTEC especially appreciates the hard and long days the delegation contributed to making this study a success.

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National Rehabilitation Information Center (NARIC). [http://www.naric.com](http://www.naric.com)

2. **WHY DO WE NEED IMPROVED MOBILITY TECHNOLOGY?**

Michael L. Boninger and Rachel E. Cowan

INTRODUCTION

As described in the Chapter 1, part of the methodology for producing the papers in this volume consisted of a group of investigators traveling to sites across Europe. The National Science Foundation (NSF) in collaboration with the World Technology Evaluation Center (WTEC) decided to make inclusion of scientists with disabilities a priority when selecting the investigators. The trip was rigorous with groups visiting multiple labs and multiple countries often in a single day. A typical day began with a 7 or 8 am checkout, a cab ride to the first location, followed by cabs to two or three more locations, all the while toting luggage. After the daily tours were complete, yet another cab ride to the airport or train station, travel to a new city, cab to the hotel, check in, hunt down dinner, and with any luck, in bed by 11 pm. This was the pattern for five days, a taxing schedule for any individual, disabled or not. The rigorous travel and obstacles encountered further emphasized the need for this study. The purpose of this paper is to highlight the obstacles our group faced during our travels as concrete example of how mobility limitations can impede participation.

Imagine

Imagine you want to take a vacation to Europe, you will visit great cities and eat wonderful food. Not hard to picture. The image is fun, unencumbered by worries of transportation, accessibility, and discrimination. Okay maybe there are some worries, but you have done this before. Now imagine you have a disability that requires you to use a wheelchair.

Air Travel

You will be the first person on each flight and last person off, adding an hour to the trips you plan to take by plane. Maybe it is not so bad hanging out in an airport, they have shopping now, right? Not for you, you will be segregated; forced to wait in special holding areas. When you do get to leave the holding area, it will not be to the local coffee shop in the terminal, you will be the first person on the plane; there when they are still cleaning up from the last flight. Why do you have to be early? Because you have to be loaded onto a very narrow chair and dragged down the aisle in order to get to your seat. You’d be blocking traffic if you loaded at the same time as everyone else. If you are lucky, there is a jet way or mechanical lift to get you to the aircraft door. If you are unlucky, you get the added fun of being dragged up the stairs. Have a seat, relax, they have just taken your wheelchair; placed it on the tarmac and will load it into the belly of the plane after the luggage goes in (you hope). If they lose that piece of valuable luggage you are stranded. I hope you went to the restroom before you got on, and didn’t drink much fluid all day, because you can’t walk to the restroom, they took your wheelchair (which wouldn’t fit down the aisle anyway). The extra transfers, four just to get on a plane, are starting to wear on your shoulders. One person must accompany you for this odyssey, you can’t travel alone. Have more than one friend, too bad, someone gets to hang out in the terminal alone.
**Trains**

The trains allow the avoidance of security, but at least with security there is someone to help. The train station is a different story. You book on a train that is listed as being accessible. It is not. You don’t know this until the train arrives and you are faced with two choices, miss the train and figure out a different way to get to the next town, or be physically lifted onto the train, about 5 steps. When you get on the train, putting your luggage up is impossible on your own. Again traveling alone is not recommended. So you bring a friend, who is just there to help you get on the train, not to travel. Unfortunately, while trying to get you situated, the train starts to move; he is stuck on the train and has to pay for a round trip fare to a location he did not want to visit. At least you have him for the other scary part, trying to get off.

**Oh the Places You Won’t Go**

The other small matter from the trip is all the places you can’t see – the wonderfully inaccessible churches, bars, restaurants, and research labs. Yes, research labs meant to study ways to improve the lives of individuals with disabilities. The planned walk across campus that is nearly impossible because of uneven pavement or steep hills, to a building where you have to go in the back door because it is the only entrance with a ramp. It has been a long day, the hotel room calls you. An accessible room? Perhaps. Then there is you night time routine, which takes longer than your non-disabled peers. Your day, already lengthened by the extra time at the airport, just got a bit longer. All the time, the one constant is the need to ask others for help.

**DISCUSSION**

Everything discussed above happened on our trip every day. Many other inconveniences, scary moments, and inaccessible locations are not included. Could we have avoided this with great planning? Some of it, but not most. This is not the fault of the person with a disability. His or her ability to travel as freely as the rest of the group is restricted because society has not taken the steps to ensure equal access. Without the kindness of strangers and friends, the trip would not have been possible and many of the obstacles could not have been surmounted.

**Imagine**

Now imagine that the goals of all the researchers we met have been achieved. Movement, the way you interact with the environment, is not restricted. Either technology has allowed for further healing, you have technology that replaces the function you have lost, or society has removed the barriers. Either way it’s a great trip.
3. Recent Trends in Assistive Technology for Mobility

Rachel E. Cowan, Benjamin J. Fregly, Michael L. Boninger, Leighton Chan, Mary M. Rodgers, and David J. Reinkensmeyer

Abstract
Loss of physical mobility makes maximal participation in desired activities more difficult and in the worst case fully prevents participation. This paper surveys recent work in assistive technology to improve mobility for persons with a disability, drawing on examples observed during a tour of academic and industrial research sites in Europe. The underlying theme of this recent work is a more seamless integration of the capabilities of the user and the assistive technology. This improved integration spans diverse technologies, including powered wheelchairs, prosthetic limbs, functional electrical stimulation, and wearable exoskeletons. Improve integration is being accomplished in three ways: 1) improving the assistive technology mechanics; 2) improving the user-technology physical interface; and 3) sharing of control between the user and the technology. We provide an overview of these improvements in user-technology integration and discuss whether such improvements have the potential to be transformative for people with mobility impairments.

INTRODUCTION
Mobility encompasses an individual’s ability to move his or her body within an environment or between environments and the ability to manipulate objects. Collectively, these activities enable the individual to pursue life activities of their choosing. An individual’s ability to perform any mobility task can be compromised by impaired body functions or structures. Impairments can onset gradually, as occurs with multiple sclerosis, or they can begin instantly, as occurs with traumatic spinal cord injury, cerebral vascular accidents, and limb amputations. The link between impairment and restricted mobility is evident for amputations and spinal cord injury. However, mobility is also affected by less obvious impairments. For example, the pain associated with knee osteoarthritis can significantly affect walking ability. Persons with reduced heat tolerance, such as those with multiple sclerosis, experience decreased endurance and increased fatigue as ambient temperature increases (1). Regardless of which body structure or function is impaired, technology can improve mobility. Wheelchairs, walking aids, and prosthetic limbs are examples of technologies that have provided widespread benefit.

To identify new opportunities for improving assistive technologies for persons with a mobility impairment, the National Science Foundation initiated a study using the World Technology Evaluation Center. A scientific panel of national experts was formed and charged with gathering information about research trends in technology that could transform mobility for people with mobility disabilities. Information gathering involved a 5-day visit by two teams to several of the leading European laboratories working in this area. Given the many pathways by which disability can impact mobility, and given the large number of possible technological solutions, the panel focused on seven mobility-based tasks: posture, balance and transfers, manipulation, walking, stair climbing, other locomotion tasks, and using transportation. Even within this limited scope, the technologies reviewed were not exhaustive, but they did provide insight into some important trends in assistive technology research.
Before describing these trends, we briefly discuss a framework for understanding different types of assistive technology. Although there are several frameworks that conceptualize disability (2), the international standard is the World Health Organization’s International Classification of Functioning, Disability and Health (ICF) framework (Figure 3.1). Like other frameworks, the ICF framework acknowledges that ‘disability’ results from the dynamic interaction of the user, technology, and the environment. When environmental demands exceed an individual’s mobility resources, participation may be restricted. Technology can facilitate participation by indirectly (via treatment or therapy) or directly (via physical assistance) enhancing and individual’s mobility such that their mobility capacity meets or exceeds the demand of the environment (Figure 3.1).

Indirect, or therapeutic, technologies enhance mobility by reducing impairments at the body structure/function level by helping the body in repairing or redressing the body structure impairment, or by supporting rehabilitation of the impaired body function. Baclofen pumps are an example of an indirect approach because they facilitate mobility by allowing a person to control his or her spasticity. Robotic therapy devices are another example of an indirect approach because they allow people to reduce impairment through repetitive movement training. Therapeutic technologies typically require clinical oversight to be set-up and operated, are one modality in an overall rehabilitation plan, and are typically not designed to be used to execute daily activities outside the clinic. A companion article reviews recent advances in therapeutic technologies (see Chapter 4 by David Reinkensmeyer and Michael Boninger).

On the other hand, direct, or assistive, technologies (AT) enhance mobility without altering the impaired body structure/function (Figure 3.1, lower figure, light arrow). Wheelchairs and walkers are prime examples: They enhance mobility, but they do not alter the impairment underlying the mobility loss. Direct technological approaches can augment or support impaired body structure or function, as in the case of a cane or walker, or they can replace the missing or impaired body structure or function, as in the case of a prosthetic limb. In contrast to therapeutic technologies, assistive technologies are operated by the user rather than a clinician and they are designed to be used to execute functional activities in the home and community. The focus of this article is on recent trends in direct technology or AT approaches to enhancing mobility.

**RECENT TRENDS IN ASSISTIVE TECHNOLOGY FOR MOBILITY: IMPROVED USER-TECHNOLOGY INTEGRATION**

As stated in the abstract, the unifying theme of the research we observed is a more seamless integration of the capabilities of the user and the assistive technologies. The observed approaches to enhance integration can be broadly classed into three non-mutually exclusive areas; 1) improvements to the assistive technology mechanics; 2) improvements to the user-technology physical interface; and 3) improved shared control between the user and the technology. Improvements in the technology mechanics include hardware and software advances. Improvements to the physical interface typically focused on better leveraging the capabilities of user to operate the technology and providing more intuitive device control.

The panel observed a trend toward better user-technology integration in four key technologies: powered wheelchairs, prosthetics, functional electrical stimulation, and robotic exoskeletons.
Figure 3.1. Upper figure: ICF Framework: Body functions are physiological functions of body systems (including psychological functions). Body structures are anatomical parts of the body such as organs, limbs, and their components. Impairments are significant deviations from normal or loss of body function or structures. An activity is the execution of a task or action by an individual. Participation is involvement in a life situation. Activity limitations are difficulties an individual has in executing activities. Participation restrictions are problems an individual experiences in involvement in life situations. Environmental factors make up the physical, social, and attitudinal environment in which people live and conduct their lives. Lower figure: Simplified ICF framework demonstrating indirect (therapeutic) pathways (black arrows) and direct (assistive) pathways (light arrow) by which technology can improve mobility. (Modified from World Health Organization. 2002. Towards a common language for functioning, disability, and health: (ICF) The International Classification for Functioning, Disability, and Health. Geneva, WHO/EIP/GPE/CAS/01.3)
Power Wheelchair Based Mobility

Power wheelchairs are traditionally operated by a joystick and one or more switches which change the function that is being controlled by the joystick. These functions include wheelchair movement, seat tilt, backrest recline, footrest elevation, and seat elevation. Not all persons who could experience increased mobility by using a powered wheelchair possess the necessary cognitive and neuromuscular capacity needed to navigate a dynamic environment with a joystick. For these users, a “shared” control approach coupled with an alternative interface is indicated.

Shared control has been considered before for powered wheelchair mobility (3). In a traditional shared control system, the assistive technology ‘assists’ the user in path navigation. Shared control systems typically have several modes that vary the assistance provided (i.e., user autonomy) and movement algorithms. Milan et al. suggest shared control approaches can be classified in two ways: 1) mode changes triggered by the user via a button or trigger or 2) mode changes hard-coded to occur when specific conditions are detected (3). Both approaches have potential problems. Requiring the user to trigger mode changes imparts a substantial mental load, can be tiring, increases complexity, and decreases user-friendliness. Hard coding mode changes may not allow customization to the individual and their specific abilities.

Dr. Etienne Burdet’s Human Robotics research group at Imperial College, in collaboration with the National University of Singapore, has developed a low cost power wheelchair shared control system based on path guidance that provides a third way to address shared control. The target population for the collaborative wheelchair assistant (CWA) is “people who find it difficult or impossible to use a standard power wheelchair but have sufficient sensory abilities to detect when stopping is necessary,” such as persons with cerebral palsy, traumatic brain injury, or locked-in individuals (4). The CWA guides the user along previously programmed paths between specific destinations. Paths are programmed by a “helper” who walks the chair through the desired pathway while the chair records the path. The user controls speed, starts, and stops, as well as any deviations required to avoid obstacles that have entered the pre-programmed path. However, the burden of navigation falls on the wheelchair, which adheres to the programmed path until the user initiates a deviation. During the deviation, the chair acts like a mass-spring-damper system being pushed away from the pre-programmed path by the user. The wheelchair thus returns to the path once the user relinquishes control. The benefit of this approach is that the cognitive load of navigation and path-planning is not born by the user. The user only needs to focus on obstacle avoidance and speed control. Before users navigate new environments, new paths must be created. It is envisioned that new ‘path libraries’ could be automatically generated from building plans. This shared approach does not fit into the categories defined by (3) as there are no mode changes triggered by the user or via automatic sensing; it is rather an approach that more seamlessly integrates the user and machine.

Other approaches toward improving powered mobility are seeking to exploit better the user’s inherent capabilities for controlling the chair through better input devices. One approach is to design an interface that can be operated by an alternate body part. An example of this approach is the development of tongue based control interfaces, such as that developed by the Sensory Motor Interaction (SMI) center of the department of health science and technology at Aalborg University. It is an inductive system relying on a ferromagnetic tongue piercing and an intraoral device embedded with 18 sensors. Ten sensors are dedicated to a keyboard and eight to joystick control. It has been designed to interface with
most power wheelchairs that can be controlled by traditional joysticks (5). In a related approach, a group at Georgia Institute of Technology has developed a tongue interface that is not dependent on a physical interface between the tongue and sensors. Instead, sensors external to the oral cavity wirelessly track tongue position via a tongue-mounted magnetic sensor. This interface has been tested in 13 persons with high cervical spinal cord injuries (6). Other related work has explored how information from sensors placed anywhere on the body can be automatically mapped to wheelchair control signals, again allowing a person to use the parts of the body that they are capable of moving well to control the wheelchair (7).

Another way to better make use of a user’s inherent capabilities is to use a brain computer interface (BCI) to detect, decode, and communicate intended movements from brain electrical activity. A previous NSF study examined recent progress in BCI technology (8) in detail, so we only summarize a few important points here. Current noninvasive BCI technology is characterized by a low information transfer rate (low bandwidth), which is a challenge for real-time wheelchair navigation. Low bandwidths can result in substantial delays between when a user initiates a maneuver and when the wheelchair responds, introducing a potential safety hazard (9). In addition, BCI driven wheelchair navigation typically requires extensive training, imposes a substantial cognitive load, and can be very tiring. If BCIs are to mature into a realistic option to control power wheelchairs, these issues must be resolved in a cost-effective manner.

Dr. Burdet’s Imperial College group has developed a possible solution to these challenges using the shared control system described previously. The computer “drives” the chair between destinations using pre-programmed paths while the user monitors the pathways for unexpected obstacles. A slow BCI is used for selecting among the destinations and a “fast” one is used for emergency stopping. This approach removes the cognitive load of navigation, preventing the inevitable fatigue, and does not require extensive training, but it limits use of the system to known environments and programmed destinations (9).

Prosthetic Limb Control

Prosthetic development challenges include replacing both the efferent nervous system (i.e., movement) and the afferent nervous system (i.e., sensory feedback). Adequate prosthetic limb control will be achieved when both efferent and afferent systems are adequately replaced. Three novel approaches were observed in Europe for better interfacing the user and their prosthetic: 1) computer-vision enhanced control, which is an example of improving both the device and the shared control system, 2) peripheral nervous system interfaces, an example of improved interfaces, and 3) kinematic/kinetic based control, a strategy which improves the mechanics of the limb through software and provides a better interface. The first two approaches target upper limb prosthetic control and the third targets lower limb.

Computer-vision Enhanced Control

When an individual reaches to grab an object, the hand assumes a given orientation and opens to accommodate the object. Typically, prosthetic hand control has a high mental burden, as the user must plan the grasp and generate step by step commands to position and shape the hand. Although a high degree of control can be achieved by this method, users prefer intuitive controls requiring less conscious involvement. In pursuit of a less demanding control strategy, researchers at the University of Aalborg have developed a camera-based shared control system that uses image recognition to autonomously select the proper hand orientation, grasp shape, and grasp size based on images of the object being manipulated (10). The user is responsible for aiming, triggering, and orienting the hand, while the camera-based
control selects and implements grasp type and size. By increasing the autonomy of the prostheses, user burden is lessened. The system was successfully tested in 13 non-disabled subjects who used it to control an artificial hand (11). Once refined, this system is targeted for application with the Pisa Hand, a product of the European Union funded Smart Hand project.

Peripheral Nervous System Interface (PNS) Control

Upper extremity prosthetic control is challenging due to both the number of possible motions to be controlled and the limited number of sites for traditional control interfaces. An appealing option is controlling a prosthetic arm or hand via the same nerve that once carried afferent and efferent information between the arm and brain. Potentially, this approach would be more intuitive to the user and provide a pathway to deliver sensory feedback.

At Scuola Superiore Sant'Anna in Italy, Dr. Silvestro Micera has explored this option by implanting thin-film longitudinal intrafascicular electrodes in the median and ulnar nerve of a trans-radial amputee. The subject was implanted with a prosthetic hand mounted directly to the distal end of the residual radius. During a four week trial, the subject was trained to imagine three distinct hand/finger movements, with the resultant muscle activity being recorded. In addition, the afferent fibers were stimulated to determine if it was possible to deliver sensory feedback to the brain. Dr. Micera concluded that it was possible to evoke muscle activity for at least three different grips using the PNS interface. He suggests that more grips should be possible but that additional interface electrodes may be required. Finally, although stimulation of the afferent fibers induced phantom tactile sensation during the first few weeks, the response dissipated by the end of the trial. Dr. Micera suggests refinements to the interfacing electrodes may help solve this problem (12). Following the four week test period, human subject regulations necessitated removal of the prosthetic hand. However, the subject was disappointed that he was not allowed to keep the hand.

A less invasive, approach for improving the control of an artificial hand is being pursued by Dr. Peter Veltink, Dr. Hans Rietman, and co-workers at the University of Twente in Enschede, in The Netherlands. Rather than using muscle activity signals from implanted electrodes to control a prosthetic hand, the Myopro Project is pursuing the use of an array of surface electrodes. Traditionally, prostheses controlled by surface electrodes (i.e., myoelectric prostheses) have had limited control ability due to the use of a small number of electrodes. To address this limitation, researchers in Enschede are using a 4 x 10 grid of electrodes distributed across the residual forearm of the amputee, thereby increasing the number of control signals. These control signals are being mapped on a patient-specific basis to 10 hand positions located at the extremes of 5 hand degrees of freedom (e.g., finger flexion-extension, wrist pronation-supination). The mapping is performed based on the same grid of signals collected from the forearms of healthy subjects performing the 10 hand positions. In testing performed thus far, the approach has over 99% accuracy in classifying hand position for healthy subjects and one amputee subject.

Kinematic/kinetic Based Control

At ETH Zurich, in the Sensory Motor Systems laboratory, Dr. Heinke Vallery has developed a novel approach to controlling a transfemoral prosthetic leg equipped with a “powered” knee. During walking, joint motions are strongly coupled. Dr. Vallery’s approach, termed complementary limb motion estimation (CLME), exploits the physiological inter-joint couplings of the intact leg to instantaneously determine the motion required of the prosthetic leg. The estimated motion is then used as a reference to drive the motion of the prosthetic limb. An advantage of CLME is that it allows a wide range of movements and the prosthetic
limb is intrinsically synchronized with the non-impaired limb. It has been tested on an amputee during treadmill walking and stair ascent/descent (13).

At the University of Twente in Enschede, Dr. Hans Rietman and colleagues have developed a microprocessor-controlled prosthetic knee for above-knee amputees (14). A common problem with passive prosthetic knee designs is that they are not stiff enough (i.e., as needed for stability) during stance phase but are too stiff during swing phase. To address this problem, Dr. Rietman’s group has designed a microprocessor-controlled knee that uses real-time position and force measurements. The microprocessor analyzes these measurements and then determines the correct actuation moment depending on the phase, speed, and loading within the gait cycle. With this approach, the need to have a mechanism for locking and unlocking the knee during stance phase is eliminated. Commercial development of the design is currently being pursued in cooperation with Össur.

At the other extreme of complexity is a simple robotic hand developed by researchers at Delft University of Technology in the Netherlands. The underactuated robotic hand possesses three fingers controlled by only one motor. The hand has no sensors, with grasping being achieved using a mechanism that distributes contact forces evenly over the three fingers. The hand is capable of grasping objects of various sizes and shapes both firmly (so that they do not drop) and gently (so that they do not break). The hand was created for industrial applications where repetitive human manipulation is currently required (e.g., packaging of bell peppers). However, it could be used equally well as an assistive device for individuals with limited hand mobility. For example, it could be attached to a wheelchair to provide a versatile option for holding objects of various sizes and shapes, or it could be used to perform a small range of functional tasks such as grasping a door handle to open a door.

**Functional Electrical Stimulation**

Functional electrical stimulation (FES) remains a technology with great potential for restoring movement. Its use is limited in part by the time and effort required to don the systems. A possible solution is to implant parts of the system. Neurodan, building on cuff electrode technology developed at the University of Aalborg, has developed one such solution, called Actigait. An example of a fully implantable solution is the Neurostep, which also times muscle stimulation based on sensing limb state from afferent activity in peripheral nerves. Neurostep relies on both an enhanced interface and improved mechanics as specified by the control software.

Another challenge with FES systems is controlling a large number of degrees of freedom in a way that can achieve functional ambulation and functional use of the upper extremity. By focusing on a non-conventional but large population of potential users, The TREMOR European project is attempting to develop a more widely used multi-channel upper extremity FES system. Tremor is the most common movement disorder, becomes more common with advancing age, and typically affects the upper extremity. Upper extremity tremors can make eating, drinking, or other reaching, grasping, and fine motor tasks extremely difficult. Drugs, surgery, and deep brain stimulation are effective treatment for 75% of cases. To provide treatment for the remaining 25%, the European union has funded the TREMOR project to develop a functional electrical stimulation (FES) orthotic ([http://www.iai.csic.es/tremor/](http://www.iai.csic.es/tremor/)). This orthotic will automatically detect and suppress the tremor by canceling it with out-of-phase muscle stimulation or by co-contraction to stabilize the limb. In this scenario, excessive, rhythmic muscle activity (tremor) is the body impairment and reaching/grasping/eating is the limited activity. The innovation of this technology AT is to improve the user’s inherent reaching/grasping/fine motor activity by removing a superimposed impairment.
Robotic Exoskeletons

Robotic exoskeleton research and development was originated by the military in the 1960’s. However, mobility for people with a disability has recently become a focus of robotic exoskeleton research. As reviewed in a companion paper (see Chapter 4 by David Reinkensmeyer and Michael Boninger). Initial work has focused on therapeutic applications of robotic exoskeletons, with a prime example being the Lokomat gait training robot. Attention is now increasing toward assistive technology applications of robotic exoskeletons in which the exoskeleton is designed to promote functional activities in the home and community.

A recent review identified four research roadblocks that must be overcome if robotic exoskeletons are to reach their maximal rehabilitative and assistive technology potential: 1) robust human-robot multimodal cognitive interaction; 2) safe and dependable physical interaction; 3) true wearability and portability; and 4) user-centered aspects such as acceptance and usability (15). As apparent from the above discussion of other assistive technologies, the last focus is critical to the success of every assistive technology. If a person cannot easily use or does not accept the assistive technology, he or she will abandon it. AT device abandonment is a well documented phenomenon (16-19) and underlies the emerging awareness that end-users should be involved as soon as possible in the development of assistive technology devices.

A European example of robotic exoskeletons is that of Dr. Jose Pons in Madrid. Dr. Pons has developed an innovative knee-ankle-foot orthosis that can assist people with leg weakness in achieving normal joint kinematics during walking (20). The normal contribution of the joints to each gait cycle phase is approximated using spring-like, force-length curves. Actuators for each joint are constructed of compression and tension springs. The actuators use solenoids, or an ankle-driven Bowden cable, to reproduce the desired spring characteristics during each phase of the gait cycle. The system has been shown to improve the gait pattern of individuals with poliomyelitis (20, 21), and is being investigated for commercialization by Össur.

In the future, the distinction between therapeutic and assistive technologies will dissolve. As robotic exoskeletons advance, patients will be able to wear them in the home and community, receiving both activity-based therapeutic interventions and supportive assistance as needed. This combined assistive-therapeutic model for assistive technology has already been demonstrated for foot drop stimulators. Long-term use of a foot drop stimulator improves the ability of a person to walk, even when the stimulation is turned off (22).

This review does not cover orthopedic implant technology such as total joint replacements. Though such technology has traditionally not been considered to be an assistive technology, it satisfies the traditional definition of assistive technology. Furthermore, it has been one of the most transformative assistive technologies in the past century, allowing millions of people to regain lost function and quality of life. As an example of innovative work in this area observed by the panel, at the Rizzoli Institute in Bologna, Italy, Dr. Alberto Leardini and colleagues have developed a novel total ankle replacement design that is being marketed by an orthopedic implant company. The design maintains natural tension in the ankle ligaments, thereby producing more natural motion and loading profiles than previous total ankle designs (23).

DISCUSSION: MOVING TOWARD TRANSFORMATION?

A key goal of the NSF Study was to identify research themes that could “transform mobility for people with a disability.” It makes sense to ask what transformative technologies will look
like, and, more specifically, will improvements in user-technology integration be transformative, or are entirely new technologies required?

To illustrate “transformative,” let us define transformative technology as that which elevates mobility performance by people with a disability to that of their non-disabled peers. An excellent example of this elevation is Oscar Pistorius, a South African paralympic bilateral trans-tibial amputee. With his advanced running prosthesis, Mr. Pistorius competes against non-disabled athletes, winning silver in the 2007 South African 400m non-disabled track championships and narrowly missing qualification for the 2008 Beijing Olympics. Without his prosthesis, he would not be able to walk, much less compete at an elite level. The transformation provided by the prosthesis and his training is so complete, so dramatic, that for a period, Mr. Pistorius was banned from non-disabled competition because it was thought his prosthesis conferred an illegal performance enhancement. While that ruling has been overturned, the scientific debate continues as to if he has an advantage over his non-disabled competitors (24-27). Regardless, the gap between what Mr. Pistorius can achieve without his prosthesis and what he achieves with his running prosthesis is transformative.

Mr. Pistorius’ transformation was not made possible by a fundamentally new type of assistive technology; rather an existing technology, a below-knee prosthesis, was designed to have mechanical properties that better integrated with his inherent running ability. Another interesting example along these lines is the iPhone, which, again, was not a new technology, but rather became transformative by providing a new interaction paradigm that simplified use of the old technology – both the iPhone and Mr. Pistorius’ are user-technology integration done well. Thus, while it is unclear whether the improvements in user-technology integration reviewed here will become transformative, these simple examples illustrate that the enhanced integration approach itself holds tremendous transformative potential.

Ultimately, while both the form and amount of change required to achieve a transformative improvement will vary according to the degree and type of impairment, the ideal path to quantify “transformative” is to ask the person with the disability. Who better to identify the “what” and “how much” of transformative changes? And yet, research groups and funding agencies have struggled to take this approach toward quantifying transformation. If transformative improvements are the end goal, it is important to develop a user-centered quantification system and to employ it throughout the development process. Ideally, individuals with a disability will invent and refine this quantification system, and furthermore, the required assistive technology themselves – who better? At the very least, continuous end-user involvement will help ensure that developed technologies match user needs and wants, as well as capabilities and impairments.

In conclusion, the panel saw no fundamentally new assistive technologies on its trip; rather the primary theme in assistive technology development observed was refinement of existing assistive technology in clever ways so that its capabilities integrated better with the user’s capabilities. These refinements are being done on an application-by-application basis through development of improved technology mechanics (e.g., knee-ankle-foot orthosis, kinetic control of a prosthetic limb); improved user interfaces (e.g., tongue or whole-body controllers, electrodes implanted in central and peripheral nervous system) and by automating target control functions in a way that blends the machine’s assistance with the natural abilities of the user. Better integrated control systems decrease user burden, enabling more refined control of highly sophisticated prosthetics or enabling persons with the most severe physical disabilities autonomous mobility in power wheelchairs.
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4. TECHNOLOGIES AND COMBINATION THERAPIES FOR ENHANCING MOVEMENT TRAINING FOR PEOPLE WITH A DISABILITY

David J. Reinkensmeyer and Michael L. Boninger

Abstract

There has been a dramatic increase over the last decade in research on technologies for enhancing movement training and exercise for people with a disability. This paper reviews some of the recent developments in this area, using examples from a National Science Foundation initiated study of mobility research projects in Europe to illustrate important themes and key directions for future research. This paper also reviews several recent studies aimed at combining movement training with plasticity or regeneration therapies, again drawing in part from European research examples. Such combination therapies will likely involve complex interactions with motor training that must be understood in order to achieve the goal of eliminating severe motor impairment.

INTRODUCTION

A key working hypothesis of rehabilitation science is that use-dependent plasticity perseveres through motor system injuries and diseases. This hypothesis drives intensive, ongoing efforts to optimize rehabilitation experiences for people with a movement disability, so as to best promote use-dependent plasticity. In the past twenty years, there has been an increasing recognition that technologies, including robotics, orthotics, wearable sensors, computer vision, computer gaming, electrical stimulation, virtual reality, machine learning, and computational modeling, can play an important role in these efforts (1-5). In this section, we first review the rationale for developing this new technology for rehabilitation therapy, then, using examples from robot-assisted therapy, we briefly characterize the state of the field in meeting its promise. In the following sections we then review approaches to improve these technologies, drawing on examples from European research, followed by a brief discussion of attempts to combine these technologies with biologic therapeutics.

There are three primary motivations for developing new technology for rehabilitation therapy. First, improved technology has the potential to allow more therapy with less supervision, improving rehabilitation cost-benefit profiles. This objective can be expressed as developing technology that optimally promotes use-dependent plasticity while lowering the cost of therapy. Second, technology has the potential to more accurately quantify therapy, including patient characteristics that predict therapy success, the dose and content of therapy, and clinical outcomes. This quantification property of technology is important for improving the mechanistic understanding of rehabilitation science, clinician decision-making, and patient feedback and motivation. Third, technology has the potential to allow entirely new types of therapy. One example is the concept of providing continuous therapy with wearable devices. Rehabilitation therapists cannot be omnipresent, but smart, wearable technology almost can, providing therapy throughout the day as people participate in activities of daily living. The therapeutic effect produced by functional electrical stimulation (FES) foot drop stimulators, in which people who use the stimulators over an extended period of time exhibit improved walking ability even when they turn the stimulator off, is one example (6). Another example of a promising new therapy that technology makes possible is manipulating limbs.
with robots in a way that precisely augments kinematic errors and thus enhances error-based learning (7).

Aiming to achieve these three goals, there has been a rapid increase in the development of therapeutic technology in the past 10 years, and a rapid growth in commercial products for rehabilitation training (1-5). However, results with this technology are mixed so far, and when and in what form this technology will deliver the desired improved outcomes for rehabilitation is unclear. We illustrate the state of the field with three recent studies of robot-assisted movement training after chronic stroke.

The first study is the recent multi-center randomized controlled trial of robot-assisted therapy sponsored by the Department of Veterans Affairs (8). In this study, 127 people with chronic stroke were randomized to receive either 1) robot-assisted upper extremity training with three modules of the MIT-Manus robot; 2) upper extremity exercise with a rehabilitation therapist that was matched in number of movements to the MIT-Manus therapy and therefore was characterized as “intense”, or 3) usual care. Robot-assisted therapy was significantly more effective than usual care, but the benefits were small—about two additional points on the upper extremity Fugl-Meyer scale, which ranges from 0 for complete paralysis to 66 for normal movement ability (9). Robot-assisted therapy was about as effective as the intense, therapist-delivered therapy. The cost of delivery of the robotic and therapist-delivered therapies was similar, in large part because of the relatively high costs of the robots used in the study. However, the amount of therapy delivered was much greater than what would normally occur in an inpatient or outpatient rehabilitation setting. Thus, if the costs of robotics decrease it may be possible to deliver this care, while delivering this type of care in the absence of robotics will likely never occur. Detailed analysis of the sensor-based data from this study is forthcoming, but, previous analysis of data obtained from similar MIT-Manus studies has been used to suggest that recovery is fundamentally characterized by a progressive blending of sub-movements (10).

In another study, 48 people with chronic stroke who were ambulatory at study start were randomized to train walking using a treadmill and the Lokomat gait robot, or a treadmill with manual assistance from a physical therapist (11). For the Lokomat training, the participants did not receive biofeedback about their contribution to the walking motion. Training with either approach produced modest but measurable benefits in walking speed; training with the Lokomat and without biofeedback was about half as effective as the therapist-delivered training in terms of improvement of gait speed. It has been hypothesized that the relatively rigid robot assistance without biofeedback, as provided in this study, may have been less effective because it caused patient slacking (11); analysis of oxygen consumption during such training (12), as well as computational modeling of the evolution of interaction forces during robot-assisted training (13), quantitatively support this idea. Another possibility is that the rigid assistance reduced variability needed for learning (14). Analysis of training data from the study itself showed that Lokomat training as implemented was indeed less variable (15); analysis of fixed robotic gait training in rodents with SCI suggests that rigid assistance that does not allow kinematic variability tends to disrupt muscle activity (16).

In a third study, 28 people with moderate to severe arm impairment due to a chronic stroke were randomized to participate in training with a passive arm exoskeleton called T-WREX or in standard table-top exercises with no technology (17). T-WREX simulated functional activities using computer games and an anti-gravity arm support orthosis which also incorporated a grip sensor that allowed patients with even trace amounts of grasp to participate in simple grasp-and release actions to control the games. Both groups only
required about 3 minutes of therapist contact following a week of training, as measured by stopwatch. Both groups improved their arm movement significantly by about 2-3 FM points; at 6 month follow-up the T-WREX group had significantly better scores, although the difference was small (2 FM points). When given a chance to try the other therapy then asked to subjectively compare the two approaches, the participants expressed a strong preference for the technology-based approach, finding it more motivating in part because the arm weight support improved their perception of self-efficacy (18).

One can extrapolate broader themes that characterize the general state of technology for rehabilitation therapy from these three illustrative studies. First, considering the goal of improving cost-benefit profiles, one can observe that technology-assisted exercise produced significant benefits in all three of the studies reviewed above, and that it is sometimes possible to use technology with only small amounts of therapist supervisory time, as directly measured in the T-WREX study. These observations support the premise that, indeed, some aspects of rehabilitation therapy do not require the immediate presence of a rehabilitation therapist to be effectively implemented with technology. However, the cost of the technology used for this substitution may still limit cost-benefit profiles, as was found, for example, in the cost analysis of the MIT-Manus study, indicating a need for lower cost technologies.

Second, considering the goal of quantification, while it is true that there is potentially a computer record of every force or movement the participants made during training in these studies, we are just beginning to understand how to use this data to predict responders, guide therapy, or define mechanisms of recovery. For example, as mentioned above, data from MIT-Manus has been used to identify a role for sub-movement blending in movement therapy, and data from the Lokomat and rodent robotic devices was used to analyze the role of kinematic variability in training. Thus, the field is just beginning to develop ways to use data from sensors incorporated into rehabilitation technology to provide insight into use-dependent plasticity.

Third, considering the goal of innovating to produce new forms of therapy that are more effective, it is apparent that some innovations in technology-based therapy are as effective as therapists for particular forms of training, few or none are more effective, and many are less effective. The reasons are complex and poorly understood at present. Understanding the reasons particular implementations decrement learning is important. At present, one might say that the only innovation that new technologies routinely make available, besides semi-automation of training, is that of a more motivating context for rehabilitation training, by virtue of helping patients achieve movements or simulated activities that they normally could not, and by providing a computer gaming context with quantitative feedback to motivate practice.

PROMISING DIRECTIONS FOR TECHNOLOGY-ENHANCED THERAPY

Given this current status, how can physical therapeutic technology be improved? Several key themes emerged during our panel's visit to Europe.

Designing Technology for Early Application After Injury

The healthcare environment in many countries in Europe has made it easier to test therapeutic technologies earlier in rehabilitation, as patients are permitted to stay in sub-acute rehabilitation facilities much longer than in the United States. Landmark studies by the group of Dr. Stefan Hesse at Charite Hospital, Berlin, found large improvements in motor function of both the upper (19) and lower (20) extremities when robot-assisted training was
provided early after stroke. This work supports the concept that the motor system exhibits a temporal window early after injury in which plasticity is relatively enhanced. The existence of this window is an important consideration for technological design because the subacute rehabilitation environment imposes design constraints on the technology to be used in the environment, since patients tend to be more impaired and stay in bed more in subacute rehabilitation. The robotic therapy group of the University of Padua has therefore, for example, developed a device that can specifically be used at bedside to provide early mobilization of the flaccid arm (21). This group again found larger changes in arm function due to robot-assisted therapy than have typically been reported with therapy delivered in the chronic phase post-stroke (22). In summary, a key direction for rehabilitation technology is to develop devices specifically for early training after neurologic injury.

**Designing Lower Cost Devices**

Another trend in the field is to develop lower-cost devices. Professor Etienne Burdet of Imperial College has observed that there is a spectrum of complexity in technology for rehabilitation therapy, starting with simple rehabilitation objects already commonly used in rehabilitation therapy, to passive devices with sensors, to simple robotic devices for decentralized use, to complex robotic systems (Figure 4.1). Moving along this complexity spectrum increases cost and the need for assistance from humans to use the technology, while decreasing safety and the number of potential users. Dr. Burdet has therefore focused his work in the middle of the spectrum, on passive devices and simple robots that could potentially be accessed by more people than the existing, more complex commercial products (e.g., 23).

![Image of robot devices](image1)

**Figure 4.1.** The spectrum of complexity in rehabilitation therapy technology, ranging from simple rehabilitation devices (left) to complex robotic systems (right) (courtesy of Dr. Etienne Burdet, Imperial College, London).

The work of Dr. Hesse is also of note again in this regard, as the robotic devices that produced the excellent clinical results mentioned above, which are now sold by a start-up company
RehaStim, are relatively simple, low degree-of-freedom robotic devices for both the upper and lower extremities. Another world leader in commercializing therapeutic technology, Hocoma A.G., recently released a simplified arm therapy device, ArmeoBoom, based on the work at U. Twente and Roessingh Rehabilitation Center (24). Major companies, such as Phillips (25) and Intel (26) have developed relatively low cost sensor-based systems for home-based therapy. An interesting possibility is to use cell phone platforms to drive therapy, an approach pursued by the Tril group in Ireland (http://www.trilcentre.org/media/news/tril-at-eric-conference.html), the Department of Electronics, Computer Sciences and Systems, at the Università Di Bologna (http://www3.deis.unibo.it/en), and others. Software on cell phones combined with movement sensors could monitor exercise performance and compliance, test a user’s physical status, and provide encouragement, motivation, and feedback. Gaming consoles, such as the Nintendo Wii, the Microsoft Kinect, and the Sony Playstation Move, although not technically for rehabilitation, could be adapted for training and assessment, and custom computer games can be developed as well (5). Despite this work, there has not yet been a breakthrough: there are still no devices or software specific to rehabilitation that people with a mobility impairment routinely use at home to engage in rehabilitation therapy.

**Developing Technology with More Degrees of Freedom**

At the same time that many groups are working to develop simpler technology, other groups worldwide are increasing the mechanical sophistication of the technology to be used in rehabilitation. The rationale for this work is that training more naturalistic movements may improve functional outcomes. For the upper extremity, groups at ETH in Zurich (27), Scuola Superiore Sant’Anna, Pisa, Italy (28), and CEA/ISIR in Paris (29) are examples of work to develop exoskeletons that allow naturalistic movement of the arm by accommodating at least four degrees of freedom of shoulder and elbow movement (Figure 4.2). The ETH exoskeleton, ArMiN, is now being commercialized by Hocoma. The exoskeleton at ISIR, commercialized by Haption, is particularly lightweight and comfortable, owing in part to patented actuators first manufactured at the CEA and carefully designed passive degrees of freedom that accommodate joint rotation center mismatches (30).

For the lower extremity, work is underway at ETH Zurich, University of Pisa, and Hocoma to add pelvic and ankle degrees of freedom to the Lokomat, and concepts from the simple gait-trainer developed by Hesse have been expanded in collaboration with Fraunhofer IPK to produce the Haptic Walker Gait Trainer 2 (31, 32). This device consists of two six degrees-of-freedom foot plates that can support the weight of the patient and be programmed to
simulate different step characteristics, including stair walking. Another device developed at Fraunhofer IPK that allows naturalistic movement for training balance and posture over a treadmill is the StringMan (33). It consists of eight force-controlled pulleys attached to a harness worn by the patient. It can be programmed to provide a virtual envelope in six degrees of freedom for the trunk and pelvis to support the patient during training. Two other examples of sophisticated gait trainers being developed in Europe are the LOPES gait trainer, developed at the University of Twente, which uses cable-driven, series elastic actuators to provide compliant assistance to naturalistic gait movement (34), and the Walktrainer robot at EPFL, which moves along with the patient as it assists in leg movements (35). Clinical testing with these devices is ongoing; this testing will help determine whether training more naturalistic movements will indeed improve functional outcomes enough to justify the added cost and complexity of these devices.

**Wearing the Therapeutic Technology**

Another major trend in technology for rehabilitation therapy is to make the technology wearable. Wearable sensor systems for therapy are reviewed in a companion article in this special issue. The rationale for developing actuated, wearable orthotic systems is, again, to make training more naturalistic, and ultimately to free training from the confines of the rehabilitation clinic. This freeing of training will break down the current distinction between assistive and therapeutic technology; people will use therapeutic technology to assist them in activities of daily living, undergoing therapy at the same time as achieving desired tasks. Such technology will be designed to continuously adapt to the user, to appropriately challenge them and progress training. This dual-purposing of therapeutic technology will increase the dosage of therapy beyond levels possible in the clinic only, and increase the likelihood that what is learned during training will be useful in the real world, since training will be in the real world.

Examples of wearable systems developed in Europe include the ActiGait system, sold by Neurodan/Otto Bock. ActiGait is a multi-channel, implantable functional electrical stimulation system for foot drop based on research at the University of Aalborg (36). Another example is the work of Dr. Jose Pons in Madrid. Dr. Pons has developed an innovative knee-ankle-foot orthosis that can assist people with leg weakness in achieving normal joint kinematics during walking (Cullell et al. 2009). The contribution of the joints to different phases of the gait cycle is approximated using spring-like, force-length curves, and actuators for each joint are constructed of compression and tension springs. The actuators use solenoids or an ankle-driven Bowden cable to switch between springs to reproduce the desired spring characteristics during each phase of the gait cycle. The system has been tested with users who have poliomyelitis and shown to improve the gait pattern (Moreno et al. 2008, Cullell et al. 2009), and is being investigated for commercialization by Össur.

**Improving Control and Feedback**

There are intensive efforts worldwide to improve the control algorithms and patient feedback algorithms for therapeutic technology. One concept is to make robotic therapy devices patient cooperative, as proposed by Professor Robert Riener at ETH Zurich (37), a strategy which can improve active participation of the patient (38). Path control provides a virtual ‘tunnel’ in which the patient can modify his or her stepping pattern (39). Guiding forces are applied when the person begins to deviate beyond the ‘tunnel’ boundaries. This group is also developing control algorithms for canceling the inherent inertia of exoskeletons, so that the patient feels less of the robot (40). The group at University of Genoa has designed innovative algorithms for adaptively reducing robot assistance during training (41).
providing progressive challenge. Recognizing that robotic training can be passive and boring, others are developing virtual reality systems to engage patients, using visual and auditory inputs (42). Physiological monitoring of exercise markers such as cardiovascular response is also being explored as a means to adapt training (43).

Another approach is to combine brain computer interface technology or functional electrical stimulation technology with robotic therapy. An example of the use of BCI technology for therapy comes from Dr. Pons, who is also the Project Coordinator for The BETTER project (Brain-Neural Computer Interaction for Evaluation and Testing of Physical Therapies in Stroke Rehabilitation of Gait Disorders). This project is focused on improving physical rehabilitation therapies by combining brain computer interfaces (BCI) with wearable exoskeletons and robotic gait trainers, such as the Lokomat. The BCI being used is an EEG-based BCI. The goal is to encourage brain plasticity by programming the robot to exert physical stimulation at the periphery as a function of the neural activation patterns at the brain. One possible benefit of this approach is to intelligently promote active participation of patients during therapy. Training of the BCI parameters may still be possible even for a person who is completely paralyzed by tapping into the mirror neuron system (44). Mirror neurons fire when an action is observed and robotic exoskeletons may be able to move a patient’s arms while a BCI records signals that can be used later for control. Other recent work combining BCI with robotics or FES for therapy includes (45, 46). Several other groups in Europe are combing electrical stimulation with robotics (35, 47, 48), a strategy that ensures that muscles stay active during repetitive, guided training.

Modeling the Mechanisms of Therapy Using Computational Neuroscience

Ideally, therapeutic technology would be designed based on experimentally verified mathematical models of how limb use drives plasticity, in the same way that new materials can be designed based on a fundamental knowledge of chemistry and solid mechanics. Such models do not exist yet; the field of “neurocomputational rehabilitation” is nascent (49-52). One key development with European contribution in this field is a computational model that explains how the motor system coordinates muscles to achieve impedance control, internal model formation and effort optimization when interacting with a dynamic environment (53). In the model, the motor system modifies motor commands to the muscles based on kinematic error sensed locally at individual muscles, using a simple, sunken, asymmetric, “V” function. This model explains a wide range of experiments from the motor adaptation literature in which humans interacted with dynamic robotic environments (53, 54). This model can likely provide a “low level” basis for helping understand patient response to physically-interactive rehabilitation therapy, as well as orthotic and prosthetic devices. However, there is still clearly a great need for “high level” models of motor plasticity and learning that are built on top of this low level. The Berlin research institute Fraunhofer IPK has identified the development of a comprehensive model of motor control and motor learning, in which the human is seen as a biocybernetic system, as a grand challenge for the field of mobility technology, and has proposed to the German government the development of a major center involving several groups across Germany focused on this problem. They see a need for an integrative model of orthopedic, muscle, and neural plasticity that can be used as a basis from which to design innovative mobility technology.

In summary, the cutting edge of rehabilitation technology involves developing technology for delivering therapy both earlier in clinics, and later at home; investigating the relative roles of both simpler and more complex technology in promoting plasticity, thereby testing the premise that training with more naturalistic movements will better promote functional
recovery; making devices wearable to extend the reach of training to the lived-in environment; improving feedback and implementing learning-based control to make training more engaging and challenging; and coordinating multiple therapeutic modalities, including robotics, FES, and BCI’s to enhance the effect of training. A new field of neuro-computational rehabilitation appears to be developing, in which computational models will be used to simulate and understand use-dependent plasticity in rehabilitation therapy.

**COMBINATION THERAPIES**

Improvements in motor performance following rehabilitation therapy, with or without technology, are often modest. While refinements in rehabilitation technology will likely improve clinical outcomes by making therapy more available, more motivating, and perhaps more targeted and effective, it is also likely that recovery will ultimately be limited unless the damaged or diseased biological systems responsible for the motor impairment are restored. We define combination therapies as rehabilitation strategies that combine drug, molecule, or cell-based therapeutics with technology for movement training. There is already evidence that loading, training, and exercise will be important for facilitating biologic therapeutics, including regeneration of skeletal and cardiac muscle, bone, and neural systems. For example, physical therapeutics appear to establish a more permissive microenvironment and help direct cell fate for regeneration (55). In the central nervous system it is likely that neural cues will be needed for regenerative therapeutics to cause effective cell differentiation and generation of needed neural pathways. A key question, however, is whether any reasonable exercise that is delivered in combination with biologic therapies will be effective, or whether there will be subtlety in the way that exercise synergizes with biologic therapeutics, and therefore a need for optimization. Recent studies examining biological therapeutics in neural injury suggest that combination therapies involve complex interactions with motor training that must be understood in order to achieve the goal of eliminating severe motor impairment (56, 57).

A key example comes from Dr. James Fawcett’s group at Cambridge University, which has been working with chondroitinase ABC, a bacterial enzyme that digests molecules that help form cartilage-like barriers to axonal growth. Using a rat model of a spinal cord injury that disrupted the corticospinal tract, they found that delivering chondroitinase to the injury site without training the rat to use its impaired paw was ineffective, where the outcome measure was the number of sugar pellets the animal retrieved from a stair-cased well (58). They studied this task because it has been shown previously to require a corticospinal tract (59), which was the tract targeted with the lesion in their study. They then found that delivering rehabilitation exercise specific to paw reach and retrieval for one hour per day, in the form of practice at retrieving seeds embedded in a plastic floor grid, led to an impressive recovery of skilled paw function, but only when coupled with chondroitinase treatment. Interestingly, delivering generalized forelimb rehabilitation for one hour per day in the form of an enriched environment (or “fun cage” with ladders, ropes, and tunnels), extinguished the rat’s ability to perform the pellet retrieval task, whether or not they received chondroitinase.

One interpretation of these results is as follows (Figure 4.3): The plasticity treatment chondroitinase induced axonal sprouting; rehabilitation exercise pruned and connected the sprouts. Thus the new neural resource made available during a window of time by chondroitinase was wasted without rehabilitation exercise. Practicing a target motor skill (i.e., skilled paw retrieval) appeared to recruit the newly available neural resources to serve and improve the skill. Practicing other motor skills (as the rats did in the fun cage), appeared to negatively affect the learning of skilled paw use. Thus, there may exist a neural competition
for the new neural resources induced by plasticity treatment. The type of movement practice experienced may drive the competition.

![Figure 4.3](image)

Figure 4.3. Conceptual diagram of competition of task-related motor circuits for new neural resources made available with a plasticity treatment. Neural resources, such as synaptic connections, are represented by blocks. Pre-injury, there are ample resources to support motor control of multiple tasks. Following a neural injury, there are fewer resources and they are disordered. Following a plasticity treatment, there are more resources, but they are still disordered. Training on motor Task A results in ordering of blocks for that task, but leaves no blocks for building a controller for Task B.

Other work has found similar evidence of competition in training. For example, rats with lesions of the corticospinal tract who were trained in skilled reaching improved in reaching ability, but made more errors in a horizontal ladder test (60, 61). The presence of this phenomenon depended on which anatomical component of the corticospinal tract was lesioned. Another study examined the individual and combined effects of locomotor training and treatment with the Anti-Nogo-A antibody, which helps prevent inhibition of neurite outgrowth following spinal cord injury in rats (62). Both therapies improved locomotor function, but in different ways, as detected by kinematic analysis of hindlimb movement. Combined treatment actually decreased functional performance on a ladder climbing task, suggesting that the mechanisms underlying the treatments were again competitive. It was noted that this interference may depend on the relatively timing of delivery of the two therapies (62). Motor training combined with another axonal growth promoter after a focal cortical infarct in rats produced primarily temporal benefits: recovery of grip function was better early (63), supporting the concept that temporal dynamics will be important in combination therapies. In another recent study, genetic deletion that reduced myelin-mediated inhibition of neural plasticity in mice combined with a novel form of technology-enabled exercise training that simultaneously challenged balance, grasping, and locomotion after partial lateral hemisection exhibited differing effects, with genotype providing improved performance on more generalized behaviors, and training a task-specific benefit, with no observed additive effect (64).
Another important example is provided by the group of Prof. Gregoire Courtine of the Experimental Neurorehabilitation Lab at the University of Zurich. This group uses animal models of SCI to help inform their clinical use of robotic devices, and is investigating use of electrical stimulation of the spinal cord for motor function combined with neuropharmacological interventions, in both murine and non-human primate models. One recent study from this group with a remarkably comprehensive quantitative analysis coupled robotic locomotor training, pharmacological intervention, and epidural electrical stimulation in rats with a complete SCI (47). The combination of approaches produced additive effects that allowed the injured rat to walk nearly normally. These authors therefore argued that the diffusely distributed and heterogeneous character of neuromotor control systems demand multiple complementary approaches.

This work has clear implications for engineering approaches to rehabilitation exercise. In the words of Dr. Fawcett and Dr. Armin Curt, “the plastic CNS may be very vulnerable to poorly planned rehabilitation” (57). Physical therapeutic technologies may help provide control over which functions are reprogrammed, and therefore may help to maximize synergism and minimize competition. Physical therapeutic technologies may also be useful for assaying the amount of and type of plasticity made possible by a treatment, so that rationale decisions can be made about what motor skills to train. Finally, there is a critical need for neuro-computational models that can be used to understand the competitive and synergistic interactions between different types of movement practice and biologic therapies.

CONCLUSIONS

There is an explosion in new rehabilitation technologies; however, the field is in its infancy. Beyond the fact that these technologies can in some case make rehabilitation exercise more engaging and less labor intensive, the gains delivered are still unclear. Fundamental scientific insight is needed into the learning and plasticity mechanisms that these technologies seek to stimulate; the current lack of insight makes device design somewhat haphazard. Regenerative therapies may enable levels of recovery far beyond those possible with rehabilitation exercise alone, but these therapies cannot progress independently of rehabilitation exercise.

Thus, the challenge of developing technologies that significantly improve on rehabilitation outcomes compared to conventional rehabilitation remains to be met. The quantification power associated with sensors incorporated into therapeutic technologies, coupled with the nascent field of neuro-computational rehabilitation will help resolve this gap. We expect there to be a “science of combination therapies” that seeks to understand the complex interactions between training, plasticity, and regeneration (55). The most effective physical therapeutic technologies of the future will likely be based on this science.

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5. PERSONALIZED NEUROMUSCULOSKELETAL MODELING TO IMPROVE TREATMENT OF MOBILITY IMPAIRMENTS

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Abstract

Mobility impairments due to injury or disease have a significant impact on quality of life. Consequently, development of effective treatments to restore or replace lost function is an important societal challenge. In current clinical practice, a treatment plan is usually selected from a standard menu of options rather than customized to the unique characteristics of the patient. Furthermore, the treatment selection process is normally based on subjective clinical experience rather than objective prediction of post-treatment function. The net result is treatment methods that are less effective than desired at restoring lost function. This paper discusses the possible use of personalized neuromusculoskeletal computer models to improve customization, objectivity, and ultimately effectiveness of treatments for mobility impairments. The discussion is based on a tour of academic and industrial research sites throughout Europe, and both clinical and technical aspects of personalized neuromusculoskeletal modeling are explored. On the clinical front, we discuss the purpose and process of personalized neuromusculoskeletal modeling, the application of personalized models to clinical problems, and gaps in clinical application. On the technical front, we discuss current capabilities of personalized neuromusculoskeletal models along with technical gaps that limit future clinical application. We conclude by summarizing recommendations for future research efforts that would allow personalized neuromusculoskeletal models to make the greatest impact possible on treatment design for mobility impairments.

INTRODUCTION

Mobility involves walking, stair climbing, posture, balance, manipulation, transfers, and other locomotion tasks and is therefore central to quality of life. When an individual incurs a mobility impairment, quality of life is diminished in proportion to the extent of the impairment. For example, mild knee osteoarthritis can limit participation in desired recreational or athletic activities without significantly affecting normal daily activities and productivity. In contrast, a stroke can make it nearly impossible to walk or manipulate objects, significantly diminishing an individual's ability to be self sufficient and function in society. Spinal cord injury can leave a person with normal upper extremity function but no remaining lower extremity function, significantly impacting only certain aspects of mobility.

Treatments for different mobility impairments are typically stereotypical, with a standard menu of treatment options existing for any particular mobility impairment. For example, severe medial compartment knee osteoarthritis may be treated using high tibial osteotomy, unicompartmental knee replacement, or total knee replacement. Once a patient seeks surgical treatment for debilitating pain and significant loss of function, the clinician must choose between these treatment options based on clinical assessment of the patient. Furthermore, the clinician must determine the optimal values of the parameters associated with the selected treatment (e.g., method, level, and amount of correction for tibial osteotomy, and implant type, size, and positioning for joint replacement). A similar situation exists for rehabilitation and surgical treatments of neurological disorders such as stroke, Parkinson’s disease, and cerebral palsy. In clinical practice, the final treatment plan is usually selected based on subjective clinical experience rather than on objective prediction of post-treatment function developed from patient data.
Personalized computational models of the neuromusculoskeletal system could facilitate objective prediction of patient-specific functional outcome for different treatment designs being considered by the clinician. Personalized models for treatment design are motivated by the fact that for many treatments, "one size fits none." Every patient is different and possesses unique anatomical, neurological, and functional characteristics that may significantly impact optimal treatment of the patient. Personalized models provide one possible avenue for increased objectivity in treatment planning, reducing the likelihood that different clinicians will plan different treatments given the same patient data. Personalized models also have the potential to identify the best treatment option for a specific patient (including identification of previously unknown treatments) and the treatment parameters to which functional outcome is highly sensitive (i.e., which treatment parameter values does the clinician need to “get right”?).

This paper explores how personalized neuromusculoskeletal models could be used to improve treatment design for mobility impairments. The exploration is based on a survey of personalized modeling research being performed in Europe. The survey was funded by the National Science Foundation (NSF) in the United States with the goal of synthesizing research recommendations and informing research funding in the area of technology to improve mobility. Two teams of four panelists recruited by NSF visited a number of academic and industrial sites throughout Europe over a one week time period. Since time and financial constraints limited the number of labs that could be visited, it was not possible to gather information from all labs in Europe performing valuable work in this area. Given the European focus of the tour, we also omit discussion of valuable work being performed by labs outside of Europe. The remainder of this paper summarizes the panel’s findings related to the potential clinical use and benefit of personalized neuromusculoskeletal modeling.

**CLINICAL ASPECTS OF PERSONALIZED MODELING**

In this section, we discuss current and future clinical uses of personalized neuromusculoskeletal models to design improved treatments for mobility impairments. To set the stage, we begin by discussing common reasons why human movement data are collected, followed by a proposal for a general process to follow when using personalized models in the treatment design process. We then discuss mobility-related clinical problems currently being addressed with personalized neuromusculoskeletal models, and we conclude this section by highlighting gaps in clinical application where personalized models could add significant value.

**Clinical Purpose of Personalized Modeling**

Pre-treatment human movement (e.g., motion capture, ground reaction, muscle electromyographic, energy consumption), strength (e.g., isometric and isokinetic dynamometer), and imaging (e.g., magnetic resonance (MR), computed tomography (CT), x-ray, fluoroscopic) data provide the experimental measurements necessary to develop objective model-based predictions of post-treatment function. As described by Dr. Maria Grazia Benedetti at the Rizzoli Orthopedic Institute in Bologna, Italy, there are three primary reasons for collecting human movement data in a clinical setting:

- **Assessment** – Assess after treatment how the treatment worked for a group of patients. This use of human movement data is relatively common.
- **Identification** – Identify on an individual patient basis which patients should be treated (but not how they should be treated). This use of human movement data remains uncommon but is becoming more common.
- **Prediction** – Predict on an individual patient basis which treatment should be performed and how it should be performed. This use of human movement data does not yet happen in clinical practice.

The focus of this paper is on how personalized neuromusculoskeletal models could be used for prediction rather than assessment or identification, though identification has significant clinical value as well. While prediction is the most challenging use, it is also the use with the greatest potential to improve functional outcome on an individual patient basis.

**Clinical Process of Personalized Modeling**

How should personalized neuromusculoskeletal models be used to predict functional outcome for various treatment plans under consideration? Expanded from ideas presented by researchers at the Rizzoli Orthopedic Institute in Bologna, Italy, and Dr. Bart Koopman at the University of Twente in Enschede, the Netherlands, we propose a three-step process for treatment design using personalized models:

1. **Model preparation steps:**
   - **Identify** model outputs to be used as indicators of clinical/functional outcome.
   - **Define** model complexity required to predict these outputs with sufficient accuracy for the intended clinical application.
   - **Collect** pre-treatment movement, strength, and imaging data (as required) to construct the personalized model and predict the outputs of interest.

2. **Model construction steps:**
   - **Calibrate** model geometry and parameter values to which the outputs of interest are sensitive using pre-treatment movement, strength, and/or imaging data.
   - **Estimate** model parameter values to which the outputs of interest are insensitive using data reported in the literature.
   - **Incorporate** surgical or rehabilitation treatment plans under consideration into the personalized model.

3. **Model utilization steps:**
   - **Predict** post-treatment patient function for each proposed treatment plan.
   - **Select** treatment plan and associated parameter values that maximize functional outcome, possibly using numerical optimization methods.
   - **Validate** personalized model predictions using post-treatment function measured from patients whose treatment was not planned with a model.
   - **Implement** optimal surgical or rehabilitation treatment plan designed with the personalized model.
   - **Collect** post-treatment movement, strength, and/or imaging data from the patient to assess clinical/functional outcome.

In this process, only the steps relevant to the mobility-related clinical application at hand need be performed. For example, clinical applications that do not require modeling of individual muscle forces may not require any imaging and strength data from the patient, and
thus steps related to calibration of patient-specific muscle and bone geometry can be omitted. Model parameter values that require calibration to patient data may necessitate collection of additional experimental data solely for calibration purposes (1).

Two critical tasks to highlight in this process are Calibrate and Validate. Unless the model is calibrated to relevant data collected from the patient prior to treatment, the model will not be sufficiently personalized to predict the patient’s post-treatment function. Similarly, unless calibrated model predictions are validated using post-treatment data collected from patients whose treatments were not planned with the model, clinicians will not have confidence in the model predictions, and personalized models will never advance toward widespread clinical utility. Validation of treatment planning using personalized models will ultimately require randomized controlled trials, where outcomes are compared between patients whose treatments were planned with a personalized model and those whose treatments were not.

Clinical Applications of Personalized Modeling

During our tour of European research labs, we sought to identify clinical applications where a personalized modeling process similar to the one outlined above was already being followed. By the end of the tour, we made three valuable observations related to clinical application of personalized neuromusculoskeletal models. First, few labs have reached the point of being able to apply this process to specific clinical problems. Second, some of the best existing clinical applications involved generic rather than personalized models. Third, most clinical applications we observed involved orthopedic surgery, with few applications involving neurorehabilitation. Below we comment further on these observations.

Three large projects funded by the European Commission (EC) are making significant strides in developing and applying personalized neuromusculoskeletal models to orthopedic clinical problems. The first is the “Osteoporotic Virtual Physiological Human” (VPHOP) project (http://www.vphop.eu/), which involves a large consortium of academic and industrial partners throughout Europe and is coordinated by Dr. Marco Viceconti at the Rizzoli Orthopedic Institute in Bologna, Italy (2-4). As stated on the project website, the goal is to “develop, validate and deploy the next generation of technology to predict the absolute risk of fracture in patients with low bone mass, thereby enabling clinicians to provide better prognoses and implement more effective treatment strategies.” One of the unique emphases of the project is on multi-scale modeling, with bone being modeled simultaneously on the cell, tissue, organ, and body levels to permit clinically useful predictions of the risk of bone fracture in different patient populations.

In a related project, Dr. Viceconti’s team at the Rizzoli Orthopedic Institute has developed personalized neuromusculoskeletal models of pediatric patients who received a surgical limb salvage procedure for bone cancer (3, 5). For this clinical problem, the challenge is to determine how the patient should load the bone allograft during the rehabilitation process such that bone loads are high enough to stimulate repair but low enough to avoid fracture. Since each clinical case is unique, surgical and rehabilitation treatment design cannot be standardized. Dr. Viceconti and his research team are using gait and imaging data to create personalized neuromusculoskeletal models that estimate muscle and bone loads in the patient’s femur during walking (Figure 5.1). These estimates inform the rehabilitation process and when the patient should be cleared for full functional loading with no restrictions. The primary challenges faced by this personalized modeling process are whether scaling of muscle and bone geometry from a generic model is sufficiently accurate for this pediatric application, and also whether the estimated muscle and bone loads (which currently cannot be validated experimentally) are sufficiently reliable.
Figure 5.1. Personalized modeling workflow for massive skeletal reconstruction, as developed by the Medical Technology Laboratory at the Rizzoli Orthopedic Institute in Bologna, Italy. (a) CT scan of the lower limbs performed at follow-up, with motion capture markers visible as well. (b) Focused view of reconstructed femur immediately after surgery. (c) Patient-specific musculoskeletal model superimposed on CT images (LHPBuilder, B3C, Italy). (d) One frame of dynamic walking simulation performed with the patient-specific model (OpenSim). (Courtesy of Dr. Giordano Valente, Rizzoli Orthopedic Institute, Bologna, Italy).

The second large EC-funded project is called “NMS Physiome” (http://www.nmsphysiome.eu/), which is also coordinated by researchers at the Rizzoli Orthopedic Institute. This project seeks to “promote a more organic cooperation in the development of Predictive, Personalised and Integrative musculoskeletal medicine” by integrating research efforts between the VPHOP project and the Center for Physics-based Simulation of Biological Structures (Simbios) at Stanford University in the United States. Integration is focused on neuromusculoskeletal software tools (MAF, OpenSim, and FEBio) and research community websites (BiomedTown and Simtk) developed by the two consortia. The goal of integration is to address the challenges posed by personalized neuromusculoskeletal modeling more effectively and efficiently.

The third large EC-funded project is entitled “Improving Safety and Predictability of Complex Musculo-skeletal Surgery using a Patient-Specific Navigation System” (TLEMsafe) (http://www.lemsafe.eu/), which involves a consortium of academic and industrial partners headed by the University of Twente in Enschede, the Netherlands. The stated goal of the project is to “create an ICT-based patient-specific surgical navigation system that helps the surgeon safely reach the optimal functional result for the patient and is a user friendly training facility for the surgeons.” In this project, the researchers proposed to use
personalized neuromusculoskeletal models as part of a three-step treatment design process. The first step is creation of the personalized model from the patient’s movement and imaging data. The model is created within the framework of the AnyBody musculoskeletal modeling software developed by researchers at the University of Aalborg in Denmark (6; Figure 5.2). The second step is for the surgeon to perform virtual surgical treatments on the personalized model and to identify the optimal surgical plan for the patient. The final step is to transfer the optimized treatment plan into a surgical navigation system to be used during actual surgery. As part of this project, Dr. Bart Koopman of the University of Twente is currently investigating the use of personalized neuromusculoskeletal models to identify optimal patient-specific tendon transfer procedures to restore hip adductor strength in patients who walk with a “drooping” swing leg hip (i.e., Trendelenburg gait due to Poliomyelitis or total hip arthroplasty).

Figure 5.2. Examples of musculoskeletal models developed for the TLEMsafe project. (Courtesy of Prof. Dr. Ir. Bart Koopman, University of Twente, Enschede, the Netherlands.)

Other research we observed involved the use of generic rather than personalized neuromusculoskeletal models. While personalized models have the greatest potential to impact clinic practice, generic models can still provide significant clinical benefits. Two clinical applications of generic models were particularly well developed. The first was the design of a total ankle replacement by Dr. Alberto Leardini and colleagues at the Rizzoli Orthopedic Institute in Italy (7, 8). The design was developed using a sagittal plane musculoskeletal model of the ankle that incorporated the ligaments and articular surfaces. The design philosophy was to maintain medial and lateral ankle ligaments in an isometric state during passive ankle motion. The team identified a novel geometric design to achieve this goal, using non-anatomically shaped tibial and talar components with a meniscal bearing interposed between them. The design has been licensed by an orthopedic implant company, and early clinical assessment is demonstrating good restoration of ankle mobility with low complication and revision rates (9, 10).

The other example was evaluation of tendon transfer surgery for massive rotator cuff tears by Dr. Frans van der Helm and colleagues at Delft University of Technology in the Netherlands (11, 12). The evaluation was performed using a high fidelity musculoskeletal shoulder and elbow model constructed from extensive measurements performed on a single
cadaver specimen (13). The model accounts for more parameters (including muscle sarcomere length measured by laser diffraction) than any other upper extremity model. Simulations performed with the generic model have provided specific recommendations for which tendons to transfer, and where to transfer them, to replace the function of a torn rotator cuff without sacrificing shoulder strength for functional tasks. Similar to the pediatric oncology application, the reliability of the model's predicted clinical outcome is only as good as the reliability of the model's predicted muscle forces. Dr. van der Helm and colleagues have attempted to validate the model's prediction of shoulder muscle and contact forces using contact forces measured by an instrumented shoulder prosthesis (11). The authors concluded that, “Although results indicated a reasonable compatibility between model and measured data, adjustments will be necessary to individualize the generic model with the patient-specific characteristics.”

The primary rehabilitation applications we observed utilized a personalized modeling method called Complementary Limb Motion Estimation (CLME, 15, 16). The method uses motion measurements made on a patient's healthy leg to predict how the patient's impaired leg should move. The predictions are made in real time by exploiting the strong coupling that exists between skeletal degrees of freedom during locomotion. These couplings (or synergies) are identified in healthy subjects using statistical dimensionality reduction methods (e.g., principal component analysis) and then applied to the healthy limb of a patient to predict the desired motion of the patient's impaired limb. CLME was first proposed to generate personalized motion trajectories for the paretic limb of patients undergoing robotic gait training following stroke (16). The goal was to maintain patient stability while minimizing unwanted interaction forces between patient and robot. More recently the same method has been proposed to personalize the control of an active knee exoprostheses to the gait pattern of patients who have undergone above-knee amputation (15). For both applications, the predicted motion of the impaired or prosthetic limb is used as a personalized reference to be tracked by the robot or prosthesis control system. While we observed other personalized rehabilitation applications, they did not have a strong neuromusculoskeletal modeling component to them.

Clinical Gaps in Personalized Modeling

Mobility-related clinical problems are typically treated by either surgery or rehabilitation and either do or do not possess a significant neurological component. Thus, use of personalized neuromuscular models to improve treatment of mobility impairments can be grouped into four categories: 1) surgical treatment without a significant neurological component, 2) surgical treatment with a significant neurological component, 3) rehabilitation treatment without a significant neurological component, and 4) rehabilitation treatment with a significant neurological component. Of these four categories, the first is the most developed and the fourth the least developed in terms of personalized neuromusculoskeletal modeling. This situation is not surprising given that technology is a more recent addition to rehabilitation treatments (e.g., rehabilitation robotics) than to surgical treatments and that neurological factors are more difficult to model than are mechanical factors. Below we present clinical gaps in personalized modeling for each of these four categories.

Osteoarthritis is a prevalent disabling disease that is commonly treated by surgical intervention. Though it clearly possesses a neurological component (17), that component is secondary to mechanical factors as far as surgical treatment design is concerned. Use of personalized neuromusculoskeletal models has been proposed by European labs for pre-operative planning of high tibial osteomities and total joint replacements (18, 19). While joint
replacement surgery is generally reliable, individual cases can pose special challenges, especially those involving revision surgery. In contrast, high tibial osteotomy (HTO) is a challenging surgical procedure with highly variable outcomes but also high potential benefits, making it an excellent target for personalized models. Use of personalized models to design customized gait modifications following HTO surgery could also be valuable for avoiding the loss of bone correction that often occurs over time. Anterior cruciate ligament replacement to avoid knee osteoarthritis is a related surgical application where personalized models could be of value (20).

In contrast, cerebral palsy and Charcot-Marie-Tooth disease are neurological disorders that are commonly treated by surgery, since no treatment exists for the underlying neurological problem. Though Charcot-Marie-Tooth disease is not well known, it is the most commonly inherited neurological disorder and limits mobility in approximately 1 in 2,500 individuals (21). Surgical treatments for both disorders typically involve muscle lengthening, tendon transfer, and/or osteotomy to improve joint range of motion, foot-ground contact pattern, gait speed, and gait symmetry. For both disorders, patients have varied and unique clinical presentations, making stereotypical treatment planning ineffective. For this reason, personalized neuromusculoskeletal models, especially those that are able to model the neurological limitations (e.g., muscle spasticity) of the patient, could play a valuable role in predicting the outcome of complex multi-level surgeries that are performed on these patients (22-24).

Stroke, spinal cord injury, and traumatic brain injury significantly affect mobility, possess a major neurological component, and are often treated by rehabilitation methods. Personalized neuromusculoskeletal models have yet to be applied to traditional or robot-assisted rehabilitation treatments for these disorders. Given this large gap, even personalized models that omit neural control models have the potential to make a significant clinical impact. For example, a number of clinical and research labs in Europe are utilizing robot-assisted therapy for neurorehabilitation (25, 26). Many of these labs are using the Lokomat gait trainer (Hocoma AG, Volketswil, Switzerland), whose programmed walking pattern is that of one of the designers. Personalized musculoskeletal models that can predict patient-specific improvements in gait pattern could be used to customize robot-prescribed gait motions. For individuals who have had a stroke, similar models could be used to predict a patient-specific sequence of gradual gait alterations leading to normal function, with the model indentifying where to focus rehabilitation efforts to maximize functional outcome.

Personalized musculoskeletal models that include personalized neural control models would be even more beneficial for improving rehabilitation of neurological disorders. Models that account for patient-specific neural control limitations and neuroplasticity could be used to identify the maximum expected improvement and how best to get there. As suggested by Dr. Herman van der Kooij of the University of Twente in the Netherlands, such models could be useful for predicting how people interact with and adapt to their environments, which could improve the effectiveness of robotic therapy systems. Furthermore, such models could be valuable for the design of neuroprostheses that use functional electrical stimulation to restore lost function (27, 28). For example, if a personalized neuromusculoskeletal model could predict a minimum set of muscles to stimulate, and how and when to stimulate them, to restore a normal gait pattern, then the personalized prescription could be investigated in a clinical environment. As stated by one of the researchers on our panel, “There is a need for . . . improved models of human motor recovery to provide a more rational framework for designing robotic therapy control strategies.” (29).
One of the primary reasons for these clinical gaps is lack of effective collaboration between clinical researchers and personalized modeling researchers. An excellent counterexample is the Rizzoli Orthopedic Institute in Italy, where clinicians and engineers share the same office space and interact during clinical decision making. These interactions create an atmosphere where clinicians routinely enter into the technical world and engineers routinely enter into the clinical world. Such an environment of shared intellectual investment in solving clinical problems is critical if personalized neuromusculoskeletal modeling is to make a broad impact in the clinic.

**TECHNICAL ASPECTS OF PERSONALIZED MODELING**

Significant research efforts are currently underway in labs throughout Europe to develop personalized neuromusculoskeletal modeling tools and methods. Recalling the section above on the Clinical Process of Personalized Modeling, the primary challenges faced by these efforts are the **Calibrate** step within *Model construction* and the **Validate** step within *Model utilization*. In this section, we discuss current technical capabilities of personalized modeling related to model calibration and validation, followed by a discussion of technical gaps that need to be filled if personalized neuromusculoskeletal models are to become clinically useful.

**Technical Capabilities of Personalized Modeling**

Despite significant computational advances over the past ten years, model personalization remains a major challenge, as does the ability to use a personalized model to predict the outcome of a clinical intervention. Personalized neuromusculoskeletal models can be applied to mobility-related clinical problems only to the extent to which key model features can be calibrated to data collected from a patient. Thus, the ability to calibrate models to patient data is a prerequisite to clinical use of personalized models, with the proposed clinical application determining the extent of model personalization required.

Since most neuromusculoskeletal models are generic, being constructed from detailed anatomic measurements performed on cadaver specimens (13, 30), a model personalization (or calibration) process is needed. Expanding on information provided by Dr. Bart Koopman of the University of Twente in the Netherlands, we propose four model calibration steps that should be performed in whole or in part to transform a generic model into a personalized model:

1. **Geometric calibration** – use of imaging data (e.g., MR, CT, x-ray) to calibrate bone geometry, muscle lines of action, and muscle moment arms in a musculoskeletal model.
2. **Kinematic calibration** – use of motion data (e.g., marker-based, inertial sensors, fluoroscopy) to calibrate joint positions and orientations in the body segments of a skeletal model.
3. **Kinetic calibration** – use of load data (e.g., ground reaction force and moment, foot contact pressure, dynamometer) to calibrate body segment mass and inertia, foot stiffness, muscle strength, and other muscle-tendon properties in a neuromusculoskeletal model.
4. **Neurologic calibration** – use of motion, load, and muscle activity data (i.e., muscle EMG) to calibrate feedforward, intrinsic feedback, reflexive feedback, and/or synergy properties of the neural control system in a neuromusculoskeletal model.

The challenge is how to construct a personalized model that is consistent with all available data from these different modalities (31).
Current methods for geometric calibration involve uniform scaling, non-uniform scaling, deformation, or direct creation of bone models and muscle lines of action from patient MR or CT data. Uniform scaling based on external measurements is inaccurate when calculating muscle moment arms, muscle-tendon lengths, muscle forces, and joint contact forces (29), especially when scaling a generic model of an adult to a pediatric patient (32). Non-uniform scaling is only slightly better at producing accurate muscle moment arms and muscle-tendon lengths (24). Creation of patient-specific geometry directly from the patient’s imaging data remains the gold standard (23), but the process is highly time consuming and somewhat subjective, depending on the imaging modality and the anatomic structures being modeled (e.g., bone edges are often poorly defined in MR data).

Kinematic calibration involves determining fixed joint positions and orientations in the body segments of a skeletal model with a pre-defined kinematic structure. The calibration process is usually performed using surface marker data, with joint angles in the model being calculated as a byproduct. European labs have used optimization methods (1) and extended Kalman filter methods (34-36) to perform kinematic calibration. Filter-based methods have the advantage of being computationally faster and less complex than most optimization methods, but they require a greater amount of algorithm tuning to achieve satisfactory performance. Despite these advances, neither approach has yet to be generalized and incorporated into commercial-grade musculoskeletal modeling software such as the AnyBody program.

Kinetic calibration typically involves calibration of segment mass properties or muscle force-generating properties. Though segment mass properties can be calibrated to force plate and motion data (37), they are often taken from regression equations developed from measurements performed on cadavers (38). Similarly, though muscle model parameter values (e.g., muscle strength) can be calibrated to isometric and/or isokinetic dynamometer data (39), this calibration step is usually omitted due to the extra effort it requires. A recent European study indicated that subject-specific muscle-tendon parameter values calibrated to dynamometer data are appropriate for use in musculoskeletal models used to analyze gait (40). Since many movement impairments involve undesirable foot-ground contact patterns, kinetic calibration of patient-specific foot-ground contact models will be essential in the future for predicting changes in gait function due to various proposed treatments, yet kinetic calibration methods for such models do not yet exist.

A promising development to address geometric, kinematic, and kinetic calibration simultaneously is research being performed by Dr. Wafi Skalli at Arts et Métiers ParisTech in Paris, France using the EOS bi-plane x-ray system (EOS Imaging SA, Paris, France). With the EOS system, a subject stands upright while a low-dose x-ray system scans the entire body from head to toe collecting one continuous distortion-free image in each of two orthogonal planes. The resulting bi-plane images are then processed and morphed using template anatomy for personalization and visualization. Geometric calibration of bone and muscle geometry via deformation of template bone and muscle models can be performed rapidly and accurately relative to geometry constructed directly from CT data (41-44). Kinematic calibration could theoretically be aided by performing scans of the relevant portion of the body in two or more poses (e.g., the lower extremities in different squatting positions, 45), especially if surface markers to be used in additional movement experiments are also visible. Kinetic calibration of segment mass properties and muscle strength parameters (based on muscle cross sectional areas) can also be performed from the images (46, 47). Thus, with improvements in automation and refinement of existing algorithms, the EOS system has the potential to improve musculoskeletal model personalization significantly.
The remaining area, neurologic calibration, has seen the least progress due to the significant challenges involved in understanding how the human neural control system functions. This calibration step can be pursued using a range of approaches, from a physiological approach that seeks to model the detailed anatomy and physiology involved in neural control, to an emergent approach that seeks to model the neural control computations implemented by the anatomy without modeling anatomic detail. An example of a physiological approach is detailed modeling of feedforward, intrinsic (i.e., muscle) feedback, and reflexive (i.e., visual, proprioceptive, and vestibular) feedback mechanisms utilized by the neural control system (48-51). To date, such high fidelity neural control models have been applied to postural control rather than movement tasks, and methods for personalizing the parameter values in these models are not yet well developed. At the other extreme, an example of an emergent approach is muscle synergy analysis, where EMG signals from a large number of muscles (e.g., 16) are decomposed into a smaller number of basis activation signals (e.g., 5) for all muscles plus a unique set of weights (often termed "modules") for each muscle that scale the activation signals (52, 53). Synergy analysis is used for dimensionality reduction (e.g., 5 basis signals are used to reconstruct 16 EMG signals) and can identify neural control limitations in patients following stroke (54). Incorporation of these limitations into personalized neuromusculoskeletal models could facilitate prediction of best possible functional outcome. Between these two extremes is a physiological approach that has successfully explained motor learning using simplified feedforward and feedback models (55). The approach uses a v-shaped learning function to model the change in muscle feedforward commands generated in response to kinematic errors experienced during the previous movement trial. Computer simulation of a sequence of arm movement trials performed in different force fields revealed that the method can successfully reproduce experimentally observed trial-to-trial changes in muscle activations (to control force) and co-contraction (to control impedance).

Validation of clinical predictions is the other major challenge faced by personalized models. This challenge can be easily surmounted when clinical outcome variables are external quantities that can be easily measured (e.g., gait speed, gait symmetry). Frequently, however, established clinical databases use coarse ordinal scales to rank movement ability, and mapping these scores to neuromechanical models is difficult. In addition, significant challenges remain when the outcome variables are either internal to the body (e.g., muscle forces, joint contact forces, bone strains) or dependent on quantities that are internal to the body. Since such quantities cannot be measured directly by non-invasive means, alternate methods are needed for personalized model validation. For example, predicted muscle forces have been evaluated indirectly using in vivo joint contact force measurements (14) or novel measurements (e.g., near infrared spectroscopy) that are likely to be highly correlated with in vivo muscle force (56).

**Technical Gaps in Personalized Modeling**

As suggested by this review of current technical capabilities in Europe, at least four critical technical gaps currently exist that limit the potential clinical applicability of personalized neuromusculoskeletal models:

*How can we make the personalized model calibration and prediction process fast and easy?*

Though several excellent musculoskeletal modeling programs exist, none of them contain functionality that automates the model calibration process and simplifies the model prediction process. Personalized model calibration and prediction currently require significant expertise and programming ability possessed by only a small number of researchers in a limited number of research labs. Making these capabilities available to the
larger neuromusculoskeletal modeling community via fast, automated algorithms will be essential for the growth of personalized modeling efforts. Ultimately, personalized modeling will be adopted for routine clinical use only when it is extremely easy to use.

**How can we calibrate “unobservable” parameters to which model predictions are sensitive?**

For some clinical problems, personalized model predictions of functional outcome will be sensitive to model parameter values that cannot be calibrated to available data. The first step in addressing this problem is identifying when it occurs, which requires performing sensitivity analyses that in some cases will be limited by existing computational capabilities. The next step is development of new experimental methods or hardware that provide sufficiently rich information to calibrate the parameter values needed to develop the predictions.

**How can we create personalized neural control models?**

Few neuromusculoskeletal models published to date account for any level of personalized neural control modeling. Such modeling would ideally account for limitations in a patient’s neural control capabilities as well as the extent of possible plasticity. Emergent approaches for modeling neural control could be incorporated into personalized musculoskeletal models as a starting point, while physiological models could be refined to the point where essential model parameters become well defined and methods for calibrating them are developed. The ability to incorporate complex personalized neural control models into personalized musculoskeletal models would greatly expand model applicability to clinical situations, especially those involving neurorehabilitation.

**How can we validate model-based predictions, especially for internal quantities such as muscle, joint, and bone loads?**

Validation of internal quantities that influence treatment design remains a major challenge. While researchers continue to refine optimization and EMG-driven methods for predicting muscle forces and related joint and bone loads, the ability to validate these predictions has lagged behind. Direct measurement of internal quantities under special conditions (e.g., instrumented implants), and the opportunity to test model-based predictions against these internal measurements, provides a valuable avenue for model validation efforts (57). Identification of novel approaches that utilize only existing data collection capabilities, as well as development of new experimental techniques, will be essential if clinicians are to gain confidence in treatment plans designed with personalized neuromusculoskeletal models.

**CONCLUSIONS**

Neuromusculoskeletal modeling has yet to make a significant difference in routine clinical practice. For this situation to change, the key gaps identified above need to be addressed by modeling researchers in close collaboration with clinical investigators. While the biggest clinical gap for personalized neuromusculoskeletal modeling is in neurorehabilitation, the gap for other mobility-related clinical problems is almost as large. The biggest technical gap is in personalized neural control and recovery models, though issues like automation of the model personalization process and development of personalized foot-ground contact models are critical as well for advancement. For clinical problems that involve highly unique patient characteristics, stereotypical treatment design is likely to yield variable functional outcomes. These types of clinical problems are where personalized neuromusculoskeletal models have the greatest potential to create a positive paradigm shift in the treatment design process.
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REFERENCES


A REVIEW OF WEARABLE SENSORS AND SYSTEMS WITH APPLICATION IN REHABILITATION

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Abstract

The aim of this review paper is to summarize recent developments in the field of wearable sensors and systems that are relevant to the field of rehabilitation. The growing body of work focused on the application of wearable technology to monitor older adults and subjects with chronic conditions in the home and community settings justifies the emphasis of this review paper on summarizing clinical applications of wearable technology currently undergoing assessment rather than describing the development of new wearable sensors and systems. A short description of key enabling technologies (i.e., sensor technology, communication technology, and data analysis techniques) that have allowed researchers to implement wearable systems is followed by a detailed description of major areas of application of wearable technology. Applications described in this review paper include applications with focus on health and wellness, safety, home rehabilitation, assessment of treatment efficacy, and early detection of disorders. The integration of wearable and ambient sensors is discussed in the context of achieving home monitoring of older adults and subjects with chronic conditions. Future work required to advance the field toward clinical deployment of wearable sensors and systems is discussed.

INTRODUCTION

The U.S. health care system faces daunting challenges. With the improvements in health care in the last few decades, residents of industrialized countries are now living longer, but with multiple, often complex, health conditions (1-3). Survival from acute trauma has also improved, but this is associated with an increase in the number of individuals with severe disabilities (4). From an epidemiological standpoint, the cohort of “baby boomers” in the United States is now reaching an age at which they will begin to severely stress the Medicare system. Finally, recent health care reform efforts may add 32 million newly insured patients to the health care system in the next few years (5).

These altered demographics raise some fundamental questions:

• How do we care for an increasing number of individuals with complex medical conditions?

• How do we provide quality care to those in areas with reduced access to providers?

• How do we maximize the independence and participation of an increasing number of individuals with disabilities?

Clearly, answers to these questions will be complex and will require changes into how we organize and pay for health care. However, part of the solution may lie in how and to what extent we take advantage of recent advances in information technology and related fields.

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Currently, there exist technologies that hold great promise to expand the capabilities of the health care system, extending its range into the community, improving diagnostics and monitoring, and maximizing the independence and participation of individuals. This paper will discuss these technologies in depth, with a focus on remote monitoring systems based on wearable technology. We chose to focus on these technologies because the recently achieved miniaturization of wearable sensors and unobtrusiveness of remote monitoring systems have led to a number of exciting clinical applications.

Wearable sensors have diagnostic, as well as monitoring applications. Their current capabilities include physiological and biochemical sensing, as well as motion sensing (6-7). It is hard to overstate the magnitude of the problems that these technologies might help solve. Physiological monitoring could help in both diagnosis and ongoing treatment of a vast number of individuals with neurological, cardiovascular and pulmonary diseases such as seizures, hypertension, dysrhythmias, and asthma. Home based motion sensing might assist in falls prevention and help maximize an individual’s independence and community participation.

Remote monitoring systems have the potential to mitigate problematic patient access issues. Nearly 20% of those in the US live in rural areas, but only 9% of physicians work in rural areas (8). Access may get worse over time as many organizations are predicting a shortfall in primary care providers as health care reform provides insurance to millions of new patients (9). There is a large body of literature that describes the disparities in care faced by rural residents (8). Compared to those in urban areas, those in rural areas travel 2 to 3 times farther to see a physician, see fewer specialists, and have worse outcomes for such common conditions as diabetes, and heart attack (9-10). Wearable sensors and remote monitoring systems have the potential to extend the reach of specialists in urban areas to rural areas and decrease these disparities.

A conceptual representation of a system for remote monitoring is shown in Figure 6.1. Wearable sensors are used to gather physiological and movement data thus enabling patient’s status monitoring. Sensors are deployed according to the clinical application of interest. Sensors to monitor vital signs (e.g., heart rate and respiratory rate) would be deployed, for instance, when one monitors patients with congestive heart failure or patients with chronic obstructive pulmonary disease undergoing clinical intervention. Sensors for movement data capturing would be deployed, for instance, in applications such as monitoring the effectiveness of home-based rehabilitation interventions in stroke survivors or the use of mobility assistive devices in older adults. Wireless communication is relied upon to transmit patient’s data to a mobile phone or an access point and relay the information to a remote center via the Internet. Emergency situations (e.g., falls) are detected via data processing implemented throughout the system and an alarm message is sent to an emergency service center to provide immediate assistance to patients. Family members and caregivers are alerted in case of an emergency but could also be notified in other situations when the patient requires assistance with, for instance, taking his/her medications. Clinical personnel can remotely monitor patient’s status and be alerted in case a medical decision has to be made.
Despite the potential advantages of a remote monitoring system relying on wearable sensors like the one described above, there are significant challenges ahead before such system can be utilized on a large scale. These challenges include technological barriers such as limitations of currently available battery technology as well cultural barriers such as the association of a stigma with the use of medical devices for home-based clinical monitoring. In the next section of this chapter, Key Enabling Technologies, we discuss technologies enabling the development and deployment of wearable technologies and remote monitoring systems. The Sensing Technology section describes wearable and ambient sensor technologies that are essential components of systems to monitor patients in the home and community settings. The section entitled Applications provides examples of applications of these technologies largely taken from a National Science Foundation initiated study of European projects focused on rehabilitation technology. Future developments that we foresee in the field of remote monitoring of patients’ status via wearable technology are discussed in Conclusions.

**KEY ENABLING TECHNOLOGIES**

Wearable systems for patients’ remote monitoring consist of three main building blocks: 1) the sensing and data collection hardware to collect physiological and movement data, 2) the communication hardware and software to relay data to a remote center, and 3) the data analysis techniques to extract clinically-relevant information from physiological and movement data. Recent advances in sensor technology, microelectronics, telecommunication, and data analysis techniques have enabled the development and deployment of wearable systems for patients’ remote monitoring. Researchers have relied upon advances in the above-mentioned fields to address shortcomings of ambulatory technologies (e.g., Holter monitors) that had previously prevented long-term monitoring of patients’ status in the home and community settings.
The miniaturization of sensors and electronic circuits based on the use of microelectronics has played a key role in the development of wearable systems. One of the major hurdles to the adoption of sensing technology, especially for wearable applications, has been the size of the sensors and front-end electronics that, in the past, made the hardware to gather physiological and movement data too obtrusive to be suitable for long-term monitoring applications. Recent developments in the field of microelectronics have allowed researchers to develop miniature circuits entailing sensing capability, front-end amplification, microcontroller functions, and radio transmission. The flexible circuit shown in Figure 6.2 is an example of such technology and allows one to gather physiological data as well as transmit the data wirelessly to a data logger using a low-power radio.

Figure 6.2. Flexible wireless ECG sensor with a fully functional microcontroller by IMEC. Developments in the field of flexible electronics are expected to lead to the advent of smaller, lighter and more comfortable wearable systems (courtesy of IMEC, The Netherlands).

Particularly relevant to applications in the field of rehabilitation are advances in technology to manufacture microelectromechanical systems (MEMS). MEMS technology has enabled the development of miniaturized inertial sensors that have been used in motor activity and other health status monitoring systems. By using batch fabrication techniques, significant reduction in the size and cost of sensors has been achieved. Microelectronics has also been relied upon to integrate other components, such as microprocessors and radio communication circuits, into a single integrated circuit thus resulting in System-on-Chip implementations (11).

Advances in material science have enabled the development of e-textile based systems. These are systems that integrate sensing capability into garments. The example shown in Figure 3 demonstrates how sensors can be embedded in a garment to collect, for instance, electrocardiographic and electromyographic data by weaving electrodes into the fabric and to gather movement data by printing conductive elastomer-based components on the fabric and then sensing changes in their resistance associated with stretching of the garment due to subject’s movements. Rapid advances in this field promise to deliver technology that will soon allow one to print a full circuit board on fabric.
Figure 6.3. Example of e-textile system for remote, continuous monitoring of physiological and movement data. Embedded sensors provide one with the capability of recording electrocardiographic data (ECG) using different electrode configurations as well as electromyographic (EMG) data. Additional sensors allow one to record thoracic and abdominal signals associated with respiration and movement data associated with stretching of the garment in association with shoulder movements (courtesy of Smartex, Italy).

Health monitoring applications of wearable systems most often employ multiple sensors that are typically integrated into a sensor network either limited to body-worn sensors or integrating body-worn sensors and ambient sensors. In the early days of body-worn sensor networks (often referred to as “body sensor networks”), the integration of wearable sensors was achieved by running “wires” in pockets created in garments for this purpose to connect body-worn sensors. An example of this technology is the MIThril system (12). Such systems by design were not suitable for long-term health monitoring. Recently developed wearable systems integrate individual sensors into the sensor network by relying on modern wireless communication technology. During the last decade, we have witnessed tremendous progress in this field and the development of numerous communication standards for low-power wireless communication. These standards have been developed keeping in mind three main requirements: 1) low cost, 2) small size of the transmitters and receivers, and 3) low power consumption. With the development of IEEE 802.15.4/ZigBee (http://www.zigbee.org/) and Bluetooth (more recently low-power Bluetooth http://www.bluetooth.com), tethered systems have become obsolete. The recently developed IEEE 802.15.4a standard based on Ultra-wide-band (UWB) impulse radio opens the door for low-power, low-cost but high data rate sensor network applications with the possibility of highly accurate location estimation (13).

Most monitoring applications require that data gathered using sensor networks be transmitted to a remote site such as a hospital server for clinical analysis. This can be achieved by transmitting data from the sensor network to an information gateway such as a mobile phone or personal computer. By now most developed countries have achieved almost universal broadband connectivity. For in-home monitoring, sensor data can be aggregated
using a personal computer and transmitted to the remote site over the Internet. Also, the availability of mobile telecommunication standards such as 4G means that pervasive continuous health monitoring is possible when the patient is outside the home environment.

Mobile phone technology has had a major impact on the development of remote monitoring systems based on wearable sensors. Monitoring applications relying on mobile phones such as the one shown in Figure 6.4 are becoming commonplace. Smart phones are broadly available. The global smart phone market is growing at an annual rate of 35% with an estimated 220 million units shipped in 2010 (14). Smart phones are preferable to traditional data loggers because they provide a virtually “ready to use” platform to log data as well as to transmit data to a remote site. Besides being used as information gateways, mobile devices can also function as information processing units. The availability of significant computing power (15) in pocket-sized devices makes it possible to envision ubiquitous health monitoring and intervention applications.

Figure 6.4 Smart phone based ECG monitoring system by IMEC. The Android based mobile application allows low power ECG sensors to communicate wirelessly with the phone. With increasing computational and storage capacity and ubiquitous connectivity, smart phones are expected to truly enable continuous health monitoring (courtesy of IMEC, The Netherlands).

Another advantage of mobile phones is that most devices include now an integrated GPS tracking system thus making it possible to locate patients in case of an emergency. Also, as storage and computation becomes more and more cloud based, health monitoring systems can become low-cost, platform-independent, rapidly deployable and universally accessible (16-17). Monitoring devices can become simpler and cheaper as the computation is pushed to the cloud. This enables users to buy off-the-shelf devices and access customized monitoring applications via cloud-based services (18). Cloud-based systems can prove especially useful for bringing health care services to rural areas. (19). In addition, monitoring applications deployed via the cloud can be easily updated without requiring that the patient installs any software on his/her personal monitoring device, thus making system maintenance quick and cost effective.

Finally, the massive amount of data that one can gather using wearable systems for patient's status monitoring has to be managed and processed to derive clinically-relevant information. Data analysis techniques such as signal processing, pattern recognition, data mining and
other artificial intelligence-based methodologies have enabled remote monitoring applications that would have been otherwise impossible. Although a discussion of the various techniques used to process and analyze wearable sensor data is outside of the scopes of this review paper, one cannot emphasize enough the fact that data processing and analysis techniques are an integral part of the design and development of remote monitoring systems based on wearable technology.

SENSING TECHNOLOGY

In this section of this review paper, we provide information concerning the sensors used in remote monitoring systems. Information gathered using body-worn (i.e., wearable) sensors is collected ubiquitously thanks to the technologies mentioned in the previous section of this review paper. Wearable sensors are often combined with ambient sensors when subjects are monitored in the home environment as schematically shown in Figure 6.5. The combination of wearable and ambient sensors is of great interest in several applications in the field of rehabilitation. For instance, when monitoring older adults while deploying interventions to improve balance control and reduce falls, one would be interested in using wearable sensors to track motion and vital signs. Specifically-designed data analysis procedures would then be used to detect falls via processing of motion and vital sign data. In this context, ambient sensors could be used in conjunction with wearable sensors to improve the accuracy of falls detection and, most importantly, to enable the detection of falls even at times when subjects do not wear the sensors. This section provides a summary of the state of the art in wearable sensor technology and the development of ambient sensors.

![Figure 6.5](image-url)

Figure 6.5. Ambient sensors can unobtrusively monitor individuals in the home environment. Ambient sensors can monitor activity patterns, sleep quality, bathroom visits etc. and provide alerts to caregivers when abnormal patterns are observed. Such sensors are expected to make the home of the future smarter and safer for patients living with chronic conditions.

**Wearable Sensors**

Physiological measures of interest in rehabilitation include heart rate, respiratory rate, blood pressure, blood oxygen saturation, and muscle activity. Parameters extracted from such measures can provide indicators of health status and have tremendous diagnostic value. Until
recently, continuous monitoring of physiological parameters was possible only in the hospital setting. But today, with recent developments in the field of wearable technology, the possibility of accurate, continuous, real-time monitoring of physiological signals is a reality.

Integrating physiological monitoring in a wearable system often requires ingenious designs and novel sensor locations. For example, Asada et al. (20) presented a ring sensor design for measuring blood oxygen saturation (SpO2) and heart rate. The ring sensor was completely self-contained. Worn on the base of the finger (like a ring), it integrated techniques for motion artifact reduction that were designed to improve measurement accuracy. Applications of the ring sensor ranged from the diagnosis of hypertension to the management of congestive heart failure. A self-contained wearable cuff-less photoplethysmographic (PPG) based blood pressure monitor was subsequently developed by the same research group (21). The sensor integrated a novel height sensor based on two MEMS accelerometers for measuring the hydrostatic pressure offset of the PPG sensor relative to the heart. The mean arterial blood pressure was derived from the PPG sensor output amplitude by taking into account the height of the sensor relative to the heart.

Another example of ingenious design is the system developed by Corbishley et al. (22) to measure respiratory rate using a miniaturized wearable acoustic sensor (i.e., microphone). The microphone was placed on the neck to record acoustic signals associated with breathing, which were band-pass filtered to obtain the signal modulation envelope. By developing techniques to filter out environmental noise and other artifacts, the authors managed to achieve accuracy greater than 90% in the measurement of breathing rate. The authors also presented an algorithm for the detection of apneas based on the above-described sensing technology.

In recent years, physiological monitoring has benefited significantly from developments in the field of flexible circuits and the integration of sensing technology into wearable items (23). An ear-worn, flexible, low-power PPG sensor for heart rate monitoring was introduced by Patterson et al. (24). The sensor is suited for long-term monitoring due to its location and unobtrusive design. Although systems of this type have been with promising results, additional work appears to be necessary to achieve motion artifact reduction (25-26). Proper attenuation of motion artifacts is essential to the deployment of wearable sensors. Some of the problems due to motion artifacts could be minimized by integrating sensors into tight fitting garments. A comparative analysis of different wearable systems for monitoring respiratory function was presented by Lanata et al. (27). The analysis showed that piezoelectric pneumography performs better than spirometry. Nonetheless, further advances in signal processing techniques to mitigate motion artifacts are needed.

Biochemical sensors have recently gained a great deal of interest among researchers in the field of wearable technology. These types of sensors can be used to monitor the bio-chemistry as well as levels of chemical compounds in the atmosphere (e.g., to facilitate monitoring people working in hazardous environments). From a design point of view, biochemical sensors are perhaps the most complex as they often require collection, analysis and disposal of body fluids. Advances in the field of wearable biochemical sensors has been slow, but research has recently picked up pace due to the development of micro and nano fabrication technologies (11). For example, Dudde et al. (28) developed a minimally-invasive wearable closed-loop quasi-continuous drug infusion system that measures blood glucose levels and infuses insulin automatically. The glucose monitor consists of a novel silicon sensor that continuously measures glucose levels using a microperfusion technique and continuous infusion of insulin is achieved by a modified advanced insulin pump. The device has
integrated Bluetooth communication capability for displaying and logging data and receiving commands from a personal digital assistant (PDA) device.

An array of bio-chemical sensors has been developed as part of the BIOTEX project, supported by the European Commission. Specifically, the BIOTEX project deals with the integration of bio-chemical sensors into textiles for monitoring body fluids. Within this project, researchers have developed a textile based fluid collecting system and sensors for in-vitro and in-vivo testing of pH, sodium and conductivity from body sweat (29-30). By in vitro and in vivo testing of the wearable system, researchers have shown that the system can be used for real-time analysis of sweat during physical activity. As part of a similar project, ProeTEX, Curone et al. (31) developed a wearable sensorized garment for firefighters, which integrates a CO₂ sensor with sensors to measure movement, environmental and body temperature, position, blood oxygen saturation, heart rate and respiration rate. The ProeTEX system can warn the firefighters of a potentially dangerous environment and also provide information about their well being to the control center.

There has been a growing interest in the development of self contained lab-on-a-chip systems. Such systems can revolutionize point-of-care medical testing and diagnosis by making testing and diagnosis fast, cheap and easily accessible. Wang et al. (32) developed a system-on-chip (SOC), which integrates a pH and temperature sensor, for remote monitoring applications. Their SOC includes generic sensor interface, ADC, microcontroller, a data encoder and a frequency-shift keying RF transmitter. Similarly, Ahn et al. (33) developed a low-cost disposable plastic lab-on-a-chip device for biochemical detection of parameters such as blood gas concentration and glucose. The biochip contains an integrated biosensor array for detecting multiple parameters and uses a passive microfluidic manipulation system instead of active microfluidic pumps.

Finally, applications in rehabilitation of remote monitoring systems relying on wearable sensors (34) have largely relied upon inertial sensors for movement detection and tracking. Inertial sensors include accelerometers and gyroscopes. Often, magnetometers are used in conjunction with them to improve motion tracking. Today, movement sensors are inexpensive, small and require very little power, making them highly attractive for patient monitoring applications.

**Ambient Sensors**

Examples of instrumented environments include sensors and motion detectors on doors that detect opening of, for instance, a medicine cabinet, refrigerator, or the home front door (35). This approach has the characteristic of being totally unobtrusive and of avoiding the problem of misplacing or damaging wearable devices. “Smart home” technology that includes ambient and environmental sensors has been incorporated in a variety of rehabilitation related applications. One such application is ambient assisted living (AAL) that refers to intelligent systems of health assistance in the individual’s living environment (36). It covers concepts, products and services that interlink and improve new technologies and the social environment. AAL technologies are embedded (distributed throughout the environment or directly integrated into appliances or furniture), personalized (tailored to the users’ needs), adaptive (responsive to the user and the user’s environment) and anticipatory (anticipating users’ desires as far as possible without conscious mediation). Stefanov et al. provide a summary of the various types of devices that can be installed in smart homes, and the associated target user populations (37).
Remote monitoring of patient status and self-management of chronic conditions represent the most often pursued applications of AAL technologies. The combination of wearable and ambient sensors is being explored and prototypes are being developed. A relevant application in the field of rehabilitation relates to the identification of a patient’s patterns of activity and on providing suggestions concerning specific behaviors and exercises for self-management of health conditions. In this context, information gathered using wearable sensors is augmented by information gathered using ambient sensors. Data collected using, for instance, body-worn accelerometers could be augmented by motion sensors distributed throughout the home environment to determine the type and intensity of the activities performed by an individual. Accordingly, an individual undergoing monitoring who suffers from, for instance, chronic obstructive pulmonary disease could receive feedback about not overexerting himself/herself and the performance of rehabilitation exercises that would be prescribed in order to maintain a satisfactory functional level.

Innovative solutions for recognizing emergencies in the home can be achieved through a combination of monitoring vital parameters of the person living at home as well as supervising the conditions of domestic appliances (38). Personal safety can be improved if vital data measures are combined with the monitoring and control of devices in the household. Remote monitoring of devices of potential sources of danger increases the individual sense of security and can make life much easier and more comfortable (e.g., checking whether the stove or the coffee machine has been switched off and to be able to turn them off remotely if necessary). Sensors embedded in electrical devices and in doors and windows may be integrated into an easy-to-use house-control system that also provides improved personal safety and security (39). An intelligent system may issue a reminder to switch off devices and/or lights in an apartment or not to forget the pill box or the mobile terminal needed to inform friends or neighbors when necessary.

Several smart home projects are currently ongoing including the Technology Research for Independent Living (TRIL) Centre in Ireland [www.trilcentre.org](http://www.trilcentre.org), the TigerPlace [http://eldertech.missouri.edu/overview.htm](http://eldertech.missouri.edu/overview.htm) in Missouri, the Oregon Center for Aging and Technology (ORCATECH) [http://www.ohsu.edu/xd/research/centers-institutes/neurology/alzheimers/about/orcatech.cfm](http://www.ohsu.edu/xd/research/centers-institutes/neurology/alzheimers/about/orcatech.cfm) in Oregon, the University of Rochester Center for Future Health [http://www.futurehealth.rochester.edu/smart_home/](http://www.futurehealth.rochester.edu/smart_home/), The University of Florida Gator-Tech Smart House [http://www.rerc.ufl.edu/](http://www.rerc.ufl.edu/), the University of Virginia MARC Smarthouse [http://smarthouse.med.virginia.edu](http://smarthouse.med.virginia.edu), the Georgia Institute of Technology Aware Home [http://www.cc.gatech.edu/fce/ahri/](http://www.cc.gatech.edu/fce/ahri/), and the Massachusetts Institute of Technology PlaceLab [http://architecture.mit.edu/house_n/](http://architecture.mit.edu/house_n/).

**APPLICATIONS**

This section of this review paper provides details about applications of wearable and ambient sensors and systems that are relevant to the field of rehabilitation. The material is organized in five sub-sections devoted to summarizing applications of wearable and ambient sensors and systems focused on: 1) health and wellness monitoring, 2) safety monitoring, 3) home rehabilitation, 4) assessment of treatment efficacy, and 5) early detection of disorders.

**Health & Wellness Monitoring**

As the world population is aging and health care costs are increasing, several countries are promoting “aging in place” programs which allow older adults and individuals with chronic conditions to remain in the home environment while they are remotely monitored for safety and for the purpose of facilitating the implementation of clinical interventions.
Monitoring activities performed by older adults and individuals with chronic conditions participating in “aging in place” programs has been considered a matter of paramount importance. Accordingly, extensive research efforts have been made to assess the accuracy of wearable sensors in classifying activities of daily living (ADL). Mathie et al. (40) showed the feasibility of using accelerometers to identify the performance of ADL by older adults monitored in the home environment. Sazonov et al. (41) developed an in-shoe pressure and acceleration sensor system that was used to classify activities including sitting, standing, and walking with the ability of detecting whether subjects were simultaneously performing arm reaching movements. Giansanti et al. (42) developed an accelerometer-based device designed for step counting in patients with Parkinson's disease. Aziz et al. (43) used wearable sensors to monitor the recovery of patients after abdominal surgery. Several research projects have suggested that activity monitoring for wellness applications has great potential to increase exercise compliance in populations at risk. For example, wearable technology has been used to monitor physical activities in obese individuals and to facilitate the implementation of clinical interventions based on encouraging an active and healthy lifestyle (44-47).

Long-term monitoring of physiological data can lead to improvements in the diagnosis and treatment, for instance, of cardiovascular diseases. Commercially available technology provides one with the ability to achieve long-term monitoring of heart rate, blood pressure, oxygen saturation, respiratory rate, body temperature and galvanic skin response. Clinical studies are currently carried out to evaluate and validate the performance of wearable sensor platforms to monitor physiological data over long periods of time and improve the clinical management of patients, for instance, with congestive heart failure (48-49).

Several ongoing studies are focused on clinically assessing wearable systems developed as part of major research projects. For instance, LiveNet, a system developed at the MIT Media Laboratory that measures 3-D acceleration, ECG, EMG, and galvanic skin conductance, is under evaluation for monitoring Parkinsonian symptoms and detecting epileptic seizures (50). LifeGuard is a custom data logger designed to monitor health status of individuals in extreme environments (space and terrestrial) (51). The system has undergone testing in hostile environments with good results. As part of the FP5 program of the European Commission, a project named AMON resulted in the development of a wrist-worn device capable of monitoring blood pressure, skin temperature, blood oxygen saturation, and ECG. The device was developed to monitor high risk patients with cardio-respiratory problems (52). Other projects worth mentioning that have been carried out as part of different programs of the European Commission are: MyHeart (53), WEALTHY (54-55), and MagIC (56-57). These projects led to the development of garment-based wearable sensors aiming at general health monitoring of people in the home and community settings.

Safety Monitoring

A number of devices have been developed for safety monitoring applications, such as detecting falls and relaying alarm messages to a caregiver or an emergency response team. The Life Alert Classic by Life Alert Emergency Response Inc. (58) and the AlertOne medical alert system (59) are examples of commercially-available devices designed for safety monitoring. These devices are simple emergency response devices consisting of a pendant or watch with a push button. Pressing the button, one has the ability to wirelessly relaying an alarm message to operators located in a remote call center. Other systems integrate sensors into the body-worn unit. For instance, the Wellcore system (60) employs advanced microprocessors and accelerometers to monitor the body's position. The system detects falls as distinct events from normal movements, and automatically relays a message to the
designated response center or nurse call station. Another device in this category is the MyHalo™ by Halo Monitoring™. The system is worn as a chest strap and detects falls while it monitors heart rate, skin temperature, sleep/wake patterns, and activity levels [61]. The BrickHouse system [62] is equipped with an automatic fall detector and a manual panic button. Finally, among the numerous commercially-available systems, it is worth mentioning the ITTM EasyWorlS, a system based on a mobile phone that is equipped with balance sensors which trigger automatic dialing SOS numbers if the system detects a sudden impact [63].

Reliable detection of falls via wearable sensors has been achieved by many research groups. Researchers at CSEM [64] developed an automatic fall detection system in the form of a wrist watch. The device implements functionalities such as wireless communication, automatic fall detection, manual alarm triggering, data storage, and a simple user interface. Even though the wrist is a challenging sensor location to detect a fall event, researchers on the project achieved 90% sensitivity and 97% specificity in the detection of simulated falls. Bourke et al. [65] took an alternative approach and used a tri-axial accelerometer embedded in a custom-designed vest to detect falls. Bianchi et al. [66] used instead a barometric pressure sensor as a surrogate measure of altitude to discriminate real fall events from normal activities of daily living. When tested in a cohort of 20 young healthy volunteers, the proposed method demonstrated considerable improvements in sensitivity and specificity compared to an existing accelerometer-based technique. Finally, among the numerous systems developed by researchers to detect falls, it is worth mentioning that Lanz et al. [67] developed SmartFall, a system that relies on an accelerometer embedded in a cane to detect falls. The authors argued that canes are assistive devices that people widely use to overcome problems associated with balance disorders and therefore that embedding the system in the cane is a very appealing solution to achieve unobtrusive monitoring while assuring safety of individuals.

Recent advances in smart phone technology have led to their use in fall detection systems. Often, these systems combine fall detection with localization of the person who fell via a GPS-based method [68-69]. Yavuz et al. [70] developed a fall detection system that relied upon the accelerometers available in smart phones and incorporated different algorithms for robust detection of falls. Their implementation leveraged the characteristics of the Android 2 operating system. The authors developed advanced signal processing techniques to achieve high accuracy of falls detection. Besides, the system provided subject's location using Google Maps. Using this approach, a warning about the fall and the location of the subject undergoing monitoring is transmitted to a caregiver or family member via SMS, email and Twitter messages. Ongoing research is geared toward the prevention of fall-related injuries. Numerous systems have been developed by leveraging airbag technology [71-74]. These systems rely upon wearable accelerometers and gyroscopes to trigger the inflation of the airbag when a fall is detected. Although these systems can potentially help to prevent fall-related injuries, further development is needed to miniaturize the airbag system that provides protection to the subject before an impact occurs.

Individuals with movement impairments require more specific approaches to detect or prevent falls. Bachlin et al. [75] developed a system to detect freezing of gait (FOG), a commonly found gait symptom in Parkinson's disease that is highly related to falls. The system was designed to provide subjects with a rhythmic auditory signal aimed to stimulate the patient to resume walking when a FOG episode is detected. Smith and Bagley [76] developed a system to be used in children with difficulty in walking, which is known to be associated with frequent falls. They collected tri-axial accelerometer data and digital video recordings for over 50 hours from 35 children with cerebral palsy and 51 control subjects.
The dataset was used to develop algorithms for automatic real-time processing of the accelerometer signals to monitor a child's level of activity and to detect falls (76). Sposaro et al. (77) focused their attention on older adults with dementia. These subjects require frequent caregivers' assistance to accomplish standard activities of daily living. The authors relied upon an Android application, iWander, which uses GPS and communication functions available via the smart phone, to provide tracking of subjects' location and assistance when needed. The system was shown to improve functional independence among dementia patients while decreasing the stress put on caregivers.

Another application of wearable sensors and systems that has received a great deal of attention among researchers and clinicians is the detection of epileptic seizures. Primary and secondary compulsive epileptic crises (EC) cause a sudden loss of consciousness. These events are accompanied by stereotypical movements that one can observe in association with characteristic changes in the electroencephalogram (EEG). During the acute phase, the subject is completely unable to interact with the environment. To detect EC, systems and methods relying upon wearable sensors have been proposed and evaluated. Electroencephalographic (EEG) sensors (78), 3D accelerometers on a wrist (79), combination of EMG and accelerometers (80), and electrodermal activity (EDA) (81) have been used to develop methods to distinguish EC from normal motor activities. Dalton et al. (82) used a Nokia N810 and the SHIMMER platform of wearable sensors to detect seizure events.

An interesting recent development is the integration of various sensors and systems in a network for comprehensive safety monitoring and smart home health care applications. AlarmNet is an example of such systems. It collects and analyzes various data streams to monitor a resident's overall wellness, known medical conditions, activities of daily living, and emergency situations. The whole project deals not only with wearable sensing technology but also with security/privacy issues in patient's data transfer, and real-time data streaming (83). A major contribution toward the development of new solutions in the field of wearable and ambient sensors and their integration in comprehensive safety monitoring and smart home health care applications is provided by the European AALIANCE (Ambient Assisted Living Innovation Alliance). AALIANCE is an active project that includes many research institutes, companies, and universities in Europe. The project aim is to define the necessary future R&D steps toward developing Ambient Assisted Living (AAL) solutions. The project builds infrastructure for practical applications of wearable technologies such as telemonitoring of patient's status and self-management of chronic diseases.

Finally, a great deal work has been done toward developing wearable systems to monitor individuals working in hostile environments in response to emergency situations. The ProeTEX project, carried out as part of the FP6 program of the European Commission, is an example of such work. The project resulted into the development of a new generation of smart garments to monitor emergency-disaster personnel (see Figure 6.6). These garments enable the detection of health status parameters of the users and environmental variables such as external temperature, presence of toxic gases, and heat flux passing through the garments. Extensive testing of the garments is being carried out both in laboratories, specialized in physiological measures, and in simulated fire-fighting scenarios (31, 84).
Figure 6.6. The ProeTEX project aims to develop smart garments for emergency responders. These smart garments integrate sensors, communication, processing and power management directly into the garment to continuously monitor emergency responders (courtesy of Smartex, Italy).

Home Rehabilitation

An emerging area of application of wearable technology is the use of wearable sensors to facilitate the implementation of home-based rehabilitation interventions. Systems that aim to facilitate the implementation of rehabilitation exercise programs often leverage the combination of sensing technology and interactive gaming or virtual reality (VR) environments. For example, The Rehabilitation Engineering Research Center at the University of Southern California is building on VR gaming to address compliance and motivation challenges. VR simulation technology using specialized interface devices has been applied to improve motor skill rehabilitation of functional deficits including reaching, hand function and walking. It has been proposed that such VR-based activities could be delivered in the home via a telerehabilitation approach to support patients’ increased access to rehabilitation and preventive exercise programming. When this is put in an interactive game-based context, the potential exists to enhance the engagement and motivation needed to drive neuroplastic changes that underlie motor process maintenance and improvement. However, home-based systems need to be affordable and easy to deploy and maintain, while still providing the interactional fidelity required to produce the meaningful motor activity required to foster rehabilitative aims and promote transfer to real world activities. An example of such systems is the Valedo system by Hocoma AG shown in Figure 7.7.
Figure 6.7. The Valedo low back pain therapy system by Hocoma AG combines wireless wearable motion sensors with interactive games to provide an engaging way to perform therapeutic exercises. Patients can set therapy goals, receive feedback on their performance and keep track of their progress (courtesy of Hocoma, Switzerland).

The Valedo system is a medical back training device, which improves patient’s compliance and allows one to achieve increased motivation by real time augmented feedback based on trunk movements. It transfers trunk movements from two wireless sensors into a motivating game environment and guides the patient through exercises specifically designed for low back pain therapy. To facilitate challenging the patient and achieving efficient training, the exercises can be adjusted according to the patient’s specific needs.

Several other systems are currently under development. For instance, GE Healthcare is developing a wireless medical monitoring system that is expected to allow one to gather physiological and movement data thus facilitating rehabilitation interventions in the home setting. Another example of home-based rehabilitation technology is the Stroke Rehabilitation Exerciser developed by Philips Research (85). The Stroke Rehab Exerciser coaches the patient through a sequence of exercises for motor retraining, which are prescribed by the physiotherapist and uploaded to a patient unit. A wireless inertial sensor system records the patient’s movements, analyzes the data for deviations from a personal movement target and provides feedback to the patient and the therapist.

Major efforts have been made by European groups to develop systems suitable for home-based interventions that rely on wearable technology. A project that was part of the MyHeart initiative (86-87) led to the development of a sensorized garment-based system to facilitate rehabilitation interventions in the home setting. The system allows patients to increase the amount of motor exercise they can perform independently, providing them with a real-time feedback based on wearable sensors embedded in the garment across the upper limb and trunk. A dynamic time warping algorithm allows for the recognition of correct and incorrect motor exercises. After the feedback phase, data are stored in a central location for review and statistics. Workstations can be installed either at home or at the hospital to support patients, regardless of their location. Another major initiative in the field is the intervention program set in place by the TRIL Centre in Dublin, Ireland. The TRIL Centre brings together industry
and academia to conduct research in older adults and examine how technology can enable health and social care. Projects at the TRIL Centre include:

- A program using a remote system to assess and improve cognitive functions among older adults in their homes.
- Building Bridges, a social networking program that allows individuals to communicate with their families and with others on the network and that engages older adults in training exercises.
- Technology to integrate online day reconstruction, psychometric measures, ecological assessments, and biological markers in real-world situations. For example, this platform has integrated heart-rate and GPS monitoring to assess the reaction in traffic.
- Clarity, a large-scale program in which computer scientists and engineers are developing technology that senses and integrates data on individuals’ preferences, intentions, and physical status.

Other projects carried out by European groups that are worth mentioning are the TeleKat project and the “Auxilium Vitae Volterra” at Rehabilitation Centre–Scuola Superiore Sant’Anna. The TeleKat project (Aalborg University, Aalborg, Denmark) is applying User Driven Innovation to develop wireless tele-homecare technology enabling patients with chronic obstructive pulmonary disease to perform self-monitoring of their status, and to maintain rehabilitation activities in their homes. The Tele-rehabilitation project “Auxilium Vitae Volterra” at Rehabilitation Centre–Scuola Superiore Sant’Anna is a cardiac rehabilitation program that leverages the use of a sensor-based system to remotely monitor patients in their home. The system includes a computerized cycle ergometer, a wireless diagnostic 12-lead ECG, a sensor for blood oxygen saturation, a non-invasive blood pressure measurement system, and a high-performance videoconferencing system.

Assessment of Treatment Efficacy

A quantitative way of assessing treatment efficacy can be a valuable tool for clinicians in disease management. By knowing what happens between outpatient visits, treatment interventions can be fine-tuned to the needs of individual patients (88). Another important application would be for use in randomized clinical trials. By gathering accurate and objective measures of symptoms, one could reduce the number of subjects and the duration of treatment required to observe an effect in a trial of a new therapy.

In patients with Parkinson’s disease (PD), careful medication titration, based on detailed information about symptom response to medication intake, can significantly improve the patient’s quality of life. Medication titration in patients with late stage PD is often challenging as fluctuations in a patient’s motor symptom manifest over several hours and hence cannot be observed in a typical outpatient appointment (often lasting no more than 30 min). Patient dairies are unreliable due to perceptual bias and inaccurate reporting about motor status. The above-mentioned issues limit the ability of physicians to optimally adjust medication dosage and to test new compounds for the treatment of PD. The use of a sensor-based system to monitor PD symptoms is a promising approach to improve the clinical management of patients in the late stages of the disease. Major PD symptoms have typical motor characteristics which can be captured using motion sensors such as accelerometers. Manson et al. (89) used a portable tri-axial accelerometer placed on the shoulder to monitor severity of dyskinesias in PD patients. Dyskinesias are a side-effect of medication intake and they can cause significant discomfort to patients. The authors showed that there is a correlation between accelerometer output and severity of dyskinesia in patients with PD. The ability to
estimate the severity of symptoms via processing sensor data recorded during activities of daily living is important for practical applications. Thielgen et al. (90) showed that accelerometers can be used to automatically quantify tremor severity scores via 24 hr ambulatory home monitoring in patients with PD. Gait impairments such as shuffling and freezing are characteristics of PD. Paquet et al. (91) have explored the correlation between gait parameters and motor scores in patients with PD. The authors used a biaxial accelerometer mounted on the lower back to measure gait features such as stride frequency, step symmetry and stride regularity. Strong correlation was found between walking regularity and motor scores capturing the severity of PD symptoms. Movement sensors can also be used to automate clinical testing procedures. Salarian et al. (92) and Weiss et al. (93) have proposed instrumented versions of the timed up-and-go test for identifying gait impairments due to PD. They have shown that instrumented tests lead to an improved sensitivity to gait impairments compared to observation methods. Besides, sensor-based methods can also be extended to long term home monitoring. Based on this body of work, an ambulatory gait analysis system, based on wearable accelerometers, for patients with PD has been proposed by Salarian et al. (94).

Intensive long-term rehabilitation post-stroke is an important factor in ensuring motor function recovery. Tracking changes in motor function can be used as a feedback tool for guiding the rehabilitation process. Uswatte et al. (95-96) have shown that accelerometer data can provide objective information about real-world arm activity in stroke survivors. In their study, 169 stroke survivors undergoing constraint-induced movement therapy wore an accelerometer on both wrists for a period of 3 days. The results indicated good patient compliance and showed that by simply taking the ratio of activity recorded on impaired and unimpaired arm using accelerometers, one can gather clinically-relevant information about upper extremity motor status. Prajapati et al. (97) performed a similar study for the lower extremities. The authors used two wireless accelerometers placed on each leg to monitor walking in stroke survivors. Results showed that the system was able to monitor the quantity, symmetry and major biomechanical characteristics of walking. Finally, Patel et al. (98) showed that, using accelerometers placed on the arm, it is possible to derive accurate estimates of upper extremity functional ability. The authors used a small subset of tasks from the Wolf Functional Ability Scale (FAS) to derive estimates of the total FAS score via analysis of the accelerometer data. As the tasks selected from the FAS closely resemble tasks performed during the performance of activities of daily living, such a system could be used for unobtrusively monitoring functional ability in the patients’ home environment.

Early Detection of Disorders

An area of growing interest in the field of wearable technology is the use of wearable sensors and systems to achieve early detection of changes in patient’s status requiring clinical intervention. An example of this type of application of wearable technology is the management of patients with chronic obstructive pulmonary disease. A major goal in the clinical management of patients with chronic obstructive pulmonary disease is to achieve early detection of exacerbation episodes. Exacerbations, commonly defined to be episodes of increased dyspnea, cough, and change in amount and character of sputum, are a prominent part of the natural history of chronic obstructive pulmonary disease, resulting in functional impairments and disability. Early detection and treatment of exacerbations are important goals to prevent worsening of clinical status and the need for emergency room care or hospital admission. Remote monitoring systems can play an important role in early detection of trends in patients’ health status that point towards an exacerbation event.
One way to approach the problem of achieving early detection of exacerbation episodes is to detect changes in the level of activity performed by a patient (99-100) and assume that a decrease in activity level would be indicative of the likelihood of a worsening of the clinical status of the individual undergoing monitoring. Atallah et al. (101) have developed an ear worn sensor that can be used for activity monitoring in patients with chronic obstructive pulmonary disease. Using sophisticated machine learning algorithms, the authors were able to identify several different types of physical activities and the intensity of those activities from a single ear worn sensor. Steele et al. (102) and Belza et al. (103) measured human movement in three dimensions over 3 days and showed that the magnitude of the acceleration vector recorded in patients with chronic obstructive pulmonary disease was correlated with measures of patient’s status such as the six-minute walk distance, the FEV1 (Forced Expiratory Volume in 1 sec), the severity of dyspnea, and the Physical Function domain of health-related quality of life scale. Hecht et al. (104) presented an algorithm for a minute-by-minute analysis of patients’ activity level, based on data recorded using a single unit. The system was tested in 22 patients who were monitored over a period of 14 days. The authors also implemented a simple empirically developed algorithm to determine if the subject was wearing the device thus providing a handle on compliance. Another interesting observation from the same study was that subjects tended to increase their activity level during the first few days of monitoring. This observation suggests that it is important that monitoring, if performed periodically, be performed periods of time sufficient to avoid observing transitory effects introduced by the fact that the subject is aware of being monitored. However, the results summarized above were limited by the inability to identify the exercise or intensity of the activity performed.

Combining physiological sensors with activity monitors is a promising way of identifying not only the type of activity performed by subjects undergoing monitoring but also the intensity with which the activity was performed. Furlanetto et al. (105) and Patel et al. (106) showed that a multi-sensor system, which measured galvanic skin response, heat flow and skin temperature in addition to motion, provided accurate estimates of energy expenditure. Although not accurate at step counting, the multi-sensor system outperformed the step counters in estimating energy expenditure at slow walking speeds. With the development of wearable sensors and systems (107-108), which can be used for simultaneous monitoring of activities and several physiological parameters such as heart rate, respiration and oxygen saturation, it becomes possible to envision a more comprehensive status monitoring of patients with chronic obstructive pulmonary disease.

Another condition that has been studied extensively in the context of field monitoring is dementia. Dementia refers to a collection of symptoms that describe impairment in cognitive function. More than 30 million people suffer from dementia worldwide and account for approximately $315 billion in medical care costs. Most of these costs are attributed to the use of nursing care facilities. Allowing patients to stay at home longer can lead to significant savings in medical care costs. Remote monitoring can play an important role in the management of patients with dementia. Systems that can assist these patients with remembering daily activities and monitoring daily behavior for early signs of deterioration can allow patients to live independently longer. Such systems range from monitoring activities of daily living to tracking medication compliance to monitoring changes in social behavior. In this context, it is of particular interest to assess the severity of dementia and its changes over time. Wang et al. (109) developed a remote monitoring system for analysis of sleep patterns in patients with early dementia. By performing objective monitoring of quality, quantity and rhythm of sleep the authors aimed to identify the level of cognitive impairment
of individuals undergoing monitoring. The monitoring system included passive infrared (PIR) and bed pressure sensors. Preliminary results suggested that the sleep patterns of patients suffering from mild dementia are of lower quality when compared to control subjects. Other efforts to achieve the goal of assessing the progression of dementia have been made by other research groups. Among others, Jimison et al. (110) developed a simple monitoring system based on the modified version of a standard computer game for early detection of dementia. Another important factor in this patient population is that the monitoring system must be totally unobtrusive and if possible collect information in a transparent way without patient intervention due to their cognitive impairment. To achieve this goal, Hayes et al. (111) developed a home monitoring system based on distributed infrared motion sensors and contact sensors. The system was used to assess activity patterns in 14 individuals with mild cognitive impairment. The sensor system was completely unobtrusive. The results of the study showed that daily activity patterns of individuals with cognitive impairments tend to be more variable than healthy controls.

CONCLUSIONS

Whereas the first decade of research in the field of wearable technology was marked by an emphasis on the engineering work needed to develop wearable sensors and systems (112), recent work has been focused on the application of such technology on health and wellness. This consideration was the basis for this review paper. This paper summarized enabling technologies developed over the past decade (6) and put a great deal of emphasis on surveying studies focused on the deployment of wearable sensors and systems in the context of a concrete clinical applications, with main focus on rehabilitation. The interest of researchers and clinicians for pursuing applications of wearable sensors and systems has caused a shift in the field of wearable technology from the development of sensors to the design of systems. Consequently, we have witness a great deal of work toward the integration of wearable technologies and communication (14) as well as data analysis technologies so that the goal of remote monitoring individuals in the home and community settings could be achieved. Besides, when monitoring has been performed in the home, researchers and clinicians have integrated ambient sensors in the remote monitoring systems. We have also witnessed a growing interest for the emerging need for establishing a telepresence in the home setting to implement clinical interventions. We envision that home robots will soon be integrated into home monitoring systems to facilitate achieving the goal of establishing a telepresence in the home environment (7). Research toward achieving remote monitoring of older adults and subjects undergoing clinical interventions will soon face the need for establishing business models to cover the costs and identify reimbursement mechanisms for the technology and its management. We envision that addressing costs and reimbursement problems will be essential to assure that wearable sensors and systems deliver on their promise of improving the quality of care provided to older adults and subjects affected by chronic conditions via remote monitoring of wellness and health in the home and community settings.

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INTRODUCTION

Over 40 million Americans live with a disability. According to the 2007 IOM report on disability, disability in the form of limited activities and restricted participation in social life is not an unavoidable result of injury and chronic disease (1). It results, in part, from choices society makes about working conditions, health care, transportation, housing, and other aspects of our environment. This is a powerful statement that places the cause of disability on society. According to the ICF model (2), disability results from an interaction between an individual and their environment. Technology for mobility can be a very important mediator of this interaction. A simple example is the well accepted assistive technology for mobility, the wheelchair. In its simplest form, the wheelchair enables an individual who cannot walk to travel from point A to point B. For the task of going from point A to B in an airport, this technology is nearly perfect. However, for getting on the airplane, it fails. The chair will not fit down the aisle and a transfer is needed to get out of the chair and into an airplane seat.

Could additional technology solve this problem in a way that is seamless to the wheelchair user? The answer is undoubtedly yes; however, the technology that enables an individual with lower limb paralysis to transfer into an airplane seat does not exist. One could easily argue that with existing materials a device could easily be fabricated, so why don't we have such a device? One answer is that society has not chosen to invest the money needed to provide true accessibility. While this answer is true, the other truth is that groups are needed that have the will and expertise to focus on fixing this and the myriad of problems faced by individuals with mobility impairment. At present there is a shortage of well trained researchers working on these problems (2). This shortage has been recognized by major research funding agencies in the United States who have set up various funding mechanisms to promote research in the critical area.

As part of a National Science Foundation (NSF) sponsored trip, a group of primarily senior scientists traveled to a number of the best rehabilitation research laboratories in Western Europe. The purpose of the trip was to explore cutting edge research in the area of technology to improve mobility. Other papers in this series explore specific technology. The purpose of this paper is to describe the education, research, technology transfer, and cooperative models that appear to have the greatest likelihood of successfully tackling the issue of technology to improve mobility. Ideally better models in each of these areas will lead to an increased number of researchers who are more productive. There will be increased international collaboration that will allow for better research with small and/or disadvantaged populations. And the research completed will lead to changes in clinical care that positively impact individuals with impair mobility. Below we discuss the four areas listed above and provide examples of what we believe to be best structures.
METHODS

A multidisciplinary team of primarily senior researchers was assembled by the NSF working in conjunction with the World Technology Evaluation Center (WTEC, http://www.wtec.org/ accessed 3/12/2012). The team consisted of two scientists working in mobility technology who had mobility impairments and were consumers of technology, two physicians specializing in Physical Medicine and Rehabilitation, five individuals with engineering degrees, one physical therapist, and one exercise physiologist with a PhD in Rehabilitation Sciences. The team came from major universities across the United States and also contained two individuals working for funding agencies. The team worked to identify European laboratories that they felt were leaders in the field and also spanned a variety of rehabilitation technology approaches. Based on the team’s findings, the WTEC organization put together an itinerary for laboratory site visits. The trip was limited to one week and therefore multiple outstanding laboratories were likely not included. In addition to visiting universities, the team also visited private companies and funding agencies.

The team gave each site a questionnaire to complete prior to the trip, and answers to the questionnaire are part of the information used to present the results below. The team broke up into two groups that traveled separately. At each location the purpose of the visit was presented. The trip covered 8 countries and approximately 30 labs. Presented below are summary findings with illustrative examples of what the team believes worked well from education, research, technology transfer, and across-country collaboration perspectives. In addition, critical gaps are identified.

WHAT WORKED

Education

To advance the field of mobility related research, structures are needed to support the creation of the next generation of scientist working in this area. A common theme across multiple programs that address more than just education is the need for multidisciplinary teams. The best educational programs embraced a multidisciplinary approach during schooling, with students studying in different areas working as a team. This approach also leads to multidisciplinary mentorship. An example of an innovative approach to interdisciplinary education is provided by the Imperial College in London. At this institution there is a course entitled REHANDFUN. In this course a multidisciplinary group of students from biology, engineering, and computer science receive a kit and are instructed to develop a therapeutic game. The intent of the course is to develop student knowledge of rehabilitation technology, human center design, and teamwork. The Arts Et Metiers ParisTech provides another example. The school works with Paris Descartes Medical University in an international master’s degree program in Biomedical Engineering. In this program half of the students admitted have an engineering background and half have a clinical background. This combination assures clinical and engineering representation throughout the coursework.

Other innovations in education include specialized course work. One recurrent theme was the growing move away from didactic lessons to more experiential based learning. The REHANDFUN course mentioned above represents such a move. This concept has been fully embraced by Aalborg University, which from its beginning has used problem-based learning as roughly 50% of its curriculum. This approach is encapsulated by the following saying:

Tell me and I will forget,
Show me and I will remember,
Involve me and I will understand,
Step back and I will act.

*Old proverb*

An observation by our group involved proximity. It is clear that in the educational setting, interdisciplinary teams work best when in close proximity to each other. Many institutions talked about interdisciplinary work, but in the absence of proximity, the collaboration often seemed to be less effective.

A major gap in the educational area—a gap that is thematic to all areas—involves a lack of individuals with mobility impairment among the student or teaching populations. While interdisciplinary teams can help, having direct involvement of technology users is critical and was largely lacking from the majority of the educational institutions visited. One notable exception was a master’s student with a mobility impairment working on the haptic trainer at the IPK Fraunhofer in Berlin. This issue is not the same as involving consumers as consumers, which is also an important part of the process. Rather, what is missing is students and teachers with disability.

**Research**

Research and education go hand in hand even in industrial or hospital settings. Thus the separate sections of this paper are really overlapping (see Figure 7.1). Given this overlap, it is not surprising that multidisciplinary teams are also critical to the research mission. In some hospital settings, we met with clinicians trying to solve relatively simple engineering problems, while at some engineering schools, we met engineers developing products with questionable clinical applicability. One key part of the interdisciplinary team at a number of institutions was an industry partner. The technology transfer circle in the figure above can be represented as an industry partner.

![Figure 7.1. Overlapping realms needed for success.](image)

A unique example of a multidisciplinary approach is provided by the Technology Research for Independent Living (TRIL) in Ireland ([http://www.trilcentre.org/who-we-are.html](http://www.trilcentre.org/who-we-are.html) accessed on 3/8/2011). The center is unique in that the multidisciplinary team extends beyond engineers and clinicians. TRIL focuses on enabling technology development and evaluation to support independent living. This center includes ethnographers and designers as part of the team. Ethnographers spend extended time understanding the day-to-day lives of end users. The design-ethnography process facilitates the development of research prototypes leading to execution of experiments with older people in their own homes.
Another important aspect of a successful program is infrastructure. Many of the research tools related to movement are expensive. These tools include kinetic and kinematic measurement devices, virtual reality, and robotic and clinical devices, all with a large price tag. Under-resourced or isolated investigators may simply not have the needed research apparatus to make an impact, even if their ideas are valuable. The resources can come from a single institution like the University of Twente (see below) or from collaborative partnerships as in Zurich. In Zurich there were a number of institutions, many of which seemed to work together well. These included ETH Zurich (http://www.ethz.ch/index_EN accessed on 3/11/2011), Balgrist Hospital, which is affiliated with the University of Zurich (http://www.balgrist.ch/desktopdefault.aspx accessed 3/11/2011), the Centre for outpatient Rehabilitation (ZAR) in Zurich, and Hocoma. These institutions are in close proximity to one another and have many projects that appear to overlap. The industry partner, Hocoma, provides one outlet for technology transfer, and the combined resources are impressive.

Similar to what was reported above, a substantial gap exists in inclusion of end users of mobility technology on the research team. We observed very few end users involved as researchers and, remarkably, many of the research laboratories devoted to mobility related research were only marginally accessible to an individual in a wheelchair. Another gap identified by the team was related to replication of work. Many laboratories seemed to be pursuing similar research ideas, and some were repeating the work of others or work done years ago. While to some extent this situation is unavoidable and even positive at times, the amount of overlap appeared to be too much. This redundancy was most noticeable in smaller programs that had not yet reached a critical research mass.

**Technology Transfer**

The ultimate test of success is transfer of research to commercially viable and clinically useful products. This goal continues to be problematic in the technology for mobility area and the cause is multi-factorial. One factor already discussed is non-inclusion of end users in the process or as part of the team. Another factor is likely regulatory hurdles and commercial expenses related to bringing medical products to market. One successful model we observed was having a built-in industry collaboration. At some locations this collaboration was achieved by having a small startup company nearby that began because of a specific technology. Such an example is the collaboration between Smartex, a company that focuses on wearable fabric based sensors, and the University of Pisa. The company and a portion of the University are located on two adjacent floors of the same building in an industrial park. While they remain separate financial entities in separate office spaces, there is obvious cross fertilization that impacts the technology transfer process, with researchers from both entities flowing freely between the two office spaces.

A large scale example is provided by the University of Twente and its affiliated programs. MIRA (Institute for Biomedical Technology and Technical Medicine), one of the affiliate programs, has government support, cuts across all departments, and assists in bringing technology to market. There are 250 researchers employed by MIRA and there have been 8 spinoff companies like Xsens (http://www.utwente.nl/mira/entrepreneurship/miras_spinoffs/ accessed 3/13/2011). Xsens makes motion capture systems used for various purposes by researchers and product developers in movement science. Researchers may obtain stake in spinoff companies, which are primarily funded by outside investors. MIRA’s role is helping to bring research to a marketable point and connecting investors with
researchers. Specific knowledge related to regulatory hurdles is one of the advantages MIRA and other University of Twente related organizations bring to the task of technology transfer.

In general, larger, better supported, more multidisciplinary organizations that included industrial partners led to more successful technology transfer. In a number of sites the government was providing clear financial support to educational institutions and companies as a means of assisting with the technology transfer process. It is clear that countries that don't support technology transfer are putting the researchers in their country at a disadvantage. However, at more than one location, there was a sense that the government funding sometimes continued despite a lack of success in commercializing a product.

Another concern related to technology transfer and the models seen was in the area of conflict of interest. It was clear that a number of investigators had an interest in companies working to commercialize their products. The mechanisms for dealing with the conflicts of interest appeared to be less defined than what is in place in the United States. Overly restrictive conflict of interest policies can likely stifle technology transfer, whereas the absence of policies could lead to conflict of interest causing bad science. This area is one that clearly needs a measured approach.

Cooperation Between Countries

It is widely acknowledged that cooperation across research groups can facilitate scientific gains. Collaborators across counties can bring unique expertise, knowledge of different cultures, and help with recruitment. Recruitment help is especially important in conditions that impact relatively small populations such as spinal cord injury. The environment in Europe is heavily influenced by European Union (EU) funding, a portion of which requires inter-country collaboration. An example of this collaboration is provided by MIMICS (Multimodal Immersive Motion rehabilitation with Interactive Cognitive Systems, http://www.mimics.ethz.ch/index.php?page_id=0 accessed 3/12/2012). The main hypothesis of this project is that movement training for neurorehabilitation can be substantially improved through immersive and multimodal sensory feedback. Figure 7.2 shows the sites involved. The collaboration is expected to end in a commercial product and the pathway from technical development through clinical evaluation and commercialization was well defined as part of the proposal.

It was clear from our visit that collaborations fostered by requirements imposed by funding mechanisms lead to positive research outcomes. It was also clear that not all collaborations were functioning in a positive fashion and that the drive for funding may bring researchers together on paper more than in reality. We observed difficulties in collaboration when investigators were separated by a few kilometers, let alone by great distances. Having stated these potential pitfalls, the forced collaboration model appears to have many more advantages than disadvantages.
CONCLUSIONS

The trip provided numerous examples of what worked when promoting education, research, and technology transfer in assistive technology to improve mobility. An overwhelming theme was the need for multidisciplinary teams that included, at a minimum, engineers, clinicians, industrial partners, and consumers. Incorporating the multidisciplinary approach into experiential learning was one way to prepare students for this future and to provide a strong education program. There appeared to be a critical mass of researchers and facilities needed, above which productivity increased. However, we did meet with small teams that had effectively brought products to market. Central to much of the discussion is the role of funding agencies. Funding agencies have the ability to force change. One target for agencies may be the inclusion of people with mobility impairment on the research team. To assure that individuals with disabilities and appropriate research training exist, a targeted effort is likely needed to attract people with disabilities to clinical and engineering disciplines. A second target area is technology transfer and the role of government regulation in conflict of interest. It was clear from our trip that in the absence of government support, many products may not have made it to market. In addition, issues related to conflict of interest and how it negatively and positively impacts technology transfer requires further assessment.

REFERENCES


APPENDIX A. STUDY TEAM BIOGRAPHIES

David J. Reinkensmeyer, Ph.D (Chair), University of California, Irvine
David Reinkensmeyer is Professor in the Departments of Mechanical and Aerospace Engineering, Anatomy and Neurobiology, and Biomedical Engineering at the University of California at Irvine. He received the B.S. degree in electrical engineering from the Massachusetts Institute of Technology and the M.S. and Ph.D. degrees in electrical engineering from the University of California at Berkeley, in 1988, 1991, and 1993, respectively, studying robotics and the neuroscience of human movement. He carried out postdoctoral studies at the Rehabilitation Institute of Chicago and Northwestern University Medical School from 1994 to 1997, building one of the first robotic devices for rehabilitation therapy after stroke. He became an assistant professor at U.C. Irvine in 1997, establishing a research program that develops robotic and sensor-based systems for movement training and assessment following neurologic injuries and disease. Since motor learning and neuroplasticity occur in response to the physical effects of motion, his group manipulates the physics of motor tasks with robots to try to enhance motor learning, developing and drawing on computational models of neuromotor learning and plasticity to provide a rational framework for device development. Increasingly his group is interested in combining technologies for movement training with regenerative therapies, including stem cell therapies. His group is also seeking to develop sensor-based technologies for movement evaluation that improve insight into regenerative clinical trials by enabling continuous, high-resolution assessment of neuro-muscular control.

Paolo Bonato, Ph.D., Harvard Medical School
Paolo Bonato received the M.S. degree in Electrical Engineering from Politecnico di Torino, Torino, Italy (1989), and the Ph.D. degree in Biomedical Engineering from Università di Roma "La Sapienza", Roma, Italy (1995). He serves as Director of the Motion Analysis Laboratory at Spaulding Rehabilitation Hospital, Boston, MA, he is Assistant Professor in the Department of Physical Medicine and Rehabilitation, Harvard Medical School, and he is member of the Affiliated Faculty of the Harvard-MIT Division of Health Sciences and Technology. Dr. Bonato is IEEE Senior Member, IEEE EMBS AdCom elected member, and past president of Kinesiology. He served as Chair of the IEEE EMBS Technical Committee on Wearable Biomedical Sensors and Systems. He founded and Editor-in-Chief of Journal on Neuroengineering and Rehabilitation. Dr. Bonato has co-authored more than 40 research papers and 150 conference proceedings. His research work is focused on wearable technology and its applications in physical medicine and rehabilitation. He has developed intelligent signal processing tools and artificial intelligence methods for the analysis of data recorded using wearable sensors with application to numerous clinical conditions such as chronic obstructive pulmonary disease, epilepsy, stroke, and Parkinson’s disease.
Michael L. Boninger, M.D., University of Pittsburgh School of Medicine and VA Pittsburgh Healthcare System

Michael Boninger is professor and Chair of the Department of Physical Medicine and Rehabilitation and Associate Dean for Medical Student Research in the School of Medicine. Since November 2007, Dr. Boninger has directed the UMPC Rehabilitation Institute, which combines medical care and research to help individuals regain independence and enhance their quality of life. Dr. Boninger also directs University of Pittsburgh’s Model Center on Spinal Cord Injury and serves as medical director of the Human Engineering Research Laboratories, a joint venture of the University of Pittsburgh Medical Center, the University of Pittsburgh, and the VA Pittsburgh Healthcare System. Dr. Boninger holds five U.S. patents and is recognized for his research on spinal cord injury, assistive technology, and overuse injuries, particularly those associated with manual wheelchair propulsion. Dr. Boninger has authored more than 150 peer-reviewed journal publications, 20 book chapters, and nearly 200 refereed conference papers. Dr. Boninger graduated from Ohio State University with both a medical doctorate and a degree in mechanical engineering.

Leighton Chan, M.D., National Institutes of Health, Clinical Center

Leighton Chan received his B.A. degree from Dartmouth College, Hanover, New Hampshire with a major in political science. He graduated from the UCLA School of Medicine in 1990. Chan then completed postgraduate training in Physical Medicine and Rehabilitation at the University of Washington. During his training he also obtained a Master of Science degree in rehabilitation science. Subsequently, he completed a Robert Wood Johnson Clinical Scholar Fellowship, earned a master of public health degree at the University of Washington School of Public Health and was a Congressional Fellow for the Honorable Jim McDermott (Washington). From 1994 to 2006, Dr. Chan was on the faculty of the University of Washington’s Department of Rehabilitation Medicine. From 2002 to 2006, he was associate professor. He is board certified in physical medicine and rehabilitation and in electrodiagnostic medicine. His research interests include health services research, quality of care given to Medicare beneficiaries, and Medicare payment policy issues. He has published more than 70 peer reviewed articles and numerous book chapters. In 2007, he was elected to the Institute of Medicine.

Rachel E. Cowan, Ph.D., University of Miami Miller School of Medicine

Rachel Cowan is a post-doctoral fellow in the laboratory of Dr. Mark Nash at The Miami Project to Cure Paralysis, received the Fritz Krauth Memorial Fellowship for her new grant funded by the Paralyzed Veterans of America (PVA) Research Foundation 2010 grant cycle. Dr. Cowan’s grant is titled “Barriers & Participation after SCI: Relationship with Fitness & Mobility.” It is known that manual wheelchair users commonly report poor fitness and the physical environment as barriers to achieving their desired level of participation in the community. Dr. Cowan hypothesizes that a person’s fitness and wheelchair self-propulsion ability are related to their participation, view of the environment as a barrier, and choices to avoid environmental barriers (such as curbs or ramps). In addition to her scientific expertise, she has extensive personal knowledge about this topic because she has a spinal cord injury herself; she utilizes a manual wheelchair for mobility and balances participation and environmental barriers on a daily basis. Her long-term research goal is to facilitate participation by improving fitness and/or self-propulsion capacity, thereby enabling persons with SCI to independently navigate environmental features which were previously unconquerable.
Benjamin J. Fregly, Ph.D., University of Florida

Benjamin J. Fregly is the director of the Computational Biomechanics Lab at the University of Florida. The research focus of the lab is on clinical problems related to knee osteoarthritis. Existing projects involve: 1) computational simulation of knee osteoarthritis development, 2) computational design of a rehabilitation treatment for knee osteoarthritis, and 3) computational estimation of knee muscle and contact forces during walking using novel surrogate modeling techniques. An overarching theme for these projects is patient-specific musculoskeletal modeling, where dynamic models calibrated to patient imaging and movement data are used to design optimal treatments. Dr. Fregly has published over 100 papers involving musculoskeletal modeling, simulation, and optimization. Before joining the University of Florida, Dr. Fregly completed a post-doctoral fellowship in biomechanics at the University of Lyon in France. He also worked in industry as a software developer for Parametric Technology Corporation. Dr. Fregly earned a B.S. degree in Mechanical Engineering from Princeton University and M.S. and Ph.D. degrees in the same field from Stanford University.

Mary M. Rodgers, Ph.D., P.T., University of Maryland School of Medicine and National Institute of Biomedical Imaging and Bioengineering/NIH

Mary Rodgers is the George R. Hepburn Dynasplint Professor and Chair, Department of Physical Therapy and Rehabilitation Science (PTRS), University of Maryland School of Medicine. Her major research interest is in rehabilitation biomechanics and overuse injury prevention. Over the past two decades, Dr. Rodgers has performed extensive clinical investigation in individuals who use manual wheelchairs that has been supported by grants from the NIH-NCMRR and the Veterans Administration. As Director of the Pilot Exploratory Studies Core and co-PI of the Research Career Development Core, Dr. Rodgers is heavily involved in the mentorship, educational and dissemination efforts of the University of Maryland Claude D. Pepper Older Americans Independence Center. Dr. Rodgers’ track-record of productive patient-oriented research includes 32 publications in high quality journals, and the mentoring of three post-doctoral fellows, 7 PhD students and four MS students in rehabilitation biomechanics. She has also published four book chapters and co-authored a book. She has published extensively on topics related to gait biomechanics and neuromuscular performance in elderly and neurologically impaired individuals. She is internationally recognized in the field of Biomechanics, and serves this community in a number of leadership roles, including serving as President of the International Society of Biomechanics, being on the editorial board of several journals, reviewing articles, and sitting on study sections.
APPENDIX B. SITE REPORTS

Site reports are arranged in alphabetical order by organization name.
Appendix B. Site Reports

Aalborg University, Denmark

Site Address: Aalborg University
Fredrik Bajersvej 7D
DK 9220
Aalborg, Denmark
45 96 35 88 11
http://www.hst.aau.dk

Date Visited: October 18, 2010

WTEC Attendees: M. Rodgers (report author), H. Ali, P. Bonato, T. Conway, D. Reinkensmeyer

Host(s): Kim Dremstrup
Head of Department of Health Science and Technology
E-mail: kdn@hst.auc.dk

OVERVIEW

Aalborg University, founded in 1974, is located in northern Denmark. It has a unique educational and research mission that stresses problem-based learning and teamwork and is organized around practical problems that are highly interdisciplinary in nature. The university emphasizes cooperation with business, organizations, and institutions. It has set internationalization as a high priority. Aalborg University is divided into three faculties: humanities; social sciences; and engineering, science, and medicine. It offers more than 60 different programs of study and has more than 13,000 students.

The Department of Health Science and Technology has four centers: Biomedicine (BM), Center for Sensory Motor Interaction (SMI), Medical Informatics (MI/VCHI), and Medical Modeling (MMDS). The department includes 200 employees (157 scientific and 43 technical and administrative) and 900 students (65 at the doctoral level). Funding is from four Danish sources, NIH, EU, and private funds. A problem-based learning approach is used for all degree areas. The focus of our visit was the Center for SMI, whose purpose is to study basic and clinical aspects of human sensory-motor interaction and to develop new diagnostic and therapeutic methods. The SMI is an interdisciplinary international center with a scientific and technical-administrative staff of 70 people. The SMI was established as a Center of Excellence in 1993 with support from the Danish National Research Foundation. External funding is €2.7 million.

FUNCTIONAL FOCUS

The primary functional focus of the SMI is motor function, including walking, manipulation, and wheelchair control.
RESEARCH FOCUS

Within the SMI Center, we visited labs under the Neural Engineering and Neurophysiology of Movement group, which investigates basic neuromuscular mechanisms; their functional consequences mediating both acute adjustments and chronic adaptations; and methods to restore, replace, and modulate lost or impaired motor functions. This group includes eight laboratories with excellent facilities for animal, human, and clinical experiments, as well as unique instrumentation and methodologies developed by the group.

Researchers in the neural prostheses lab have developed novel neural prosthesis applications by chronically interfacing the central or peripheral nervous system. This group developed high-density surface EMG sensors—closely spaced electrodes that can record from more muscle and neurological aspects. The motor control lab has an impressive collection of equipment, including a split-belt treadmill, a zero-gravity assist, and a virtual reality system. The FES/Assistive Technology lab has investigated TMS enhancement that appears to demonstrate a 10 msec window. This TMS is a single-pulse coupling of the two types of stimulation. Researchers are also investigating the effect of motor imagination and are getting ready to publish findings showing spinal excitability at the level of the cortex. They have found changes in force production with MVC increases of 10% to 15% that last approximately 30 min. This enhancement was not seen in athletes when testing was conducted in New Zealand.

The neurorehabilitation group is studying enhancing the ability to relearn motor tasks after stroke with BCI technology. With BCI, the response lasts approximately 30 min after stimulation. Richard Stein in Canada did find differences in pairing. An issue with TMS is that it is not applicable to home use.

Research in FES for bladder control includes collaboration with researchers in Barcelona and Holland. Issues include high power requirements and the need for rechargeable systems. This system is being manufactured by the Medtronic company.

The Laboratory for Rehabilitation Engineering has developed a mobile balance support for walking called a Walkaround. It is an integral part of the development of FET for walking. The Walkaround is now equipped with a robotic wheel drive that allows automated progress and turning control and an actuated belt that controls the center of mass of the user within the walker. Evaluation experiments have involved people with hemiplegic stroke.

The most important research contributions from SMI include sensors to control prostheses, cuff electrode sensors for peripheral nerves, thin-film systems for decoding the neural drive to muscles (EMG), tongue control for motorized wheelchair, and control of prostheses. The prosthetic hand has a camera and laser, uses vision recognition to move the hand, and includes an automatic grip. Other strong areas of research include FES for tremor control, high-density sensors, implantable foot drop FES device, sensors for prosthetic control.

Grand challenges of mobility science and technology include the following:

- Making applications patient specific and personalizing applications
- Making systems portable, flexible, and robust
- Solving data management and analysis issues (i.e., implanted system has more data coming out)
- Improving biocompatibility
- Tuning applications to be patient specific
• Detecting user interface with FES
• Resolving issues—ensuring the selectivity of sensors is application specific
• Controlling prosthetic devices
• Exploring sensory feedback and feed-forward issues

TRANSLATION
Technology transfer includes the foot drop stimulator that is now owned by the company Otobach, Neurodan. The incubator program is very helpful in translating discoveries.

SOURCES OF SUPPORT
The major funding sources are private foundations, national research and research training programs, international programs, and industrial collaboration. Funding is primarily from Danish government sources.

ASSESSMENT
Within the focus areas of this group are several important applications for mobility technology, especially in FES and mechanisms for walking balance. The emphasis on dissemination is relatively recent, and publications have increased substantially in recent years. Collaborations are primarily with other groups in Denmark and Europe.

SELECTED REFERENCES
Kinesiology [CD-ROM], edited by Deborah Falla and Dario Farina. Aalborg, Denmark: Aalborg University. Department of Health Science and Technology.


Assistance Publique, Hopitaux De Paris, Raymone Poincaré

Site Address: 104 bd Rayond Poincaré
92380 Garches
+33 01 47 10 79 00

Date Visited: October 22, 2010 (NOTE: Visit included presentations from two other groups that collaborate with the center.)

WTEC Attendees: M. Boninger (report author), B. Fregly, L. Chan, R. Cowan, D. Reinkensmeyer, M. Rodgers

Host(s): Agnes Roby-Brami
Doctor
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Djamel Bensmail
Professor
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Marc Maier
Professor
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OVERVIEW

Raymond Poincaré is a hospital with a focus on rehabilitation and orthopedics. The hospital has 450 beds and is part of Assistance Publique, Hopitaux De Paris, a 35-hospital network. Our visit focused on physical medicine and rehabilitation. There are 140 rehabilitation beds dedicated to stroke, traumatic brain injury, spinal cord injury, multiple sclerosis, cerebral palsy, and other neurologic diseases. Substantial research facilities are mixed into the clinical complex, including two motion analysis labs, a neurophysiology lab, a new technology platform lab, and a wheelchair trial center. The hospital has collaborations across France and Europe.

The Laboratory of Neurophysics and Physiology (LNP; UMR 8819, Directed by Dr. C. Meunier) is a laboratory of the CNRS affiliated to the Université Paris Descartes) focuses on basic sciences and aims at elucidating the mechanisms that underlie the physiological functions of the central nervous system. It studies the mechanisms at work when a neuron is active in a network and is exposed to physiological stimuli. The initial aim of the laboratory was to understand proprioceptive afferents and their actions on spinal neurons and the control of movement. This interest extended to the operating principles of basal ganglia and the motor strategies in healthy subjects and patients. Investigators are currently working to understand the mechanisms underlying severe motor pathologies, such as spasticity, Parkinson’s disease, and apraxia. The laboratory is part of the Faculty of Biomedical Sciences and belongs to the
new Institute of Neurosciences and Cognition of Paris Descartes University. It is a member of the Saints-Pères Interdisciplinary Institute of Life Sciences.

The Centre d’Étude de la SensoriMotricité (CESEM, UMR 8194, Directed by Dr. P-P Vidal) is a laboratory of the CNRS affiliated to the Université Paris Descartes. focuses on basic research in functional and integrative neuroscience. Questions being asked by this laboratory include the following:

- What are the respective contributions of the emergent properties of neural networks compared with the biophysical and neuropharmacological properties of individual neurons in information processing within the CNS?
- What is the neural substrate and molecular plasticity after CNS injury or degeneration during learning?
- What role does the electrical activity of neural network have during development?
- What are the molecular factors that regulate neuronal development and muscle?

The CESEM is part of the Faculty of Biomedical Sciences and member of the Saints-Pères Interdisciplinary Institute of Life Sciences. Among other disciplines is the CESEM develops the interface between basic and applied research in three areas: clinical research, space research, and exercise physiology.

**FUNCTIONAL FOCUS**

Raymond Poincaré focuses on all aspects of clinical rehabilitation, including posture, balance, transfers, manipulation, and walking. Additional areas include wheelchair research and assistive technology research related to computer access and communication. The LNP laboratory and the CESEM laboratory each have one team that shares a functional focus on upper-limb movement and manual dexterity and collaborates with teams at Raymond Poincaré.

**RESEARCH FOCUS**

Raymond Poincaré has a diverse set of research projects that focuses on all aspects of the patients treated. This includes replacing function through wheelchair research and rehabilitation robotics. Investigators have a Lokomat, and several projects focusing on its clinical use. They are engaging in drug studies with pharmaceuticals. Projects worth mentioning but outside of movement include work on cognitive disorders, hemineglect, and working memory. There is also work on bladder and sexual function.

The team headed by Dr. Roby-Brami of the LNP laboratory has a research focus on understanding how the CNS controls the mechanical structure of the limb. Researchers are primarily looking at the stroke and upper-limb function using kinematic and kinetic techniques. Many tools are used in this research, including TMS and FES. Using these tools, researchers are investigating the techniques used by stroke patients to cope with impairment. Another area of focus related to upper-limb movement is scapular motion.

The team headed by Dr. Maier of the CESEM laboratory investigates the behavioral principles and neural structures involved in human grasp and object manipulation. Using motion analysis, TMS, electromyography, brain imaging, and artificial neural networks, researchers are attempting to model, at a basic level, human movement. Projects focus on understanding how impedance is controlled by the CNS. Another area of research focus is robotics for
replacement of upper-limb function. They are involved in the development of a robotic hand (Figure B.1) and are working on the control aspects of the artificial hand.

Figure B.1. LNS Hand, CNRS UPR 3346.

TRANSLATION

Raymond Poincare’s work is mostly immediately translatable into the clinical setting. Almost all of the projects involve clinical work, and the results are likely modifying how they treat patients. The two teams of the LNP and CESEM laboratory that work in collaboration with the Hospital Raymond Poincaré are not involved in clinical care and do not develop technology for transfer to applied clinical sciences.

SOURCES OF SUPPORT

Raymond Poincaré receives significant support from a private foundations (Fondation Garches and Fondation AXA) and support from the French government. It has funded pharmaceutical studies and, through interactions with others, has competitive research funding as well. The LNP and CESEM laboratory both have competitive funding from multiple areas including the French government, the European Union and private foundations.

ASSESSMENT

Raymond Poincaré has a large clinical patient population and very strong clinical experience. The internal support for research and care through the Garche Foundation enables research in areas of the highest perceived need. Researchers are looking for stronger engineering input, which would greatly assist the program. The team of the LNP laboratory has a strong expertise in motor neuroscience and in clinical assessment of motor disorders. It has clinicians as part of the team and a great clinical focus. The team of the CESEM laboratory has a multidisciplinary approach to motor neuroscience and focuses on the control of the upper limb in humans and robots.

SELECTED REFERENCES


**BAAT Medical Engineering BV**

**Site Address:** Twekkelerweg 263  
7553 LZ Hengelo  
The Netherlands  
+31 (0)74 256 95 14  
www.baatmedical.com

**Date Visited:** October 21, 2010

**WTEC Attendees:** M. Boninger (report author), B. Fregly, L. Chan, R. Cowan

**Host(s):** Gert Nijnbanning  
Founder of BAAT Medical Engineering  
E-mail: info@baatmedical.com

**OVERVIEW**

BAAT Medical Engineering was founded in 1999. It is a spinoff of the University of Twente. In the early years, BAAT focused on the development of general medical products. Later, clients asked BAAT to take care of manufacturing and CE Mark the products developed. In 2009, the company employed 10 people; in that year, BAAT made the strategic decision to focus completely on the orthopedic market. It is now a specialist in product development for the orthopedic market and is active throughout Europe. BAAT supplies a complete service package, from idea generation and engineering toward production and CE Marking of orthopedic products under private label.

BAAT Medical Engineering products include orthopedic screws and plates; hand, knee, and wrist orthotics; and orthopedic instruments. Its business expertise includes idea generation, regulatory support, design, and engineering.

**FUNCTIONAL FOCUS**

This corporation has expertise in the medical device arena. As such, mobility at the joint level is the functional focus, including both gait and manipulation.

**RESEARCH FOCUS**

This is a technology transfer company that assists with all aspects of bringing orthopedic-related products to market.

**TRANSLATION**

The entire purpose of the company is technology transfer. It has a very successful model, which has led to the growth of the company.
SOURCES OF SUPPORT

The current major source of support is sales of products or revenue. BAAT Medical Engineering has the support of the government of the Netherlands.

ASSESSMENT

The United States has attempted a similar model—companies closely associated with universities. However, the model at Enscheda appears to be less encumbered by government regulation. Just the opposite, the government appears to support this enterprise. The idea of a company that brings the intellectual capital that enables clearance of regulatory and manufacturing hurdles associated with bringing products to market is outstanding.

SELECTED REFERENCES

Bioengineering Group, Center for Automation and Robotics

Site Address: Consejo Superior de Investigaciones Científicas
Spanish National Research Council
Madrid, Spain
(34) 91 871 19 00
http://www.iai.csic.es/users/gb/default_EN.asp

Date Visited: October 22, 2010 (NOTE: Presentation to panel conducted in Paris.)


Host(s): Jose Luis Pons
Research Professor
E-mail: jlp ons@iai.csic.es

OVERVIEW
Dr. Pons helps lead the bioengineering group at Consejo Superior de Investigaciones Científicas (CSIC), which has more than 30 people focused on new technologies for rehabilitation. He collaborates with a broad range of groups across Europe and around the world.

FUNCTIONAL FOCUS
The functional focus of this group is walking and manipulation.

RESEARCH FOCUS
Dr. Pons has developed an innovative knee–ankle–foot orthosis that can assist people with leg weakness in achieving normal joint kinematics during walking (Cullell et al. 2009). The contribution of the joints to different phases of the gait cycle is approximated using spring-like, force-length curves, and actuators for each joint are constructed of compression and tension springs. The actuators use solenoids or an ankle-driven Bowden cable to switch between springs to reproduce the desired spring characteristics during each phase of the gait cycle. The system has been tested with users who have poliomyelitis and has been shown to improve the gait pattern (Moreno et al. 2008; Cullell et al. 2009).

Dr. Pons is currently leading two large EU projects focused on rehabilitation technology. The first is focused on tremor reduction. Tremor is a common movement disorder that is increasing in prevalence with aging. However, tremor treatments, including drugs, surgery, and deep brain stimulation, are ineffective in approximately 25% of patients. The TREMOR project uses FES to eliminate tremor. (see http://www.iai.csic.es/users/gb/asp/Proyecto_EN.asp?Boton=%2B&num_registro=84). Two strategies are under investigation.
The first is to cancel tremor by out-of-phase stimulation of the muscles. The second is to stiffen the limb by electrical stimulation to produce a co-contraction to reduce tremor amplitude. Both strategies use a sensor fusion approach using data from EEG, EMG, and Inertial Measurement Units (Gallego et al. 2010) to detect and distinguish voluntary motion and tremor.

Dr. Pons is also the project coordinator for The BETTER project (Brain-Neural Computer Interaction for Evaluation and Testing of Physical Therapies in Stroke Rehabilitation of Gait Disorders). This project is focused on improving physical rehabilitation therapies by combining brain computer interfaces (BCI) with wearable exoskeletons and robotic gait trainers, such as the Lokomat (http://www.iai.csic.es/users/gb/asp/Proyecto_EN.asp?Boton=%2B&num_registro=90). The BCI being used is an EEG-based BCI. The goal is to encourage brain plasticity by programming the robot to exert physical stimulation at the periphery as a function of the neural activation patterns at the brain. One possible benefit of this approach is to intelligently promote active participation of patients during therapy. With a wearable robot, it could also allow naturalistic therapy in the patient's home environment.

Dr. Pons identified several major challenges for rehabilitation technology:

- To combine FES systems in which the stimulation is designed to be more selective and less painful with robotic or orthotic technology
- To develop actuators and mechanisms for walking that lower the metabolic cost of walking, exploiting the passive dynamics of walking
- To develop more sophisticated controllers that can grade their assistance to the level of the patient and are focused on the stage of recovery, including acute, subacute, and chronic conditions

A difficult challenge is to make wearable systems that can be used at home.

**TRANSLATION**

A U.S. patent application has been filed on the knee–ankle–foot orthosis, and Össur has licensed technology related to the knee–ankle–foot orthosis. Dr. Pons noted collaborations with Fatronik, which is a private nonprofit Spanish organization dedicated to technology transfer.

**SOURCES OF SUPPORT**

Funding sources are approximately 50% from the European Union and 50% from the Spanish government.

**ASSESSMENT**

Dr. Pons’s group is a leader in developing wearable exoskeletons for both assistive and rehabilitative purposes. The concept of combining a BCI with a wearable orthosis seems promising to improve therapeutic outcome or allow the orthosis to be used more effectively in a naturalistic environment.

**SELECTED REFERENCES**


Cambridge Brain Repair Centre

Site Address: E.D. Adrian Building
Forvie Site
Robinson Way
Cambridge CB2 0PY UK
+44 1223 331160
http://www.brc.cam.ac.uk/

Date Visited: October 20, 2010


Host(s): James Fawcett
Chairman
E-mail: jf108@cam.ac.uk

OVERVIEW

Dr. Fawcett traveled to Imperial College to meet with the panel. He is the chairman of the Cambridge Centre for Brain Repair and Head of the Department of Clinical Neurosciences at Cambridge University. His research interests are in axon regeneration in the damaged CNS, plasticity in the CNS, and interfacing the nervous system with electronics.

Although the panel’s focus was primarily on engineering strategies for enhancing mobility, the panel was also interested in the possible combination of engineering strategies with drug- or cell-based therapeutic strategies. These two strategies are typically pursued independently of each other; a key question is whether an approach that considers their interaction would enable faster progress. Dr. Fawcett presented recent research results that suggest that there will be a dynamic interactions between forthcoming plasticity treatments and rehabilitation exercise. Engineering approaches to rehabilitation exercise technology will therefore benefit from considering these interactions.

FUNCTIONAL FOCUS

The primary functional focus of the Cambridge Brain Repair Centre is manipulation.

RESEARCH FOCUS

Dr. Fawcett’s group has been working with chondroitinase ABC, a bacterial enzyme that digests molecules that help form cartilage-like barriers to axonal growth. Using a rat model of a spinal cord injury that disrupted the corticospinal tract, they found that delivering chondroitinase to the injury site without training the rat to use its impaired paw was ineffective, where the outcome measure was the number of sugar pellets the animal retrieved from a stair-cased well (García-Alías et al. 2009). They studied this task because it has been shown previously to require a corticospinal tract (Whishaw et al. 1998), which was the tract targeted with the lesion in their study.
Delivering rehabilitation exercise specific to paw reach and retrieval for 1 hour per day, in the form of practice at retrieving seeds embedded in a plastic floor grid, led to a substantial recovery of skilled paw function, but only when coupled with chondroitinase treatment. Delivering generalized forelimb rehabilitation for 1 hour per day in the form of an enriched environment (or “fun cage” with ladders, ropes, and tunnels), extinguished the rat’s ability to perform the pellet retrieval task, whether or not they received chondroitinase.

One interpretation of these results is as follows. The plasticity treatment chondroitinase induces axonal sprouting; rehabilitation exercise prunes and connects the sprouts. Thus, the new neural resource made available during a window of time by chondroitinase is wasted without rehabilitation exercise. Practicing a target motor skill (i.e., skilled paw retrieval) appears to recruit the new neural resources to serve and improve the skill. Practicing other motor skills (as the rats did in the fun cage), appears to negatively affect the learning of skilled paw use. Thus, there appears to be a neural competition for the new neural resources induced by plasticity treatment. The type of movement practice experienced drives this competition.

TRANSLATION

Acorda Therapeutics (www.acorda.com) licensed technology related to chondroitinase on the basis of the work of Dr. Fawcett and is moving the technology toward clinical application.

SOURCES OF SUPPORT

Sources of support include the Christopher and Dana Reeve Foundation, Medical Research Council, Wellcome Trust, and European Union Frameworks 6 and 7.

ASSESSMENT

Dr. Fawcett’s work has implications for engineering approaches to rehabilitation exercise. In the words of Dr. Fawcett and Dr. Amin Curt, “the plastic CNS may be very vulnerable to poorly planned rehabilitation” (Fawcett and Curt 2009). Rehabilitation technologies may help provide control over which functions are reprogrammed, given the limited new potential of a partially restored neural network. Rehabilitation technologies may also be useful for assaying the amount of and type of plasticity made possible by a treatment, so that rationale decisions can be made about what motor skills to train. Finally, there is a need for neurocomputational models that can be used to understand the competitive interaction between different types of movement practice after plasticity treatment.

SELECTED REFERENCES


Cisanello Hospital, University of Pisa

Site Address: Via Paradisa 2
56100 Pisa, Italy
+39 50 996964
http://www.ao-pisa.toscana.it/

Date Visited: October 18, 2010

WTEC Attendees: B. Fregly (report author), M. Boninger, L. Chan, R. Cowan

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Silvestro Micera
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OVERVIEW
The Neurorehabilitation Lab at Cisanello Hospital performs mobility-related research in close collaboration with the University of Pisa and Scuola Superiore Sant’Anna. The lab possesses excellent research facilities, including a six-camera gait lab with two force plates, a Lokomat robotic gait trainer, and an isokinetic dynamometer. Laboratory facilities are used for both research and clinical purposes, so researchers remain in touch with the needs of patients. The laboratory accommodates 12 inpatients with neurological diseases and sees 4 outpatients per day. Medical doctors, therapists, and engineers work together to make treatment decisions for individual patients. These close research and clinical ties began in 2007 and have brought a well-informed perspective to the research performed by the lab.

FUNCTIONAL FOCUS
The functional focus of the lab is on neurorehabilitation with an emphasis on walking and upper-extremity mobility.

RESEARCH FOCUS
The research focus of the lab is on the development of rehabilitation techniques using high-technology devices. The lab consists of four areas, each focused on a particular aspect of the research.
The first area is the gait lab, where patient motion and muscular activity during walking can be measured. One of the current research emphases is on analysis of muscle synergies in patients who have had a stroke. The lab started by analyzing muscle synergies in healthy patients and has recently moved on to analyzing synergies after stroke. The ultimate goal is to use analysis of muscle synergies to determine when a rehabilitation approach has successfully modified a patient’s neuromuscular control strategy. These muscle synergy analyses are based on principle component analysis or nonnegative matrix factorization.

Rather than relying on muscle synergy analyses alone, the lab has begun to use spinal maps to analyze neuromuscular control strategies. Spinal maps relate muscle EMG signals to their locations in the spinal cord and create a color plot to show which spinal regions are highly active over the walking cycle. The approach was introduced by Yakovenko et al. (2002) to estimate motoneuronal activity in cats. It has since been used by others to study motoneuronal activity in patients after spinal cord injury as well as in healthy patients with different walking patterns. The lab has used spinal maps for both research and clinical purposes. It is currently investigating whether spinal maps can help clinicians identify differences between healthy versus stroke versus elderly gait patterns. Monaco et al. (2010) investigated whether muscle coordination during walking at different speeds changes as people age. Muscle synergies calculated from factor analysis of muscle EMG signals said “no,” while “spinal maps” calculated from muscle EMG signals said “yes.” In the future, the lab would like to use spinal maps to identify how rehabilitation modifies muscle coordination in specific patients (e.g., after stroke).

The second area of focus is the Lokomat robotic gait training lab, where patients who have had a stroke or spinal cord injury are trained with the goal of improving their walking ability. For hemiplegic patients, the lab is seeking to determine whether benefits from gait training on the Lokomat are caused by peripheral modifications or central pattern modifications. At the end of treatment, is there an increase in motor unit firing that could be related to changes in central pattern generation? In 2007, the lab started a clinical trial with 10 patients with incomplete spinal cord injury and 13 healthy patients to investigate whether Lokomat training affects healthy people as well. EMG signals were recorded from both legs (Rectus Femoris, Tibialis Anterior, Gastrocnemius, Biceps Femoris), and patients were trained at two different speeds (1.6 and 2.4 km/hr) using two different amount of body weight support (30% and 60%). Furthermore, participants were trained using three different modes: (1) no active contribution to movement (passive mode), (2) active contribution to movement (active mode), and (3) no robot—just treadmill and body weight support. After 4 weeks of treatment, muscular recruitment improved the most using the active mode. Similar results have been reported in the literature, but the lab also found improved recruitment of distal muscles, which had not been previously reported. In one patient, the lab also found that only the active mode affects EEG of the cortex attention region of the brain, and it is moving toward integration of EEG/EMG recordings with Lokomat gait training. More patients are being enrolled in the study, and some patients have gone from being confined to a wheelchair to independent walking with a cane.

The lab has a strong link with Hocoma (the manufacturer of the Lokomat) and is working with the company to enhance the Lokomat’s capabilities. Locomotion in the Lokomat is not physiological because only sagittal plane motion is permitted (i.e., no frontal plane trunk and pelvis motion can occur) and no active actuation of the ankle is provided. Furthermore, approximately 45 min of set up time is required for training, and patients often get tired by the time training starts. The lab is working with Hocoma to add active actuation of the ankle to the robot and to add controlled nonsagittal motions of the trunk and pelvis. Because
investigators believe that position control is too passive for neurorehabilitation, they are also working with Hocoma to add a force control option to the Lokomat’s control system. The problem, however, is that their robot will lose CE European certification if investigators make such changes.

The third area of focus is the muscle function and dynamometer lab. The lab possesses an isokinetic dynamometer that can be used for both isokinetic and isometric testing of the upper and lower limb. The dynamometer is being used with EMG measurements before and after Lokomat training. The goal is to determine whether gait training in the Lokomat can modify the central pattern of muscle activation, as well as to assess muscle fatigue characteristics with the dynamometer.

The fourth area of focus is the human–computer interface lab, whose goal is to develop improved rehabilitation strategies for patients who have had a stroke. The lab has an exoskeleton for the right upper limb that is actuated at the shoulder and elbow. A force sensor and a grasp sensor are present on the handle. The main difference of the lab’s robotic system compared with other available systems is that the shoulder, elbow, and forearm are all driven. The robot is well developed, is being used clinically, and shows some promise, but it has not been used on enough patients yet to prove its value.

The lab is not currently engaged in any neuromusculoskeletal modeling and simulation work, although the researchers believe that such an addition to their experimental studies would be helpful.

One of the main problems faced by the lab is testing enough patients to prove that a new rehabilitation methodology works. The lab is seeking to develop multicenter trials to address and properly randomize patients.

TRANSLATION

The clinical research lab at Cisanello Hospital provides a direct tie between clinical research and clinical treatment. In effect, the normal clinical environment and the research environment have been merged into a single environment. Thus, any potential research advances developed by the lab can be translated directly to patient care at the hospital.

SOURCES OF SUPPORT

The hospital provides funding for research hardware and clinical and research trials. Other projects require competitive funding from the Italian government and the European Union.

ASSESSMENT

The Neurorehabilitation Lab at Cisanello Hospital provides an excellent environment for clinical and engineering researchers to work collaboratively on important clinical problems. This environment is an excellent model for mobility-related research in the United States.

SELECTED REFERENCES


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Delft University of Technology

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Date Visited: October 21, 2010 (NOTE: Dr. van der Helm came to Enschede and presented to WTEC panel.)

WTEC Attendees: L. Chan and B.J. Fregly (report authors), M. Boninger, R. Cowan

Host(s): Frans van der Helm
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OVERVIEW

The Delft University of Technology is the oldest and largest technical university in the Netherlands, with eight schools, 16,500 students, and 7,000 scientific publications per year. Delft University, Leiden University Medical Center, and Erasmus Medical Center (Rotterdam) form a triangle of three collaborative institutions called the “Medical Delta,” collaborating on medical research in four areas—cancer, the cardiovascular system, neurology, and the musculoskeletal system—and studying the full gamut of translational medicine, from basic science to clinical care. These four treatment areas are each integrated into three functional areas: molecular medicine, imaging and image guided medicine, and interventions and care. Delft University itself organizes its research around four focus areas: energy, environment, infrastructures, and health.

The presentation by Professor van der Helm covered Delft research initiatives related to the health focus area. Health related research initiatives occur across multiple faculties within the university:

Faculty of Applied Physics
- Image acquisition and processing
- Nuclear therapy
- Targeted molecular medicine

Faculty of Mechanical, Maritime, and Materials Science
- Minimal invasive surgery and intervention techniques, which included a steerable catheter
- Biomechatronics
- Tissue biomechanics and implants
- Biomaterials

Faculty of Electrical Engineering, Computer Science, and Mathematics
Appendix B. Site Reports

- Bioinstrumentation, biosensors
- Neural stimulation, cochlear implants

Faculty of Industrial Design Engineering
- Surgical cockpit

The Department of BioMechanical Engineering resides within the Faculty of Mechanical, Maritime, and Materials Science. Within the department, diverse health-related research is performed in the following areas:

Medical Instruments (Prof.dr. Jenny Dankelman)
- Design of operation room
- Design of medical instruments
- Training of minimal invasive surgical techniques

Biomechatronics & Biorobotics (Prof. dr. Frans C.T. Van der Helm)
- Neuromuscular models and measurement techniques
- Prosthetics and orthotics
- Balanced mechanisms
- Humanoid robots
- Haptic Interfaces

Robot Vision for Control (Prof.dr.ir. Pieter P. Jonker)
- Intelligent camera systems
- Motion compensation mechanisms

FUNCTIONAL FOCUS

Research on mobility at Delft is remarkably broad, covering many functional domains. For the upper extremity, this group has produced one of the most sophisticated musculoskeletal models of the shoulder and elbow, and also works on upper extremity prosthetics, robot-assisted therapy, and functional electrical stimulation. They are also leaders in bipedal robots, and in creating robots that mimic human motion and sensory capabilities. Investigators believe that this approach will ultimately produce machines that “can go where people go” and provide spin-offs that can be adapted to humans.

RESEARCH FOCUS

- A major contribution of this group is in developing large-scale computer models of the upper extremity – the Delft Shoulder and Elbow Model, an effort of almost 25 years. The DSEM is distinguished in the level of detail of the musculoskeletal biomechanics, and in the extensive experimental validation it has undergone. The model includes the thorax, clavicle, scapula, humerus, ulna, and radius, is actuated by 31 muscles defined by 139 muscle lines of action that are curved around bony contours, possesses a sliding scapulo-thoracic constraint and a glenohumeral stability constraint, and has parameter values measured from cadaver studies. Inputs to the model are recorded motions, and outputs are muscle forces estimated via optimization methods. The model has been used to predict loading for wheelchair users, for design and control of upper extremity FES
systems, and for understanding biomechanics of shoulder implants, including experimental evaluation with instrumented shoulder implants. The group is working on incorporating neural control models into the model, and has a working model of the reflexive control system, including muscle spindles, Golgi Tendon organs, and the visual and vestibular systems. They are also developing large scale models of the hand and the head-neck system.

- The Delft group is also developing prosthetics and orthotics for the upper extremity. An interesting project is an underactuated robotic hand that possesses three fingers controlled by only one motor. The hand has no sensors, with grasping being achieved using a mechanism that distributes contact forces evenly over the three fingers. The hand is capable of grasping objects of various sizes and shapes both firmly (so that they do not drop) and gently (so that they do not break). The hand was created for industrial applications where repetitive human manipulation is currently required (e.g., packaging of bell peppers). However, it could be used equally well as an assistive device for individuals with limited hand mobility. For example, it could be attached to a wheelchair to provide a versatile option for holding objects of various sizes and shapes, or it could be used to perform a small range of functional tasks such as grasping a door handle to open a door.

- The group has made significant advances in the design of exoskeletons that allow for more naturalistic movement of the upper extremity using carefully designed passive degrees of freedom, and in balanced mechanisms that assist in upper extremity movement.

- Another major accomplishment of this group is in humanoid robots, particularly in the areas of bipedal walking using passive dynamics.

- The group is developing intelligent camera systems with the ability to follow moving objects using visual servoing. Such advances in computer vision may be useful for personal assistants to enhance mobility.

- Other work outside of the direct scope of the study, but related and compelling, relates to surgery, including improving the design of the operating room, in advanced design of surgical instruments, including terminal devices with multiple degrees of freedom, and in training of minimally invasive surgical techniques, including haptic devices for epidural steroid injection training.

**GRAND CHALLENGES**

- Dr. van der Helm identified several grand challenges in the field of mobility technology. One was to provide people who use a wheelchair with other options for mobility, especially for short distances, which would allow them to do more tasks. One possibility is that of actuated exoskeletons, but there remain challenges in achieving stability, adequate control, and energy efficiency. The approach of combining exoskeletons with functional electrical stimulation may help solving some of these problems. Another outstanding problem is to increase the efficiency of manual wheelchair propulsion and to prevent shoulder disorders. Key roadblocks to achieving many challenges for mobility technology are developing more efficient actuators and improving the design of the human-device interaction.

- Another key challenge in mobility identified by Dr. van der Helm is improving models of human movement. This group has developed perhaps the most sophisticated model of the upper extremity, but sees that there is still major work to do with such models,
particularly in adding neural control mechanisms, including reflexive feedback and descending control, for both people with and without impairment. This group is also performing groundbreaking work in showing how such models can be personalized to better predict the shoulder and elbow loading. Ultimately, patient-specific, neuromusculo-skeletal models will allow a more in-depth analysis of human performance, and therefore provide a more rational basis from which to design new technology.

TRANSLATION
The Delft group has patented many innovations from their research and is pursuing commercialization, but there are no commercial products yet. The DSEM is being used in collaborative projects with other major centers.

SOURCES OF SUPPORT
Support comes from the Netherlands government, European Union, and industry. The laboratory noted that there are no sources of substantial funding that promote collaboration between European Union and United States research groups. Despite this limitation, the group has extensive collaborations with Northwestern University on the neural control of patients with stroke, and with Case Western Reserve University for the control of functional electrical stimulation of the upper extremity following spinal cord injury.

ASSESSMENT
The research enterprise at Delft is broad, well developed, and well funded. It has made significant progress in the areas of biomechanical modeling, prostheses and orthoses, bipedal robotics, minimally invasive surgery and interventional technology, and vision-based robotics. Delft is an excellent example of how a critical mass of researchers are using a multi-disciplinary approach to drive a host of innovations relevant to mobility technology.

SELECTED REFERENCES


Demcon Advanced Mechatronics

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Date Visited: October 21, 2010 (Note: Presentation given at the University of Twente.)

WTEC Attendees: R. Cowan (report author), B.J. Fregly, M. Boninger, L. Chan

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OVERVIEW

Demcon is a University of Twente spin-off company established in 1993. It specializes in development and production of high-tech mechatronic systems and products, and could be described as an incubator company. Demcon supports product development along a continuum from concept through first-run series. Typically, a company contracts with Demcon to provide a product solution for a specific problem. However, Demcon may also develop products both independently and in joint ventures. Demcon exits the product lifecycle before mass production but has small-scale production capabilities to support product development. For high volume products, the goal is to transition the product to a larger company or to enter into a joint venture with another company. Demcon is International Organization for Standardization (ISO) 13485 certified, which is important for the medical industry.

As described on the Demcon web site (http://www.demcon.nl/), “Mechatronics is the integration of many disciplines (including mechanics, electronics, computing, control engineering, physics, optics, materials science and sensor technology).”

FUNCTIONAL FOCUS

Demcon indirectly supports mobility by supporting development of the LOPES and robotic devices that result from the MIAS-ATD project. The goal of the MIAS-ATD project is to develop a functional arm/hand training device that combines upper-extremity robotics and FES for use at home without a therapist.

RESEARCH FOCUS

Demcon’s focus is product development rather than research. Its primary industries include semiconductors, manufacturing, and the medical devices industry. Within the medical industry, it has provided product development support for a variety of items: blood and fluid warmers, activity sensors, digital hearing aids, a modular therapeutic modality system, flexible minimally invasive endoscopic robotic surgical instruments (Teleflex), and rehabilitation robotics (LOPES, Mias).
TRANSLATION
Technology transfer; supports existing companies or academic centers in product development.

SOURCES OF SUPPORT
Support comes from contracts with industry and Dutch government funding provided jointly with university collaborators.

ASSESSMENT
Demcon, as an incubator company with tight ties to an academic center (University of Twente), is a very interesting concept and quite nicely solves the "how" of transferring technology from a proof-of-concept, academic prototype to a commercially viable product. I think supporting development of active mechanisms that support the transition from prototypes to commercial products is a worthy focus.

SELECTED REFERENCES
European Commission, Components and Systems: Microsystems

Site Address: European Commission
http://ec.europa.eu/index_en.htm
Information Society and Media Directorate-General
Directorate G: Components and Systems
G.2: Microsystems
Avenue de Beaulieu, B-1160
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32 2 2996978

Date Visited: October 22, 2010

WTEC Attendees: P. Bonato (report author), H. Ali, T. Conway

Host(s): Andreas Lymberis
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OVERVIEW

The Microsystems Unit (http://cordis.europa.eu/fp7/ict/micro-nanosystems/) is part of Directorate G: Components and Systems (http://cordis.europa.eu/fp7/ict/browse/org_en.html#keywords-unit-g_en.html) within the Information Society and Media Directorate-General (http://ec.europa.eu/dgs/information_society/index_en.htm). Dr. Andreas Lymberis served as our host during the visit. The research and development activities presented to our group by Dr. Lymberis are part of the 7th Framework Program (FP7), which is a 6-year program (2007–2013) to support research and innovation within the European Union. The total allocation of funding for the FP7 is approximately € 54.6 billion. More than half of this funding (€ 32.3 billion) goes to the “Cooperation” portion of the program, namely to major research and development activities based largely on collaborative efforts across research and development groups of different EU countries. Approximately € 9.1 billion of the € 32.3 billion of funding allocated for the Cooperation Program is assigned to the Information and Communication Technologies topical area, which is the focus of the Information Society and Media Directorate-General. In turn, the Information Society and Media Directorate-General is organized in five directorates devoted to (1) converged networks and services, (2) digital content and cognitive systems, (3) emerging technologies and infrastructure, (4) components and systems, and (5) Information and Communication Technologies (ICT) addressing societal challenges. Each directorate is organized in four or five units. For instance, the Directorate G: Components and Systems (http://cordis.europa.eu/fp7/ict/browse/org_en.html#keywords-unit-g_en.html) is divided into five units devoted to (1) nanoelectronics, (2) microsystems, (3) embedded systems and control, (4) ICT for transport, and (5) photonics.

The overarching goal of the policies underlying the design of the FP7 is to increase public investment toward knowledge creation and excellence in research and development through pan-European collaborations involving the private sector and academia. Initiatives supported
by the FP7 are synergistic with the programs supported via the Joint Technology Initiatives (JTI) (http://ec.europa.eu/information_society/tl/research/priv_invest/jti/index_en.htm) also supported by the European Union but with a focus on creating long-term relationships between public and private players. FP7 and JTI both contribute to create a single research market across the European Union while raising research and development investments. The bulk of these initiatives is expected to increase the competitiveness of European entities, both in academia as well as in the private sector.

FUNCTIONAL FOCUS

An example of the projects carried out with funding provided by the Microsystems Unit (http://cordis.europa.eu/fp7/ict/micro-nanosystems/) is Healthy Aims (http://www.healthyaims.org/). The project involves 25 partners across 10 EU countries, with players coming from academia, the clinical community, and the private sector. The project has a budget of approximately € 23 million. The network of partners for this project is organized in three major areas of expertise: (1) medical systems suppliers, (2) technology suppliers, and (3) providers of clinical services. The project has delivered several systems at different prototyping stages, ranging from simple prototypes of sensors to be bench tested before moving ahead with animal and human testing to advanced systems already tested in human participants that are ready for clinical evaluation (http://usir.salford.ac.uk/1635/1/getPDF.pdf).

The Healthy Aims project delivered a system for functional electrical stimulation named the STIMuGRIP (http://www.finetech-medical.co.uk/Projects/HealthyAimsinnovativeimplants/HealthyAimsSTIMuGRIPdevelopment/tabid/163/language/en-GB/Default.aspx). The system was tested in three patients. The project also delivered a glaucoma sensor in the form of a lens (http://www.healthyaims.org/PRESENTATION07/EPFL%20Braga%20WP09g.pdf). The sensor has been tested so far in five participants. Two other major portions of the project are devoted to the development of a retinal system and to the design and implementation of an intracranial pressure monitoring system (http://www.healthyaims.org/presentations06/Intra-cranial%20pressure%20sensor%20-%20CMT.pdf). Finally, the project delivered the Pegasus activity monitor, an activity monitor that the investigators proved to be capable of accurately identifying the performance of tasks such as walking and stair ascending/descending.

The current call for proposals for projects to be supported by the Microsystems Unit puts a great deal of emphasis on several objectives that the unit sees as strategic to the advancement of the field: (1) increasing the level of intelligence embedded in the systems to be developed; (2) improving the miniaturization of devices; and (3) decreasing obtrusiveness and cost of these systems while improving the reliability of the data. Examples of recently initiated projects in this research area are the projects titled “Transversal Intrafascicular Multichannel Electrode” and “Neuroprosthetic Interface Systems for Restoring Motor Function.” In addition to the objectives summarized here, the Microsystems Unit has identified three areas of future research and development work: (1) the integration of bioinformatics and medical data management; (2) the integration in the fabrication process of design criteria to achieve desired functions; and (3) the development of new surface chemistry, biomarkers, and methods to achieve immobilization of molecules on surfaces.

RESEARCH FOCUS

A major research area supported by the Microsystems Unit is devoted to the development of systems to monitor the health status of individuals. The work done in this area includes the
development of (1) sensors for both physiological and environmental data gathering, (2) methodologies to analyze physiological data, and (3) sensors and systems to obtain genomic data from physiological samples. The European Commission vision is that information gathered using the tools listed here (i.e., sensors, systems, and methodologies for data analysis) would be stored in integrated health records that would be mined to derive clinically relevant information. This process would lead to improving the current level of medical care provided to individuals when they are in need of an intervention in acute care or when they are affected by a chronic condition, thus requiring long-term management of symptoms and potential complications.

The ongoing research program supported by the Microsystems Unit within the FP7 builds on the successes achieved during the Framework Program 6 (FP6). The microsystems area in the FP6 emphasized the need for building smart systems, namely systems providing functions such as detecting the occurrence of a clinically relevant situation, predicting potential problems on the basis of physiological data trends, and enabling decisions concerning clinical interventions that are automatically delivered by the smart system. The program for the FP7 aims at further advancing the work achieved during the FP6. In the initiatives pursued within the FP7, the emphasis is put on (1) the integration of monitoring, diagnosis, and treatment; (2) the development of devices for the automated delivery of drugs and genes; (3) the integration of neural stimulation and interfaces; and (4) the development of methodologies to integrate this information in electronic records. Micro and nano-systems have tremendous potential in this context.
European Commission, Future and Emerging Technologies

Site Address: European Commission
http://ec.europa.eu/index_en.htm
Information Society & Media Directorate-General
Directorate F: Emerging Technologies and Infrastructure
F.1: Future and Emerging Technologies (FET) - Proactive Unit
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Date Visited: October 22, 2010

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Julian Ellis
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OVERVIEW

The Future and Emerging Technologies Unit is part of the Directorate F (Emerging Technologies and Infrastructure) of the Information Society and Media Directorate-General. The goal of this unit is to foster multidisciplinary transformative research aimed at bridging scientific discovery (in biology, life science, material science, neuroscience, and cognitive science) and technology. Research projects supported by this unit are typically high risk/high pay off and aim at pursuing visionary ideas. Two units within the Emerging Technologies and Infrastructure Directorate are devoted to future and emerging technologies. The first, referred to as “Open,” is based on a bottom-up approach in which investigators propose ideas with no boundaries on the topic. The second, referred to as “Proactive,” is based on a top-down approach, with preselected themes within which investigators submit their applications.

The hosts of the meeting were with the Proactive Unit. Their portfolio of sponsored projects is organized at the intersection of three major technological areas: components, intelligence, and systems. Over the past 4 years, the unit has allocated approximately €330 million for research projects. Projects recently funded (as part of the last call for proposals) are organized around the following thematic areas:

Brain-Inspired ICT: Projects in this thematic area target the development of multiscale models of information processing and communication mimicking the central and peripheral nervous system and hardware implementations of neural circuits that mimic information processing in the central and peripheral nervous system.

Human–Computer Confluence: Projects in this thematic area focus on the development of new methods to leverage human sensory perception and cognition to interpret massive amounts of data, new methods to implement augmented and virtual environments, and new forms of interaction with the real world, virtual models and abstract information.

Examples of rehabilitation technology projects recently supported by the Future and Emerging Technologies–Proactive Unit are Collective Experience of Empathic Data Systems (http://ceeds-project.eu/), Virtual Embodiment and Robotic Re-Embodiment (http://www.vereoproject.eu/), Cyberhand Neurobotics (http://www.youtube.com/watch?v=0fls1nE_yzE), and Closed Loop Neural prosthesis for vestibular disorders (http://www.clons-project.eu/).
European Commission, ICT for Inclusion, Ageing (Sector)

Site Address: European Commission
http://ec.europa.eu/index_en.htm
Information Society and Media Directorate-General
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H.3: ICT for Inclusion
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Date Visited: October 22, 2010

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Luiz Alves dos Santos
Scientific Officer

OVERVIEW

The Information and Communication Technologies (ICT) for Inclusion Unit is part of Directorate H: ICT Addressing Societal Challenges, which accomplishes its work within the Information Society and Media Directorate-General. A major sector within the ICT for Inclusion Unit is the one focused on “Ageing” led by Peter Wintlev-Jensen. The meeting with Dr. Wintlev-Jensen and Dr. dos Santos focused on the Ageing Sector of the ICT for Inclusion Unit. The interest for the aging population is justified by the numbers associated with this demographic phenomenon. The population aged 80 and older is expected to double by 2050 when only two individuals will work for every retiree. This dramatic increase in the population of older adults is likely to significantly increase the costs sustained by European governments for the pension plans of the growing population of retirees. Medical costs are also likely to rise significantly as the number of older adults increases. The population of individuals age 50 and older is affected more often (i.e., >20% more) than younger individuals by vision and hearing impairments and by mobility limitations. Consequently, with the aging population, the costs accounting for healthcare and long-term care are expected to increase. Once costs associated with retirement are factored in, the costs of supporting older adults can be estimated to easily reach 4% to 8% of gross domestic product by 2025. The objective of the projects supported by Ageing Sector aim at empowering older adults to live independently and to increase the wealth and revenues for individuals age 65 and older. The number of people who could be directly affected by these initiatives accounts for about 85 million Europeans today. This number is expected to reach 150 million by 2050.

The Ageing Sector is part of the ICT Work Program (ftp://ftp.cordis.europa.eu/pub/fp7/ict/docs/ict-wp-2011-12_en.pdf), so projects supported as part of the portfolio of
the Ageing Sector have a special emphasis on the potential impact of information and communication technologies on older adults. These initiatives have to be examined in the context of the European Digital Agenda (http://ec.europa.eu/information_society/digital-agenda/index_en.htm). Adoption of information and communication technologies among older adults is modest compared with younger sections of the European population. Therefore, a portion of the activities supported by the Ageing Sector is geared toward removing barriers to facilitate the adoption of information and communication technologies among older adults. A large portion of the portfolio, however, is used to support research and innovation with potential future impact on older adults.

**RESEARCH FOCUS**

Research and development projects that are part of the Ageing Sector portfolio within the FP7 are organized in three major categories for which different funding mechanisms are used. The first group of projects is focused on the development of advanced prototypes of information and communication systems for older adults. These projects are devoted to four main areas of work related to the development of systems to (1) enhance mobility and reduce falls; (2) assist people with cognitive impairments; (3) monitor and improve the ability of older adults to perform activities of daily living; and (4) provide services via technologies such as robotics. Examples of projects within this group are CONFIDENCE (http://www.confidence-eu.org/), SENSATION-AAL (http://www.sensaction-aal.eu/), HERMES (http://www.fp7-hermes.eu/), and SRS (http://srs-project.eu/). The second group of projects supported within the Ageing Sector portfolio is devoted to the development of open platforms and tools. Examples of projects within this group are OASIS (http://www.oasis-project.eu/) and UNIVERS-AAL (http://www.universaal.org/). Finally, the third group of projects within the Ageing Sector portfolio is constituted by supporting action initiatives aimed at collecting data of use to the European Commission and the community. Examples of such projects are CAPSIL (http://www.capsil.org/) and BRAID (http://www.braidproject.eu/). All these projects are directly supported by the FP7.

The Ambient Assisted Living (AAL) Joint Program (JP; http://www.aal-europe.eu/) provides funding for projects that have a high likelihood of delivering products that could reach the market within 2 to 3 years. EU countries contribute approximately €150 million to this program. The figure is matched by the European Commission, which contributes another €150 million. The private sector matches the public investment, thus leading to approximately €300 million of private investment. The focus is on assisted living technology and services for older adults. Initiatives carried out with the Competitiveness and Innovation Framework Program (CIP; http://ec.europa.eu/cip/) have similar objectives, but they target small- and medium-sized enterprises that are less likely than large players in the industry to participate in the AAL JP. Finally, initiatives carried out within funding provided by the ICT Policy Support Program (PSP; http://ec.europa.eu/information_society/activities/ict_psp/index_en.htm) are focused on facilitating the implementation of the European Digital Agenda (http://ec.europa.eu/information_society/digital-agenda/index_en.htm) by addressing obstacles hindering the use of ICT-based products and services and barriers for the development of high growth businesses in this field.

All the initiatives mentioned here are subject to periodic assessment by the European Commission. The European Commission evaluates that projects meet technical objectives and achieve substantial socioeconomic impact. For projects that are regional in nature, the European Commission expects that wider application to the European Union is shown in the long term. An example of the type of evaluation that projects undergo is the assessment of the

**SOURCES OF SUPPORT**

Three major mechanisms support research in areas relevant to the aging population: the FP7 ([http://ec.europa.eu/research/fp7/index_en.cfm?pg=understanding](http://ec.europa.eu/research/fp7/index_en.cfm?pg=understanding)), AAL JP ([http://www.aal-europe.eu/](http://www.aal-europe.eu/)), CIP ([http://ec.europa.eu/cip/](http://ec.europa.eu/cip/)), and the ICT Policy Support Program ([http://ec.europa.eu/information_society/activities/ict_psp/index_en.htm](http://ec.europa.eu/information_society/activities/ict_psp/index_en.htm)). All these programs have funding that has been specifically allocated for initiatives targeting the aging population. The FP7 has allocated approximately €33 million for the 2011 to 2012 period for initiatives specifically devoted to the aging population. The AAL JP has set aside €60 million for the 2011 to 2013 period to be spent in this area of research and innovation. The CIP and ICT PSP have made a €10 million investment in this area for 2011.
Hocoma AG

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Date Visited: October 20, 2010

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OVERVIEW

Hocoma designs, manufactures, and markets functional movement therapy solutions using advanced technology (robots, sensors, controllers, software). Hocoma was founded in 2000 as spin-off of the Spinal Cord Injury Center of the Balgrist University Hospital in Zurich by the electrical and biomedical engineers Gery Colombo and Matthias Joerg, and the economist Peter Hostettler. It currently has 130 employees with offices in Switzerland (headquarters), the United States, and Singapore. The company invests in research and conferences to remain the market leader but does not fund external research directly so that external studies remain the objective. The current products focus on the upper and lower extremities using both robotic devices (Lokomat and Erigo) and mechanical devices (Armeo and Andago; Figure B.2).
The company has seen consistent sales growth since its first product, the Lokomat robotic gait trainer, was sold in 2001. To date, more than 340 Lokomat systems are installed in approximately 40 countries worldwide. More than 80 Lokomat studies have been published to date, and approximately 50 of these studies focus on clinical investigation. Approximately 30 research centers are currently conducting clinical studies using the Lokomat. Outcomes thus far have been as good as with conventional rehabilitation methods. Further research is needed to maximize the benefits of using an automated gait training approach.

The company has been successful for several reasons. First, it had its first product in hand when it sought initial investment dollars. Second, the first product was high quality and worked right out of the box. Third, its products have offered new capabilities that were not possible before. Fourth, the company has a strong research network with top research labs. Fifth, the company has some good luck along the way.

**FUNCTIONAL FOCUS**

Neurorehabilitation (e.g., after stroke or spinal cord injury) is the current functional focus of Hocoma products. This focus spans gait rehabilitation with intensive locomotion therapy, upper-extremity rehabilitation and early mobilization following stroke as well as therapy solutions for low back pain patients. Orthopedic rehabilitation is viewed as a potentially large future market where similar technologies could make a valuable and significant clinical impact. Customization of robot function to individual patients could also be important in the future (with a possible role for personalized modeling).

**RESEARCH FOCUS**

Hocoma’s research focus, frequently pursued collaboratively with academic research labs, is on advanced functional movement therapy solutions for the upper and lower extremities. These solutions use state-of-the-art technologies involving sensors, robots, controllers, and software. The company wants to remain the market leader in the field, so it invests in research to stay on top. One current research focus is on the use of augmented virtual environments to engage the patient to the fullest extent possible during the rehabilitation process.

**TRANSLATION**

Hocoma products are examples of academic research that has been successfully transferred to a company (or developed in collaboration with a company) with the goal of clinical utility.
**SOURCES OF SUPPORT**

Government funding provides the impetus to bring new ideas developed in universities to the market as companies. Hocoma follows that pattern and has developed its products using funding provided by the Swiss government’s Commission for Technology and Innovation (CTI) and by the European Union. CTI’s mission is to fund joint projects between Swiss universities and companies. CTI funding has been instrumental in supporting the development and commercialization of the following Hocoma products:

- Lokomat
- Assessment tools for Lokomat
- Valedo: Augmented feedback-based therapy for low back pain
- Smart Armeo: Textile neuroprosthesis with Armeo therapy device
- Lokomat: Free walking (in progress)

**ASSESSMENT**

Hocoma provides an outstanding model for how companies and universities can work together to move valuable technology from the research lab to the clinic. Funding from the Swiss government has been instrumental in that process, and a better understanding of how that funding mechanism works could be valuable for developing more effective funding mechanisms in the United States to foster closer productive ties between academic research labs and small companies seeking to package and market new technologies.

**SELECTED REFERENCES**


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OVERVIEW
Dr. Burdet heads the Human Robotics Research Group in the Department of Bioengineering at Imperial College. His group integrates neuroscience and robotics to study human motor control and to design assistive devices and virtual-reality based training for rehabilitation and surgery.

FUNCTIONAL FOCUS
The functional focus is on manipulation and wheelchair control.

RESEARCH FOCUS
Three highlights of Dr. Burdet's work in the last 10 years are as follows. First, he helped produce clear evidence of impedance control by the human motor system (Burdet et al. 2001), which then led to the development of a computational model that explains how the motor system coordinates muscles to achieve not only impedance control but also internal model formation and effort optimization (Franklin et al. 2008). In the model, the motor system uses sensory information in the form of kinematics errors expressed in a muscle coordinate frame to modify motor commands to the muscles. The change in muscle activation on the next movement attempt is specified by a sunken, asymmetric, “V” function relating change in muscle activation to muscle length error, where the V-shape accounts for impedance control, the asymmetry for internal model formation, and the sunkenness of the V for effort optimization. Each muscle adjusts itself independently of the other muscles. This simple formulation explains a wide range of experiments from the motor adaptation literature (Franklin et al. 2008; Tee et al. 2010). It has significant potential to aid in the understanding of the consequences of neurologic injury and disease, to optimize rehabilitation therapy, and to design robots that can learn behaviors with optimal force and impedance.
The second highlight is in wheelchair technology. Dr. Burdet’s group developed a low-cost powered wheelchair that uses path guidance assistance to significantly reduce the effort necessary to control the wheelchair (Zeng et al. 2008). The chair uses a sensor on the wheel to measure its location and requires that a helper walk the chair through the environment in which it is to move, so that the chair can create a target path for navigating through the environment. The user can then modify the target path using a graphical user interface or an elastic path controller. For the latter strategy, the user deforms the desired path by moving the joystick as he or she drives the chair. The chair has been tested by people with cerebral palsy and traumatic brain injury who have substantial difficulty using a standard powered wheelchair (Zeng et al. 2009). Collisions happened regularly without the guidance, but no collisions occurred in guided mode. Dr. Burdet and his collaborators have also developed a P300-based, brain-controlled wheelchair that users have successfully maneuvered in indoor environments (Rebsamen et al. 2010).

A third area of achievement is in robotic devices for decentralized rehabilitation of hand function. This work addresses the problem that people with stroke receive too little rehabilitation training, due in part to the high cost of therapists. Dr. Burdet has developed robotic interfaces with a reduced number of degrees of freedom. This approach has advantages for cost and safety but still allows programmable forces to be applied to the hand and for the patient to interact in virtual environments. The goal is to use the devices so that patients can train independently in rehabilitation centers or at home. Initial tests on chronic patients have demonstrated a lasting improvement of hand and arm function.

Dr. Burdet has also helped lead the development of fMRI-compatible robotic devices for measuring brain activation during upper-extremity movement (Gassert et al. 2006). This work is providing tools for a new generation of neuroscience focused on understanding neural substrates that support motor learning and rehabilitation. Understanding these substrates should improve the design of technology for rehabilitation.

Dr. Burdet is developing an innovative approach to interdisciplinary engineering education using mobility technology. He has designed a new course on human-centered design of assistive and rehabilitation devices. Small groups of students receive a kit of sensors along with a microprocessor and must develop an assistive device or rehabilitation system, learning about mechatronics, human factors, and computer games.

Dr. Burdet identified the following grand challenges of mobility science and technology:

- Computer-aided assessment of motor function
- Practical systems for rehabilitation and assistance that can be integrated into the health system at sustainable costs
- Semi-autonomous rehabilitation systems that address specific parts of therapy but that do not require the presence of a physiotherapist, and are still safe and efficient

**TRANSLATION**

Two provisional patents on the robotic therapy technology were filed in 2008.

**SOURCES OF SUPPORT**

Funding sources are grants from the European Union and the United Kingdom.
ASSESSMENT

Dr. Burdet’s work on modeling human–robot interaction is significant because of its ability to predict trial-to-trial changes in muscle activation in response to robot forces. This model can likely provide a low-level model for helping understand patient response to rehabilitation therapy or user response to mechanically assistive devices, although there is still a need for high-level models of motor plasticity and learning to build on to the low-level model. The panel saw little work focused on modeling human response to assistive or therapeutic technology, and thus this work is pioneering.

Dr. Burdet’s wheelchair project illustrates the growing trend toward incorporation of sensors into assistive technology to make the technology intelligent. A core need is an intelligent sharing of control between the user and the device, a problem that Dr. Burdet addressed with a collaborative control algorithm for the wheelchair.

The middle-ground approach in the provision of robotic therapy, in which the devices are still active and sensorized but do not have many degrees of freedom, may allow greater accessibility to robot-assisted therapy.

SELECTED REFERENCES


Institut des Systèmes Intelligents et de Robotique (ISIR)

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OVERVIEW

The Institut des Systèmes Intelligents et de Robotique (ISIR) is part of the Department of Engineering at Université Pierre et Marie Curie. ISIR was created in 2007 from the reorganization of the Laboratoire de Robotique de Paris, the Groupe Perception et Réseaux Connexionnistes of the Laboratoire des Instruments et Systèmes d’Île de France, and the AnimatLab group of the Laboratoire d'Informatique de Paris 6. ISIR is associated with the Centre National de la Recherche Scientifique and is a Unité Mixte de Recherche, where both teaching and research take place. It hosts 48 academic and staff members, 78 doctoral students, and 15 postdoctoral researchers. Three major research teams are part of ISIR, namely the Interactive Systems, Human Perception and Motion, and Autonomous Systems. Each research team has access to significant laboratory space. The total laboratory space amounts to approximately 12,000ft². During our visit, several members of the institute met with us and presented summaries of their work: Dr. Vincent Hayward presented his work on human perception and the design of haptic interfaces, Dr. Emmanuel Guigon spoke about optimal and adaptive control of posture and movement, Dr. Ludovic Saint-Bauzel summarized the work of the Interactive Systems Group on lower-limb rehabilitation robots, and Dr. Nathanael Jarrassé presented ISIR's work in the area of upper-limb rehabilitation robotics.

FUNCTIONAL FOCUS

The work our group was exposed to during the visit (including the slide presentations and walk through the laboratory space) focused on manipulation, walking, and postural stability.
RESEARCH FOCUS

The research work presented during the visit related to three major areas of research at ISIR: tactile perception, modeling of posture and movement, and rehabilitation robotics.

Dr. Hayward and his research team presented their work on the design of haptic interfaces. Two major contributions by Dr. Hayward’s team are summarized in a seminal paper published in *Nature* in 2001 (Robles-De La Torre and Hayward, 2001) and a manuscript published in *Experimental Brain Research* in 2005 (Dostmohamed and Hayward, 2005). The work published in *Nature* demonstrates that force cues can overwrite geometric cues in tactile perception. The authors proved the concept by designing experiments using paradoxical stimuli. The stimuli provided contrasting geometrical and force cues (e.g., geometrical cues of a hole and force cues of a bump). The results summarized in the paper show that force cues determine the type of surface perceived by subjects during the experiments. The paper published in *Experimental Brain Research* in 2005 (Dostmohamed and Hayward, 2005) shows that an actuated plate in contact with the fingerpad can be controlled to cause the perception of touching an object of a given shape. Another phenomenon reported in the Transactions on Applied Perception in 2005 and 2008 (Levesque et al., 2005; Wang and Hayward, 2008) makes possible to engineer high resolution tactile displays (Wang and Hayward 2010). The work presented in these papers constitutes the basis of the tactile interfaces designed by the research team. Dr. Hayward’s team demonstrated to our group several interfaces, including the aforementioned tactile display systems and interfaces designed for individuals with visual impairments (Levesque et al., 2005; Petit et al., 2008).

Dr. Guigon presented an overview of the research work done at ISIR in the area of modeling human posture and movement control. The overview focused on the work contributed by researchers at ISIR in computational motor control. Dr. Guigon presented several models attempting to capture the way the central nervous system controls kinematically redundant biomechanical systems. For instance, one model is based on four major assumptions: (1) static (i.e., gravitational) and dynamic (i.e., inertial) forces are processed separately by the central nervous system, (2) the central nervous system uses principles of optimal feedback control to generate appropriate dynamic forces, (3) the “magnitude” of motor commands (which determines the effort exerted by the subject) is used by the central nervous system as an optimality criterion, and (4) the central nervous system can estimate movement duration based on the magnitude of motor commands (Guigon et al., 2007). Simulations demonstrated the suitability of the model to reproduce complex movements of the upper limbs. Movements of kinematic chains with 2, 4, and 7 degrees of freedom were simulated. Other models and their neurobiological basis were presented (e.g., Guigon et al., 2008; Guigon et al., 2010). Different models appear to capture different aspects of the control of movement.

Next, Dr. Saint-Bauzel presented selected work carried out by the Interactive Systems Group. First, Dr. Saint-Bauzel summarized the results of a research project aimed at developing a robotic walker (Saint-Bauzel et al., 2009). The robotic system is not only capable of providing assistance during ambulation but is also able to facilitate sit-to-stand by controlling the height of handles that patients grab with their hands to support themselves. The implementation of the system is based on extensive studies with particular emphasis on modeling pathological patterns observed during the sit-to-stand task. The proposed model was built in a way that is particularly suitable to achieving the design and implementation of the robotic walker (Saint-Bauzel et al., 2007). The presentation continued with a summary of research work focused on the development of robotic systems for gait training (IsiWalk) and
postural control training (IsiMove). IsiWalk is conceptually similar to the Gait Trainer (Hesse et al., 2001) because it makes use of an end-effector design to facilitate ambulation. In this design, the subject’s feet are attached to two separate footplates moving the feet according to a trajectory mimicking the one observed during ambulation. However, the mechanical design of the footplate is more sophisticated than others previously proposed. The footplates are embedded in a mechanical structure that is flat when the footplates are in the “rest” condition. Linear actuators, which are positioned in the anteroposterior direction, are used to raise the footplates during training. IsiMove is a system to train individuals with balance impairments by means of exposing them to perturbations via an actuated platform. Both systems (i.e., IsiWalk and IsiMove) appear to have found a path to commercialization through a newly formed company, ASSISTMOV (http://www.assistmov.com/), which is expected to bring these products to market in 2011. The remainder of Dr. Saint-Bauzel’s presentation was devoted to ongoing mathematical work by researchers at ISIR aimed at improving on existing techniques for controlling human movement via robotics.

Finally, Dr. Nathanael Jarrassé provided a summary of ISIR’s work in the area of robotics for upper-limb motor training. Several exoskeleton systems were presented, including one that was demonstrated during a visit to the laboratory. The system is named the ABLE exoskeleton and was first manufactured by CEA-LIST (http://www-list.cea.fr/gb/actualites/news_2008/news_27_10_4.htm). The current version of the ABLE exoskeleton is unique in the way it couples exoskeleton and upper-limb body segments. The design of the human–robot interface is based on a general methodology that allows patients minimize the effect of the exoskeleton on point-to-point movements via an array of kinematic and force measurements (Jarrasse et al., 2010). This work motivated the design of mechanical components providing optimal coupling between the exoskeleton and the body segments of interest (Jarrasse et al., 2009). The panel was impressed with the mechanical transparency of the exoskeleton.

**TRANSLATION**

The work presented by researchers at ISIR is original and, as such, has provided opportunities for technology transfer. The relationship between ISIR and ASSISTMOV (http://www.assistmov.com/) appears to have taken the lead to achieve commercialization of robotic systems for rehabilitation designed and prototyped at ISIR. Other interactions with the private sector were also noted. Among others, the relationship with Haption (www.haption.com) appears to have provided ISIR with the opportunity for manufacturing refined robotic systems for medical applications.

**SOURCES OF SUPPORT**

ISIR benefits from multiple sources of support. The annual budget of the Institute (see http://www.isir.upmc.fr/telechargements/Rapport_activite_institut.pdf for 2007 data) is approximately €2 million. Approximately 40% of the budget is secured via funding provided by the European Commission. Approximately 10% of it comes from contracts with industries. Approximately 30% of ISIR budget comes from state and regional sources of funding. The remaining comes from other research grant mechanisms.

**ASSESSMENT**

ISIR has an outstanding program in robotics with significant contributions relevant to rehabilitation. Ongoing work toward the design of haptic interfaces is remarkable and of significant interest. Research carried out in the institute in the area of rehabilitation robotics
is quite impressive. The work on lower-limb rehabilitation robotics is very advanced. It is worth noting that it has led to commercialization through collaboration with the private sector. Research aimed at developing exoskeletons for upper-limb rehabilitation is unique. The ABLE robotic system appears to be one of the best-designed arm orthoses currently available in the field. In addition, the institute has been engaged in collaborative work involving clinicians (e.g., Hôpital Raymond Poincaré), with clear benefits to the clinical applicability of the robotic systems developed by researchers at ISIR.

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OVERVIEW
The goal of the group is to improve functionality by combining research activities, ranging from basic to applied sciences. The group’s core areas include interface technology for electrical stimulation, neural control models for hand and leg motion, and development of control systems for clinical rehabilitation. The group was originally established in 1994 in close collaboration between the Automatic Control Laboratory of ETH Zurich and the Spinal Cord Injury Center of the University Hospital Balgrist. Its aim was developing and applying state-of-the art neuroprostheses for spinal cord injury and stroke patients. This group has developed very strong clinical ties with cohorts of stroke and spinal cord injury patients. The group is based in an outpatient stroke center that contains a large stroke population. Investigators see patients 3 months after inpatient rehabilitation. The group covers basic science and applied research.

FUNCTIONAL FOCUS
This group focuses on upper-limb and lower-limb mobility, using robotics to enhance recovery.

RESEARCH FOCUS
This group uses two Hocomo products, the Lokomat and the Armeo. The Armeo has been adapted with an enhanced control system to enhance patient effort and follow patients
longitudinally. In addition, researchers were experimenting with FES as an adjunctive treatment. In the same manner, Mark Bolinger, the postdoctoral fellow, was also experimenting with using FES in the Lokomat. Both of these projects seem to be in the prototype stage and are not ready for clinical trials. In addition, this group has an animal model of SCI that helps inform clinical use of robotic. This research is focused on using electrical stimulation of the spinal cord for motor function combined with neuropharmacological interventions. This work has been done in murine and nonhuman primate models.

The Balgrist Hospital–based group is also a small research program related to upper-limb function. This includes development of the a new SCI assessment tool—the Graded and Redefined Assessment of Strength, Sensibility and Prehension (GRASSP)—which is now in its validation phase, and a NeuroAssess Glove to measure hand motion.

**TRANSLATION**

The clinical work directly includes patients and is likely affecting care. However, the innovations at this center have not yet lead to direct translation through commercialization.

**SOURCES OF SUPPORT**

The group received $3 million in private donations to start testing rehab robotics.

**ASSESSMENT**

The strengths of this program were its deep connections to clinical medicine and its access to patients. In addition, investigators were adapting preexisting robots for new uses.

**SELECTED REFERENCES**


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**OVERVIEW**

Founded in 1896, the Rizzoli Orthopaedic Institute has a long history of providing state-of-the-art orthopedic care. The institute’s hospital sees more than 150,000 patients per year, and the institute possesses a separate research center that contains nine research laboratories. The Movement Analysis Laboratory within the Rizzoli Institute was founded in 1989 with the purpose of performing functional evaluations of the human locomotor system under normal and pathological conditions. Dr. Leardini and Dr. Benedetti have worked in the lab since 1990. The lab possesses the latest instrumentation, including stereophotogrammetric, force plate, fluoroscopic, baropodometric, and electromyographic systems for performing quantitative analysis of human movement. Researchers in the lab collaborate with the orthopedic clinic and engineering faculty at the University of Bologna, as well as with nearby rehabilitation clinical and research centers that see neurological patients.

One of the most unusual aspects of the laboratory is the close integration between surgeons, physiatrists, and engineers within the research environment. People from all three areas share a common laboratory and office area, facilitating discussions and research interactions on a regular basis. The ability to identify clinical problems in which a technical perspective could improve treatment design and outcome is one of the key benefits of this environment.
FUNCTIONAL FOCUS
The primary functional focus of the lab is on orthopedic and neurological disorders affecting gait the lower limbs. A relatively new focus is on the trunk for treating low back pain.

RESEARCH FOCUS
The primary goal of the Movement Analysis Laboratory is to develop a complete understanding of the reasons for the success or failure of orthopedic surgeries and rehabilitation treatments. The lab seeks to understand the entire story of the disease and treatment process for individual patients. These reasons for treatment success or failure relate to variations in outcome caused by different types of implant designs, different surgical procedures, and different patients. The hope is that the understanding gained can be used to improve existing treatment techniques as well as to develop new ones.

Given this goal, the focus of the laboratory is on a combination of methodological, biomechanical, and clinical research. The laboratory has worked extensively on designing and verifying a standardized experimental protocol for gait analysis to make results highly repeatable. The lab views the development of this protocol, and its incorporation into commercial software, as one of its greatest accomplishments. This protocol is currently being used for diagnosis and functional evaluation of patients with orthopedic and neurological problems. The laboratory is also seeking to identify critical clinical variables that it can measure and that the clinician can use to monitor and evaluate the success or failure of a particular treatment. Activities of the laboratory span the full spectrum from clinical evaluation to surgery to rehabilitation activities after surgery.

Strong interactions exist between an orthopedic surgeon (Dr. Fabio Catani), a physiatrist (Dr. Maria Grazia Benedetti), and a biomedical engineer (Dr. Alberto Leardini), and a number of relevant research assistants. Each member of the research team has a different mix of research, clinical, and teaching duties. Dr. Catani has a combination of clinical and research duties, with approximately a 50–50 mix between the two. Dr. Benedetti performs a combination of research and teaching, with a very heavy teaching load. Dr. Leardini also performs a combination of research and teaching.

The laboratory has a very strong research focus on joint replacements, especially on total knee and ankle replacements where the mechanics of the articulating surfaces is important. Within this research domain, the lab works in three-dimensional fluoroscopy and radiostereophotogrammetric analysis (i.e., dynamic X-ray measurement of in vivo implant motion), movement analysis using motion capture, joint modeling, surgical navigation, and prosthesis design. This research focus includes advances for minimally invasive surgery and surgical navigation using robotic approaches. A recent advance is adding tracking of the patella to a surgical navigation system so that the best possible alignment of the femoral component and patellar button can be determined before bone cuts are made.

A unique focus related to joint replacements is the development of biological joint replacements (i.e., whole-joint cartilage surfaces) for ankles, knees, and shoulders. The director of the lab, Dr. Sandro Giannini, has performed approximately 60 to 70 biological ankle replacements thus far with generally good results. Biological knee replacements have been more difficult. One biological shoulder replacement has also been performed. Biological joint replacements are mainly for younger patients who are likely to outlive a traditional joint replacement. In vivo and in vitro study of implant biomaterials is also a related area of focus. Given this focus on joint replacement, it is not surprising that the lab undertakes significant research activities with major orthopedic implant companies.
The lab is also exploring early cartilage repair or replacement surgery as a way to avoid the need for total joint replacement in the future. Dr. Giannini, has developed some highly successful cartilage transplantation surgical techniques that are now being used clinically at the Rizzoli Institute.

Dr. Benedetti provided a very helpful description of three possible uses of gait analysis in a clinical environment:

- **Assessment**—Assess after treatment how the treatment worked for a group of patients.
- **Identification**—Identify on an individual patient basis which patients should be treated (but not how they should be treated).
- **Prediction**—Predict on an individual patient basis which treatment should be performed and how it should be performed.

She noted that assessment is common, identification is becoming more common, and prediction does not yet happen. Not all clinical problems require prediction, and the potential value of prediction depends on the clinical problem at hand. Thus, gait analyses performed in the lab are not yet used for clinical decision making but are still used for clinical assessment (e.g., to evaluate the effectiveness of different surgical treatments in a general sense, not used on a single case basis). The lab recently moved into the identification arena by using gait analysis to identify clinical problems that need to be addressed in children with cerebral palsy.

One of the most practical and exciting developments in the lab is the design of a new total ankle replacement, by Dr. Giannini, Dr. Leardini, Dr. Catani and also Prof. J.J. O’Connor from the University of Oxford. The design is based on an understanding of mobility in the natural ankle joint, accounts for the mutual role of articular surfaces and ligaments, and the replacement maintains this compatibility by all ligaments and original prosthetic surfaces. In 160 patients implanted thus far, nearly all have excellent results after 3 years. The research team is now studying mobility in the knee to design a new total knee replacement.

The lab collaborates closely with the neighboring Medical Technology Laboratory lab, under the technical coordination of Dr. Marco Viceconti, which focuses on personalized musculoskeletal modeling to predict treatment outcomes for various proposed treatments on an individual patient basis. Development of patient-specific models involves fusion of diagnostic imaging (computed tomography, magnetic resonance) and movement data. The developed models are validated comparing their predictions, in term of strength, with experimentally measured data. An interesting current application involves rehabilitation planning after limb salvage due to tumor excision. The goal for this application is to determine, using predictions made by patient-specific bone model, a safe activity level for the patient during rehabilitation so that the bone allograft heals properly. A related goal is determining the point at which activity restrictions can be lifted. A significant amount of work is currently ongoing related to multiscale modeling technology designed to predict the strength of a bone segment of any patient. This technology considers activity level of the patient as well the effective bone segment condition obtained from conventional diagnostic images (MR, CT). The final aim is to predict the risk of bone and to suggest preventive treatments to reduce the risk fracture.

**TRANSLATION**

Research performed in the lab has resulted in a new protocol for gait analysis that has been implemented in clinical software. Research done in the lab has also resulted in a new total
ankle replacement design that is being marketed by an orthopedic implant company and that has shown excellent initial clinical success.

**SOURCES OF SUPPORT**

Most the funding used to support laboratory research activities comes from a combination of Italian funding agencies, European-level funding agencies and industry funded research.

**ASSESSMENT**

One of the most valuable lessons provided by the Rizzoli Institute is the strong collaboration that exists between orthopedic surgeons, physiatrists, and biomedical engineers. Creation of research environments in the United States such as the one that exists at the Rizzoli would be valuable for greater cross-fertilization and better application of engineering technology to relevant clinical problems related to mobility.

**SELECTED REFERENCES**


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OVERVIEW

The Medical Park Berlin Humboldtmühle is a modern rehabilitation hospital with approximately 300 beds. Approximately 200 of these beds are devoted to neurological patients. Dr. Stefan Hesse serves as Head of the Department of Neurology. He was the host for this visit along with Dr. Cordula Werner. Dr. Hesse is a pioneer in the development and clinical use of robotics for rehabilitation. The motivation for this visit was to gather information about the integration of robotics in a clinical setting and to discuss with Dr. Hesse clinical protocols that rely on this technology for both upper- and lower-limb rehabilitation.

A typical patient at the Medical Park Berlin Humboldtmühle would be admitted to the inpatient unit after 8 to 10 days spent in an intensive care unit. He or she would then spend approximately 10 to 12 weeks of intensive rehabilitation at the Medical Park Berlin Humboldtmühle. The clinical center is focused on inpatient services. Patients are typically not seen (in an outpatient setting) at the Medical Park Berlin Humboldtmühle after discharge. The use of robotics is part of the therapeutic intervention in a large portion of patients. The general criterion used to assess eligibility of patients for robotic therapy is that patients with moderate to severe disabilities undergo robotic therapy whereas high-functioning patients undergo rehabilitation interventions one-on-one with physical and occupational therapists.

FUNCTIONAL FOCUS

The interventions we focused on during the visit were mostly related to manipulation and walking. However, the Medical Park Berlin Humboldtmühle provides comprehensive management of complex patients and, therefore, has many services to meet the needs of such patients.
RESEARCH FOCUS

Dr. Hesse and his research and clinical team have extensive experience with the use of robotic systems for both upper- and lower-limb rehabilitation (Hesse et al., 2006). The group has been innovative in the way it has contributed to developing, testing, and integrating the clinic’s robotic systems for upper-limb rehabilitation. Dr. Hesse and his associates contributed to developing and testing the Bi-Manu-Track (http://www.reha-stim.de/cms/index.php?id=12; currently commercialized by Reha Stim http://www.reha-stim.de/cms/index.php?id=48; Hesse et al., 2003, 2005). The system enables bimanual practice of forearm pronation–supination and wrist flexion–extension. Clinical results indicate that the Bi-Manu-Track allows patients to achieve better results than those achievable using, for instance, EMG-initiated electrical stimulation of the paretic wrist extensors. The Bi-Manu-Track has been more recently integrated into an Arm Studio (Buschfort et al., 2010) to provide intensive upper-limb rehabilitation after stroke. The Arm Studio includes, in addition to the Bi-Manu-Track, the Reha Digit (http://www.reha-stim.de/cms/index.php?id=109) for training finger movements, the Reha-Slide (http://www.reha-stim.de/cms/index.php?id=15) for training bilateral symmetric movements, and the Reha-Slide Duo (http://www.reha-stim.de/cms/index.php?id=103) for training bilateral symmetric and nonsymmetric movements.

During our visit, we also observed the use of the Amadeo system by Tyromotion (http://www.tyromotion.com/index.php?id=6&L=1). The integration of these systems in a single environment to provide intensive upper-limb training is uniquely innovative because of the variety of systems available to patients in the Arm Studio and because the Arm Studio offers a structured approach to choosing the rehabilitation regimen. In a recent study (Buschfort et al., 2010), Dr. Hesse’s group assessed the effectiveness of the Arm Studio concept by prescribing the use of these robotic systems according to the patient’s functional and impairment level. Patients with a paralyzed hand with an appreciable movement of the wrist and finger extensors who could mostly show synergistic movements of shoulder and elbow were assigned to a group undergoing rehabilitation using the Bi-Manu-Track and the Reha Digit systems. For this group, the Fugl-Meyer arm section score was typically <14. Patients who showed selective proximal or distal movements and a distinct movement with gravity elimination for shoulder elevation and abduction were assigned to a second group, which received therapy using the Bi-Manu-Track and the Reha-Slide systems. Participants in this second group typically showed a Fugl-Meyer arm section score between 14 and 34. Finally, patients who were able to grasp, reposition, and release a tennis ball placed on a table were assigned to a third intervention group that received arm training using the Reha-Slide and Reha-Slide Duo systems. Patients in this group typically had a Fugl-Meyer arm section score >34. As a final note concerning the technology-based program for upper-limb rehabilitation at the Medical Park Berlin Humboldtühle, Dr. Hesse’s group has explored the use of transcranial direct current stimulation in combination with robotic-assisted arm training (Hesse et al., 2007). The results of their study indicate that the technique can be safely used in stroke survivors. However, the design of the study (with no control group) and limited number of participants recruited to assess the safety of the technique in stroke survivors did not allow the authors to make any conclusion concerning the effectiveness of combining transcranial direct current stimulation and robotic-assisted arm training.

Dr. Hesse and his team also contributed very significantly to the field of robotic-assisted gait training. The group led the development of the Gait Trainer (Hesse et al, 2000) (http://www.reha-stim.de/cms/index.php?id=108) now commercialized by Reha-Stim. Further development of the system later resulted in the HapticWalker (Schmidt et al., 2005).
based on the contribution of researchers with the Fraunhofer Institute. Both designs are based on an end-effector approach by which the foot is attached to a footplate that controls its trajectory. However, whereas the Gait Trainer is based on the use of a simple planetary gear similar to the one used in elliptical machines commonly found in fitness centers, the HapticWalker is based on a complex actuation mechanisms that allows one to control the footplates to achieve virtually any trajectory of interest including level walking, ramp ambulation, and stair ambulation. The drawback of the HapticWalker is the excessive cost of the system that prevents its clinical adoption. To address this issue, the research team led by Dr. Hesse has recently proposed the G-EO System Robot (Hesse et al., 2010) also commercialized by Reha Stim (http://www.reha-stim.de/cms/index.php?id=86). The system allows investigators to train patients with essentially the same flexibility of choice of ambulatory tasks (i.e., level walking, ramp ambulation, and stair ambulation) provided by the HapticWalker but at a fraction of its cost. The Gait Trainer has been extensively studied from a clinical standpoint. In a clinical trial involving four rehabilitation centers (Pohl et al., 2007), the investigators recruited 155 nonambulatory stroke survivors. The authors randomized patients to two groups: one group received robotic-assisted gait training and physiotherapy whereas the other group received only physiotherapy. The results of the study indicated that the group receiving robotic-assisted gait training and physiotherapy achieved better gait ability than the group receiving only physiotherapy.

TRANSLATION

The research work contributed by Dr. Hesse’s group is an example of strong integration of clinical and technical work. It also demonstrates the feasibility of involving the private sector. The robotic systems developed by Dr. Hesse’s group are currently commercialized with great success by Reha Stim (http://www.reha-stim.de/cms/index.php?id=48).

SOURCES OF SUPPORT

Overall, according to its web sites, University Hospital Charité has 1.2 billion Euros in yearly turnover (2009), of which 189.8 million Euros is from third-party funding and 189.8 million Euros is from subsidies for teaching and research. More than 50% of the Berlin state subsidy is based on performance.

Medical Park AG is a contractual partner of private, public and state health insurance companies and bodies. Within a contractual framework for purposes of integrated health care (e.g., in the areas of orthopedics and cardiology) Medical Park AG actively cooperates with compulsory health insurance companies and acute-care hospitals. On a regional and national level Medical Park clinics cooperate, based on their specialist therapeutic area, with associations and organizations who seek to focus on prevention, rehabilitation, sports medicine or particular illnesses such as Parkinson’s, MS, Bechterew disease, and osteoporosis.

ASSESSMENT

The group led by Dr. Hesse has provided an outstanding contribution to the field of robotic-assisted rehabilitation. The integration of new technologies in the clinics is remarkable. The attempt to provide a structured approach to establish rehabilitation protocols that rely on rehabilitation robotics has to be particularly appreciated given the complexity of the task.
SELECTED REFERENCES


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**Date Visited:** October 21, 2010

**WTEC Attendees:** L. Chan (report author), M. Boninger, B.J. Fregly, R. Cowan

**Host(s):** Martijn Kuit  
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**OVERVIEW**

The Netherlands has taken a very active role in the translation of medical research into small business. MIRA, the University of Twente’s Research Institute for Biomedical Technology and Technical Medicine, is a prime example. Based in the University of Twente, MIRA cuts across all departments, gathering expertise from many organizations and assisting them in bringing technology to market. MIRA currently has 250 researchers and will likely add 150 more in the next few years. It has been involved in 18 spin-off companies and plans to have 3 to 5 per year in the future. Researchers may obtain some stake in these companies, but the companies are primarily funded by outside investors. MIRA’s role is helping bring research to a marketable point and connecting investors with researchers.

**FUNCTIONAL FOCUS**

MIRA’s functional focus on mobility has been on the lower extremity with the LOPES ambulatory assist system. In addition, it has focused on development of service robots.

**RESEARCH FOCUS**

MIRA’s prime focus covers four tracks: tissue regeneration, targeted therapeutics, imaging and diagnostics, and neural and motor systems. MIRA has performed little work related to the current NSF topic. However, researchers from the group did develop the advanced robot trainer, LOPES, which is designed to help patients to walk again after a stroke. They have also designed a service robot. Much of the other robotics work is related to improving surgical outcomes.

**TRANSLATION**

MIRA’s focus is related to translation. It is working to bring a mobility-related device to market (LOPES).
**SOURCES OF SUPPORT**

MIRA originally started with university and government support.

**ASSESSMENT**

MIRA is a very interesting model of how a university can stimulate translation of research into small business. It is an organization that cuts across schools and departments to bring researchers together, with an eye toward commercialization. This enterprise is relatively new, but already it has started up nearly 20 companies. Although none of these companies are related to human mobility, it is only a matter of time before they are able to bring a product to market.

**SELECTED REFERENCES**

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Date Visited: October 18, 2010 (NOTE: The hosts came to Pisa to present to the WTEC panel.)

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OVERVIEW

The Motor Learning and Rehabilitation Lab (MLRlab) at the Italian Institute of Technology (IIT) and NeuroLab at University of Genoa cooperate closely in the field of movement training, exercise, and rehabilitation therapy, including robotic, computer, biofeedback, and virtual reality-based approaches, with particular emphasis on the use of robotic and virtual reality-based approaches for the treatment of neuromotor impairments of the upper limbs. Research in the field of neural control of movement and rehabilitation engineering at the University of Genoa dates back to the early 1970s and originated from exchanges and collaborations (which are still ongoing) with Massachusetts Institute of Technology (E. Bizzi) and later McGill University (D. Ostry) and Northwestern University (F. A. Mussa Ivaldi). Today, research in this field is carried out at NeuroLab in collaboration with local and national clinical institutions.
The IIT, a large interdisciplinary research foundation that started in 2006, has its headquarters in Genoa. The Motor Learning and Rehabilitation lab is the research unit more directly involved in rehabilitation engineering, although cross-connections exist and are increasing with other labs, such as the Brain Computer Interface lab and the Biomechanics lab. The IIT is a very large institution with almost 500 scientific personnel working in several areas, including genetics, nanotechnology, and robotics. The University of Genoa (Department of Informatics, Systems and Telecommunications) is also very large with 170 scientific staff working in the following areas: systems and control, computer science, communications, operation research, bioengineering, environmental science, industrial and business management.

**FUNCTIONAL FOCUS**

Most of the work of these two sites is related to the BdF (Braccio di Ferro) upper-limb robot, which has been developed in two versions: monomanual (two degrees of freedom) and bimanual (four degrees of freedom). This device focuses on improving upper-limb dysfunction associated with neurological disorders. A wrist robot (three degrees of freedom) and a grasp-unit (one degree of freedom) have also been developed, allowing different combinations up to 12 degrees of freedom. All the degrees of freedom are back-drivable, allowing soft/gentle/safe haptic interaction between the robot and the user.

**RESEARCH FOCUS**

The basic concept that inspires the research is that of a “research pipeline” encompassing experimentally validated models of neural control of movement, models of motor learning, models of functional recovery, and principle-based robot therapy control strategies. Investigators believe this is a necessary prerequisite for carrying out well-formulated comparisons of different control strategies, as well as mixed strategies of robot–human treatment in the framework of randomized controlled clinical trials. For this reason, they designed several haptic robots that can implement bidirectional interaction paradigms, based on force fields, capable of characterizing the learning mechanisms of normal subjects when exposed to novel dynamic environments or supporting the emergence of voluntary control schemes in neuromotor patients. The different robots have a different number of degrees of freedom and have been designed in a modular way to assemble them in different ways. Much effort has been devoted to the software, using standard, open-source software platforms that allow rapid prototyping and transfer from one robotic platform to another.

**TRANSLATION**

The BdF robot is currently commercialized (under the name of Physioassistant) for upper-limb rehabilitation of neuromotor disabilities. The BdF system, originally developed at the Department of Informatics, Systems and Telecommunications, has been licensed to a company (Celin srl, La Spezia, Italy), which engineered the design and obtained the mark, required by law to certify that a product meets European Union consumer safety, health, or environmental requirements. A similar procedure will be pursued in the near future for the wrist and grasp robots. No patent has been generated. Investigators chose the route of open source for both software and hardware under the assumption that to be effective and to become widespread, this technology must be shared by the community of researchers and developers.
SOURCES OF SUPPORT

Funding has come from European Union, the Ministry of University and Research, the National Research Council (relatively small grants for basic and applied research projects in the field of bioengineering), and the Ministry of Health (midsize funding to research hospitals, in cooperation with engineering and industrial partners). Private charities and foundations, often related to specific patient groups, are another source of funding for highly focused projects (e.g., Italian Multiple Sclerosis Foundation grant to NeuroLab).

ASSESSMENT

This research group had the only bimanual upper-extremity robot evaluated on this trip. Having solved some technical issues with the physical design of the upper-extremity haptic devices, it is now focusing on the control mechanism that will maximize recovery in diseases such as stroke and multiple sclerosis and will illuminate issues related to neural control and neuroplasticity.

SELECTED REFERENCES


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Date Visited: October 18, 2010

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OVERVIEW

Federico Posteraro is a physiatrist in the Department of Neurological Rehabilitation, Auxilium Vitae Rehabilitation Center. The Neurological Rehabilitation Unit has 50 inpatient beds (15 brain injury; 35 for other neurological disorders, particularly stroke). Within this department, Dr. Posteraro has fostered a strong collaboration between physicians, engineers, therapists, and physiotherapists who collectively are interested in technologically advanced devices and research activities. This collaborative group is the result of 10 years of effort, with most of the growth and expansion occurring within the previous 2 to 3 years. To facilitate this collaboration, engineers have been placed in the hospital to support rehabilitation technology utilization (e.g., therapeutic robotics, haptic feedback, virtual reality).

Dr. Posteraro gave an overview of the Neurological Rehabilitation Unit. He noted the strong integration of engineers and clinicians at the hospital and identified what he felt were the necessary technological specifications for a useful neurorehabilitation robotic device: (1) It would be active rather than passive. (2) It would be able to sense the patients movements, providing assistance as needed to help the patient finish the “trajectory,” and provide proprioceptive feedback. (3) It would have very low impedance when the system did not work. (4) It would adequately stabilize and “fixate” the trunk to prevent the patient from
using a compensatory kinematic strategy, thereby facilitating a more desirable kinematic strategy.

He then reviewed the available technology, noting which system types were available: passive versus active, low versus high impedance, and systems that control the end-effector versus all joints (i.e., MIT-Manus vs. exoskeletons). He noted that a comparison of end-effector versus exoskeleton systems would be very interesting. Finally, he presented two questions for which the answer is unknown: (1) Which system is more effective and (2) Which system is best for the upper limb and which system is best for the lower limb?

**FUNCTIONAL FOCUS**

The functional focus is on ambulation and reaching in subacute and chronic stroke. Technology utilization is through ambulation training via treadmill, upper-limb therapeutic robotics using the MIT-Manus (shoulder/elbow module and wrist module).

**RESEARCH FOCUS**

The broad focus of the presented research is refinement of therapeutic robotic rehabilitation protocols. General research themes pursued include (1) determining whether the optimal therapeutic program and recovery mechanism (neuroplasticity vs. compensation) differs between subacute and chronic stroke, (2) developing alternative research strategies to better target specific joint actions (i.e., supporting active elbow extension via a fan-like reaching pattern), (3) assessing new therapeutic protocols on the basis of motor learning theory (i.e., error augmentation via divergent fields), and (4) determining whether robotic therapy could stimulate cortex activity in the damaged hemisphere (via EEG).

In addition to therapeutic robotic rehabilitation, this group is pursuing respiratory and cardiological telerehabilitation and telemonitoring research themes.

**TRANSLATION**

Discussions with Dr. Posteraro and Dr. Mazzoleni indicated much of their work had not yet been implemented as clinical practice. It is unclear whether large-scale clinical trials are under way or are in an active planning stage. In addition, there does not seem to be a relationship with the robotic manufacturers by which their research findings are or could be implemented into the robotic device by the manufacturer. Finally, we did not discuss whether their research group had produced any spin-off companies.

**SOURCES OF SUPPORT**

Support is provided by the European Commission, Italian government, and regional government.

**ASSESSMENT**

Based on the presentations and subsequent discussion, this appears to be a fairly young research group/program (<10 years) whose research themes are still maturing, especially compared with other sites visited. However, it appears to be resource rich, growing rapidly, and to have the capacity to bring added value to international collaborations.
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Mazzoleni, S., R. Crecchi, M.C. Carrozza, and F. Posteraro. 2010. Effects of different upper limb robot-aided approaches in chronic hemiparetic patients. 17th Physical and Rehabilitation Medicine European Congress, Venice, Italy.


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OVERVIEW

Paristech is a relatively new consortium of 11 leading technical universities that includes 4,500 students. The Technologies and Health Network has 30 participants from various labs and is run by Dr. Wafa Skalli. The focus of our visit was the Laboratory of Biomechanics (LBM), with a staff of 50, including engineers and clinicians organized in three research teams. LBM is focused on musculoskeletal biomechanics with a wide range of approaches for subject-specific modeling, along with in vitro analysis and in vivo functional evaluation. LBM's 35 faculty members include 5 clinicians and 20 PhD candidates and postdoctoral fellows who participate on three teams: biomechanics and nervous system (movement analysis and restoration); biomechanics, sport, health and safety; and musculoskeletal modeling and clinical innovation. Degree programs include master’s of science and PhD in musculoskeletal and tissue biomechanics. The international master’s degree program in biomedical engineering is a collaboration between ParisTech and Paris Descartes Medical University. This pluridisciplinary master’s degree is open to students from both clinical and engineering background. This program emphasizes research toward innovation; within this program, surgeons learn biomechanical modeling.

FUNCTIONAL FOCUS

The primary functional focus of the lab is on neuromusculoskeletal disorders affecting walking.

RESEARCH FOCUS

The main research focus of the LBM is neuromusculoskeletal subject-specific modeling, with the development of in vivo methods and devices for in vivo characterization of tissues and structures, to set relevant models and to validate them in a routine clinical environment. Research highlights include the following innovations:
Co-invention of the innovative EOS low-dose biplanar x-ray system with the associated methods for accurate three-dimensional reconstruction of the skeleton

- Subject-specific bone and joint models, particularly for early detection of progressive scoliosis, for osteoporosis fracture risk estimation or for surgery planning
- Innovative methods for building subject specific musculoskeletal models by fusion of optoelectronic, MRI, and biplanar x-ray data

In the impact biomechanics area, researchers have developed a finite element analysis for crash analysis, especially for the head and neck. Subject-specific modeling of joints and spine has been developed to support orthopedic implant decision making as well as osteoporosis prevention. This has also provided analysis of cervical range of motion and muscular modeling of the cervical spine, especially during impact. HUMOS 2 provides a postural description of the driver and developed a specific test from FEM to understand the mechanism of injury. Primary finding of the whiplash project is the influence of interindividual geometry—different cervical curvatures produce different risk.

EOS is a low-dose biplanar x-ray system that enables the x-rays to be taken in the standing, weight-bearing position, from head to feet. The Biospace Med company created by G. Charpak (Nobel prize winner in physics) manufactures and markets the EOS three-dimensional reconstruction for scoliosis. The radiation dosage is lower than standard x-ray by a factor of 8. It is used to analyze the mechanisms of adolescent idiopathic scoliosis progression using geometrical and mechanical modeling. It is used to create a personalized vertebral FEM that shows the influence of load location displacement on stress and strain distribution.

**TRANSLATION**

This group has advances both in multiscale modeling approaches, from a structural and from a control point of view, and in *in vivo* characterization of the geometric and material properties both in statics and in dynamics, from simple cheap exams compatible with routine clinical analysis. The group has registered 10 patents in the last 8 years. It needs approval of "service du don des corps" faculty ethical committee for the use of human cadaveric specimens and approval of "Comité de Protection des Personnes" ethical committee for exploration of human volunteers or patients.

**SOURCES OF SUPPORT**

Some research involves the military or veterans. Funding is from several sources: University funding, governmental or European grants, and private contracts. More recently, support was provided through chair funding, and revenues are expected from patent royalties. These partners can be involved in the generated patents in the scientific committee proposals (the level of implication depends on the nature of the funding mechanism). Funding mechanisms are typically multi-investigator or multi-institutional, which is important because of the complexity of this multidisciplinary field. This group engages in well-defined multi-investigator multi-institutional research in which the complementary role of each party is clearly established and the research is beneficial for all the parties (keeping in mind the aim of the major end benefit for the patient and for the society).

**ASSESSMENT**

This laboratory is through its EOS and powerful modeling providing potentially transformative work. The whole area of neuromusculoskeletal modeling would be worth
exploring for collaborations with U.S. mobility science and technology programs. This neuromusculoskeletal biomechanics laboratory is progressing toward a multiscale, subject-specific human model that would bring drastic improvement in understanding the mechanisms of injury or progressive disability and provide a personalized and optimized solution. This lab's biomechanical models have the potential to help in the following areas:

- Early detection of slight abnormalities in balance, control, and tissues that could initiate a biomechanical cascade leading to a severe impairment
- Design specification of innovative devices for prevention or treatment
- Assessment of the most adapted strategy for treatment and rehabilitation program for a given patient, either by simulating the treatment or by being able to quantify its real effects

SELECTED REFERENCES


Rehabilitation Robotics Group, Fraunhofer IPK Institut für Produktionsanlagen und Konstruktionstechnik (Institute for Production Systems and Design Technology)

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OVERVIEW

Dr. Schmidt leads the Rehabilitation Robotics group at the Fraunhofer Institute in Berlin, which is part of the Automation Technology Division, led by Dr. Krüger. Dr. Krüger provided an introduction to Fraunhofer IPK, a member of the Fraunhofer Society and the Institute for Machine Tools and Factory Management, of the Technical University of Berlin. The Fraunhofer Society is the largest society in the world focused on applied science and engineering, and consists of 59 institutes with approximately 17,000 employees and a budget of €1.6 billion. Of note, the MP3 compression algorithm was invented by Fraunhofer IIS and generated approximately €100 million in revenue for the society in 2005. The founder of Fraunhofer IPK is famous for integrating some of the first computers in Germany with machine tools.

Fraunhofer IPK is housed in an architecturally stunning, award-winning facility built in 1986; it has 517 employees, approximately 50% of which are students. The institute's budget is approximately €24.6 million. The mission of Fraunhofer IPK is optimization of industrial processes, from product idea through manufacture, and the institute seeks to aid in rapid transfer from research and development to practical applications.

The Automation Technology Division is focused on developing innovative technologies that combine robotics, control, and machine vision. An interesting example of their work is the development of machine vision algorithms that helped solve the “Stasi Puzzle,” which was the problem of reconstructing documents that the secret police in the GDR ripped into 660 million pieces. Dr. Krüger's vision for the Automation Technology Division encompasses
human-centered automation, defined as automation in which man and machine work closely together. Thus, the Automation Technology Division is very interested in understanding how humans move to build better collaborative robots and has been a world leader in developing robotics for human rehabilitation.

**FUNCTIONAL FOCUS**

The primary focus has been on walking, although there is also some work on manipulation.

**RESEARCH FOCUS**

Dr. Schmidt provided an overview of devices developed by the Rehabilitation Robotics group at IPK. Some of this work has been collaborative with Dr. Stefan Hesse at Charite Hospital Berlin, who hosted a visit by the panel at the hospital in the afternoon, as described in another report.

The Gait Trainer GT1 is a device for assisting patients in retraining walking (Uhlenbrock et al. 1997; Hesse and Uhlenbrock 2000). It was developed first by Dr. Hesse, and now IPK is working to improve the device. The GT1 uses the so-called end effector principle to help move the legs; that is, it attaches by means of footplates to the distal end of the limb (the bottom of the foot), rather than providing exoskeletal support for each joint in the leg. It uses a single-degree of freedom mechanism to simulate the natural trajectory of the foot during walking and a pulley system to assist in weight shift. It is controlled by a single knob, which adjusts the velocity of the footplates. RehaStim is a start-up company. The company has sold more than 150 GT1s, and the device has been extensively tested with positive results (Hesse et al. 2006; Pohl et al. 2007). The Rehabilitation Robotics group is developing new modules for the GT1. Researchers have integrated an industrial computer with it and added force sensors to the footplates. They are developing patient-adaptive compliant control algorithms for the device, along with computer programs for visual biofeedback of patient performance.

The StringMan is a system for training balance and posture over a treadmill, developed by Dragoljub Surdilovic at IPK (Surdilovic et al. 2007). It consists of eight force-controlled pulleys attached to a harness worn by the patient. It can be programmed to provide a virtual envelope in six degrees of freedom for the trunk and pelvis to support the patient during training. Within the envelope, the system can behave in a “free-mode” with minimum tension applied to the patient, accurately measuring the trunk position and orientation. The robot can also achieve zero moment point control, a technique used in humanoid robots to control their balance.

The HapticWalker (or GT2) is an impressive achievement in collaborative robotics that is a joint project between IPK and Charite Hospital (Schmidt et al. 2002; Schmidt et al. 2005). It consists of two six degrees-of-freedom footplates that can support the weight of the patient and be programmed to simulate different step characteristics, including stair walking. The device was designed so that the therapist could be physically close to the patient, to help the patient generate physiologic electromyographic patterns, and for quick transfer of the patient into and out of the machine. Dr. Schmidt showed a video of a patient with a spinal cord injury working with a therapist to practice climbing stairs. In the video, the therapist is helping to position and stabilize the patient’s legs so that the patient can try to move up a step. Dr. Schmidt observed that without that positioning help, the patient would not be able to practice stair climbing. The HapticWalker automates such positioning assistance, and thus could relieve the work burden of the therapist while allowing the patient to safely practice more steps. Current work on the HapticWalker includes integrating haptic feedback with force
feedback and developing compliance control algorithms for the device. One engineering student with a disability caused by a stroke completed a master’s thesis on the HapticWalker.

Current research also focuses on devices for upper extremity, such as extensions for the Bi-Manu-Track arm therapy robot. The goal is to add more sophisticated therapy modes, visual biofeedback, therapy data acquisition modules, and telerehabilitation connectivity for remote supervision of home rehabilitation and interactive therapy.

**TRANSLATION**

Approximately 12% of Fraunhofer’s IPK employees have helped spin-off 60 companies that have created an estimated 2,000 jobs. Some of the rehabilitation robotics work at IPK has been commercialized by a start-up company Reha-Stim (http://www.reha-stim.de/cms/index.php?id=60).

**SOURCES OF SUPPORT**

Approximately one-third of Fraunhofer IPK’s funding is provided by the German state, and approximately two-thirds of the funding is provided by competitive contracts from the German government, the European Union, and industry.

**ASSESSMENT**

Work in rehabilitation robotics at Fraunhofer IPK includes development of some of the most sophisticated gait training robots in the world (HapticWalker and StringMan). IPK is a leading facility in integrating medical expertise into robot-human interaction control design, achieving robust control of force-coupled interactions between robots and humans, and in innovative kinematic design of machines for assisting in walking.

This group identified the development of a comprehensive model of motor control and motor learning, in which the human is seen as a biocybernetic system, as a grand challenge for the field of mobility technology, and has proposed to the German government the development of a major research center involving all relevant groups in the Berlin area focused on this problem. It sees a need for an integrative model of orthopedic, muscle, and neural plasticity that can be used as a basis from which to design innovative mobility technology. A key question is how such plasticity can be controlled. Another grand challenge is to understand how transfer to the home can be facilitated with technology. Learning success achieved in the hospital is often lost, and thus there is a need to reduce the size and complexity of machines to be able to apply them at home.

**SELECTED REFERENCES**


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Date Visited: October 21, 2010 (NOTE: Presentation given at the University of Twente.)

WTEC Attendees: R. Cowan (report author), B.J. Fregly, M. Boninger, L. Chan

Host(s): Michiel Jannink
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OVERVIEW

RoboNED is an internal Dutch industry, academic, and consumer innovation partnership supported by the Dutch government through a parent organization, ICTRegie (ICT = information and communication technology, research and innovation). RoboNED is the result of a top-down initiative (i.e., it fills a governmentally identified need). RoboNED will develop a strategic robotic research agenda for the Netherlands. This agenda will identify existing robotic research themes and research themes to pursue, with the ultimate goal of developing commercially viable products. This group is expected to encourage synergistic cooperation across the stakeholders. RoboNED’s focus is diverse, including, but not limited to medical care, surgical, therapeutic, manufacturing, household, entertainment, agricultural, inspection, defense, and construction robotics.

The Leo Center for Service Robotics is a newly formed initiative and was founded after a physical survey of robotic research (industry and academic) in Japan and the United States. By contrast with RoboNED, LEO is a bottom-up initiative—filling a need identified by industry and academics. The Web site says, “The focus of LEO–Center for Service robotics, will be to conduct applied research, build demonstrators, explore the economic potential, and inform society about the vast potential of robotics.” The LEO Center will be located at University of Twente and will include a physical collaborative space. LEO has identified three service robotic themes: medical (e.g., surgical, rehabilitation, prosthetics); inspection, infrastructure, and agriculture; and humanoid.
FUNCTIONAL FOCUS

Given RoboNED has just been formed, and the portfolio is still evolving, it is difficult to identify which functional outcome will be most strongly influenced. Thus, we hoped to convey optimism without speculation. We believe RoboNED is positioned to have a substantial impact on mobility. In the future, the portfolio could affect many of the mobility tasks that were the foci of the panel (i.e., posture, balance and transfers, manipulation, walking, stair climbing, other locomotion tasks, using transportation). Currently, there is no clear, immediate pathway by which the portfolio projects improve mobility (i.e., used clinically).

RESEARCH FOCUS

RoboNED and LEO were designed to develop robotics research in the Netherlands. The application areas are diverse and include, but are not limited to, medical care, surgery, therapeutics, manufacturing, household, entertainment, agriculture, inspection, defense, and construction robotics.

TRANSLATION

The goal of both groups is commercially viable products, but currently, there is no translation.

SOURCES OF SUPPORT

Dutch Government and European Commission provide funding.

ASSESSMENT

There appears to be a series of overlapping and supporting organizational structures in the Netherlands that foster collaboration across government, industry, and academics in pursuit of a unified goal. In addition, a subset of these structures and organizations (e.g., MIRA and Demcon) actively supports technology translation from academic prototypes to a commercial product, with spin-off companies encouraged and potential conflicts of interests minimized. RoboNED and LEO–Center for Service Robotics appear to be recent additions to this structure.

During the University of Twente facility tour, we stopped by a robotics research lab. The primary goal of this lab was to foster innovation and discovery through the development and refinement of robotic technology. The robots in and of themselves were not all intended to have commercial application or to solve a problem. Nevertheless, some activities are intended to prove applicable concepts for real applications that could then be taken over for an engineering phase either by spin offs or external enterprises.

All running research is externally funded by national or European subsidy and industry collaborations. The focus is on medical, inspection, and household robotics.

SELECTED REFERENCES


Scuola Superiore Sant’Anna (SSSA)

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Date Visited: October 18, 2010

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OVERVIEW

Scuola Superiore Sant’Anna is part of a 200-year-old university that is included in a network of a universities surrounding Pisa. This network forms the largest research area in Italy and is the home of Galileo. The network is highly competitive for funding with substantial government support. There is a high-intensity investment in research, which is focused on multidisciplinary collaboration across a wide variety of disciplines. Fields highlighted include economics, clinical medicine, and engineering.

The center quotes many independent metrics for outstanding performance. It has the highest funding per researcher in Italy and a high ranking on both number of papers published and citations of the papers according to the Thomson Reuters (formerly ISI) Web of Knowledge. Twenty-nine spinoff companies have been developed out of this center, and it has submitted numerous patent applications.

SSSA Biorobotics Institute has a new structure that includes three labs: The ARTS lab, CRIM Lab (Centre of Research in MicroEngineering), and the EZ Lab (Research Centre on Aging). We observed several of the research projects from the labs that span all aspect of robotic and sensor-based neurorehabilitation.

FUNCTIONAL FOCUS

The focus varied by laboratory; as a result of the multiple labs, the focus was broad. There was a focus in the assessment of neurologic disorders. In a pediatric population, this focus included means of assessing very young children. On the opposite end of the age spectrum, there was a treadmill-based fall-risk assessment that included lateral movement of the treadmill tracks.
Replacing movement for manipulation was another focus area. This work included a multiple degree of freedom hand and a clinical program that included implantation in a single subject with a direct nerve recording technique. This area also included a modeling component as a method of understanding the means by which movement can be replaced. One unique model involved a two-degree-of-freedom upper arm that incorporated agonist and antagonist muscles. 

Robotic-based rehabilitation was represented through an elbow-based exoskeleton. The elbow had multiple degrees of freedom, thus allowing for a concise understanding of deficits. The group was also worked in robotic rehabilitation in a hospital bed based on footplate movement. The foot plates and movement patterns where anthropomorphically correct.

RESEARCH FOCUS
A main research focus was biorobotics. This area crossed into the realm of exoskeleton-based rehabilitation and neuroprosthetics. Another broad research focus was in human machine interactions. In this area, investigators had worked with a geriatric population in which they were setting up an experimental town to test interventions. Modeling was involved in several studies, including one focus area that used robots to understand human motor control. Sensory technology was incorporated into numerous projects, as needed, for modeling and feedback related to neuroprosthetics. An example in this area was the skin sense optical sensor for detecting pressure related to axial loading.

TRANSLATION
The group has spawned multiple spin-off companies with various levels of success. The group also includes strong clinical partners in the Pisa area. Direct translation resulting in changes in clinical care was not observed.

SOURCES OF SUPPORT
The group has a variety of sources of funding, including the Italian government. Impressively, 80% of funding comes from the European Union. The group is highly competitive in Europe.

ASSESSMENT
The SSSA Biorobotics Institute is an effective center. It has spawned positive spin-off companies. It exhibits the importance of a multidisciplinary effort and a strong research milieu, as well as strong leanings to national and international collaborative efforts.

SELECTED REFERENCES
Appendix B. Site Reports

Sensory-Motor Systems Lab, Institute of Robotics and Intelligent Systems, ETH Zürich & Spinal Cord Injury Center

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Date Visited: October 20, 2010

WTEC Attendees: R. Cowan (report author), B.J. Fregly, M. Boninger, L. Chan

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OVERVIEW

The research of the Sensory-Motor Systems (SMS) Lab focuses on the study of human sensory-motor control, the design of novel mechatronic machines, and the investigation and optimization of human-machine interaction. The main application area is the field of rehabilitation. Further applications are within sports and medical education. SMS Lab personnel include doctoral students, postdoctoral fellows, a physician, therapists, electronic and machine technicians, undergraduates (thesis work, internships), and support staff.

The lab investigates the sensory-motor actions in and interactions between humans and machines. Human sensors (receptors) record the physical state of the human body and the surrounding environment. Sensory information is perceived by the human central nervous system. Human cognition is required to interpret the perceived information and generate a motor reaction. Similarly, in machines, technical sensors detect the state of the machine and its environment. Sensor data are processed to drive actuators and displays. Humans and machines can interact with each other via sensory and motor channels.

Mechatronics can be generalized as the synergistic integration of multiple engineering disciplines in the design, development, and manufacturing of products and processes. The specific discipliners involved as well as the specific products and processes vary according to the topic of interest (www.wtec.org/loyola/mechtron/01_02.htm).

The SMS Lab is affiliated with the Institute for Robotics and Intelligent Systems at ETH Zürich and the Spinal Cord Injury Center at University Hospital Balgrist. Offices and laboratories are located at ETH Zürich, with additional space for clinical interactions at the University Hospital Balgrist. Technologies developed and refined at ETH are tested with clinical populations at Balgrist.

Dr. Riener described the requirements of human-machine interactions: (1) rigid movement guidance versus cooperative guidance; (2) multimodal integration (i.e., haptic, visual, audio,
feedback/stimulation); and (3) task-specific training (ADLs vs. general motions). These requirements are reflected in the rehabilitation robotics, prosthetics, and motor control and sports research themes. The SMS Laboratory has a close relationship with Hocoma, the manufacturer and distributor of several rehabilitative robotic systems which are the focus of SMS research (Lokomat, Armeo, and Erigo). This relationship is synergistic, and the inherent possible conflicts of interest appear to be adequately managed.

FUNCTIONAL FOCUS

A primary SMS focus is robotic-based upper- and lower-extremity therapeutic rehabilitation, with an emphasis on reaching and gait training after stroke and spinal cord injury. However, control systems for lower-limb prosthetics and multisensory virtual reality motor learning/sleep evaluation were represented (Figure B.3).

![SMS Projects Overview](image)

Figure B.3. SMS projects cover a variety of upper- and lower-extremity therapeutic rehabilitation.

RESEARCH FOCUS

SMS Lab research can be generalized as research and development on the enhancement of robotic therapy, with a primary focus on the robotic–human interface. The goal appears to be to increase robotic rehabilitation effectiveness through one or more of the following pathways: alternate control strategies (pattern vs. path control, complementary limb estimation), better human movement pattern mimicry (i.e., increased joint degrees of freedom), decreasing the impact of the robot on movement (i.e., hiding the robot), or automated multimodal stimulation.

The ARMin III (Figure B.4) is an upper-extremity robotic rehabilitation device that will be the Armeo Power when it is produced commercially by Hocoma. It advances the current Armeo product line by adding power and additional degrees of freedom. The additional power and degrees of freedom allow more custom fitting to patients' anthropometrics and enable the robot to assist motion as needed—even of more severely lesioned patients. In addition, a therapist can record a specific motion pattern that the robot can then repeat without therapist guidance. Finally, the ARMin III is being integrated with virtual reality, so ADL-specific tasks can be trained. In conjunction, path control is being implemented as an
alternative to fixed trajectory controls. Previous Armeo versions provided spring-assisted or counterweight-supported gravity offloading.

![ARMin III robotic exoskeleton for upper extremity therapy](image)

Figure B.4. Research prototype ARMin III robotic exoskeleton for upper extremity therapy (courtesy of ETH Zürich).

The current Lokomat, a robot-aided treadmill training device (Figure B.5), allows 4 degrees of freedom in the sagittal plane. SMS is working to increase the Lokomat to 7 degrees of freedom by adding thigh internal/external rotation, medial lateral hip/lower body movement, and superior/inferior hip oscillation. These additions will allow movement patterns to better match overground ambulation. The Lokomat traditionally has a single trajectory based stepping pattern from which the patient cannot deviate. Path control provides a virtual tunnel in which the patient can modify his or her stepping pattern. Guiding forces are applied when the person begins to deviate beyond the tunnel boundaries.

![Path Control](image)

Figure B.5. The Lokomat is a robot-aided treadmill training device (courtesy of ETH Zürich).

Any exoskeleton (e.g., Lokomat, Armeo) invariably affects patient motion, in part because the exoskeleton’s inherent inertia is not fully offset. The patient can feel the inertia and adapts his or her gait accordingly. Ideally, the exoskeleton’s inertia would be fully offset. To the extent that the patient could not feel the robot and it would thus be hidden. The SMS Lab is working to achieve this hiding with the hopes that it will improve guidance technique and functional rehabilitation outcome.

Gait training can be very passive and boring. A virtual reality system is being developed to engage patients and open the brakes of neuroplasticity in higher ages. Visual and auditory inputs will be used in a game-based interaction to engage patients. As with the AwaCon,
physiological monitoring would be used to monitor the cardiovascular response and the stimulus intensity adjusted accordingly to prevent the training from exceeding a given stress/intensity threshold. This is a closed loop control system, with a human as a part of the loop, and uses common filter estimates to estimate and adapt its own state. This project is multisite and is funded by the European Commission as a part of the Multimodal Immersive Motion rehabilitation with the Interactive Cognitive Systems project.

The AwaCon (Figure B.6) is based on the Erigo, a Hocoma product. The Erigo is a tilt table integrated with a step trainer. This combination facilitates early mobilization of neurological and bedridden patients. The AwaCon advances the Erigo by integrating physiological monitors and automated tilt and stepping rate and loading to maintain cardiovascular homeostasis within parameters set by medical professionals.

![Intensive Care Unit](image)

**Figure B.6.** The AwaCon integrates physiological monitors and automated tilt, stepping rate, and loading to maintain cardiovascular homeostasis (courtesy of ETH Zürich).

Conceptually, the physiological data would be processed by a control algorithm, which would accordingly adjust some combination of the table tilt, step rate, or step loading to achieve a predefined cardiovascular goal. The vision is to use the body’s inherent physiological responses to regulate the cardiovascular system of ICU patients, thereby attenuating the negative effects of extended inactivity (bedrest), and hopefully replacing or minimizing pharmacological cardiovascular control therapies, and shortening ICU stays. The current control algorithm was mapped using young, healthy volunteers, and the current prototype is being used in acute stroke patients to stabilize the cardiovascular system.

In addition, it is envisioned that the AwaCon could be integrated with multimodal sensory input (images, sounds, tilt, stepping frequency, and load) to stimulate patients in vegetative states as an assist to regaining consciousness. Physiological sensors would be used to monitor patient arousal.

Dr. Heike Vallery, a postdoctoral fellow, is developing an alternative control strategy to control lower-limb prosthesis, specifically for control of powdered knees. The Complementary Limb Motion Estimation (CLME) approach exploits existing physiological couplings to instantaneously map the needed movement of the prosthetic device based on the position of the remaining leg. This control process has been tested in at least one amputee. CLME is also used in gait robots to determine the position of a leg paralyzed due to stroke. Using CLME in this manner produces a patient-specific gait pattern, which is then used by the robot to retrain ambulation.
The goal of the magnetic resonance compatible robotics project is to develop upper- and lower-limb robots for use during magnetic resonance evaluation. The vision is to use these robots during fMRI to create a neurological representation of motion to better understand recovery and optimize therapy (Figure B.7).

Figure B.7. MARCOS, a 1 degree-of-freedom, sagittal-motion lower extremity fMRI robot.

The Multi-Modal Motion (M3) Generation in 3D (3D, 3 modalities: graphics, sound, haptics) simulator is essentially a three-walled room equipped with surround sound and a sophisticated set of rope-like tethers. The walls are video screens proving visual context; the speakers provide stereo sound to accompany the visual immersion; and the tethers are attached to the end effector (e.g., oar, tennis racket), providing haptic feedback to matching interactions with the virtual reality environment. The primary use of this lab has been sports training, but there is a vision to expand it into a rehabilitation context.

TRANSLATION

Based on the provided information, SMS research translation appears to be primarily technology transfer. As stated previously, the SMS Lab appears to have a strong relationship with Hocoma, the company that produces and sells the Lokomat and Armeo and Erigo (the basis for the AwaCon). It seems logical that SMS research efforts can and will be rapidly implemented into commercially available clinical products. Clinical studies research appears to be mostly small N test studies intended to guide device development. However, a small randomized clinical trial involving the ARMin III (Armeo Power) is under way (n >80).

SOURCES OF SUPPORT

Forty percent of the annual budget is from the university and is noncompetitive as part of faculty appointment. Sixty percent is from the European Commission, Swiss Science Foundation (SNF), NSF, and other foundations.

ASSESSMENT

The strong engineering research and development by the SMS Lab is clinically grounded at multiple stages. Physicians and therapists are a part of the laboratory team, helping to inform design requirements. Affiliation with and space at Balgrist hospitals allows for prototype evaluation, both from clinician operators and patient clients. A strong working relationship with Hocoma helps to ensure much of the research will become available to clinicians. Industry-academic relationships automatically raise conflict of interest questions. Discussions with Professor Riener and Hocoma suggest the inevitable concerns are managed as best as possible. In addition, the European Commission's Seventh Framework Programme
appears to encourage (and possibly require) public-private relationships as a funding requirement.

The SMS Lab is an example of a successful interaction across multiple disciplines, secondary education, research, industry, clinics, and funding sources. Noncompetitive university funding (40% annual budget) supports pilot data/proof-of-concept developments, which then are leveraged to secure larger competitive grants (60% annual budget). Students at all levels are involved, from undergraduate interns through postdoctoral fellows. These students appear to run the projects described, with advanced content support provided as required. Students acquire knowledge in multiple disciplines and develop many skills, but when advanced concepts/skills outside of the student’s core area are required (e.g., programming, machining), non-student expert staff members provide assistance. This strategy facilitates student learning without compromising a project (i.e., requiring the project be tailored to the knowledge of the student, which could hinder project advancement).

SELECTED REFERENCES


Smartex

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Date Visited: October 18, 2010

WTEC Attendees: L. Chan (report author), M. Boninger, B.J. Fregly, R. Cowan

Host(s): Rita Paradiso
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OVERVIEW

This program combines a private company with a university program to create a novel enterprise that designs and fabricates a variety of cloth-based sensors. The goal is to use textiles as a platform for unobtrusive physiological monitors. The enterprise has been in existence for 10 years and has approximately 15 employees, including faculty members from the University of Pisa.

To date the company has commercialized one product and has several other prototypes:

- Shirt (commercialized, EKG, respiratory rate, three-dimensional accelerometers for activity)
- Bed sheet that measures sleep quality (EKG, respiratory rate, activity)
- Jumpsuit/pants (inertial sensors)
- Seat pressure monitor (force sensors)
- Elbow sleeve (EMG, FES)
- Glove (inertial sensors, microbubbles for force measurement)

FUNCTIONAL FOCUS

This line of research is related to several mobility-related domains, including manipulation, posture, balance, transfers, and locomotion. Its primary benefit appears to be in the assessment of physiologic measures, some of which are intimately related to mobility. A
secondary focus discussed was a textile covering for a neural prosthetic to allow for sensory feedback.

**RESEARCH FOCUS**

The primary focus of this enterprise has been to put piezoelectric sensors in cloth. Investigators have devised a novel way of “printing” these sensors onto elastic cloth at a very low cost. This has allowed for the creation of several novel, wearable sensors. Investigators are now trying to add functionality, including EMG, near infrared spectroscopy, FES, and microbubble technology for force measurement.

**ENVIRONMENT**

Pisa is a rich environment for research with many established research institutions. Smartex is located in a building with several technology start-ups. It has strong links with other research institutes and a rehab hospital. There are two labs, including one in a local hospital.

**TRANSLATION**

The Smartex Shirt has been commercialized and is now being sold for research purposes. Their instrumented bed sheet is currently undergoing testing in two hospitals. The other prototypes are still in development. There are firewalls between the researchers and the business to ensure that items are commercialized appropriately.

**SOURCES OF SUPPORT**

The enterprise and funding come from a variety of sources, including textile manufactures, the Italian government, and some profits from the sale of its product. Past sources include the United States (Defense Advanced Research Projects Agency (DARPA) and NIH).

**ASSESSMENT**

This research group has created a novel assembly of measurement instruments that is worthy of further exploration. Its technology is still unproven, however, if investigators can solve the technical issues, they may be able to revolutionize how physical activity is monitored, taking this invention into the community. There do not appear to be any related labs in the United States.

**SELECTED REFERENCES**


Appendix B. Site Reports


Appendix B. Site Reports

Technology Research for Independent Living (TRIL), Institute for Sport and Health

Site Address: Newstead Building
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Ireland
01-7163241
www.trilcentre.org
http://www.ucd.ie/instituteforsportandhealth/research/majorresearchprojects/stimxdpproject/

Date Visited: October 20, 2010 (NOTE: Dr. Caulfield met the WTEC panel in London, UK.

WTEC Attendees: M. Rodgers (report author), H. Ali, P. Bonato, T. Conway,
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Host(s): Brian Caulfield
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OVERVIEW

Dr. Caulfield presented to the WTEC panel his work with the TRIL Centre and the StimXDP Research Group, Institute for Sport and Health, University College, Dublin. His research work exploits technologies developed by colleagues in computer science and biomedical engineering for the advancement of human function in health and sport. He collaborates with researchers from other fields, as evidenced by his roles as principal investigator in the CLARITY Centre for Sensor Web Technologies and leader of the StimXDP collaboration between University College, Dublin, and Biomedical Research Ltd. He has published more than 60 papers and coauthored 6 patent applications arising from this work focused on the integration of sensor and wearable computer technology to develop unobtrusive methods of motion and physiological analysis and therapies for sport and health, including the development of novel methodologies for electrical stimulation of muscle. Dr. Caulfield’s research focus covers a wide range of areas based on assessment and enhancement of human performance, including development and evaluation of wearable motion sensor applications for sport and health, design and validation of novel electrical muscle stimulation technologies, and identification of causes and optimal intervention strategies for recurrent musculoskeletal injuries such as patellofemoral pain and ankle instability.

FUNCTIONAL FOCUS

The primary functional focus of TRIL is fall prevention and mobility issues in the elderly population. The primary functional focus of the StimXDP Research Group is on EMS for treating a range of conditions, including low back pain, incontinence, obesity, and heart failure.
RESEARCH FOCUS

The StimXDP work is concerned with developing novel surface electrical stimulation technologies to enhance mobility by means of promoting increased cardiovascular fitness and muscle strength in patient groups who have barriers to engagement in voluntary exercise (some target groups include patients with diabetes, spinal cord injury, COPD, or heart failure). The technology development overcomes the barrier of cost and access. The StimXDP Research Group is based in the University College, Dublin, Institute for Sport and Health and has conducted numerous investigations over the past 10 years using EMS in a range of conditions, including low back pain, incontinence, obesity, and heart failure. The group developed and applied a novel form of EMS that permits passive aerobic exercise by rhythmic isometric contractions of the leg muscles. This system uses large electrodes and induces shivering. It allows patients who cannot exercise normally to increase their bodily oxygen demand and thereby exercise their cardiovascular system at therapeutic levels of training intensity. The system can also lead to muscle strengthening effects in some populations. The group is lead by Brian Caulfield with Louis Crowe, and Garrett Coughlan, five masters and four PhD students, and two support staff.

The TRIL work is primarily concerned with development and validation of clinical assessment or intervention protocols based on using sensor technologies to enhance mobility in the elderly population. This is achieved by using sensor technologies to develop clinical tools that will objectively assess the risk of falling in community-dwelling adults. The same sensor platform is then used to implement falls risk reduction exercise programs in the home environment by means of providing biofeedback during targeted therapeutic exercise. The TRIL research program brings together gerontologists, perceptual and cognitive scientists, and engineers to design and build technology that will predict and prevent the onset of perceptual decline with ageing. The TRIL Technology and Design Team consists of software/hardware engineers and interaction designers who ensure that (1) all hardware and software interfaces are as intuitive as possible for older adults, and (2) all technology deployments, in the home or clinic, are unobtrusive. Three key principles underpin their technology and design effort:

- **Avoid technology push**—rather than developing technologies for the sake of innovation, the investigators do so as a response to a research requirement or as an appropriate intervention for a challenge associated with ageing.
- **Learn from the users**—the investigators are committed to a user-centered approach to technology development.
- **Re-use**—where the investigators can, they use off-the-shelf technologies and avoid developing their own technology.

TRIL has five research areas: falls prevention, perceptual function, cognitive function, social and mental health, and wellness and exercise. In all five areas, the primary research focus is technology for monitoring older adults. At this point, the investigators have deployed home monitoring systems with 620 people in Ireland. They are building predictive models, including those that predict fall risk to 85% accuracy.

The TRIL frailty assessment is optimized to produce detailed information across a wide range of bio–psycho–social elements and provide characterization of frailty. A frailty index has been created using data collected during the first phase of TRIL. Another well-established and accepted marker of frailty is the occurrence of falls. Falls continue to be a central focus of TRIL research, with more than one third of people over the age of 65 having at least one fall.
each year. Because current intervention strategies result in only a 30% reduction in the reoccurrence of falls after 1 year, the focus of the work is to elucidate the factors contributing to falls and to use this information to develop assessment tools to identify those at risk of falls. Appropriate intervention therapies and technologies may then be developed to assist older people in the management of falls risk and the prevention of future falls.

In research examining the possible role multisensory perception has on the incidence of falls in older persons, technology developed in TRIL is used to improve diagnosis of deficits in combining sensory information during ageing. Researchers at TRIL have found that adults with a history of falling make more mistakes in combining multisensory information than do adults of the same age with no history of falls, suggesting that multisensory efficiency may be an important diagnostic tool for predicting falls. Their findings also suggest that assessment procedures need to develop from the current emphasis on measuring sensory acuity, because falling is only partially linked to eyesight or hearing alone. They have established a series of cross-sectional studies to understand the nature of the deficits in multisensory integration that occur with ageing. These tests assess how the senses are combined in recognizing, interacting with, and navigating in the immediate environment and are performed using TRIL technology by attendees at the TRIL Clinic. Validation of a multisensory retraining kit that could be used at home by older people is in progress.

TRIL is also developing technologies that can remotely monitor cognitive health and help target appropriate intervention. In the context of large rises in the incidence of dementia and Alzheimer’s disease, the long-term objective is to reduce the burden on clinical resources by enabling new models of care. The cognitive research strand is running two projects. “Dear Diary” is concerned with identifying markers of cognitive decline in speech and language. “Training for Focused Living” is developing technology tools and training protocols that allow older people to increase their levels of alertness.

Some examples of projects currently ongoing within the social and mental health strand include the following:

- Definitions of loneliness: This study is exploring the distinction between social and emotional loneliness through statistical models. Social loneliness refers to an absence of social contact. Emotional loneliness relates to dissatisfaction with existing opportunities to socialize. This analysis will help customize interventions toward different types of loneliness.

- Bio-psycho-social correlates of sleep: This study is looking at how sleep disturbances relate to mental and physical health. This study will provide further insight into the role of sleep for cognitive functioning, as well as social and emotional well-being.

- Psychological distress: This study is developing a brief screening tool for psychological distress, which refers to a negative emotional state that can affect daily living.

- Perceived health: This study explores the psychological and personality factors that influence how older adults rate their own health status.

- Teleconferencing for caregivers: This study is exploring how social engagement through telephone conferencing can be used to reduce risks of loneliness and isolation among caregivers of people with dementia.

The wellness and exercise strand uses recent concurrent advances in exercise science and sensor technologies to create novel approaches in implementing successful therapeutic exercise programs in the ageing population. It focuses on three main areas:
Identification of optimal prescription for exercise programs that can be carried out in the home (or in any other nonclinical environment) on an ongoing basis by the ageing population: Particular focus has been given to the use of short duration bouts of moderate- to high-intensity exercise, targeting multiple components of fitness and functional capacity.

Identification of a key set of biomarkers indicating changes in neuromuscular, skeletal, and cardiovascular function that can be used to effectively track participant progress: In addition, it is imperative that the resulting data can be translated into formats that will be understood by both the healthcare community and the population performing the exercise to achieve effective biofeedback.

Development of a technological platform that will facilitate implementation of exercise in the home or community in a manner that will see it embedded into daily life: The key to this will be the deployment and evaluation of a sensor-based system that will deliver effective exercise performance and compliance monitoring, physical status testing, encouragement and motivation, and feedback to the target population.

Current Research “Stepping Stones” is a short-term, high-intensity program of physical exercise to improve fitness levels in healthy middle-aged people (55–65 years).

TRANSLATION

StimXDP has four patents in multiple territories, one licensed and a second in progress. For patents, the university owns the intellectual property and gives inventors a share of royalties (on a sliding scale) if income is generated. The regulatory framework surrounding clinical investigations constitutes a substantial hurdle to this research.

SOURCES OF SUPPORT

Current funding mechanisms include both state and private funding, as well as a mixture of both. More than 50% of funding comes from interactions with industry partners. Typically, grants involve multiple investigators, as they frequently are in EU funding schemes. There is a dedicated NSF–SFI scheme for partnerships between Ireland and United States. The StimXDP group is funded under an Enterprise Ireland Innovation Partnership in conjunction with BioMedical Research, an Irish company based in Galway, the world’s leading producers of EMS products including Slendertone and Neurotech.

ASSESSMENT

The StimXDP research group is the first international enterprise to develop a surface EMS application that can be used to elicit a cardiovascular exercise effect at therapeutic training intensities in neurologically intact adults. This is achieved by means of developing a new approach to surface EMS that involves switching nonstandard pulse pathways among multiple electrodes in an array.

TRIL’s work is potentially transformative in the area of mobility for aging populations. It is novel in its ethnocentric approach to technology development and deployment. The interdisciplinary composition of the research team and the collaborations with industry provide a platform for effectively addressing mobility and enabling independent mobility with aging and chronic conditions. The shivering-inducing EMS research by The StimXDP Research Group is novel and has the potential to transform mobility for a range of conditions including low back pain, incontinence, obesity, and heart failure.
A unique feature of TRIL is involvement of the end user in the complete design cycle of technologies. Therefore, people with a disability are involved in the development process right from the start through to the point where we go into their homes to evaluate said technologies. The StimXDP group works with a variety of clinical partners and patient advocacy groups depending on the clinical context.

SELECTED REFERENCES


OVERVIEW

Researchers at Institut Telecom SudParis perform health-related research in three general areas:

- Advanced methodologies and technologies for multidimensional imaging (called ARTEMIS), directed by Françoise Préteux
- New technologies for independence (called Handicom), directed by Mounir Mokhtari
- Telemedicine in the service of patients at home (called TeleMeDom), directed by Jérôme Boudy

Researchers from Institut Telecom SudParis also work with the ADEP Foyer d’Every. ADEP is the government-run Aid Association for People with Handicaps and Polio, and the Foyer d’Every is an ADEP-funded group home close to Institut Telecom SudParis for people with severe movement limitations. The home houses approximately 40 people with different mobility limitations. Each person there requires high-level care. Some technologies
developed at Institut Telecom SudParis are implemented at Foyer d’Every for the benefit of the patients living there.

**FUNCTIONAL FOCUS**

The functional focus of Institut Telecom SudParis is on technologies that allow individuals with movement impairments to maintain as high a quality of life as possible. These technologies seek to allow patients to manage their environment or to be monitored for safety in their environment.

**RESEARCH FOCUS**

During our visit, we saw three different environments (one clinical and two research) where research is occurring. The first was the ADEP Foyer d’Every group home. The facilities at the home were developed with input from both people who live there and researchers at Institut Telecom SudParis. The team visited a “technology room” used to demonstrate some of the assistive technologies under development for the home. The room contained a special television that allows patients to make calls and receive calls; call a doctor or nurse; and change the room temperature, lights, or bed position, all with one simple remote control. Services in the home are set up to facilitate the work done by the caregivers, who receive on their cell phones requests for assistance from patients. Researchers developed a special joystick input connected to a custom Android phone program to control the television.

The room also contained a demonstration of an interactive software program with instrumented room elements to assist individuals with cognitive impairments. The program uses a radiofrequency token to detect what a person wants to do. For example, if the program detects that a person removed a can from the cupboard, the program automatically helps the person determine what to do next with the can (by providing several choices) and then provides each step of the desired task.

We also visited two labs on the Institut Telecom SudParis campus. The first was the Telesurveillance Lab. The goal of the research presented was to detect when a person is in distress due to a fall or cardiac event in a home environment. To be clinically useful, the detection algorithm needs to minimize the rate of false detections. The system uses an accelerometer and tilt sensor to detect changes in body position. To track the person’s location within the room, the system uses a combination of overhead infrared sensors and microphones. A vision system can also be used to attempt to identify which room the person is in as well as the person’s location within the room.

The second lab we visited was the Interactions for Multimedia Lab. The goal of the research presented was to perform real-time three-dimensional tracking of human movement and facial gestures using a single web cam (i.e., monocular vision). The tracked positions of the subjects are then animated in software using an articulated avatar model. The system calculates the model’s joint angles in real time using the computational capabilities of an NVIDIA graphics card (i.e., graphics processing unit computing). The two-dimensional to three-dimensional pose estimation is performed by determining the three-dimensional pose of the model such that its projected edges match the edges detected in the two-dimensional real image.
TRANSLATION

The ADEP group home close to Institut Telecom SudParis provides researchers with an excellent opportunity to develop and test new technologies with input from patients, thereby making it possible to achieve an immediate and tangible impact on patient care.

SOURCES OF SUPPORT

Funding for research activities at Institut Telecom SudParis comes primarily from French government sources, the European Union, and contracts with private companies.

ASSESSMENT

Institut Telecom SudParis is using a unique approach to technology transfer. Its technology transfer office has entered an agreement with the technology transfer office at Virginia Polytechnic Institute and State University. Under this agreement, Institut Telecom SudParis’ patents are actively marketed in the United States by Virginia Tech, and Virginia Tech’s patents are actively marketed in the France by Institut Telecom SudParis. This approach gives new technologies from both universities access to potential markets in a large and normally inaccessible international market.

SELECTED REFERENCES


University of Bologna, Department of Electronics, Computer Sciences and Systems

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40136 Bologna, Italy
+39 335 7111250
http://www3.deis.unibo.it/en/

Date Visited: October 19, 2010

WTEC Attendees: M. Boninger (report author), B. Fregly, L. Chan, R. Cowan

Host(s): Rita Stagni
Assistant Professor
E-mail: Rita.stagni2@unibo.it

OVERVIEW

Established in 1088, the university is home to an effort to harmonize European higher education. Multiple campus locations offer numerous degrees. Four main investigators are working in the movement area: Angelo Cappello, Lorenzo Chiari, Rita Stagni, and Silvia Fantozzi. There is broad collaboration with University of Padua, which provides medical expertise. We heard presentations from Dr. Stagni and several students working with Dr. Cappello and Dr. Chiari.

FUNCTIONAL FOCUS

The functional foci of the investigators are assessment and prevention. In the fall and injury assessment area, there is a focus on neuropsychology and gait. Accelerometer-based systems were used to investigate balance and fall risk. The accelerometers allow for quantitative evaluation of the timed up and go (TUG) test. In a group of patients with Parkinson’s disease, the accelerometer-based measures were more discriminative than the temporal approaches were. Also presented was the Co.Eva, which is a computerized neuropsychological evaluation. Computerizing the evaluation resulted in better speed, metrics, and reliability.

To prevent amputations, investigators are working on a multimodal orthotic design approach that involves kinematics, kinetics, plantar pressures, electromyography, and modeling. They are also working on design, implementation, and validation of an audio (video) biofeedback system, based on accelerometer signal of the trunk for balance and posture improvement and rehabilitation. The device gives audio feedback based on balance. They are actively working to translate this device to a smart phone or PDA to allow broader distribution.

RESEARCH FOCUS

Dr. Cappello's research focus is in biomechanical analysis and three-dimensional human tracking. Tools used in this focus include visual-inertial sensors, accelerometer-based measurement systems, EMG, and modeling. Dr. Chiari's focuses in the motor control area
using wearable systems as a means to classify activities and, possibly, personal health. Dr. Stagni focuses on modeling with multiple inputs, including biomechanics, metabolic, muscle force estimation, motion stability estimation, and three-dimensional fluoroscopy methodology.

**TRANSLATION**

All projects are easily clinically applicable. It is not clear that any of the projects have resulted in a clinical product. No business partners were mentioned.

**SOURCES OF SUPPORT**

Sources of support include the European Union and the Italian government.

**ASSESSMENT**

Using computerized testing to better evaluate outcomes is important in all aspects of assessment. Accelerometer-based feedback is likely to become ubiquitous, and an application in the TUG is a strong one. Most presentations were made by students who were very invested in their projects. This demonstrates a strong tie to the educational mission.

**SELECTED REFERENCES**


University of Padua, Faculty of Engineering

Site Address: Department of Innovation in Mechanics and Management (DIMEG)
Via Venezia 1 - 35131
Padua, Italy
+39 049 827 6809
http://www.mechatronics.it/
http://www.rehabrobotics.it/
http://www.dimeg.unipd.it/

Date Visited: September 22, 2010 (NOTE: Report based on interview of Dr. Rosati conducted at the University of California, Irvine.)

WTEC Attendees: D. J. Reinkensmeyer (report author)

Host(s): Giulio Rosati
Associate Professor
E-mail: giulio.rosati@unipd.it

OVERVIEW
Dr. Rosati’s research interests include robot-assisted rehabilitation and surgery; haptic interfaces, including cable-driven systems; and industrial automation systems. He is a member of the research group headed by Aldo Rossi at the University of Padua.

FUNCTIONAL FOCUS
The functional focus is manipulation.

RESEARCH FOCUS
Dr. Rosati and collaborators, including Dr. Stefano Masiero at the University Hospital in Padua, have developed and tested a cable-driven robot called NeReBot. NeReBot gently assists in range-of-motion exercises of the shoulder and elbow (Rosati et al. 2007). The device is designed to be usable by very severely impaired patients directly from the patients’ beds. These researchers performed a study of additional therapy with NeReBot starting <7 days after stroke, which is early compared with many robotic therapy studies. In this study, they found good improvement in the ability to perform activities of daily living in the NeReBot group compared with the control group (Masiero et al. 2007). Improvements in activities of daily living have typically been small in robotic therapy. A more recent study of substitutive NeReBot therapy starting 10 days after stroke showed comparatively similar gains in activities of daily living in the NeReBot group and in the controls, suggesting that a proper mix of addition and substitution may be the right trade-off between clinical outcome and costs of therapy (Masiero et al., 2011).

Dr. Rosati discussed several challenges for rehabilitation robotics. One is to improve the forms of feedback used to drive learning. He is interested in using auditory feedback to motivate patients to train in a proper way and to train complex functional movements. In addition, many robot therapy devices prescribe a desired trajectory; devices that allow more
autonomy and freedom of movement may be more useful. More research is needed into what type of exercises and robotic control are effective for subacute patients compared with chronic patients. More research is also needed to elucidate the motor control and motor learning principles especially for the first stage of recovery.

Dr. Rosati noted that, in Italy, there is some resistance to therapeutic technology in the clinic, particularly by older therapists, who may perceive robots as a threat. Therefore, he sees a major challenge being the creation of a culture of technology in rehabilitation, in which rehabilitation therapists understand robots as tools that complement their own strengths. For example, robots should be used for increasing intensity, especially in the very early stages of recovery. In Italy, the standard is only 1.5 hr of therapy a day. Dr. Rosati pointed out that we cannot afford increased intensity without technologies such as robotics or gaming technology.

Dr. Rosati noted the need for more clinical trials of robotic therapy, but he also noted that these trials are expensive. He observed that it is not feasible to have a clinical trial to test each specific control algorithm or feedback technique—it would be too labor intensive and costly. Thus, there is a need to try to optimize the way technology stimulates the patient, then, after that, to perform more clinical trials. However, there is also a lack of understanding on how the patient’s interaction with the robot promotes recovery and of how feedback can be used to improve recovery. Surmounting these knowledge gaps will speed the development of more effective robots.

**TRANSLATION**

NeReBot has not been commercialized yet.

**SOURCES OF SUPPORT**

Dr. Rosati’s work in rehabilitation robotics is mainly funded by the Ministry of Research and the Ministry of Health; there is also some regional funding.

**ASSESSMENT**

NeReBot is unique in that it was explicitly designed to be used very early after stroke. The positive clinical results obtained with this device suggest that greater consideration should be given in therapeutic technology development to the stage of recovery during which the technology will be applied.

**SELECTED REFERENCES**


University of Twente (Cooperating Laboratories)

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Date Visited: October 21, 2010

WTEC Attendees: B.J. Fregly (report author), M. Boninger, L. Chan, R. Cowan

Host(s): Hermie Hermens
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OVERVIEW

This site report covers presentations given by three collaborating laboratories at the University of Twente. The three labs work closely with the Institute for Biomedical Technology and Technical Medicine, or MIRA. MIRA seeks to facilitate integration of fundamental, applied, and clinical research so that new healthcare advances can reach the marketplace rapidly. MIRA works closely with the University of Twente, hospitals, businesses, and government organizations to facilitate technology transfer and seeding of new companies germinated through university research.

The three labs also work on collaborative projects with Roessingh Research and Development, an independent research and development organization that is the largest Dutch scientific research center in rehabilitation technology. Roessingh Research and Development was founded in 1990; in 2000, it formalized a relationship with the University of Twente. Roessingh Research and Development has a strong interdisciplinary research team and seeks to be an internationally recognized research institute that generates new knowledge and actively supports productization of this knowledge for rehabilitation
applications. Product development errors in technology-assisted rehabilitation are performed in cooperation with University of Twente.

**FUNCTIONAL FOCUS**

Research performed by the three labs included in this site report involves posture and balance; manipulation; and walking, stair climbing, and locomotion.

**RESEARCH FOCUS**

**Remote Monitoring and Remotely Supervised Training and Treatment (Dr. Hermens)**

The goal of Dr. Hermie Hermens's lab is to create new healthcare services by combining biomedical engineering with information and communication technology. The laboratory theme is “Enabling monitoring and treatment of subjects anywhere, anytime, and intervene when needed.” Remote monitoring involves remote measurement of vital biosignals without interfering with daily activities. Remotely supervised training and treatment involves monitoring and feedback that enable a patient to train when and where it is convenient and with the same quality of training as in a clinical environment.

There are many significant benefits to remote monitoring and remotely supervised training and treatment. Remote monitoring reduces hospital care (as well as costs), provides more freedom for patients, and provides peace of mind. Remotely supervised treatment makes high-intensity training possible (more = better), achieves more effective training because of training in a natural environment, puts the patient in the driver's seat, and allows the clinician to “treat” several patients at the same time. The main challenges are technological feasibility and clinic/patient acceptance.

Dr. Hermens shared two examples in which remote monitoring and treatment demonstrated initial success. The first example was teletreatment of chronic back pain. Studies report a change in activity level because of chronic back pain. To investigate the relationship between activity level and chronic back pain, Dr. Hermens and his collaborators initiated a clinical study involving 29 chronic back pain patients and 20 asymptomatic control participants. Activity levels were monitored for 7 consecutive days using a three-dimensional inertial motion sensor. Overall activity levels between the two groups were the same, but activity patterns were different between groups. The question still being investigated in this clinical study is whether normalization of activity patterns through feedback will improve outcome.

The second example was teletreatment of neck and shoulder pain. Chronic neck and shoulder pain typically shows no clear physiological overloading. The solution proposed by Dr. Hermens and his collaborators was to design a remote feedback system to warn patients when insufficient relaxation occurs. Muscle relaxation was assessed by means of surface electromyography with real-time feedback provided to both the patient and the therapist. Thus far, 100 patients have been treated in Belgium, Germany, Sweden, and the Netherlands. Outcomes have been as good as classical treatment, and the approach has been appreciated by patients as well as therapists.

**Active Assistive Devices (Dr. Rietman)**

The focus of Dr. Rietman’s lab is the development of active assistive devices. Two clinical examples were described. The first example was an intelligent knee prosthesis. An important problem with above-knee prostheses is that swing phase control of knee stiffness is either too weak or too stiff. The solution developed by Dr. Rietman’s lab is a “Power Knee”
prosthesis, which is a microprocessor-controlled knee with adaptive compensation. The next goal of the group is to develop a “Reflex Leg” prosthesis, which uses reflexive control integrated with physiological motor control. The goal is to develop a knee prosthesis with energy storage and transfer and controllable stiffness and torque.

The second example was the development of a myoelectric forearm prosthesis. An important problem for these prostheses is that their clinical use is limited because of a lack of adequate control and lack of sensory feedback. The solution developed by Dr. Rietman's lab was the use of a grid of 40 surface EMG electrodes in which measured muscle activity on residual stump was successfully mapped to 10 movements using the five degrees of freedom of the prosthesis. The next step for the research team is exploring providing sensory information by means of vibrotactile feedback.

**Patient-specific Musculoskeletal Models (Dr. Koopman)**

The goal of Dr. Koopman's lab is to use patient-specific musculoskeletal models to improve the design of orthopedic treatments. Three high-level examples presented included design of an intramedullary leg-lengthening device, design of a brace for scoliosis correction, and design of a patient-specific surgical navigation system.

Model customization to the anatomic, movement, and control characteristics of the patient remains a challenge. The main problem is that most musculoskeletal models are generic, and uniform scaling is inaccurate. The solution proposed by Dr. Koopman’s group is to use nonuniform scaling and deform a generic parametric model to match each patient. This process involves image-based scaling of bone geometry using computed tomography or magnetic resonance imaging data; functional kinematic scaling of joint positions/orientations using marker-based motion, laser scan, or inertial sensor data; and functional dynamic scaling of muscle strength using dynamometer data. A key challenge in this process is how to fuse data from different modalities.

Dr. Koopman provided a more detailed description of an example application involving Trendelenburg gait (i.e., patients whose swing leg hip drops during gait). The goal is to determine, on a patient-specific basis, which tendon to transfer to restore hip abduction strength and eliminate hip drop. The challenge is that several different tendons could be transferred, and transfer of the wrong tendon could actually worsen a patient's gait pattern. The approach outlined by Dr. Koopman was as follows:

1. Collect pretreatment imaging, kinematic, and dynamic data.
2. Construct the patient-specific musculoskeletal model using these data.
3. Simulate surgical scenarios and parameters with the patient-specific model.
4. Select the scenario and parameters that are most likely to optimize post-treatment outcome.
5. Implement the surgical plan in surgical navigation system.
6. Validate model predictions using surgical cases not planned with model.

**TRANSLATION**

Research performed by Dr. Hermens and Dr. Rietman makes its way to clinical trials and eventual clinical implementation through Roessingh Research and Development. Research performed by Dr. Koopman can make its way to commercialization through spinoff companies seeded by MIRA efforts.
**SOURCES OF SUPPORT**

Funding for these research efforts comes from Dutch government agencies and the European Union. Two Dutch government agencies in particular support the research efforts:

- **SenterNovem**—serves as a single government point of contact for business advice, financing, networking, and regulatory matters
- **ZonMw**—stimulates the entire innovation cycle, from fundamental research to implementation of new treatments, preventive interventions, and improvements to healthcare structure

**ASSESSMENT**

Research at the University of Twente provides an outstanding model for collaboration between university researchers, a local private research company, and a university organization that actively seeks to spin off new companies rapidly from promising university research endeavors. The surprising element in these interactions is the proactive position of both MIRA and Roessingh Research and Development in getting University of Twente research advances productized and into the marketplace rapidly. The intellectual properties issues have apparently been worked out between these three organizations so that no significant barriers exist to turning good idea into commercial products.

**SELECTED REFERENCES**


University of Twente, Biomedical Signals and Systems Research Group

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Date Visited: October 21, 2010

WTEC Attendees: R. Cowan (report author) B. Fregly, M. Boninger, L. Chan

Host(s): Peter H. Veltink
Chair Biomedical Signals and Systems
E-mail: P.H.Veltink@utwente.nl

OVERVIEW

Dr. Veltink is a professor of technology for the restoration of human function and chairman of the Biomedical Signals and Systems Department (BSS) at the University of Twente. Within the MIRA structure the BSS is one of the Neural and Motor Systems Strategic Research Organization research groups. According to the MIRA Web site, "MIRA is the University of Twente’s Institute for Biomedical Technology and Technical Medicine . . . MIRA combines fundamental and applied research with clinical practice. This unique scientific path stimulates a successful application of fundamental concepts and enables healthcare to rapidly introduce new treatments."

The presentation was titled, “Ambulatory analysis of human movement and dynamic interaction with the environment during daily life.” Two technologies were presented: a wearable motion capture system and a shoe equipped to assess ground reaction forces. The ultimate goal of these projects is to allow a patient to be assessed in his or her home or in a natural environment rather than in a traditional gait lab.

The wearable motion capture system relies on inertial and magnetic sensors. It has been successfully transitioned into a commercial product and company, Xsens, and has been used as a data collection device in for peer-reviewed publications. The shoe is instrumented under the heel and forefoot with two 6-degree-of-freedom force/moment sensors and two inertial sensors and has been validated against traditional force platforms. In addition, the shoe satisfactorily estimates center-of-mass movement during ambulation. The shoe is currently in the process of being commercialized.

Finally, the BSS group is also developing an instrumented glove to assess hand–object interaction forces.
During follow-up questioning, Dr. Cowan asked Professor Veltink what challenges must be overcome to realize the grand vision of these projects. Technology and application challenges were identified:

**Technology Challenges**
- How to measure finger movement
- How to estimate environment dynamics

**Application Challenges**
- How to use this technology clinically:
  - Convincing clinicians that this information can improve clinical treatment
  - Assimilating the technology into the clinical process
  - Defining which data are most clinically useful

**FUNCTIONAL FOCUS**

The projects presented do not directly support improved mobility. However, should the ultimate goal of enabling in-home, in-community, clinically relevant motion analysis be achieved, these products could be used to generate externally valid data to support evidence-based practice.

**RESEARCH FOCUS**

Instrument development was the presentation focus, specifically, development of instruments to allow ambulatory analysis of human movement (kinematics and kinetics). However, the BSS research focus is much broader, including neural engineering and telemonitoring.

**TRANSLATION**

Professor Veltink’s work on wearable motion capture has been translated to a spin-off company, Xsens. The Xsens system has been used by industry and academics, but it is not clear if it has been used to inform clinical decisions. The instrumented shoes and instrumented gloves will likely follow this example and become commercial products.

**SOURCES OF SUPPORT**

Support is provided by Dutch government agencies and the European Union.

**ASSESSMENT**

The University of Twente has a comprehensive and impressive research portfolio. Examination of the MIRA Web site suggests the presentations given were an extremely small subsample of their research program. MIRA may be an excellent collaborator for U.S. research and development programs.

In addition, the organizational structure of MIRA may be worth translating to the United States, namely, creating a continuous pipeline within one organization from basic research through product commercialization and clinical application. It appears this pipeline is supported by having separate chairs working together for fundamental science, clinical translation, and business translation.
The application challenges identified by Professor Veltink were echoed across multiple sites, specifically, getting clinicians to use new technologies to improve outcomes, integrating these technologies into practice, and determining which information is most valuable in informing clinical decisions.

**SELECTED REFERENCES**


University of Twente, Faculty of Engineering Technology

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Date Visited: October 21, 2010

WTEC Attendees: M. Boninger (report author), B.J. Fregly, L. Chan, R. Cowan

Host(s): Herman van der Kooij
Professor of Mechatronics and Rehabilitation Technology.
h.vanderkooij@utwente.nl

OVERVIEW
The goal of the Mechatronics and Rehabilitation Technology section of biomechanical engineering is to contribute to a better understanding of human balance, gait, and hand–eye coordination. This is accomplished through the combination of computational modeling of the neuromechanical system and experiments using techniques from system and control engineering, such as closed loop system identification. This basic research drives the development of devices to contribute to the improved diagnosis and treatment of participants with movement disorders. The Mechatronics and Rehabilitation Technology section is part of a large university, medical center, and industry consortium that has significant government support.

FUNCTIONAL FOCUS
The functional focus of this site is in therapeutic robotics and assistive technologies. These foci cross many diagnostic categories, including stroke, cerebral palsy, and Parkinson’s disease. Examples of assistive technologies include exoskeletons that would enable over-ground mobility in the face of paralysis or other disorders (e.g., MindWalker, EVRYON). These actuated exoskeletons have the potential to improve stability, control, energy efficiency, and act in concert with functional electrical stimulation.
Therapeutic robotics are exemplified by the LOPES system, which is an exoskeleton device for gait training. The LOPES is an example of a robotic gait trainer less constrained than those currently available.

**RESEARCH FOCUS**

The research focus crosses many areas, including modeling, simulation, and system identification techniques. These foci are summarized by the term biomechatronics, which requires a strong theoretically framework to achieve optimal control. Optimal control would enable substitution strategies, which, in the absence of brain control, could enable better movement strategies for exoskeletons or other devices. It also used electromyography (EMG) and transcranial magnetic stimulation (TMS) to support learning theory and subject selection. Key accomplishments related to this approach include the application of musculoskeletal models of the lower extremities and human balance control and estimation of position, velocity and force feedback parameters, for example, as a function of perturbation frequency, environmental impedance, and task instruction.

**TRANSLATION**

This site is in the planning stage of a clinical trial of a robotics device. The department is fortunate to have a clinical partner in the local medical center, which was one of the presenters the same morning. It has strong industry partners for translation. LOPES, which was featured in presentations and the tour, is being reengineered to be smaller and more clinically friendly.

**SOURCES OF SUPPORT**

There are several sources of support. These include university funding. Funding has also been obtained from National Science Foundation (NSF) for more fundamental research projects, government funding for collaborative projects with companies, EU funding for applied or fundamental projects, and direct company funding.

**ASSESSMENT**

The Mechatronics and Rehabilitation Technology section is a great environment and has very strong investigators. Its engineering expertise, small business start-up mechanisms, and clinical connections make it an excellent choice as a collaborator. The Netherlands has the ability to do multisite, nationwide trials that can help with the needed efficacy studies. The clinical tools have strong foundations in motor learning theory and modeling. Investigators have leadership positions at an international level.
SELECTED REFERENCES


Xsens Technologies B.V.

Site Address: Pantheon 6a
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Date Visited: October 21, 2010

WTEC Attendees: B.J. Fregly (report author), M. Boninger, L. Chan, R. Cowan

Host(s): Per Slycke
CTO and Founder
E-mail: per.slycke@xsens.com

OVERVIEW

Xsens is a privately held company founded 10 years ago by two University of Twente graduates. The product focus is on three-dimensional motion tracking systems using micro electrical mechanical system (MEMS) inertial sensors, specifically for the following three industries: (1) industrial applications (unmanned vehicles), (2) entertainment/training and simulation (movie special effects and video games), and (3) movement science (which is how they started). The company has 65 employees with 50% of them working in research and development. The company recently added a sales office in Los Angeles and serves clients in more than 60 companies. Deloitte ranked Xsens as one of the fastest growing technology companies in Europe.

FUNCTIONAL FOCUS

Xsens markets commercial motion capture systems using MEMS inertial sensor units. The sensor systems can be used for any human movement measurement application, including lower-extremity motion, upper-extremity motion, and full-body gait motion.

RESEARCH FOCUS

The company is constantly investing in research to continue to improve the performance and capabilities of its motion capture systems. The research strengths of the company are in sensor fusion and use of Kalman filtering for state estimation. Its first-generation system provides real-time motion capture system capability though a wired suit with power packs required. The system is usable indoors or outdoors (outdoors is difficult for video motion capture) with no marker occlusion issues. Thus, the system is very portable (it can be taken as hand luggage on an airplane) and is not restricted to a laboratory environment. However, integration drift was an issue that affected position estimates over time. Consequently, the company developed an indoor local positioning sensor system that can be added to the system to eliminate the integration drift issue.
The company recently released a second-generation system that eliminates the need for wires and power packs. The system still provides real-time motion capture and is still usable indoors or outdoors with no occlusion issues. The new system has increased accuracy and resolves the integration drift issue through the use of ultra wide band radio frequency technology. Time synchronization between sensors in the new system is within 10 µs.

The inertial system can deal with magnetic distortions, for example, such as those created by prostheses, making these systems suitable for deployment on users of prostheses for measurement and monitoring of three-dimensional motion.

**TRANSLATION**

Xsens motion capture systems can already be used for clinical or research movement analysis applications where the accuracy of the system is sufficient for the problem at hand.

**SOURCES OF SUPPORT**

Xsens is a privately funded company that is self-supporting.

**ASSESSMENT**

Xsens is another example of a successful European technology company created as a spinoff of university research. Establishing an environment that encourages the development of spinoff companies from university research developments could help to create better commercialization of university technology developments in the United States.

**SELECTED REFERENCES**


## APPENDIX C. GLOSSARY OF ACRONYMS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AAL</td>
<td>ambient assisted living</td>
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<tr>
<td>AALIANCE</td>
<td>Ambient Assisted Living Innovation Alliance (Europe)</td>
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<tr>
<td>ADL</td>
<td>activity of daily living</td>
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<tr>
<td>BAN</td>
<td>body area network</td>
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<tr>
<td>BCI</td>
<td>brain computer interface(s)</td>
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<tr>
<td>CLME</td>
<td>Complementary Limb Motion Estimation</td>
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<tr>
<td>CNS</td>
<td>central nervous system</td>
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<tr>
<td>COPD</td>
<td>chronic obstructive pulmonary disease</td>
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<tr>
<td>CT</td>
<td>computed tomography</td>
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<tr>
<td>CTI</td>
<td>Commission for Technology and Innovation (agency of the Swiss government)</td>
</tr>
<tr>
<td>DSEM</td>
<td>Delft Shoulder and Elbow Model</td>
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<tr>
<td>EC</td>
<td>elliptic crisis</td>
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<tr>
<td>EC</td>
<td>European Commission</td>
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<tr>
<td>ECC</td>
<td>Elliptic Curve Cryptography</td>
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<tr>
<td>EDA</td>
<td>electrodermal activity</td>
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<td>EEG</td>
<td>electroencephalogram</td>
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<tr>
<td>EMG</td>
<td>electromyography</td>
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<tr>
<td>EMS</td>
<td>electrical muscle stimulation</td>
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<tr>
<td>EU</td>
<td>European Union</td>
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<tr>
<td>FAS</td>
<td>functional ability scale</td>
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<tr>
<td>FEM</td>
<td>finite element modeling</td>
</tr>
<tr>
<td>FES</td>
<td>functional electrical stimulation (a method of measurement)</td>
</tr>
<tr>
<td>FET</td>
<td>functional electrical therapy</td>
</tr>
<tr>
<td>FEV1</td>
<td>forced expiratory volume in 1 second</td>
</tr>
<tr>
<td>fMRI</td>
<td>functional magnetic resonance imaging</td>
</tr>
<tr>
<td>FOG</td>
<td>freezing of gait</td>
</tr>
<tr>
<td>GEMU</td>
<td>Gastrocnemius Expansion Measurement Unit</td>
</tr>
<tr>
<td>GRASSP</td>
<td>Graded and Redefined Assessment of Strength, Sensibility and Prehension (a spinal cord injury assessment tool)</td>
</tr>
<tr>
<td>GTWM</td>
<td>Georgia Tech Wearable Motherboard</td>
</tr>
<tr>
<td>HUMOS 2</td>
<td>Human Model for Safety 2</td>
</tr>
<tr>
<td>ICT</td>
<td>Information and Communication Technologies (European Union)</td>
</tr>
<tr>
<td>ICU</td>
<td>intensive care unit</td>
</tr>
<tr>
<td>iTUG</td>
<td>instrumented timed up and go</td>
</tr>
<tr>
<td>LBM</td>
<td>Laboratory of Biomechanics</td>
</tr>
<tr>
<td>LOPES</td>
<td>Lower Extremity Powered ExoSkeleton</td>
</tr>
<tr>
<td>MEMS</td>
<td>micro electrical mechanical system</td>
</tr>
<tr>
<td>MEMS</td>
<td>microelectromechanical systems</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
</tr>
<tr>
<td>MICS</td>
<td>Medical Implant Communication Service</td>
</tr>
<tr>
<td>MRI</td>
<td>magnetic resonance imaging</td>
</tr>
<tr>
<td>MVC</td>
<td>maximum voluntary contraction</td>
</tr>
<tr>
<td>NIH</td>
<td>National Institutes of Health (United States)</td>
</tr>
<tr>
<td>PDA</td>
<td>personal digital assistant</td>
</tr>
<tr>
<td>PDPU</td>
<td>personal data processing unit</td>
</tr>
<tr>
<td>PIR</td>
<td>passive infrared</td>
</tr>
<tr>
<td>SCI</td>
<td>spinal cord injury</td>
</tr>
<tr>
<td>SCM</td>
<td>sensor communication module</td>
</tr>
<tr>
<td>SFI</td>
<td>Science Foundation Ireland</td>
</tr>
<tr>
<td>SOC</td>
<td>system-on-chip</td>
</tr>
<tr>
<td>SPINE</td>
<td>Signal Processing in Node Environment</td>
</tr>
<tr>
<td>TMS</td>
<td>transcranial magnetic stimulation</td>
</tr>
<tr>
<td>TUG</td>
<td>timed up and go</td>
</tr>
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</table>
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