Guest Editorial: Special Issue on Haptics in Rehabilitation and Neural Engineering

Antonio Frisoli, Marcia O'Malley, Domenico Campolo, and Kathleen Sienko

THIS special issue on Haptics in Rehabilitation and Neural Engineering is focused on broadening our understanding of the role of touch in sensorimotor coordination, including rehabilitation of motor deficits and use of advanced prostheses and orthoses. The articles presented in this issue confirm that the science and technology of haptics has great potential to affect the outcomes of rehabilitation and adoption of advanced prosthetic and orthotic devices.

A first topic addressed in the issue is how rehabilitation robots that employ kinesthetic or tactile feedback can lead to an enhancement of therapeutic results. The engagement of the sensorimotor system, and in particular the provision of haptic feedback to the participant during rehabilitation, is an important factor in regaining motor control. In fact, robotic devices have been shown to be effective at delivering the intensive and repetitive therapy that is known to induce brain plasticity and foster restoration of motor coordination after stroke, spinal cord injury, and other neural impairments. This area saw the largest number of submissions, and featured in the special issue. Carlo Alberto Avizzano, Massimo Satler, and Emanuele Ruffaldi present a mobile haptic interface capable of providing two degree-of-freedom force rendering intended for upper limb rehabilitation in their article titled, "Portable Haptic Interface with Omni-Directional Movement and Force Capability." The paper characterizes a novel control architecture and force feedback performance. In the paper by Sumner L. Norman, Andrew J. Doxon, Brian T. Gleeson, and William R. Provancher, "Planar Hand Motion Guidance Using Fingertip Skin-Stretch Feedback," the authors investigated how skin stretch feedback provided to the fingerpad as corrective path feedback can accurately guide users through planar hand movements, with potential application to human-machine interaction, such as upper-extremity rehabilitation. "Design of a Robotic Mobility System with a Modular Haptic Feedback Approach to Promote Socialization in Children" by Xi Chen, Christina Ragonesi, James C. Galloway, and Sunil K. Agrawal is a novel study in which a powered mobility device, a tracking system and modular haptic feedback are combined within a ball-chasing game (including several children and a caregiver) with the goal of promoting socialization. In particular, an 'assist as needed' haptic algorithm was implemented and used with five toddlers (training group) while another five toddlers (control group) operated without force field feedback. Results showed that children in the training group drove closer to the ball possessed by a group of peers with the help of the force field and also demonstrated short-term learning. This study opens interesting possibilities of exploiting haptic channels to reduce mobility barriers and to promote socialization in children. The article "Neurocognitive Robot-Assisted Therapy of Hand Function" by Jean-Claude Metzger, Olivier Lambercy, Antonella Califfi, Fabio M. Conti, and Roger Gassert is a preliminary study on the rehabilitation of hand functions in patients with neurological disorders. A two degree-of-freedom haptic device, ReHapticKnob, is used to train hand opening/closing as well as forearm rotation during exercises which involve motor, sensory as well as cognitive aspects. Unlike conventional visually guided rehabilitation tasks, high-definition haptic rendering of virtual objects was used in neurocognitive exercises. Preliminary tests on five patients suffering from different neurological disorder and different impairment levels, showed positive results in terms of feasibility and acceptance of the proposed exercises, underlining the potential of this approach to integrate haptics for intensive sensorimotor therapy of hand function. Fabien Vérité, Wael Bachta, and Guillaume Morel, in their article, "Closed Loop Kinesthetic Feedback for Postural Control Rehabilitation," describe the implementation of a closed-loop kinesthetic characterize responses of 11 healthy subjects using open-versus closed-loop feedback. The results demonstrate that subjects are better able to control their center of pressure using closed-loop feedback. The study also investigates how other conditions (e.g., vision, secondary task) affect performance and conclude that this type of kinesthetic feedback has potential uses for rehabilitative balance training. Andrew Theriault, Mark Nagurka, and Michelle J. Johnson, in their article "Design and Development of an Affordable Haptic Robot with Force-Feedback and Compliant Actuation to Improve Therapy for Patients with Severe Hemiparesis," focus on a safe, robust, low cost, and adaptive robotics device, suitable to be used at home and in small clinical centers. Safety, robustness and low-cost requirements are balanced via mechanical torque-limiting mechanisms. An impedance controller is also proposed that adapts its parameters to the evolving performance of its users. Finally, Stefano Mazzoleni, Luciano Puzzolante, Loredana Zollo, Paolo Dario, and Federico Posteraro present a clinical study in their paper "Mechanisms of Motor Recovery in Chronic and Subacute

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Stroke Patients Following a Robot-Aided Training" aimed at evaluating velocity and force levels observed in stroke patients during robot-aided therapy. The planar end-effector rehabilitation device was used for quantifying and discriminating the recovery mechanism of sub-acute and chronic stroke subjects.

A second topic investigated in this issue is how haptic information can be used to improve the performance of advanced orthoses and prostheses. Haptic feedback can enhance the natural control, utility, and efficacy of advancement of prosthetic and orthotic devices that restore mobility and manipulability to lower- and upper-extremity amputees. However, advanced prosthetic devices, for example, have decoupled the normal afferent-efferent loop and rely heavily on visual feedback to the amputee for control in the absence of haptics. Three articles in this special issue address the application of haptics in orthotics and prosthetics applications. "HyVE–Hybrid Vibro-Electrotactile Stimulation–Is an Efficient Approach to Multi-Channel Sensory Feedback" by Marco D'Alonzo, Strahinja Dosen, Christian Cipriani, and Dario Farina, addresses the issue of restoring the missing tactile and/or proprioceptive information in actuated prosthetic hand users. Their hybrid vibro-electrotactile (HyVE) combined vibrotactile and electrotactile stimulation in order to provide multimodal sensory feedback. Their study demonstrates that multiple HyVE units could be used to provide multi-channel sensory information with better or equivalent performance to the single modality interfaces (vibro- or electro-tactile) larger in size and with better performance than vibrotactile interfaces with the same size. This opens up interesting avenues for interfacing with multi-functional prostheses with multiple sensors. The paper by Ruben D. Ponce Wong, Randall B. Hellman, and Veronica J. Santos titled "Spatial Asymmetry in Tactile Sensor Skin Deformation Aids Perception of Edge Orientation During Haptic Exploration" presents a novel approach and perspective for the study of non-traditional robotic sensing for haptics, with the aim of paving the way to new semi-autonomous capabilities in prosthetic or robotic hands. In particular, the authors investigate edge orientation perception through a robot showing that they can predict, under certain circumstances, the orientation of an explored edge, and that some exploratory procedures yield better orientation information than others. Finally, Arash Ajoudani, Sasha B. Godfrey, Matteo Bianchi, Manuel G. Catalano, Giorgio Grioli, Nikos Tsagarakis, and Antonio Bicchi in their article "Exploring Teleimpedance and Tactile Feedback for Intuitive Control of the Pisa/IIT SoftHand" study the effect of tactile feedback, exploiting for this purpose both mechanotactile and vibrotactile feedback, for improving the intuitiveness of teleimpedance control of the Pisa/IIT SoftHand, in order to facilitate execution of safe and stable grasps.

Most of the articles presented in this issue share a common experimental approach to evaluation of hypotheses, in that they refer to sensory-motor neuroscience experiments that leverage haptic systems for assessment and/or analysis. The adoption of such a common methodological approach allows one to correctly interpret the observed experimental results and generalize them into significant scientific conclusions. Four articles specifically address the neural foundations for haptics, and the development of haptic devices and controlled interactions that enable the rigorous study of motor control and motor learning. In their paper "Validating a Population Model of Tactile Mechanotransduction of Slowly Adapting Type I Afferents at Levels of Skin Mechanics, Single-Unit Response and Psychophysics" Gregory J. Gerling, Isabelle I. Rivest, Daine R. Lesniak, Jacob R. Scanlon, and Lingtian Wan describe a comprehensive model of fingertip skin deformation, transduction in SAI afferents, and tactile discrimination. The authors present the first validated multi-level model computational model of tactile neurons embedded in skin. Julius Klein, Nicholas Roach, and Etienne Burdet describe the design, implementation and testing of a planar three degree-of-freedom robot for rehabilitation and motor control studies in their paper, "3DOM: A 3 Degree of Freedom Manipulandum to Investigate Redundant Motor Control." A unique feature of this device is that the pose of the arm can be fully constrained. The authors illustrate the advantages of their device for investigation of redundant motor control. The paper, "Motor Learning Perspectives on Haptic Training for the Upper Extremities," by Camille K. Williams and Heather Carnahan provides a review of haptic training strategies for motor skill acquisition, clarifies definitions and terminology, and relates the findings (primarily upper extremity findings) to motor learning principles and robotic rehabilitation. Finally, the article by Giulio Rosati, Fabio Oscari, Claudio Pacchierotti, and Domenico Prattichizzo titled, "Effect of Kinesthetic and Cutaneous Stimulation During Learning of a Viscous Force Field," by Giulio Rosati, Fabio Oscari, Claudio Pacchierotti, and Domenico Prattichizzo characterizes human motor adaptation to dynamic perturbations during reaching motions in which the subjects can feel the movement of their hand and the force between the joystick and their fingertips, and see the hand's movement. Based on the results, the authors suggest that kinesthetic forces are responsible for the observed changes in subjects' movements, that visual distortion caused effects but no adaptation, and that cutaneous stimuli did not change the subjects' movements.

We received many outstanding submissions for this special issue, which reflects the research community's strong interest in haptics in neural engineering and rehabilitation. We are grateful to Editors in Chief Ed Colgate and Lynette Jones, who were extremely supportive of this topic and went to great lengths to see it succeed. We are also appreciative of the numerous reviewers who provided high quality and timely reviews. Finally, we would like to express our thanks to the ToH editorial staff, Kristen Vermeire, Samantha Jacobs, and Pilar Hawthorne, for their guidance and gentle encouragement to stay on schedule. We hope you agree that these articles address many of the current challenges facing our field, in particular as we strive to define new applications for haptics. It has been extremely rewarding to participate in the organization of this special issue.

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Antonio Frisoli (Eng., Ph.D.) received the PhD degree in 2002 with honors in industrial and information engineering from Scuola Superiore Sant'Anna, Italy, and the MSc degree in 1998 in mechanical engineering, minor in robotics, from the University of Pisa—Italy. He is an associate professor of mechanical engineering at Scuola Superiore Sant'Anna, where he is currently head of the Human–Robot Interaction area at PERCRO laboratory of TeCIP and chair of the IEEE Technical Committee on Haptics. Currently, he is studying new designs for exoskeletons systems, portable fingertip haptics and new brain–robot interfaces. He is the author of more than 150 papers in peer-reviewed international conferences and scientific journals. His research interests include the field of design and control of haptic devices and robotic systems, rehabilitation robotics and human motor control, virtual reality, and advanced human computer interfaces for training.

Marcia O'Malley received the BS degree from Purdue University in 1996, and the PhD degree in mechanical engineering from Vanderbilt University in 2001. She is an associate professor of mechanical engineering and of computer science at Rice University, where she directs the Mechatronics and Haptic Interfaces Lab. She is also an adjunct associate professor in the Departments of Physical Medicine and Rehabilitation at both Baylor College of Medicine and the University of Texas Medical School at Houston, and she is the director of rehabilitation engineering at TIRR-Memorial Hermann Hospital. Her research interests include the issues that arise when humans physically interact with robotic systems, with a focus on applications in motor skill training, and rehabilitation of the upper limb after stroke and spinal cord injury. She was awarded the Best Paper Award at the 2011 IEEE World Haptics Conference in Istanbul, Turkey. She is the former chair of the IEEE Technical Committee on Haptics and was on the founding editorial board for the *IEEE Transactions on Haptics*. She also served on the editorial board of the *ASME/IEEE Transactions on Mechatronics.*

Domenico Campolo received the laurea degree (Hon) in electrical and electronics engineering from the University of Pisa in 1998. In 2002, he received the PhD degree from Scuola Superiore Sant'Anna, Pisa. In 2000–2003, he was at UC Berkeley first as a visiting scholar and then as a post-doc. In 2003–2008, he was a researcher at Campus Bio-Medico University in Rome, Italy. Since 2009, he has been an assistant professor in the School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore. His research interests include human motor strategies, from a neuroscientific perspective, and with application to robotics.

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