Rehabilitation Robotics

Robert Riener
Sensory-Motor Systems Lab
ETH Zurich
Switzerland
and
Medical Faculty
University of Zurich
Switzerland

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Robert Riener
Sensory-Motor Systems Lab,
Department of Health Sciences and Technology,
ETH Zurich,
Switzerland

and

Spinal Cord Injury Center,
University Hospital Balgrist,
Medical Faculty,
University of Zurich,
Switzerland

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Abstract

Robotic rehabilitation devices have become increasingly important and popular in clinical and rehabilitation environments to facilitate prolonged duration of training, increased number of repetitions of movements, improved patient safety, less strenuous operation by therapists, and eventually, to improve the therapeutic outcome. Novel assistive technologies are becoming available as wearable devices that allow transferring the therapeutic training into home and work environments or assist the patient in day-to-day activities. This monograph summarizes the rationale for robot-assisted therapy and presents the technological steps in the evolution of the design and development of lower and upper extremity rehabilitation robots. After presenting the basic mechanisms of natural and artificial movement restoration, and the rationale of robot-aided movement therapy, this monograph shows several design criteria that are relevant for the development of effective and safe rehabilitation robots. The robotic design depends on the kind of application (i.e., therapeutic or assistive), and varies with respect to different kinds of actuation and patient interaction principles, robotic complexities, and kinematic approaches. Several examples of gait and arm rehabilitation robots are presented that are in developmental status or already commercially available. Novel patient-cooperative strategies are presented, such as impedance control, assistance-as-needed control and tunnel (path) control. Such patient-cooperative strategies can increase movement variability and patient activity; both can have a positive effect on the therapeutic outcome. Special bio-cooperative control strategies and biofeedback methods are introduced that increase engagement and motivation during the therapy session. Standardized assessment tools implemented in robotic devices have shown to be a convenient and accurate method to evaluate the rehabilitation process of individual patients and entire patient groups, which can allow therapists and researchers to perform better intra and inter-subject comparisons. This monograph, which in several parts has an emphasis on the work from the author's laboratory, finishes with a short overview about existing clinical trials that have been performed

showing that the application of rehabilitation devices is at least as effective as the application of conventional therapies. It concludes with the finding that further clinical studies are required to find predictors for the success of a robot-aided treatment.

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1

Introduction

1.1 Sociomedical need and motivation

Loss of the abilities to walk and grasp represents a major disability for millions of individuals worldwide, and a major expense for health care and social support systems. More than 700,000 people in the U.S. suffer from a stroke each year; 60–75% of these individuals will live beyond one year after the incident, resulting in a stroke survivor population of about 3 million people [190, 370]. Almost two-thirds of all stroke survivors have no functional ability and cannot move without assistance in the acute phase following the incident [176]. Similarly, for many of the 10,000 Americans who are affected by a traumatic spinal cord injury (SCI) per year, the most visible lingering disability is the lost or limited ability to walk [362].

One major goal in the rehabilitation of patients suffering from a movement disorder, such as stroke or SCI, is retraining locomotor and upper extremity function. The approach to stroke physiotherapy is diverse, as are the theoretical bases assumed by the physiotherapists who provide the therapy [76, 82, 225, 249, 277, 282]. Traditional methodology includes neuro-developmental training (NDT) [26], the motor relearning program [49], proprioceptive neuromuscular facilitation [198], and the Rood approach [332].

The effects of the different kinds of training on gait have been shown to be modest, irrespective of the exact type of training [219]. NDT is particularly prevalent [21, 76, 225, 305], with the best known stream being the Bobath concept. Better outcomes in gait rehabilitation have been elicited from the more direct approach of body weight supported treadmill training [13, 86, 141, 148, 221, 237, 289, 340, 365, 366], where the patient walks on a treadmill with the body weight partially supported, and two or more therapists support the patient and guide their limbs where required. This type of therapy has the advantages of being task specific and repetitive but is often very physically intensive [282]. As a result, the training duration can be limited by the fitness of the therapists themselves.

Restoration of arm and hand function is essential to resuming daily-living tasks and regaining independence in life. Plenty of studies show that sensorimotor arm therapy has positive effects on the rehabilitation progress of stroke patients (see [15, 93, 288] to mention just a few).

1.2 Natural and artificial mechanisms of movement restoration

Motion impairments resulting from neural and musculoskeletal lesions can be restored by natural and artificial mechanisms. The central nervous system is characterized by three basic natural mechanisms that can enable partial or complete restoration of sensor and motor functions. First, lost motor functions can be adapted or compensated by other existing functions not being affected by the lesion. Second, tasks of injured brain regions can be transferred to other non-affected brain regions by generation of new synaptic connections. This property is known as “plasticity” of the central nervous system. And third, damaged brain regions can partly recover via different regeneration principles. These mechanisms can be enhanced and accelerated by pharmaceutical, physiotherapeutic, or surgical treatments.

However, the recovery of the central nervous system is limited due to the presence of inhibiting factors. These inhibiting factors are missing in the peripheral nervous system. Therefore, minor nerve damages (neuropraxies) can heal without any additional treatment. After full nerve transection, an artificial nerve graft can be surgically inserted to support nerve growth.

Natural restoration of the musculoskeletal system is limited to healing effects of muscles and bones, e.g., after muscle fiber lesions or bone fracture, whereas any kind of amputations cannot be restored by natural mechanisms (such as in certain animals).

If the impairment of the nervous or musculoskeletal system cannot be restored by natural mechanisms, artificial technical support is required. Totally lost functions can be substituted by prostheses, whereas orthoses are used to support remaining (but impaired) body functions. A mechanical orthosis is an orthopedic apparatus used to stabilize, support, and guide body limbs during movements. Typical examples for mechanical orthoses are crutches, shells, and gait and stance orthoses. Orthotic devices for upper and lower extremities can be applied in two different ways: first, as therapy devices, usually in clinical settings that aim at restoring movement function based on intensive training, and second, as assistive devices that support activities of daily living (ADL) tasks in home and work environments, and at leisure. Also assistive devices can have a therapeutic effect on the patient.

1.3 Rationale for movement therapy

Task-oriented repetitive movements can improve muscular strength and movement coordination in patients with impairments due to neurological or orthopedic problems. A typical repetitive movement is the human gait. Treadmill training has been shown to improve gait and lower limb motor function in patients with locomotor disorders. Manually assisted treadmill training was first used approximately 20 years ago as a regular therapy for patients with SCI or stroke. Currently, treadmill training is well-established at most large neuro-rehabilitation centers, and its use is steadily increasing. Numerous clinical studies support the effectiveness of the training, particularly in SCI and stroke patients [12, 86, 141].

Similarly, arm therapy is used for patients with paralyzed upper extremities after stroke or SCI. Several studies prove that arm therapy has positive effects on the rehabilitation progress of stroke patients (see [288], for review). Besides recovering of motor function and improving movement coordination, arm therapy serves also to learn new motion strategies, so-called "trick movements" or "compensatory movements", to better cope with different ADL tasks.

Lower and upper extremity movement therapy serves also to prevent secondary complications such as muscle atrophy, osteoporosis, and spasticity. It was observed that longer training sessions and a longer total training duration have a positive effect on the motor function. In a meta-analysis comprising nine controlled studies with 1051 stroke patients Kwakkel et al. [212] showed that increased training intensity yields positive effects on neuromuscular function and ADL. This study did not distinguish between upper and lower extremities. The finding that the rehabilitation progress depends on the training *intensity* motivates the application of robot-aided arm therapy.

1.4 Neuronal basis underlying movement training

Stroke and traumatic brain or spinal cord injury result in neurological disorders associated with impaired or total loss of locomotion, hand function, and other body functions. Basic research studies in the animal model including the cat have shown that repetitive execution of the movement (supported by any external help) can improve motor function of the affected limbs, especially during locomotion [13]. These improvements seem to be based on neuroplasticity of the central nervous system at many levels and result in compensation for the loss of lesioned brain or spinal cord areas [70, 88, 246]. In SCI, the supraspinal control over the neural circuitry in the spinal cord is impaired, while the spinal and supraspinal neural centers underlying locomotion remain intact. Evidence for the existence of a human spinal pattern generator is indicated by the observation of spontaneously occurring step-like movements [46] and myoclonus [43] as well as from late flexion reflexes [43] and from locomotor movements induced in body-weight supported paraplegic patients walking on a treadmill [85, 86]. Other studies have shown that a locomotor pattern may be induced and trained even in completely paraplegic patients when leg movements are assisted externally and an appropriate afferent input to the spinal cord is provided [84, 85, 86, 87, 92]. Nevertheless, the amplitude of leg muscle electromyographic (EMG) activity in these patients is small when compared with healthy subjects but increases during locomotor training sessions [86]. These studies provide indirect but sufficient evidence for the existence of a Central Pattern Generator (CPG) in human subjects. The spinal pattern generator and an appropriate proprioceptive feedback can be implemented in a training system to target neural circuits to induce plastic changes. Body un-loading and re-loading are considered to be of crucial importance to induce training effects upon the neurological locomotor centers because the afferent input from receptors signaling contact forces during the stance phase is essential for the activation of spinal locomotor centers [136]. Therefore, this cyclic loading is considered to be important for achieving training effects in cat [280] and man [83, 90]. Because the available muscle force is not sufficient to support the body weight during walking, partial body weight unloading is necessary in order to allow for stable and safe locomotor training. Recent findings demonstrated that following an acute, incomplete SCI in humans, an improvement of locomotor function was observed and was specifically attributed to the functional locomotor training [88, 373] in addition to the spontaneous recovery of spinal cord function that can occur over several months following SCI [72, 73, 74, 184].

1.5 Rationale for robot-aided training

Manually assisted movement training has several major limitations. Treatment for stroke, SCI, and other neurological diseases is very costly and accounts for a large percentage of health care budgets [305]. The training is labor-intensive, and, therefore, training duration is usually limited by personnel shortage and fatigue of the therapist, not by that of the patient. During treadmill training, therapists often suffer from back pain, because the training has to be performed in an ergonomically unfavorable posture. During upper extremity training, the therapist has to lift the arm of the patient, thus, carrying the complete weight of the upper limb or a portion of it. The disadvantageous consequence is that the training sessions are shorter than required to gain an optimal therapeutic outcome. Finally, manually-assisted movement training lacks repeatability and objective measures of patient performance and progress.

In contrast, with automated, i.e., robot-assisted, gait and arm training the duration and number of training sessions can be increased, while reducing the number of therapists required per patient. Long-term automated therapy can be an efficient way to make intensive movement training affordable for clinical use. One therapist may be able to train two or more patients at a time. Thus, personnel costs can be significantly reduced and more patients can be treated satisfying the need for a higher treatment capacity due to the increasing number of age-related neurological patients.

Furthermore, the robot provides quantitative measures, thus, allowing the observation and quantitative assessment of the rehabilitation process. Even more, some of the recorded data can be online-processed and displayed to the patient as "biofeedback" signals so that the patient immediately understands how she or he performs. This can help the patient to try to improve the movement pattern and performance during the robot-aided training sessions. This kind of feedback can be further exploited via the application of virtual reality (VR) technologies. Allowing the patient to perform a movement task within a virtual environment, does not only allow to instruct the patient in an easy, convenient, and very intuitive way, but it also increases the patient's engagement during task execution and the general motivation to participate in the rehabilitation program.

These advantages of the use of robots as compared to conventional therapy are based on common wisdom and plausibility. Not many publications exist that prove these arguments yet.

1.6 Definition of "Rehabilitation Robotics" and scope of this monograph

The term "Rehabilitation Robotics" has become popular in the early nineties of the last century, when the first assistive technologies, and a bit later, also rehabilitation training devices have been developed and become available for clinical use, some of them even on a commercial level. To better understand the meaning of the term "Rehabilitation Robotics" and to formulate a definition, it is worth to look into meaning of the two sub-terms "Robotics" and "Rehabilitation".

According to Wikipedia a "Robot" can be defined as "a mechanical or virtual agent, usually an electro-mechanical machine that is guided by a computer program or electronic circuitry. Robots can be autonomous or semi-autonomous and range from humanoids [...] to industrial robots [...]". According to Oxford Dictionaries (2011) and Wikipedia, the term "Robotics" can be defined as "the branch of technology that deals with the design, construction, operation, and application of robots as well as computer systems for their control, sensory feedback, and information processing. These technologies deal with automated machines that can take the place of humans in dangerous environments or manufacturing processes, or resemble humans in appearance, behavior, and/or cognition."

W. Reich from Uppsala University, Sweden, once described a robot as "an artificial, physically embodied 'agent tool' " (Robots Podcast & Community, March 12, 2010 `www.robotspodcast.com`). According to his definition, a robot is a physical object, which has been constructed by someone and fulfills a function for someone, which makes it a 'tool', etc. Similarly, K. Makice defines a robot as "a physical machine manipulated to automatically perform an undesirable work function that supports a desired human outcome" and P. Agius claims that "A robot is an intelligent machine that moves, reacts and interacts with its environment in an autonomous manner" (Robots Podcast & Community, March 12, 2010 `www.robotspodcast.com`).

Many further definitions exist that are similar or deviate from above-mentioned descriptions. Robots applied to the field of rehabilitation can be considered as "service robots", which have been defined as "those robotics systems that assist people in their daily lives at work, in their houses, for leisure, and as part of assistance to the handicapped and elderly. [...] service robotics' tasks are performed in spaces occupied by humans and typically in direct collaboration with people" [64].

The term "Rehabilitation" has its original meaning from the Latin term "habilitare" (to enable). State lawyer, physician, and politician Franz Josef Ritter von Buss was one of the first, who gave the term "Rehabilitation" its current meaning already in 1844. According to unconfirmed sources, he said that the "invalid person should rise up from the position he was descended", and that "he should regain his/her feeling of dignity and with it a new life". He already considers rehabilitation has a recovery of function to improve quality of life rather than (only) a healing of body structures.

A more modern definition was presented by C. Robinson, who defined rehabilitation as "the (re-)integration of an individual with a disability into society. This can be done either by enhancing existing capabilities or by providing alternative means to perform various functions or to substitute for specific sensations" [313]. His definition comprises two important aspects of rehabilitation. First, he mentions "enhancement of existing capabilities", which can be achieved through therapy and training. And second, he speaks about "alternative means" to perform functions or to substitute sensations, which can be reached by the application of assistive technologies. Both meanings are relevant to reintegrate disabled people into society so that they can regain their dignity and reach a satisfactory quality of life, even if an impaired body structure cannot be completely restored (i.e., healed), such as limb amputation or spinal cord injury.

From the above-mentioned definitions, one could derive the following most generous definition:

Rehabilitation Robotics is the application of robotic methods to train or assist an individual with a disability, supporting this individual to get (re-)integrated into society.

This broad definition includes a variety of different mechatronic machines that support gait and arm therapy in a clinical setting, powered orthotics for use in daily life environments, actuated exo-prosthetics, ranging even to intelligent wheelchairs that have some autonomous function of mobility. Also devices supporting human sensory and vegetative functions can be included, when the technology is based on robotic methods.

This monograph focuses on robotic devices that provide a technical support to the impaired human motor system. A large overview of different technologies and approaches is presented that can be used for the therapeutic training or daily assistance of mainly neurologically impaired patients. Therefore, prosthetic technologies as well as sensory restoration systems were excluded. Also wheelchair technologies have not been treated in this overview. Several parts of this monograph have an emphasis on the work from the author's laboratory, thus this monograph is not a complete, though a broad review of the field.

References

[1] R. J. Adams, M. R. Moreyra, and B. Hannaford, editors. Stability and performance of haptic displays: Theory and experiments. In *Proceedings ASME International Mechanical Engineering Congress and Exhibition*. 1998.

[2] M. L. Aisen, H. I. Krebs, N. Hogan, F. McDowell, and B. T. Volpe. The effect of robot-assisted therapy and rehabilitative training on motor recovery following stroke. *Archives of Neurology*, 54(4):443–446, 1997.

[3] M. Akman, R. Bengi, M. Karatas, S. Kilinc, S. Sözay, and R. Özker. Assessment of spasticity using isokinetic dynamometry in patients with spinal cord injury. *Spinal Cord*, 37(9):638–643, 1999.

[4] R. M. Alqasemi, E. J. McCaffrey, K. D. Edwards, and R. V. Dubey, editors. Analysis, evaluation and development of wheelchair-mounted robotic arms. In *International Conference on Rehabilitation Robotics, 2005 ICORR*. Chicago, 2005.

[5] C. H. An, C. G. Atkeson, J. D. Griffiths, and J. M. Hollerbach. Experimental evaluation of feedforward and computed torque control. *IEEE Transactions on Robotics and Automation*, 5(3):368–373, 1989.

[6] D. Aoyagi, W. E. Ichinose, S. J. Harkema, D. J. Reinkensmeyer, and J. E. Bobrow. A robot and control algorithm that can synchronously assist in naturalistic motion during body-weight-supported gait training following neurologic injury. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 15(3):387–400, 2007.

[7] S. Aruin, AS, Rob Larkins, and A. Gouri Chaudhuri. Knee position feedback: Its effect on management of pelvic instability in a stroke patient. *Disability & Rehabilitation*, 22(15):690–692, 2000.

[8] B. Ashworth. Preliminary trial of carisoprodol in multiple sclerosis. *The Practitioner*, 192:540–542, 1964.

[9] S. K. Banala, S. K. Agrawal, and J. P. Scholz, editors. Active leg exoskeleton (ALEX) for gait rehabilitation of motor-impaired patients. In *IEEE International Conference on Rehabilitation Robotics, 2007 ICORR 2007*. 2007.

[10] R. Banz, M. Bolliger, G. Colombo, V. Dietz, and L. Lünenburger. Computerized visual feedback: An adjunct to robotic-assisted gait training. *Physical Therapy*, 88(10):1135–1145, 2008.

[11] R. Banz, M. Bolliger, S. Muller, C. Santelli, and R. Riener. A method of estimating the degree of active participation during stepping in a driven gait orthosis based on actuator force profile matching. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 17(1):15–22, 2009.

[12] H. Barbeau and S. Rossignol. Enhancement of locomotor recovery following spinal cord injury. *Current Opinion in Neurology*, 7(6):517–524, 1994.

[13] H. Barbeau, M. Wainberg, and L. Finch. Description and application of a system for locomotor rehabilitation. *Medical and Biological Engineering and Computing*, 25(3):341–344, 1987.

[14] A. Bardorfer, M. Munih, A. Zupan, and A. Primozic. Upper limb motion analysis using haptic interface. *IEEE/ASME Transactions on Mechatronics*, 6(3):253–260, 2001.

[15] S. Barreca, S. L. Wolf, S. Fasoli, and R. Bohannon. Treatment interventions for the paretic upper limb of stroke survivors: A critical review. *Neurorehabilitation and Neural Repair*, 17(4):220–226, 2003.

[16] M. Batavia, J. G. Gianutsos, and M. Kambouris. An augmented auditory feedback device. *Archives of Physical Medicine and Rehabilitation*, 78(12):1389–1392, 1997.

[17] M. Batavia, J. G. Gianutsos, A. Vaccaro, and J. T. Gold. A do-it-yourself membrane-activated auditory feedback device for weight bearing and gait training: A case report. *Archives of Physical Medicine and Rehabilitation*, 82(4):541–545, 2001.

[18] N. A. Bayona, J. Bitensky, K. Salter, and R. Teasell. The role of task-specific training in rehabilitation therapies. *Topics in Stroke Rehabilitation*, 12(3):58, 2005.

[19] R. F. Beer, J. P. Dewald, and W. Z. Rymer. Deficits in the coordination of multijoint arm movements in patients with hemiparesis: Evidence for disturbed control of limb dynamics. *Experimental Brain Research*, 131(3):305–319, 2000.

[20] S. Beer, B. Aschbacher, D. Manoglou, E. Gamper, J. Kool, and J. Kesselring. Robot-assisted gait training in multiple sclerosis: A pilot randomized trial. *Multiple Sclerosis*, 14(2):231–236, 2008.

[21] S. Beeston and H. Simons. Physiotherapy practice: Practitioners' perspectives. *Physiotherapy Theory and Practice*, 12(4):231–242, 1996.

[22] N. A. Bernstein. *The Co-ordination and Regulation of Movements*. Pergamon Press Ltd, first english edition, 1967.

[23] Z. Bien, M.-J. Chung, P.-H. Chang, D.-S. Kwon, D.-J. Kim, and J.-S. Han, et al. Integration of a rehabilitation robotic system (KARES II) with human-friendly man-machine interaction units. *Autonomous Robots*, 16(2):165–191, 2004.

[24] J. A. Blaya and H. Herr. Adaptive control of a variable-impedance ankle-foot orthosis to assist drop-foot gait. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 12(1):24–31, 2004.

[25] J. U. Blicher and J. F. Nielsen. Cortical and spinal excitability changes after robotic gait training in healthy participants. *Neurorehabilitation and Neural Repair*, 23(2):143–149, 2009.

[26] B. Bobath. *Adult Hemiplegia: Evaluation and Treatment*. Heinemann Medical Books, Oxford, 1990.

[27] R. Bogue. Exoskeletons and robotic prosthetics: A review of recent developments. *Industrial Robot: An International Journal*, 36(5):421–427, 2009.

[28] R. W. Bohannon and M. B. Smith. Interrater reliability of a modified ashworth scale of muscle spasticity. *Physical Therapy*, 67(2):206–207, 1987.

[29] M. Boiteau, F. Malouin, and C. L. Richards. Use of a hand-held dynamometer and a kin-com® dynamometer for evaluating spastic hypertonia in children: A reliability study. *Physical Therapy*, 75(9):796–802, 1995.

[30] J. E. Bolek. A preliminary study of modification of gait in real-time using surface electromyography. *Applied Psychophysiology and Biofeedback*, 28(2):129–138, 2003.

[31] M. Bolliger, L. Lunenburger, S. Bircher, G. Colombo, and V. Dietz, editors. Reliability of measuring isometric peak torque in the driven gait orthosis “lokomat”. In *World Congress of Neurorehabilitation Hong Kong*. 2006.

[32] I. Borggraefe, L. Kiwull, J. S. Schaefer, I. Koerte, A. Blatschek, and A. Meyer-Heim, et al. Sustainability of motor performance after robotic-assisted treadmill therapy in children: An open, non-randomized baseline-treatment study. *Eur J Phys Rehabil Med*, 2010.

[33] I. Borggraefe, A. Meyer-Heim, A. Kumar, J. S. Schaefer, S. Berweck, and F. Heinen. Improved gait parameters after robotic-assisted locomotor treadmill therapy in a 6-year-old child with cerebral palsy. *Movement Disorders*, 23(2):280–283, 2008.

[34] I. Borggraefe, J. S. Schaefer, M. Klaiber, E. Dabrowski, C. Ammann-Reiffer, and B. Knecht, et al. Robotic-assisted treadmill therapy improves walking and standing performance in children and adolescents with cerebral palsy. *European Journal of Paediatric Neurology*, 14(6):496–502, 2010.

[35] M. Bortole. A robotic exoskeleton for overground gait rehabilitation. In *IEEE International Conference on Robotics and Automation (ICRA)*. Karlsruhe, Germany, 2013.

[36] C. Bosecker, L. Dipietro, B. Volpe, and H. I. Krebs. Kinematic robot-based evaluation scales and clinical counterparts to measure upper limb motor performance in patients with chronic stroke. *Neurorehabilitation and Neural Repair*, 24(1):62–69, 2010.

[37] B. R. Brewer, S. K. McDowell, and L. C. Worthen-Chaudhari. Post-stroke upper extremity rehabilitation: A review of robotic systems and clinical results. *Topics in Stroke Rehabilitation*, 14(6):22–44, 2007.

[38] S. Brunnstrom. Motor testing procedures in hemiplegia: Based on sequential recovery stages. *Physical Therapy*, 46(4):357–375, 1966.

[39] K. Brutsch, A. Koenig, L. Zimmerli, S. Merillat-Koeneke, R. Riener, and L. Jancke, et al. Virtual reality for enhancement of robot-assisted gait training in children with neurological gait disorders. *Journal of Rehabilitation Medicine*, 43(6):493–499, 2011.

[40] K. Brütsch, T. Schuler, A. Koenig, L. Zimmerli, S. Mérillat, and L. Lünenburger et al. Influence of virtual reality soccer game on walking performance in robotic assisted gait training for children. *Journal of NeuroEngineering and Rehabilitation*, 7(1):15, 2010.

[41] R. Bruzek. *Leitfaden Gelenkmessung*. Elsevier, Urban & Fischer, 2006.

[42] G. Burdea, V. Popescu, V. Hentz, and K. Colbert. Virtual reality-based orthopedic telerehabilitation. *IEEE Transactions on Rehabilitation Engineering*, 8(3):430–432, 2000.

[43] B. Bussel, A. Roby-Brami, P. Azouvi, A. Biraben, A. Yakovleff, and J. Held. Myoclonus in a patient with spinal cord transection possible involvement of the spinal stepping generator. *Brain*, 111(5):1235–1245, 1988.

[44] L. L. Cai, A. J. Fong, C. K. Otoshi, Y. Liang, J. W. Burdick, and R. R. Roy, et al. Implications of assist-as-needed robotic step training after a complete spinal cord injury on intrinsic strategies of motor learning. *The Journal of Neuroscience*, 26(41):10564–10568, 2006.

[45] L. L. Cai, A. J. Fong, C. K. Otoshi, Y. Q. Liang, J. G. Cham, and H. Zhong, et al., editors. Effects of consistency vs. variability in robotically controlled training of stepping in adult spinal mice. In *International Conference on Rehabilitation Robotics, 2005 ICORR*. IEEE, Chicago, 2005.

[46] B. Calancie, B. Needham-Shropshire, P. Jacobs, K. Willer, G. Zych, and B. A. Green. Involuntary stepping after chronic spinal cord injury evidence for a central rhythm generator for locomotion in man. *Brain*, 117(5):1143–1159, 1994.

[47] D. G. Caldwell, N. G. Tsagarakis, S. Kousidou, N. Costa, and I. Sarakoglou. "Soft" exoskeletons for upper and lower body rehabilitation — design, control and testing. *International Journal of Humanoid Robotics*, 4(3):549–573, 2007.

[48] C. Carignan, M. Liszka, and S. Roderick, editors. Design of an arm exoskeleton with scapula motion for shoulder rehabilitation. In *Proceedings, International Conference on Advanced Robotics, 2005 ICAR'05*. 2005.

[49] J. H. Carr and R. B. Shepherd. Stroke rehabilitation: Guidelines for exercise and training to optimize motor skill, 2003.

[50] M. Casadio and V. Sanguineti. Learning, retention, and slacking: A model of the dynamics of recovery in robot therapy. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 20(3):286–296, 2012.

[51] O. Celik, M. K. O'Malley, C. Boake, H. S. Levin, N. Yozbatiran, and T. A. Reistetter. Normalized movement quality measures for therapeutic robots strongly correlate with clinical motor impairment measures. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 18(4):433–444, 2010.

[52] G. Chen, D. Schwandt, H. Van der Loos, J. Anderson, D. Ferris, and F. Zajac, et al., editors. Compliance-adjustable, force-sensing harness support for studying treadmill training in neurologically impaired subjects. In *Proceedings of the 6th Annual Gait and Clinical Movement Analysis Meeting*. Sacramento, CA, 2001.

[53] A. Chu, H. Kazerooni, and A. Zoss, editors. On the biomimetic design of the berkeley lower extremity exoskeleton (BLEEX). In *Proceedings of the 2005 IEEE International Conference on Robotics and Automation, 2005 ICRA*. 2005.

[54] G. L. Cobb. Walking motion. US Patent 2,010,482, 1935.

[55] G. R. Colborne, S. J. Olney, and M. P. Grifin. Feedback of ankle joint angle and soleus the rehabilitation of hemiplegic gait. *Arch Phys Med Rehabil*, 74(10):1100–1106, 1993.

[56] E. Colgate and N. Hogan, editors. An analysis of contact instability in terms of passive physical equivalents. In *Proceedings of IEEE International Conference on Robotics and Automation*. 1989.

[57] J. E. Colgate. *The Control of Dynamically Interacting Systems*. Massachusetts Institute of Technology, 1988.

[58] F. Collen, D. Wade, G. Robb, and C. Bradshaw. The rivermead mobility index: A further development of the rivermead motor assessment. *Disability & Rehabilitation*, 13(2):50–54, 1991.

[59] S. H. Collins, M. Wisse, and A. Ruina. A three-dimensional passive-dynamic walking robot with two legs and knees. *The International Journal of Robotics Research*, 20(7):607–615, 2001.

[60] G. Colombo and R. Bucher. Device for adjusting the prestress of an elastic means around a predetermined tension or position. US Patent 8,192,331 B2, 2010.

[61] G. Colombo, R. Bucher, and R. Riener. Device for adjusting the height of and the relief force acting on a weight. EP Patent 1,586,291 B1, 2008.

[62] G. Colombo, M. Joerg, R. Schreier, and V. Dietz. Treadmill training of paraplegic patients using a robotic orthosis. *Journal of Rehabilitation Research and Development*, 37(6):693–700, 2000.

[63] A. Compston. Aids to the investigation of peripheral nerve injuries. Medical Research Council: Nerve Injuries Research Committee. His Majesty's Stationery Office, p. 48, 1942. (iii) and 74 figures and 7 diagrams; with aids to the examination of the peripheral nervous system. By Michael O'Brien for the Guarantors of Brain. Saunders Elsevier: 2010; pp. [8] 64 and 94 Figures. *Brain*, 133(10):2838–2844, 2010.

[64] C. C. Consortium. A roadmap for US robotics: From Internet to robotics. Available: `http://robotics-vous/sites/default/files/2013{%}20Robotics{%}20Roadmap-rspdf`, 2013.

[65] G. Cook. Exercise hoist. US Patent No. US 2002/0065173 A1, 2002.

[66] S. Coote, B. Murphy, W. Harwin, and E. Stokes. The effect of the GENTLE/s robot-mediated therapy system on arm function after stroke. *Clinical Rehabilitation*, 22(5):395–405, 2008.

[67] S. Coote, E. K. Stokes, F. Amirabdollahian, R. Loureiro, and W. Harwin. Robot mediated therapy for the upper extremity post stroke. *Irish Journal of Medical Science*, 170:127, 2002.

[68] C. Cozean, W. Pease, and S. Hubbell. Biofeedback and functional electric stimulation in stroke rehabilitation. *Archives of Physical Medicine and Rehabilitation*, 69(6):401–405, 1988.

[69] J. A. Cozens. Robotic assistance of an active upper limb exercise in neurologically impaired patients. *IEEE Transactions on Rehabilitation Engineering*, 7(2):254–256, 1999.

[70] S. C. Cramer and J. D. Riley. Neuroplasticity and brain repair after stroke. *Current Opinion in Neurology*, 21(1):76–82, 2008.

[71] J. Crow, N. Lincoln, F. Nouri, and Weerdt, Wd. The effectiveness of EMG biofeedback in the treatment of arm function after stroke. *Disability & Rehabilitation*, 11(4):155–160, 1989.

[72] A. Curt and V. Dietz. Traumatic cervical spinal cord injury: Relation between somatosensory evoked potentials, neurological deficit, and hand function. *Archives of Physical Medicine and Rehabilitation*, 77(1):48–53, 1996.

[73] A. Curt and V. Dietz. Ambulatory capacity in spinal cord injury: Significance of somatosensory evoked potentials and ASIA protocol in predicting outcome. *Archives of Physical Medicine and Rehabilitation*, 78(1):39–43, 1997.

[74] A. Curt, M. E. Keck, and V. Dietz. Functional outcome following spinal cord injury: Significance of motor-evoked potentials and ASIA scores. *Archives of Physical Medicine and Rehabilitation*, 79(1):81–86, 1998.

[75] D. L. Damiano, J. M. Quinlivan, B. F. Owen, P. Payne, K. C. Nelson, and M. F. Abel. What does the ashworth scale really measure and are instrumented measures more valid and precise? *Developmental Medicine & Child Neurology*, 44(2):112–118, 2002.

[76] I. Davidson and K. Waters. Physiotherapists working with stroke patients: A national survey. *Physiotherapy*, 86(2):69–80, 2000.

[77] M. C. F. De Castro and A. Cliquet Jr. Artificial sensorimotor integration in spinal cord injured subjects through neuromuscular and electrotactile stimulation. *Artificial Organs*, 24(9):710–717, 2000.

[78] H. U. Debrunner and W. R. Hepp. *Orthopädisches Diagnostikum*. Georg Thieme Verlag, 6 edition, 2004.

[79] S. Del Din, S. Patel, C. Cobelli, and P. Bonato, editors. Estimating fugl-meyer clinical scores in stroke survivors using wearable sensors. In *Engineering in Medicine and Biology Society, EMBC, 2011 Annual International Conference of the IEEE*. 2011.

[80] J. Dewald and R. F. Beer. Abnormal joint torque patterns in the paretic upper limb of subjects with hemiparesis. *Muscle & Nerve*, 24(2):273–283, 2001.

[81] J. Dewald, M. Ellis, B. Holubar, T. Sukal, and A. Acosta. The robot application in the rehabilitation of stroke patients. *Neurol Rehabil*, 4:S7, 2004.

[82] R. Dickstein, S. Hocherman, T. Pillar, and R. Shaham. Stroke rehabilitation three exercise therapy approaches. *Physical Therapy*, 66(8):1233–1238, 1986.

[83] V. Dietz. Human neuronal control of automatic functional movements: Interaction between central programs and afferent input. *Physiological Reviews*, 72(1):33–69, 1992.

[84] V. Dietz. Body weight supported gait training: From laboratory to clinical setting. *Brain Research Bulletin*, 78(1):I–VI, 2009.

[85] V. Dietz, G. Colombo, and L. Jensen. Locomotor activity in spinal man. *The Lancet*, 344(8932):1260–1263, 1994.

[86] V. Dietz, G. Colombo, L. Jensen, and L. Baumgartner. Locomotor capacity of spinal cord in paraplegic patients. *Annals of Neurology*, 37(5):574–582, 1995.

[87] V. Dietz, S. Grillner, A. Trepp, M. Hubli, and M. Bolliger. Changes in spinal reflex and locomotor activity after a complete spinal cord injury: A common mechanism? *Brain*, 132(8):2196–2205, 2009.

[88] V. Dietz and S. J. Harkema. Locomotor activity in spinal cord-injured persons. *Journal of Applied Physiology*, 96(5):1954–1960, 2004.

[89] V. Dietz and R. Müller. Degradation of neuronal function following a spinal cord injury: Mechanisms and countermeasures. *Brain*, 127(10):2221–231, 2004.

[90] V. Dietz, R. Müller, and G. Colombo. Locomotor activity in spinal man: Significance of afferent input from joint and load receptors. *Brain*, 125(12):2626–2634, 2002.

[91] V. Dietz and R. R. Young. The syndrome of spastic paresis. In C. T. Brandt, L. Caplan, J. Dichgans, C. Dienev, and C. Kannard, editors, *Neurological Disorders: Course and Treatment*, pages 1247–1257. Academic Press, San Diego (CA), 2nd edition, 2003.

[92] B. Dobkin, S. Harkema, P. Requejo, and V. Edgerton. Modulation of locomotor-like EMG activity in subjects with complete and incomplete spinal cord injury. *Journal of Neurologic Rehabilitation*, 9(4):183–190, 1995.

[93] B. H. Dobkin. Strategies for stroke rehabilitation. *The Lancet Neurology*, 3(9):528–536, 2004.

[94] A. M. Dollar and H. Herr. Lower extremity exoskeletons and active orthoses: Challenges and state-of-the-art. *IEEE Transactions on Robotics*, 24(1):144–158, 2008.

[95] A. Domingo and D. P. Ferris. Effects of physical guidance on short-term learning of walking on a narrow beam. *Gait & Posture*, 30(4):464–458, 2009.

[96] A. W. Dromerick, D. F. Edwards, and M. Hahn. Does the application of constraint-induced movement therapy during acute rehabilitation reduce arm impairment after ischemic stroke? *Stroke*, 31(12):2984–2988, 2000.

[97] V. G. Duffy. *Handbook of Digital Human Modeling*. CRC Press, 2008.

[98] P. W. Duncan, D. Wallace, S. M. Lai, D. Johnson, S. Embretson, and L. J. Laster. The stroke impact scale version 2.0 evaluation of reliability, validity, and sensitivity to change. *Stroke*, 30(10):2131–2140, 1999.

[99] A. Duschau-Wicke, A. Caprez, and R. Riener. Patient-cooperative control increases active participation of individuals with sci during robot-aided gait training. *Journal of Neuroengineering and Rehabilitation*, 7(43):1–13, 2010.

[100] A. Duschau-Wicke, J. von Zitzewitz, A. Caprez, L. Lunenburger, and R. Riener. Path control: A method for patient-cooperative robot-aided gait rehabilitation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 18(1):38–48, 2010.

[101] A. Duschau-Wicke, J. von Zitzewitz, M. Wellner, A. König, L. Lunenburger, and R. Riener, editors. Path control a strategy for patient-cooperative training of gait timing. In *Proc 7th Automed Workshop*. Munich, 2007.

[102] M. D. Ellis, T. M. Sukal-Moulton, and J. Dewald. Impairment-based 3-D robotic intervention improves upper extremity work area in chronic stroke: Targeting abnormal joint torque coupling with progressive shoulder abduction loading. *IEEE Transactions on Robotics*, 25(3):549–555, 2009.

[103] J. L. Emken, J. E. Bobrow, and D. J. Reinkensmeyer, editors. Robotic movement training as an optimization problem: Designing a controller that assists only as needed. In *International Conference on Rehabilitation Robotics, 2005 ICORR 2005*. Chicago, 2005.

[104] J. L. Emken, S. J. Harkema, J. A. Beres-Jones, C. K. Ferreira, and D. J. Reinkensmeyer. Feasibility of manual teach-and-replay and continuous impedance shaping for robotic locomotor training following spinal cord injury. *IEEE Transactions on Biomedical Engineering*, 55(1):322–334, 2008.

[105] J. R. Engsberg, K. S. Olree, S. A. Ross, and T. Park. Quantitative clinical measure of spasticity in children with cerebral palsy. *Archives of Physical Medicine and Rehabilitation*, 77(6):594–599, 1996.

[106] A. Esquenazi, M. Talaty, A. Packel, and M. Saulino. The rewalk powered exoskeleton to restore ambulatory function to individuals with thoracic-level motor-complete spinal cord injury. *American Journal of Physical Medicine & Rehabilitation*, 91(11):911–921, 2012.

[107] R. J. Farris. *Design of a Powered Lower-limb Exoskeleton and Control for Gait Assistance in Paraplegics*. Vanderbilt University, 2012.

[108] J. Fasola and M. J. Mataric. Using socially assistive human–robot interaction to motivate physical exercise for older adults. *Proceedings of the IEEE*, 100(8):2512–2526, 2012.

[109] S. E. Fasoli, H. I. Krebs, J. Stein, W. R. Frontera, and N. Hogan. Effects of robotic therapy on motor impairment and recovery in chronic stroke. *Archives of Physical Medicine and Rehabilitation*, 84(4):477–482, 2003.

[110] V. G. Femery, P. G. Moretto, J.-M. G. Hespel, A. Thévenon, and G. Lensel. A real-time plantar pressure feedback device for foot unloading. *Archives of Physical Medicine and Rehabilitation*, 85(10):1724–1728, 2004.

[111] D. P. Ferris, Z. A. Bohra, J. R. Lukos, and C. R. Kinnaird. Neuromechanical adaptation to hopping with an elastic ankle-foot orthosis. *Journal of Applied Physiology*, 100(1):163–170, 2006.

[112] D. P. Ferris, J. M. Czerniecki, and B. Hannaford. An ankle-foot orthosis powered by artificial pneumatic muscles. *Journal of Applied Biomechanics*, 21(2):189–197, 2005.

[113] D. P. Ferris, K. E. Gordon, G. S. Sawicki, and A. Peethambaran. An improved powered ankle–foot orthosis using proportional myoelectric control. *Gait & Posture*, 23(4):425–428, 2006.

[114] D. P. Ferris, G. S. Sawicki, and A. R. Domingo. Powered lower limb orthoses for gait rehabilitation. *Topics in Spinal Cord Injury Rehabilitation*, 11(2):34–49, 2005.

[115] K. K. Firoozbakhsh, C. F. Kunkel, A. E. Scremin, and M. S. Moneim. Isokinetic dynamometric technique for spasticity assessment. *American Journal of Physical Medicine & Rehabilitation*, 72(6):379–385, 1993.

[116] C. Fisher. Pure sensory stroke and allied conditions. *Stroke*, 13(4):434–447, 1982.

[117] B. M. Fleerkotte, J. H. Buurke, B. Koopman, L. Schaake, H. van der Kooij, and E. H. F. van Asseldonk, et al. Effectiveness of the lower extremity powered exoskeleton (LOPES) robotic gait trainer on ability and quality of walking in SCI patients. In *Converging Clinical and Engineering Research on Neurorehabilitation*, pages 161–165. Springer, 2013.

[118] D. C. Fowles, A. E. Fisher, and D. T. Tranel. The heart beats to reward: The effect of monetary incentive on heart rate. *Psychophysiology*, 19(5):506–513, 1982.

[119] A. Franzoi, C. Castro, and C. Cardone. Isokinetic assessment of spasticity in subjects with traumatic spinal cord injury (ASIA A). *Spinal Cord*, 37(6):416–420, 1999.

[120] M. Frey, G. Colombo, M. Vaglio, R. Bucher, M. Jorg, and R. Riener. A novel mechatronic body weight support system. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 14(3):311–321, 2006.

[121] M. Frey, J. Hoogen, R. Burgkart, and R. Riener. Haptic interaction with a virtual knee joint — The 9 DOF haptic display of the munich knee joint simulator. Submitted for publication.

[122] A. Frisoli, L. Borelli, A. Montagner, S. Marcheschi, C. Procopio, and F. Salsedo, et al., editors. Arm rehabilitation with a robotic exoskeleleton in virtual reality. In *IEEE International Conference on Rehabilitation Robotics, 2007 ICORR 2007*. 2007.

[123] A. Fugl-Meyer, L. Jääskö, I. Leyman, S. Olsson, and S. Steglind. The post-stroke hemiplegic patient. 1. a method for evaluation of physical performance. *Scandinavian Journal of Rehabilitation Medicine*, 7(1):13–31, 1975.

[124] J. Fung, F. Malouin, B. McFadyen, F. Comeau, A. Lamontagne, and S. Chapdelaine, et al., editors. Locomotor rehabilitation in a complex virtual environment. In *Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2004 IEMBS'04*. 2004.

[125] F. Gazzani, A. Fadda, M. Torre, and V. Macellari. WARD: A pneumatic system for body weight relief in gait rehabilitation. *IEEE Transactions on Rehabilitation Engineering*, 8(4):506–513, 2000.

[126] M. Girone, G. Burdea, M. Bouzit, V. Popescu, and J. Deutsch. Orthopedic rehabilitation using the "Rutgers ankle" interface. *Studies in Health Technology and Informatics*, pages 89–95, 2000.

[127] K. Gordon, D. Ferris, M. Roberton, J. Beres, and S. Harkema, editors. The importance of using an appropriate body weight support system in locomotor training. In *Society for Neuroscience Proceedings*. 2000.

[128] K. Gordon, B. Svendesen, S. J. Harkema, and S. El-alami. Closed-loop force controlled body weight support system. US Patent 2003/0153438 A1, 2003.

[129] J. Grundmann and A. Seireg, editors. Computer control of multi-task exoskeleton for paraplegics. In *Proceedings of the CISM/IFTOMM International Symposium on the Theory and Practice of Robots and Manipulators*. 1977.

[130] M. Guidali, M. Büchel, V. Klamroth, T. Nef, and R. Riener, editors. Trajectory planning in ADL tasks for an exoskeletal arm rehabilitation robot. In *Proceedings of the European Conference on Technically Assisted Rehabilitation*. Berlin, 2009.

[131] M. Guidali, A. Duschau-Wicke, M. Büchel, A. Brunschweiler, T. Nef, and R. Riener. Path control — a strategy for patient-cooperative arm rehabilitation. *AUTOMED,* Berlin: Fortschritt-Berichte VDI, Reihe 17, No. 274, 2009.

[132] M. Guidali, S. Broggi Duschau-Wicke A, V. Klamroth-Marganska, T. Nef, and R. Riener. A robotic system to train activities of daily living in a virtual environment. *Medical & Biological Engineering & Computing*, 49(10):1213–1223, 2011.

[133] M. Guidali, P. Schlink, A. Duschau-Wicke, and R. Riener, editors. Online learning and adaptation of patient support during ADL training. In *IEEE International Conference on Rehabilitation Robotics (ICORR)*. 2011.

[134] M. Guidali, M. Schmiedeskamp, V. Klamroth, and R. Riener, editors. Assessment and training of synergies with an arm rehabilitation robot. In *IEEE International Conference on Rehabilitation Robotics, 2009 ICORR*. Kyoto, 2009.

[135] A. Gupta and M. K. O'Malley. Design of a haptic arm exoskeleton for training and rehabilitation. *IEEE/ASME Transactions on Mechatronics*, 11(3):280–289, 2006.

[136] S. J. Harkema, S. L. Hurley, U. K. Patel, P. S. Requejo, B. H. Dobkin, and V. R. Edgerton. Human lumbosacral spinal cord interprets loading during stepping. *Journal of Neurophysiology*, 77(2):797–811, 1997.

[137] J. E. Harris and J. J. Eng. Strength training improves upper-limb function in individuals with stroke a meta-analysis. *Stroke*, 41(1):136–140, 2010.

[138] W. Harwin, R. Loureiro, F. Amirabdollahian, M. Taylor, G. Johnson, and E. Stokes, et al. The GENTLE/s project: A new method of delivering neuro-rehabilitation. *Assistive Technology — Added Value to the Quality of Life AAATE*, 1:36–41, 2001.

[139] T. Hayashi, H. Kawamoto, and Y. Sankai, editors. Control method of robot suit hal working as operator's muscle using biological and dynamical information. In *IEEE/RSJ International Conference on Intelligent Robots and Systems, 2005(IROS 2005)*. 2005.

[140] J. He, R. Kram, and T. A. McMahon. Mechanics of running under simulated low gravity. *Journal of Applied Physiology*, 71(3):863–870, 1991.

[141] S. Hesse, C. Bertelt, M. Jahnke, A. Schaffrin, P. Baake, and M. Malezic et al. Treadmill training with partial body weight support compared with physiotherapy in nonambulatory hemiparetic patients. *Stroke*, 26(6):976–981, 1995.

[142] S. Hesse, G. Schulte-Tigges, M. Konrad, A. Bardeleben, and C. Werner. Robot-assisted arm trainer for the passive and active practice of bilateral forearm and wrist movements in hemiparetic subjects. *Archives of Physical Medicine and Rehabilitation*, 84(6):915–920, 2003.

[143] S. Hesse and D. Uhlenbrock. A mechanized gait trainer for restoration of gait. *Journal of Rehabilitation Research and Development*, 37(6):701–708, 2000.

[144] S. Hesse, A. Waldner, and C. Tomelleri. Research innovative gait robot for the repetitive practice of floor walking and stair climbing up and down in stroke patients. *J NeuroEngineering and Rehabilitation*, 7(30), 2010.

[145] S. Hesse and C. Werner. Connecting research to the needs of patients and clinicians. *Brain Research Bulletin*, 78(1):26–34, 2009.

[146] S. Hesse, C. Werner, M. Pohl, J. Mehrholz, U. Puzich, and H. I. Krebs. Mechanical arm trainer for the treatment of the severely affected arm after a stroke: A single-blinded randomized trial in two centers. *American Journal of Physical Medicine & Rehabilitation*, 87(10):779–788, 2008.

[147] S. Hesse, C. Werner, M. Pohl, S. Rueckriem, J. Mehrholz, and M. Lingnau. Computerized arm training improves the motor control of the severely affected arm after stroke: A single-blinded randomized trial in two centers. *Stroke*, 36(9):1960–1966, 2005.

[148] S. Hesse, C. Werner, S. von Frankenberg, and A. Bardeleben. Treadmill training with partial body weight support after stroke. *Physical Medicine and Rehabilitation Clinics of North America*, 14(1 Suppl):S111–123, 2003.

[149] J. Hidler, D. Brennan, I. Black, D. Nichols, K. Brady, and T. Nef. ZeroG: Overground gait and balance training system. *Journal of Rehabilitation Research and Development*, 48(4):287, 2011.

[150] J. Hidler, D. Nichols, M. Pelliccio, K. Brady, D. D. Campbell, and J. H. Kahn, et al. Multicenter randomized clinical trial evaluating the effectiveness of the lokomat in subacute stroke. *Neurorehabilitation and Neural Repair*, 23(1):5–13, 2009.

[151] M. R. Hillman. Assistive robotics. *Wiley Encyclopedia of Biomedical Engineering*, 2006.

[152] S. Hirokawa and K. Matsumura. Biofeedback gait training system for temporal and distance factors. *Medical and Biological Engineering and Computing*, 27(1):8–13, 1989.

[153] N. Hogan. Impedance control: An approach to manipulation: Parts I, II, and III. *Journal of Dynamic Systems, Measurement, and Control*, 107:1–23, 1985.

[154] N. Hogan, H. I. Krebs, A. Sharon, and J. Charnnarong. Interactive robotic therapist. US Patent 5,466,213, 1995.

[155] M. K. Holden. Virtual environments for motor rehabilitation: Review. *Cyberpsychology & Behavior*, 8(3):187–211, 2005.

[156] J. M. Hollerbach, I. W. Hunter, and J. Ballantyne, editors. A comparative analysis of actuator technologies for robotics. *The Robotics Review*, 2, 1992. MIT Press.

[157] C. Hollnagel, M. Brügger, H. Vallery, P. Wolf, V. Dietz, and S. Kollias et al. Brain activity during stepping: A novel MRI-compatible device. *Journal of Neuroscience Methods*, 201(1):124–130, 2011.

[158] C. Hollnagel, H. Vallery, R. Schädler, I. G.-L. López, L. Jaeger, and P. Wolf, et al. Non-linear adaptive controllers for an over-actuated pneumatic MR-compatible stepper. *Medical & Biological Engineering & Computing*, 51(7):799–809, 2013.

[159] J. Hoogen, R. Riener, and G. Schmidt. Control aspects of a robotic haptic interface for kinesthetic knee joint simulation. *Control Engineering Practice*, 10(11):1301–1308, 2002.

[160] T. G. Hornby, D. D. Campbell, D. H. Zemon, and J. H. Kahn. Clinical and quantitative evaluation of robotic-assisted treadmill walking to retrain ambulation after spinal cord injury. *Topics in Spinal Cord Injury Rehabilitation*, 11(2):1, 2005.

[161] T. G. Hornby, D. H. Zemon, and D. Campbell. Robotic-assisted, body-weight–supported treadmill training in individuals following motor incomplete spinal cord injury. *Physical Therapy*, 85(1):52–66, 2005.

[162] J. A. Hosp, A. Pekanovic, M. S. Rioult-Pedotti, and A. R. Luft. Dopaminergic projections from midbrain to primary motor cortex mediate motor skill learning. *The Journal of Neuroscience*, 31(7):2481–2487, 2011.

[163] S. J. Housman, K. M. Scott, and D. J. Reinkensmeyer. A randomized controlled trial of gravity-supported, computer-enhanced arm exercise for individuals with severe hemiparesis. *Neurorehabilitation and Neural Repair*, 23(5):505–514, 2009.

[164] V. S. Huang and J. W. Krakauer. Robotic neurorehabilitation: A computational motor learning perspective. *Journal of NeuroEngineering and Rehabilitation*, 6(1):5, 2009.

[165] K. Hunt, L. Jack, A. Pennycott, C. Perret, M. Baumberger, and T. Kakebeeke. Control of work rate-driven exercise facilitates cardiopulmonary training and assessment during robot-assisted gait in incomplete spinal cord injury. *Biomedical Signal Processing and Control*, 3(1):19–28, 2008.

[166] B. Husemann, F. Müller, C. Krewer, S. Heller, and E. Koenig. Effects of locomotion training with assistance of a robot-driven gait orthosis in hemiparetic patients after stroke a randomized controlled pilot study. *Stroke*, 38(2):349–354, 2007.

[167] J. Inglis, M. Donald, T. Monga, M. Sproule, and M. Young. Electromyographic biofeedback and physical therapy of the hemiplegic upper limb. *Archives of Physical Medicine and Rehabilitation*, 65(12):755–759, 1984.

[168] M. Ishii, K. Yamamoto, and K. Hyodo. Stand-alone wearable power assist suit-Development and availability. *Journal of Robotics and Mechatronics*, 17(5):575–583, 2005.

[169] J. F. Israel, D. D. Campbell, J. H. Kahn, and T. G. Hornby. Metabolic costs and muscle activity patterns during robotic-and therapist-assisted treadmill walking in individuals with incomplete spinal cord injury. *Physical Therapy*, 86(11):1466–1478, 2006.

[170] D. Jack, R. Boian, A. S. Merians, M. Tremaine, G. C. Burdea, and S. V. Adamovich, et al. Virtual reality-enhanced stroke rehabilitation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 9(3):308–318, 2001.

[171] Y. Jeong, Y. Lee, K. Kim, Y.-S. Hong, and J.-O. Park, editors. A 7 DOF wearable robotic arm using pneumatic actuators. In *Proceedings of the ISR (International Symposium on Robotics)*. 2001.

[172] S. Jezernik, G. Colombo, and M. Morari. Automatic gait-pattern adaptation algorithms for rehabilitation with a 4-DOF robotic orthosis. *IEEE Transactions on Robotics and Automation*, 20(3):574–582, 2004.

[173] S. Jezernik, K. Jezernik, and M. Morari, editors. Impedance control based gait-pattern adaptation for a robotic rehabilitation device. In *Proceedings of the 2nd IFAC Conference on Mechatronic Systems*. Berkeley, 2002.

[174] S. Jezernik, R. Schärer, G. Colombo, and M. Morari. Adaptive robotic rehabilitation of locomotion: A clinical study in spinally injured individuals. *Spinal Cord*, 41(12):657–666, 2003.

[175] A. Jobin and M. F. Levin. Regulation of stretch reflex threshold in elbow flexors in children with cerebral palsy: A new measure of spasticity. *Developmental Medicine & Child Neurology*, 42(8):531–540, 2000.

[176] H. S. Jørgensen, H. Nakayama, H. O. Raaschou, and T. S. Olsen. Recovery of walking function in stroke patients: The Copenhagen Stroke Study. *Archives of Physical Medicine and Rehabilitation*, 76(1):27–32, 1995.

[177] T. Kagawa and Y. Uno, editors. Gait pattern generation for a power-assist device of paraplegic gait. In *The IEEE International Symposium on Robot and Human Interactive Communication, 2009 RO-MAN*. 2009.

[178] T. Kakebeeke, H. Lechner, M. Baumberger, J. Denoth, D. Michel, and H. Knecht. The importance of posture on the isokinetic assessment of spasticity. *Spinal Cord*, 40(5):236–243, 2002.

[179] S. Kalsi-Ryan, A. Curt, M. C. Verrier, and M. G. Fehlings. Development of the Graded Redefined Assessment of Strength, Sensibility and Prehension (GRASSP): Reviewing measurement specific to the upper limb in tetraplegia. *Journal of Neurosurgery: Spine*, 17(1):65–76, 2012.

[180] K. Kamibayashi, T. Nakajima, M. Takahashi, M. Akai, and K. Nakazawa. Facilitation of corticospinal excitability in the tibialis anterior muscle during robot-assisted passive stepping in humans. *European Journal of Neuroscience*, 30(1):100–109, 2009.

[181] P.-C. Kao and D. P. Ferris. The effect of movement frequency on interlimb coupling during recumbent stepping. *Motor Control*, 9(2):144–163, 2005.

[182] N. C. Karavas, N. G. Tsagarakis, and D. G. Caldwell. Standing and sitting motion assistance using a compliant knee exoskeleton. In *IEEE International Conference on Robotics and Automation (ICRA)*. Karlsruhe, Germany, 2013.

[183] S. Karlin. *Raytheon Sarcos's Exoskeleton Nears Production*. IEEE Spectrum, 2011.

[184] S. Katoh and W. El Masry. Neurological recovery after conservative treatment of cervical cord injuries. *Journal of Bone & Joint Surgery, British Volume*, 76(2):225–228, 1994.

[185] H. Kawamoto and Y. Sankai. Power assist system HAL-3 for gait disorder person. In *Computers Helping People with Special Needs*, pages 196–203. Springer, 2002.

[186] H. Kazerooni, J.-L. Racine, L. Huang, and R. Steger, editors. On the control of the berkeley lower extremity exoskeleton (BLEEX). In *Proceedings of the 2005 IEEE International Conference on Robotics and Automation, 2005 ICRA*. 2005.

[187] R. E. Kearney, R. B. Stein, and L. Parameswaran. Identification of intrinsic and reflex contributions to human ankle stiffness dynamics. *IEEE Transactions on Biomedical Engineering*, 44(6):493–504, 1997.

[188] U. Keller, G. Rauter, and R. Riener. Assist-as-needed path control for the pascal rehabilitation robot. In *IEEE International Conference on Rehabilitation Robotics (ICORR)*. IEEE, Seattle, 2013.

[189] R. Kelly and R. Salgado. Pd control with computed feedforward of robot manipulators: A design procedure. *IEEE Transactions on Robotics and Automation*, 10(4):566–571, 1994.

[190] M. Kelly-Hayes, J. T. Robertson, J. P. Broderick, P. W. Duncan, L. A. Hershey, and E. J. Roth, et al. The American Heart Association stroke outcome classification: Executive summary. *Circulation*, 97(24):2474–2478, 1998.

[191] D. Kelsey and A. Walls. Therapeutic unloading apparatus and method. US Patent, 5,273,502, 1993.

[192] E. Keshner, R. Kenyon, and Y. Dhaher, editors. Postural research and rehabilitation in an immersive virtual environment. In *Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2004 IEMBS'04*. 2004.

[193] D.-J. Kim, R. Lovelett, and A. Behal, editors. Eye-in-hand stereo visual servoing of an assistive robot arm in unstructured environments. In *IEEE International Conference on Robotics and Automation, 2009 ICRA'09*. IEEE, Kobe, 2009.

[194] S. Kim, H. Shin, S.-H. Jung, J.-J. Lee, and B.-O. Kim. Supporting force control of walking training robots. *International Journal of Human-Friendly Welfare Robotic Systems*, 3:2–7, 2002.

[195] V. Klamroth-Marganska, M. Guidali, M. Schmiedeskamp, and R. Riener. Synergy assessment after stroke with the arm assessment robot armin. Technically Assisted Rehabilitation TAR 2011; Berlin, 2011.

[196] J. Klein, S. Spencer, J. Allington, J. E. Bobrow, and D. J. Reinkensmeyer. Optimization of a parallel shoulder mechanism to achieve a high-force, low-mass, robotic-arm exoskeleton. *IEEE Transactions on Robotics*, 26(4):710–715, 2010.

[197] J. Klein, S. Spencer, J. Allington, K. Minakata, E. Wolbrecht, and R. Smith, et al., editors. Biomimetic orthosis for the neurorehabilitation of the elbow and shoulder (BONES). In *IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics, 2008 BioRob*. 2008.

[198] M. Knott, D. E. Voss, H. D. Hipshman, and J. B. Buckley. *Proprioceptive Neuromuscular Facilitation: Patterns and Techniques*. Hoeber Medical Division, Harper & Row, 1968.

[199] A. Koenig, K. Brutsch, L. Zimmerli, M. Guidali, A. Duschau-Wicke, and M. Wellner, et al., editors. Virtual environments increase participation of children with cerebral palsy in robot-aided treadmill training. In *Virtual Rehabilitation, IEEE*. 2008.

[200] A. Koenig, D. Novak, X. Omlin, M. Pulfer, E. Perreault, and L. Zimmerli, et al. Real-time closed-loop control of cognitive load in neurological patients during robot-assisted gait training. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 19(4):453–464, 2011.

[201] A. Koenig, X. Omlin, J. Bergmann, L. Zimmerli, M. Bolliger, and F. Müller, et al. Controlling patient participation during robot-assisted gait training. *Journal of Neuroengineering and Rehabilitation*, 8(1):14, 2011.

[202] A. Koenig, X. Omlin, L. Zimmerli, M. Sapa, C. Krewer, and M. Bolliger, et al. Psychological state estimation from physiological recordings during robot assisted gait rehabilitation. *J Rehabil Res Develop*, 48(4):367–386, 2011.

[203] J. W. Krakauer. Motor learning: Its relevance to stroke recovery and neurorehabilitation. *Current Opinion in Neurology*, 19(1):84–90, 2006.

[204] R. Kram, A. Domingo, and D. P. Ferris. Effect of reduced gravity on the preferred walk-run transition speed. *Journal of Experimental Biology*, 200(4):821–826, 1997.

[205] H. Krebs, B. Volpe, M. Aisen, and N. Hogan. Increasing productivity and quality of care: Robot-aided neuro-rehabilitation. *Journal of Rehabilitation Research and Development*, 37(6):639–652, 2000.

[206] H. I. Krebs, M. Ferraro, S. P. Buerger, M. J. Newbery, A. Makiyama, and M. Sandmann et al. Rehabilitation robotics: Pilot trial of a spatial extension for MIT-Manus. *Journal of NeuroEngineering and Rehabilitation*, 1(1):5, 2004.

[207] H. I. Krebs, N. Hogan, M. L. Aisen, and B. T. Volpe. Robot-aided neurorehabilitation. *IEEE Transactions on Rehabilitation Engineering*, 6(1):75–87, 1998.

[208] H. I. Krebs, J. J. Palazzolo, L. Dipietro, M. Ferraro, J. Krol, and K. Rannekleiv, et al. Rehabilitation robotics: Performance-based progressive robot-assisted therapy. *Autonomous Robots*, 15(1):7–20, 2003.

[209] H. I. Krebs, B. T. Volpe, D. Williams, J. Celestino, S. K. Charles, and D. Lynch, et al. Robot-aided neurorehabilitation: A robot for wrist rehabilitation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 15(3):327–335, 2007.

[210] C. Krishnan, D. Kotsapouikis, Y. Y. Dhaher, and W. Z. Rymer. Reducing robotic guidance during robot-assisted gait training improves gait function: A case report on a stroke survivor. *Archives of Physical Medicine and Rehabilitation*, 94(6):1202–1206, 2013.

[211] C. Krishnan, R. Ranganathan, S. S. Kantak, Y. Y. Dhaher, and W. Z. Rymer. Active robotic training improves locomotor function in a stroke survivor. *Journal of Neuroengineering and Rehabilitation*, 9(1):1–13, 2012.

[212] G. Kwakkel, R. C. Wagenaar, T. W. Koelman, G. J. Lankhorst, and J. C. Koetsier. Effects of intensity of rehabilitation after stroke a research synthesis. *Stroke*, 28(8):1550–1556, 1997.

[213] G. Kwakkel, R. C. Wagenaar, J. W. Twisk, G. J. Lankhorst, and J. C. Koetsier. Intensity of leg and arm training after primary middle-cerebral-artery stroke: A randomised trial. *The Lancet*, 354(9174):191–196, 1999.

[214] H. Kwee, J. Duimel, J. Smit, A. T. de Moed, J. van Woerden, and L. V. D. Kolk. The manus wheelchair-mounted manipulator: Developments toward a production model. *Int Conf Assoc Advancement Rehab Technol*, pages 460–462, 1988.

[215] O. Lambercy, L. Dovat, R. Gassert, E. Burdet, C. L. Teo, and T. Milner. A haptic knob for rehabilitation of hand function. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 15(3):356–366, 2007.

[216] O. Lambercy, L. Dovat, H. Yun, S. K. Wee, C. Kuah, and K. Chua, et al., editors. Robotic assessment of hand function with the haptic-knob. In *Proceedings of the International Convention on Rehabilitation Engineering & Assistive Technology*. Singapore Therapeutic, Assistive & Rehabilitative Technologies (START) Centre, 2010.

[217] A. Lamontagne, F. Malouin, C. L. Richards, and F. Dumas. Evaluation of reflex-and nonreflex-induced muscle resistance to stretch in adults with spinal cord injury using hand-held and isokinetic dynamometry. *Physical Therapy*, 78(9):964–975, 1998.

[218] J. W. Lance. *Spasticity: Disordered Motor Control*. Year Book Medical Publishers, Chicago (IL), 1980.

[219] P. Langhorne, F. Coupar, and A. Pollock. Motor recovery after stroke: A systematic review. *The Lancet Neurology*, 8(8):741–754, 2009.

[220] P. Langhorne, F. Coupar, and A. Pollock. Motor recovery after stroke: A systematic review. *Lancet Neurol*, 8(8):741–754, 2009.

[221] Y. Laufer, R. Dickstein, Y. Chefez, and E. Marcovitz. The effect of treadmill training on the ambulation of stroke survivors in the early stages of rehabilitation. *J Rehabil Res Dev*, 38:69–78, 2001.

[222] D. A. Lawrence, editor. Impedance control stability properties in common implementations. In *IEEE International Conference on Robotics and Automation, 1988 Proceedings*. IEEE, Philadelphia, 1988.

[223] C.-Y. Lee, K.-H. Seo, C. Oh, and J.-J. Lee. Newly designed rehabilitation robot system for walking-aid with pneumatic actuator. *International Journal of Human-Friendly Welfare Robotic Systems*, 4:42–46, 2003.

[224] L. Leifer. Rehabilitative robots. *Robotics Age*, 3(3):4–15, 1981.

[225] S. Lennon. Physiotherapy practice in stroke rehabilitation: A survey. *Disability & Rehabilitation*, 25(9):455–461, 2003.

[226] M. D. Lewek, T. H. Cruz, J. L. Moore, H. R. Roth, Y. Y. Dhaher, and T. G. Hornby. Allowing intralimb kinematic variability during locomotor training poststroke improves kinematic consistency: A subgroup analysis from a randomized clinical trial. *Physical Therapy*, 89(8):829–839, 2009.

[227] A. Lo, P. Guarino, L. Richards, J. Haselkorn, G. Wittenberg, and D. Federman, et al. Robot-assisted therapy for long-term upper-limb impairment after stroke. *New England Journal of Medicine*, 362(19):1772–1783, 2010.

[228] A. C. Lo and E. W. Triche. Improving gait in multiple sclerosis using robot-assisted, body weight supported treadmill training. *Neurorehabilitation and Neural Repair*, 22(6):661–671, 2008.

[229] M. Lotze, C. Braun, N. Birbaumer, S. Anders, and L. G. Cohen. Motor learning elicited by voluntary drive. *Brain*, 126(4):866–872, 2003.

[230] P. S. Lum, C. G. Burgar, P. C. Shor, M. Majmundar, and M. Van der Loos. Robot-assisted movement training compared with conventional therapy techniques for the rehabilitation of upper-limb motor function after stroke. *Archives of Physical Medicine and Rehabilitation*, 83(7):952–959, 2002.

[231] P. S. Lum, D. J. Reinkensmeyer, and S. L. Lehman. Robotic assist devices for bimanual physical therapy: Preliminary experiments. *IEEE Transactions on Rehabilitation Engineering*, 1(3):185–191, 1993.

[232] S. Lum, S. L. Lehman, and D. J. Reinkensmeyer. The bimanual lifting rehabilitator: An adaptive machine for therapy of stroke patients. *IEEE Transactions on Rehabilitation Engineering*, 3(2):166–174, 1995.

[233] L. Lünenburger, G. Colombo, and R. Riener. Biofeedback for robotic gait rehabilitation. *Journal of Neuroengineering and Rehabilitation*, 4(1):1, 2007.

[234] L. Lünenburger, G. Colombo, R. Riener, and V. Dietz, editors. Biofeedback in gait training with the robotic orthosis lokomat. In *IEMBS'04 26th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. 2004.

[235] L. Lunenburger, G. Colombo, R. Riener, and V. Dietz, editors. Clinical assessments performed during robotic rehabilitation by the gait training robot lokomat. In *International Conference on Rehabilitation Robotics, 2005 ICORR*. 2005.

[236] L. Lunenburger, M. Wellner, R. Banz, G. Colombo, and R. Riener, editors. Combining immersive virtual environments with robot-aided gait training. In *IEEE International Conference on Rehabilitation Robotics, 2007 ICORR*. 2007.

[237] R. F. Macko, F. M. Ivey, L. W. Forrester, D. Hanley, J. D. Sorkin, and L. I. Katzel et al. Treadmill exercise rehabilitation improves ambulatory function and cardiovascular fitness in patients with chronic stroke a randomized, controlled trial. *Stroke*, 36(10):2206–2211, 2005.

[238] N. Maclean and P. Pound. A critical review of the concept of patient motivation in the literature on physical rehabilitation. *Social Science & Medicine*, 50(4):495–506, 2000.

[239] V. Magagnin, E. Caiani, L. Fusini, M. Turiel, V. Licari, and I. Bo, et al., editors. Assessment of the cardiovascular regulation during robotic assisted locomotion in normal subjects: Autoregressive spectral analysis vs empirical mode decomposition. In *Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2008 EMBS*. 2008.

[240] V. Magagnin, A. Porta, L. Fusini, V. Licari, I. Bo, and M. Turiel, et al. Evaluation of the autonomic response in healthy subjects during treadmill training with assistance of a robot-driven gait orthosis. *Gait & Posture*, 29(3):504–508, 2009.

[241] M. Malik. Heart rate variability — standards of measurement, physiological interpretation and clinical use. *European Heart Journal*, 17:28, 1996.

[242] A. Mandel, J. Nymark, S. Balmer, D. Grinnell, and M. O'Riain. Electromyographic versus rhythmic positional biofeedback in computerized gait retraining with stroke patients. *Archives of Physical Medicine and Rehabilitation*, 71(9):649–654, 1990.

[243] L. Marchal-Crespo and D. J. Reinkensmeyer. Haptic guidance can enhance motor learning of a steering task. *Journal of Motor Behavior*, 40(6):545–557, 2008.

[244] L. Marchal-Crespo, M. van Rai, G. Rauter, P. Wolf, and R. Riener. The effect of haptic guidance and visual feedback on learning a complex tennis task, 2013. submitted for publication.

[245] G. Rauter Marchal-Crespo L, D. Wyss, and R. Riener, editors von Zitzewitz J. Synthesis and control of an assistive robotic tennis trainer. In *IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*. 2012.

[246] G. Martino. How the brain repairs itself: New therapeutic strategies in inflammatory and degenerative CNS disorders. *The Lancet Neurology*, 3(6):372–378, 2004.

[247] S. Masiero, M. Armani, and G. Rosati. Upper-limb robot-assisted therapy in rehabilitation of acute stroke patients: Focused review and results of new randomized controlled trial. *J Rehabil Res Dev*, 48(4):355–366, 2011.

[248] M. J. Mataric, J. Eriksson, D. J. Feil-Seifer, and C. J. Winstein. Socially assistive robotics for post-stroke rehabilitation. *Journal of NeuroEngineering and Rehabilitation*, 4(5), 2007.

[249] K. H. Mauritz. Gait training in hemiplegia. *European Journal of Neurology*, 9(s1):23–29, 2002.

[250] A. Mayr, M. Kofler, E. Quirbach, H. Matzak, K. Fröhlich, and L. Saltuari. Prospective, blinded, randomized crossover study of gait rehabilitation in stroke patients using the lokomat gait orthosis. *Neurorehabilitation and Neural Repair*, 21(4):307–314, 2007.

[251] J. Mehrholz, A. Hädrich, T. Platz, J. Kugler, and M. Pohl. Electromechanical and robot-assisted arm training for improving generic activities of daily living, arm function, and arm muscle strength after stroke. *Cochrane Database Syst Rev.*, page 6, 2012.

[252] A. Meyer-Heim, C. Ammann-Reiffer, A. Schmartz, J. Schaefer, F. H. Sennhauser, and F. Heinen, et al. Improvement of walking abilities after robotic-assisted locomotion training in children with cerebral palsy. *Archives of Disease in Childhood*, 94(8):615–620, 2009.

[253] A. Meyer-Heim, I. Borggraefe, C. Ammann-Reiffer, S. Berweck, F. Sennhauser, and G. Colombo, et al. Feasibility of robotic-assisted locomotor training in children with central gait impairment. *Developmental Medicine & Child Neurology*, 49(12):900–906, 2007.

[254] M. Mihelj, T. Nef, and R. Riener. A novel paradigm for patient-cooperative control of upper-limb rehabilitation robots. *Advanced Robotics*, 21(8):843–867, 2007.

[255] M. Mihelj, D. Novak, M. Milavec, J. Ziherl, A. Olenšek, and M. Munih. Virtual rehabilitation environment using principles of intrinsic motivation and game design. *Presence: Teleoperators and Virtual Environments*, 21(1):1–15, 2012.

[256] E. L. Miller, L. Murray, L. Richards, R. D. Zorowitz, T. Bakas, and P. Clark, et al. Comprehensive overview of nursing and interdisciplinary rehabilitation care of the stroke patient a scientific statement from the american heart association. *Stroke*, 41(10):2402–2448, 2010.

[257] W. H. Miltner, H. Bauder, M. Sommer, C. Dettmers, and E. Taub. Effects of constraint-induced movement therapy on patients with chronic motor deficits after stroke a replication. *Stroke*, 30(3):586–592, 1999.

[258] M. Mirbagheri, H. Barbeau, M. Ladouceur, and R. Kearney. Intrinsic and reflex stiffness in normal and spastic, spinal cord injured subjects. *Experimental Brain Research*, 141(4):446–459, 2001.

[259] K. Molina-Luna, A. Pekanovic, S. Röhrich, B. Hertler, M. Schubring-Giese, and M.-S. Rioult-Pedotti, et al. Dopamine in motor cortex is necessary for skill learning and synaptic plasticity. *PLoS One*, 4(9):e7082, 2009.

[260] R. Montoya, P. Dupui, B. Pages, and P. Bessou. Step-length biofeedback device for walk rehabilitation. *Medical and Biological Engineering and Computing*, 32(4):416–420, 1994.

[261] J. D. Moreland, M. A. Thomson, and A. R. Fuoco. Electromyographic biofeedback to improve lower extremity function after stroke: A meta-analysis. *Archives of Physical Medicine and Rehabilitation*, 79(2):134–140, 1998.

[262] M. E. Morris, T. M. Bach, and P. A. Goldie. Electrogoniometric feedback: Its effect on genu recurvatum in stroke. *Arch Phys Med Rehabil*, 73(12):1, 1992.

[263] T. Nef, M. Guidali, and R. Riener. ARMin III — arm therapy exoskeleton with an ergonomic shoulder actuation. *Applied Bionics and Biomechanics*, 6(2):127–142, 2009.

[264] T. Nef, M. Mihelj, and R. Riener. ARMin: A robot for patient-cooperative arm therapy. *Medical & Biological Engineering & Computing*, 45(9):887–900, 2007.

[265] T. Nef and R. Riener. Three-Dimensional Multi-Degree-of-Freedom Arm Therapy Robot (ARMin). In V. Dietz, Z. Rymer, and T. Nef, editors, *Neurorehabilitation Technology*, pages 141–157. Springer, London, 2012.

[266] T. Nef, R. Riener, R. Müri, and U. P. Mosimann. Comfort of two shoulder actuation mechanisms for arm therapy exoskeletons: A comparative study in healthy subjects. *Medical & Biological Engineering & Computing*, pages 1–9, 2013.

[267] P. D. Neuhaus, J. H. Noorden, T. J. Craig, T. Torres, J. Kirschbaum, and J. E. Pratt, editors. Design and evaluation of mina: A robotic orthosis for paraplegics. In *IEEE International Conference on Rehabilitation Robotics (ICORR)*. 2011.

[268] J. Nikitczuk, B. Weinberg, and C. Mavroidis, editors. Rehabilitative knee orthosis driven by electro-rheological fluid based actuators. In *Proceedings of the 2005 IEEE International Conference on Robotics and Automation, 2005 ICRA*. 2005.

[269] K. E. Norman, A. Pepin, M. Ladouceur, and H. Barbeau. A treadmill apparatus and harness support for evaluation and rehabilitation of gait. *Archives of Physical Medicine and Rehabilitation*, 76(8):772–778, 1995.

[270] D. Novak, M. Mihelj, and M. Munih. Psychophysiological responses to different levels of cognitive and physical workload in haptic interaction. *Robotica*, 29(03):367–374, 2011.

[271] D. Novak, M. Mihelj, J. Ziherl, A. Olensek, and M. Munih. Psychophysiological measurements in a biocooperative feedback loop for upper extremity rehabilitation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 19(4):400–410, 2011.

[272] D. Novak, J. Ziherl, A. Olensek, M. Milavec, J. Podobnik, and M. Mihelj, et al. Psychophysiological responses to robotic rehabilitation tasks in stroke. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 18(4):351–361, 2010.

[273] M. Ohsuga, Y. Tatsuno, F. Shimono, K. Hirasawa, H. Oyama, and H. Okamura. Development of a bedside wellness system. *CyberPsychology & Behavior*, 1(2):105–112, 1998.

[274] S. J. Page, D. R. Gater, and P. Bach-y-Rita. Reconsidering the motor recovery plateau in stroke rehabilitation. *Archives of Physical Medicine and Rehabilitation*, 85(8):1377–1381, 2004.

[275] M. Palankar, K. J. De Laurentis, R. Alqasemi, E. Veras, R. Dubey, and Y. Arbel, et al., editors. Control of a 9-DoF wheelchair-mounted robotic arm system using a P300 brain computer interface: Initial experiments. In *IEEE International Conference on Robotics and Biomimetics, 2008 ROBIO*. IEEE, Bangkok, 2009.

[276] A. Pandyan, C. Price, H. Rodgers, M. Barnes, and G. Johnson. Biomechanical examination of a commonly used measure of spasticity. *Clinical Biomechanics*, 16(10):859–865, 2001.

[277] C. Partridge and S. Edwards. The bases of practice — neurological physiotherapy. *Physiotherapy Research International*, 1(3):205–208, 1996.

[278] I. Pathirage, K. Khokar, E. Klay, R. Alqasemi, and R. Dubey, editors. A vision based P300 brain computer interface for grasping using a wheelchair-mounted robotic arm. In *IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*. IEEE, Wollongong, Australia, 2013.

[279] J. Patton, G. Dawe, C. Scharver, F. Mussa-Ivaldi, and R. Kenyon, editors. Robotics and virtual reality: The development of a life-sized 3-D system for the rehabilitation of motor function. In *Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2004 IEMBS'04*. 2004.

[280] K. Pearson and D. Collins. Reversal of the influence of group Ib afferents from plantaris on activity in medial gastrocnemius muscle during locomotor activity. *Journal of Neurophysiology*, 70(3):1009–1017, 1993.

[281] A. Pennycott, H. Vallery, D. Wyss, M. Spindler, A. Dewarrat, and R. Riener. A novel body weight support system extension for balance training. In *IEEE International Conference on Rehabilitation Robotics (ICORR)*. Seattle, USA, 2013.

[282] A. Pennycott, D. Wyss, H. Vallery, and R. Riener. Towards more effective robotic gait training for stroke rehabilitation. *Journal of NeuroEngineering and Rehabilitation*, 9(65), 2012.

[283] K. Perell, A. Scremin, O. Scremin, and C. Kunkel. Quantifying muscle tone in spinal cord injury patients using isokinetic dynamometric techniques. *Paralegia*, 34(1):46–53, 1996.

[284] M. A. Perez, B. K. Lungholt, K. Nyborg, and J. B. Nielsen. Motor skill training induces changes in the excitability of the leg cortical area in healthy humans. *Experimental Brain Research*, 159(2):197–205, 2004.

[285] J. Petrofsky. The use of electromyogram biofeedback to reduce trendelenburg gait. *European Journal of Applied Physiology*, 85(5):491–495, 2001.

[286] S. H. Peurala, O. Airaksinen, P. Huuskonen, P. Jakala, M. Juhakoski, and K. Sandell, et al. Effects of intensive therapy using gait trainer or floor walking exercises early after stroke. *Journal of Rehabilitation Medicine*, 41(3):166–173, 2009.

[287] C. Phillips, R. Koubek, and D. Hendershot. Walking while using a sensory tactile feedback system: Potential use with a functional electrical stimulation orthosis. *Journal of Biomedical Engineering*, 13(2):91–96, 1991.

[288] T. Platz. Evidence-based arm rehabilitation — a systematic review of the literature. *Der Nervenarzt*, 74(10):841–849, 2003.

[289] M. Pohl, J. Mehrholz, C. Ritschel, and S. Rückriem. Speed-dependent treadmill training in ambulatory hemiparetic stroke patients: A randomized controlled trial. *Stroke*, 33(2):553–558, 2002.

[290] M. Pohl, C. Werner, M. Holzgraefe, G. Kroczek, I. Wingendorf, and G. Hoölig et al. Repetitive locomotor training and physiotherapy improve walking and basic activities of daily living after stroke: A single-blind, randomized multicentre trial (DEutsche GAngtrainer-Studie, DEGAS). *Clinical Rehabilitation*, 21(1):17–27, 2007.

[291] V. G. Popescu, G. C. Burdea, M. Bouzit, and V. R. Hentz. A virtual-reality-based telerehabilitation system with force feedback. *IEEE Transactions on Information Technology in Biomedicine*, 4(1):45–51, 2000.

[292] G. A. Pratt, M. M. Williamson, P. Dillworth, J. E. Pratt, and A. Wright, editors. Stiffness isn't everything. In *The International Symposium on Experimental Robotics (ISER)*. Springer-Verlag, 1995.

[293] J. E. Pratt, B. T. Krupp, C. J. Morse, and S. H. Collins, editors. The RoboKnee: An exoskeleton for enhancing strength and endurance during walking. In *IEEE International Conference on Robotics and Automation, 2004 Proceedings ICRA'04*. 2004.

[294] S. D. Prior. An electric wheelchair mounted robotic arm-a survey of potential users. *Journal of Medical Engineering & Technology*, 14(4):143–154, 1990.

[295] S. D. Prior and P. R. Warner, editors. Wheelchair-mounted robots for the home environment. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems' 93, IROS'93*. 1993.

[296] R. G. Querry, F. Pacheco, T. Annaswamy, L. Goetz, P. K. Winchester, and K. E. Tansey. Synchronous stimulation and monitoring of soleus H reflex during robotic body weight-supported ambulation in subjects with spinal cord injury. *Journal of Rehabilitation Research and Development*, 45(1):175–186, 2008.

[297] A. K. Raj, P. D. Neuhaus, A. M. Moucheboeuf, J. H. Noorden, and D. V. Lecoutre. Mina: A sensorimotor robotic orthosis for mobility assistance. *Journal of Robotics*, 2011.

[298] P. Rani, J. Sims, R. Brackin, and N. Sarkar. Online stress detection using psychophysiological signals for implicit human-robot cooperation. *Robotica*, 20(6):673–685, 2002.

[299] G. Rauter, N. Gerig, H. Vallery, R. Sigrist, R. Riener, and P. Wolf. Hybrid path control enables haptic guidance along self-crossing paths. In *IEEE Transactions on Robotics*. 2013. submitted for publication.

[300] G. Rauter, R. Sigrist, L. Marchal-Crespo, H. Vallery, R. Riener, and P. Wolf, editors. Assistance or challenge? filling a gap in user-cooperative control. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2011.

[301] G. Rauter, J. von Zitzewitz, A. Duschau-Wicke, H. Vallery, and R. Riener, editors. A tendon-based parallel robot applied to motor learning in sports. In *IEEE RAS and EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*. 2010.

[302] D. J. Reinkensmeyer, D. Aoyagi, J. L. Emken, J. A. Galvez, W. Ichinose, and G. Kerdanyan, et al. Tools for understanding and optimizing robotic gait training. *Journal of Rehabilitation Research and Development*, 43(5):657–670, 2006.

[303] D. J. Reinkensmeyer, B. D. Schmit, and W. Z. Rymer. Assessment of active and passive restraint during guided reaching after chronic brain injury. *Annals of Biomedical Engineering*, 27(6):805–814, 1999.

[304] D. J. Reinkensmeyer, E. T. Wolbrecht, V. Chan, C. Chou, S. C. Cramer, and J. E. Bobrow. Comparison of three-dimensional, assist-as-needed robotic arm/hand movement training provided with Pneu-WREX to conventional tabletop therapy after chronic stroke. *American Journal of Physical Medicine & Rehabilitation*, 91(11):232–241, 2012.

[305] M. J. Riddoch, G. W. Humphreys, and A. Bateman. Stroke: Stroke issues in recovery and rehabilitation. *Physiotherapy*, 81(11):689–694, 1995.

[306] R. Riener, A. Brunschweiler, L. Lünenburger, and G. Colombo, editors. Robot-supported spasticity evaluation. In *Annual Conference of the International FES Society*. Bournemouth, England, 2004.

[307] R. Riener and T. Fuhr. Patient-driven control of FES-supported standing up: A simulation study. *IEEE Transactions on Rehabilitation Engineering*, 6(2):113–124, 1998.

[308] R. Riener, L. Lünenburger, and G. Colombo. Human-centered robotics applied to gait training and assessment. *Journal of Rehabilitation Research and Development*, 43(5):679–694, 2006.

[309] R. Riener, L. Lunenburger, S. Jezernik, M. Anderschitz, G. Colombo, and V. Dietz. Patient-cooperative strategies for robot-aided treadmill training: First experimental results. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 13(3):380–394, 2005.

[310] R. Riener, L. Lünenburger, I. C. Maier, G. Colombo, and V. Dietz. Locomotor training in subjects with sensori-motor deficits: An overview of the robotic gait orthosis Lokomat. *Journal of Healthcare Engineering*, 1(2):197–216, 2010.

[311] R. Riener and M. Munih. Guest editorial special section on rehabilitation via bio-cooperative control. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 18(4):337–338, 2010.

[312] G. Riva. Virtual reality in paraplegia: A VR-enhanced ortho-paedic appliance for walking and rehabilitation. *Stud Health Technol Inform*, 58:209–218, 1998.

[313] C. Robinson. Rehabilitation engineering, science and technology. In J. Bronzino, editor, *Biomedical Engineering Handbook*, pages 2045–2054. CRC Press, 1995.

[314] M. Rohafza, G. G. Fluet, Q. Qiu, and S. Adamovich, editors. Correlations between statistical models of robotically collected kinematics and clinical measures of upper extremity function. In *Engineering in Medicine and Biology Society (EMBC), 2012 Annual International Conference of the IEEE*. 2012.

[315] G. Rosati, P. Gallina, and S. Masiero. Design, implementation and clinical tests of a wire-based robot for neurorehabilitation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 15(4):560–569, 2007.

[316] J. Rosen, J. C. Perry, N. Manning, S. Burns, and B. Hannaford, editors. The human arm kinematics and dynamics during daily activities-toward a 7 DOF upper limb powered exoskeleton. In *Proceedings, International Conference on Advanced Robotics, 2005 ICAR'05*. 2005.

[317] A. Roy, H. I. Krebs, D. J. Williams, C. T. Bever, L. W. Forrester, and R. M. Macko, et al. Robot-aided neurorehabilitation: A novel robot for ankle rehabilitation. *IEEE Transactions on Robotics*, 25(3):569–582, 2009.

[318] R. J. Sanchez, J. Liu, S. Rao, P. Shah, R. Smith, and T. Rahman et al. Automating arm movement training following severe stroke: Functional exercises with quantitative feedback in a gravity-reduced environment. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 14(3):378–389, 2006.

[319] T. D. Sanger, M. R. Delgado, D. Gaebler-Spira, M. Hallett, and J. W. Mink. Classification and definition of disorders causing hypertonia in childhood. *Pediatrics*, 111(1):89–97, 2003.

[320] B. Scassellati, H. Admoni, and M. Mataric. Robots for use in autism research. *Annual Review of Biomedical Engineering*, 14:275–294, 2012.

[321] A. Schiele and F. C. van der Helm. Kinematic design to improve ergonomics in human machine interaction. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 14(4):456–469, 2006.

[322] R. E. Schleenbaker and A. G. Mainous. Electromyographic biofeedback for neuromuscular reeducation in the hemiplegic stroke patient: A meta-analysis. *Archives of Physical Medicine and Rehabilitation*, 74(12):1301–1304, 1993.

[323] H. Schmidt, S. Hesse, R. Bernhardt, and J. Krüger. HapticWalker — a novel haptic foot device. *ACM Transactions on Applied Perception (TAP)*, 2(2):166–180, 2005.

[324] I. Schwartz, A. Sajin, I. Fisher, M. Neeb, M. Shochina, and M. Katz-Leurer, et al. The effectiveness of locomotor therapy using robotic-assisted gait training in subacute stroke patients: A randomized controlled trial. *PM&R*, 1(6):516–523, 2009.

[325] A. Seireg and J. Grundmann. Design of a multitask exoskeletal walking device for paraplegics. *Biomechanics of Medical Devices*, pages 569–644, 1981.

[326] R. Shadmehr and F. A. Mussa-Ivaldi. Adaptive representation of dynamics during learning of a motor task. *The Journal of Neuroscience*, 14(5):3208–3224, 1994.

[327] B. Siciliano and O. Khatib. *Springer Handbook of Robotics*. Springer, 2008.

[328] C. Simons, E. van Asseldonk, J. Folkersma, J. van den Hoek, M. Postma, and J. Buurke. First clinical results with the new innovative robotic gait trainer LOPES, 2009.

[329] A. H. Stienen, E. E. Hekman, H. ter Braak, A. M. Aalsma, F. C. van der Helm, and H. van der Kooij. Design of a rotational hydroelastic actuator for a powered exoskeleton for upper limb rehabilitation. *IEEE Transactions on Biomedical Engineering*, 57(3):728–735, 2010.

[330] A. H. Stienen, E. E. Hekman, F. C. Van der Helm, G. B. Prange, M. J. Jannink, and A. M. Aalsma, et al., editors. Dampace: Dynamic force-coordination trainer for the upper extremities. In *IEEE International Conference on Rehabilitation Robotics, 2007 ICORR*. 2007.

[331] A. H. Stienen, E. E. Hekman, G. B. Prange Van der Helm FC, M. J. Jannink, and A. M. Aalsma, et al., editors. Freebal: Dedicated gravity compensation for the upper extremities. In *IEEE International Conference on Rehabilitation Robotics, 2007 ICORR*. 2007.

[332] S. A. Stockmeyer. An interpretation of the approach of rood to the treatment of neuromuscular dysfunction. *American Journal of Physical Medicine & Rehabilitation*, 46(1):900–956, 1967.

[333] K. A. Strausser and H. Kazerooni, editors. The development and testing of a human machine interface for a mobile medical exoskeleton. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2011.

[334] K. A. Strausser, T. A. Swift, A. B. Zoss, H. Kazerooni, and B. C. Bennett, editors. *Mobile Exoskeleton for Spinal Cord Injury: Development and Testing*. ASME, 2011.

[335] D. Surdilovic and R. Bernhardt, editors. STRING-MAN: A new wire robot for gait rehabilitation. In *IEEE International Conference on Robotics and Automation 2004 Proceedings ICRA'04*. IEEE, New-Orleans, 2004.

[336] S. Tanabe, E. Saitoh, S. Hirano, M. Katoh, T. Takemitsu, and A. Uno, et al. Design of the Wearable Power-Assist Locomotor (WPAL) for paraplegic gait reconstruction. *Disability and Rehabilitation: Assistive Technology*, 8(1):84–91, 2013.

[337] A. Tapus, C. Tapus, and M. J. Mataric. User—robot personality matching and assistive robot behavior adaptation for post-stroke rehabilitation therapy. *Intelligent Service Robotics*, 1(2):169–183, 2008.

[338] A. Tapus and A.-M. Vieru. Robot cognitive stimulation for the elderly. In *Natural and Artificial Models in Computation and Biology*, pages 94–102. Springer, 2013.

[339] E. Taub, G. Uswatte, and R. Pidikiti. Constraint-induced movement therapy: A new family of techniques with broad application to physical rehabilitation-a clinical review. *Journal of Rehabilitation Research and Development*, 36(3):237–251, 1999.

[340] R. W. Teasell, S. K. Bhogal, N. C. Foley, and M. R. Speechley. Gait retraining post stroke. *Topics in Stroke Rehabilitation*, 10(2):34–65, 2003.

[341] A. A. A. Timmermans, H. A. M. Seelen, R. D. Willmann, and H. Kingma. Technology-assisted training of arm-hand skills in stroke: Concepts on reacquisition of motor control and therapist guidelines for rehabilitation technology design. *Journal of NeuroEngineering and Rehabilitation*, 6(1), 2009.

[342] N. Tsagarakis, D. Caldwell, and G. Medrano-Cerda, editors. A 7 DOF pneumatic muscle actuator (pMA) powered exoskeleton. In *IEEE International Workshop on Robot and Human Interaction, 1999 RO-MAN'99*. 1999.

[343] K. Tsui, H. Yanco, D. Kontak, and L. Beliveau, editors. Development and evaluation of a flexible interface for a wheelchair mounted robotic arm. In *Proceedings of the ACM/IEEE International Conference on Human–Robot Interaction*. ACM, Amsterdam, 2008.

[344] A. Turner. *The Practice of Occupational Therapy: An Introduction to the Treatment of Physical Dysfunction*. Churchill Livingstone, 1987.

[345] T. E. Twitchell. The restoration of motor function following hemiplegia in man. *Brain*, 74(4):443–480, 1951.

[346] H. Vallery, A. Duschau-Wicke, and R. Riener, editors. Optimized passive dynamics improve transparency of haptic devices. In *IEEE International Conference on Robotics and Automation, 2009 ICRA'09*. 2009.

[347] H. Vallery and R. Riener, editors Duschau-Wicke A. Generalized elasticities improve patient-cooperative control of rehabilitation robots. In *IEEE International Conference on Rehabilitation Robotics, 2009 ICORR*. 2009.

[348] H. Vallery, O. Lutz, J. Von Zitzewitz, G. Rauter, M. Fritschi, and C. Everarts, et al. Multidirectional transparent support for overground gait training. In *IEEE International Conference on Rehabilitation Robotics (ICORR)*. Seattle, USA, 2013.

[349] A. J. van den Bogert. Exotendons for assistance of human locomotion. *Biomedical Engineering Online*, 2(1):17–24, 2003.

[350] R. Q. Van der Linde, P. Lammertse, E. Frederiksen, and B. Ruiter, editors. The HapticMaster, a new high-performance haptic interface. *Proc Eurohaptics*, 2002.

[351] H. Van der Loos, S. Michalowski, and L. Leifer, editors. Development of an omnidirectional mobile vocational assistant robot. In *Proceedings of International Conference of the Association for the Advancement of Rehabilitation Technology*. 1988.

[352] R. P. Van Peppen, G. Kwakkel, S. Wood-Dauphinee, H. J. Hendriks, P. J. Van der Wees, and J. Dekker. The impact of physical therapy on functional outcomes after stroke: What's the evidence? *Clinical Rehabilitation*, 18(8):833–862, 2004.

[353] J. F. Veneman, R. Ekkelenkamp, R. Kruidhof, F. C. van der Helm, and H. van der Kooij. A series elastic-and bowden-cable-based actuation system for use as torque actuator in exoskeleton-type robots. *The International Journal of Robotics Research*, 25(3):261–281, 2006.

[354] J. F. Veneman, R. Kruidhof, E. E. Hekman, R. Ekkelenkamp, E. H. Van Asseldonk, and H. van der Kooij. Design and evaluation of the lopes exoskeleton robot for interactive gait rehabilitation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 15(3):379–386, 2007.

[355] R. Vertechy, A. Frisoli, A. Dettori, M. Solazzi, and M. Bergamasco, editors. Development of a new exoskeleton for upper limb rehabilitation. In *IEEE International Conference on Rehabilitation Robotics, 2009 ICORR*. 2009.

[356] B. T. Volpe, M. Ferraro, H. I. Krebs, and N. Hogan. Robotics in the rehabilitation treatment of patients with stroke. *Current Atherosclerosis Reports*, 4(4):270–276, 2002.

[357] B. T. Volpe, H. I. Krebs, N. Hogan, L. Edelstein, C. Diels, and M. Aisen. A novel approach to stroke rehabilitation robot-aided sensorimotor stimulation. *Neurology*, 54(10):1938–1944, 2000.

[358] J. Von Zitzewitz, A. Morger, G. Rauter, L. Marchal-Crespo, F. Crivelli, and D. Wyss, et al. A reconfigurable, tendon-based haptic interface for research into human-environment interactions. *Robotica (ISSN: 0263-5747)*, 31:441–453, 2013.

[359] M. Vukobratovic, D. Hristic, and Z. Stojiljkovic. Development of active anthropomorphic exoskeletons. *Medical and Biological Engineering*, 12(1):66–80, 1974.

[360] C. J. Walsh, K. Endo, and H. Herr. A quasi-passive leg exoskeleton for load-carrying augmentation. *International Journal of Humanoid Robotics*, 4(3):487–506, 2007.

[361] C. J. Walsh, K. Pasch, and H. Herr, editors. An autonomous, under-actuated exoskeleton for load-carrying augmentation. In *International Conference on Intelligent Robots and Systems, 2006 IEEE/RSJ*. 2006.

[362] R. Waters, R. Adkins, J. Yakura, and I. Sie. Donal Munro lecture: Functional and neurologic recovery following acute SCI. *The Journal of Spinal Cord Medicine*, 21(3):195–199, 1998.

[363] M. Wehner, B. Quinlivan, P. M. Aubin, E. Martinez-Villalpando, M. Baumann, and L. Stirling, et al. A lightweight soft exosuit for gait assistance. In *IEEE International Conference on Robotics and Automation (ICRA)*. Karlsruhe, Germany, 2013.

[364] C. Werner, S. Von Frankenberg, T. Treig, M. Konrad, and S. Hesse. Treadmill training with partial body weight support and an electromechanical gait trainer for restoration of gait in subacute stroke patients a randomized crossover study. *Stroke*, 33(12):2895–2901, 2002.

[365] A. Wernig and S. Müller. Laufband locomotion with body weight support improved walking in persons with severe spinal cord injuries. *Spinal Cord*, 30(4):229–238, 1992.

[366] A. Wernig, A. Nanassy, and S. Müller. Laufband (treadmill) therapy in incomplete paraplegia and tetraplegia. *Journal of Neurotrauma*, 16(8):719–726, 1999.

[367] R. G. West. Powered gait orthosis and method of utilizing same. U.S Patent No. 6,689,075, 2004.

[368] K. P. Westlake and C. Patten. Pilot study of lokomat versus manual-assisted treadmill training for locomotor recovery post-stroke. *Journal of Neuroengineering and Rehabilitation*, 6:18, 2009.

[369] WHO. *International Classification of Functioning Disability and Health (ICF)*. 2001.

[370] WHO. *The World Health Report, 2003: Shaping the Future*. World Health Organization, 2003.

[371] P. Winchester, R. McColl, R. Querry, N. Foreman, J. Mosby, and K. Tansey, et al. Changes in supraspinal activation patterns following robotic locomotor therapy in motor-incomplete spinal cord injury. *Neurorehabilitation and Neural Repair*, 19(4):313–324, 2005.

[372] C. J. Winstein, P. S. Pohl, and R. Lewthwaite. Effects of physical guidance and knowledge of results on motor learning: Support for the guidance hypothesis. *Research Quarterly for Exercise and Sport*, 65(4):316–323, 1994.

[373] M. Wirz, D. H. Zemon, R. Rupp, A. Scheel, G. Colombo, and V. Dietz et al. Effectiveness of automated locomotor training in patients with chronic incomplete spinal cord injury: A multicenter trial. *Archives of Physical Medicine and Rehabilitation*, 86(4):672–680, 2005.

[374] E. T. Wolbrecht, V. Chan, D. J. Reinkensmeyer, and J. E. Bobrow. Optimizing compliant, model-based robotic assistance to promote neurorehabilitation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 16(3):286–297, 2008.

[375] E. T. Wolbrecht, D. J. Reinkensmeyer, and J. E. Bobrow. Pneumatic control of robots for rehabilitation. *The International Journal of Robotics Research*, 29(1):23–38, 2010.

[376] S. L. Wolf and S. A. Binder-Macleod. Electromyographic biofeedback applications to the hemiplegic patient changes in upper extremity neuromuscular and functional status. *Physical Therapy*, 63(9):1393–1403, 1983.

[377] S. L. Wolf, P. A. Catlin, M. Ellis, A. L. Archer, B. Morgan, and A. Piacentino. Assessing wolf motor function test as outcome measure for research in patients after stroke. *Stroke*, 32(7):1635–1639, 2001.

[378] S. L. Wolf, D. E. Lecraw, L. A. Barton, and B. B. Jann. Forced use of hemiplegic upper extremities to reverse the effect of learned nonuse among chronic stroke and head-injured patients. *Experimental Neurology*, 104(2):125–132, 1989.

[379] K. Yamamoto, K. Hyodo, M. Ishii, and T. Matsuo. Development of power assisting suit for assisting nurse labor. *JSME International Journal Series C*, 45(3):703–711, 2002.

[380] K. H. G. K. K. Yasuhara. Control system for walking assist device. EP Patent 1,547,567, 2009.

[381] N. Yu, C. Hollnagel, A. Blickenstorfer, S. S. Kollias, and R. Riener. Comparison of MRI-compatible mechatronic systems with hydrodynamic and pneumatic actuation. *IEEE/ASME Transactions on Mechatronics*, 13(3):268–277, 2008.

[382] J. Zariffa, N. Kapadia, J. L. Kramer, P. Taylor, M. Alizadeh-Meghrazi, and V. Zivanovic, et al. Relationship between clinical assessments of function and measurements from an upper-limb robotic rehabilitation device in cervical spinal cord injury. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 20(3):341–350, 2012.

[383] G. Zeilig, H. Weingarden, M. Zwecker, I. Dudkiewicz, A. Bloch, and A. Esquenazi. Safety and tolerance of the ReWalk^{TM} exoskeleton suit for ambulation by people with complete spinal cord injury: A pilot study. *The Journal of Spinal Cord Medicine*, 35(2):96–101, 2012.

[384] L.-Q. Zhang, H.-S. Park, and Y. Ren, editors. Developing an intelligent robotic arm for stroke rehabilitation. In *IEEE International Conference on Rehabilitation Robotics, 2007 ICORR 2007*. 2007.

[385] M. Zhang, B. Lange, C.-Y. Chang, A. A. Sawchuk, and A. A. Rizzo, editors. Beyond the standard clinical rating scales: Fine-grained assessment of post-stroke motor functionality using wearable inertial sensors. In *Engineering in Medicine and Biology Society (EMBC), Annual International Conference of the IEEE*. 2012.

[386] M. Zinn, B. Roth, O. Khatib, and J. K. Salisbury. A new actuation approach for human friendly robot design. *The International Journal of Robotics Research*, 23(4–5):379–398, 2004.

[387] A. Zoss, H. Kazerooni, and A. Chu, editors. On the mechanical design of the berkeley lower extremity exoskeleton (BLEEX). In *IEEE/RSJ International Conference on Intelligent Robots and Systems, 2005 (IROS 2005)*. 2005.