

Functional Electrical Stimulation in Neurorehabilitation

Synergy Effects of Technology
and Therapy

Thomas Schick
Editor

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Preface

Within the treatment of neurological diseases, neurorehabilitation is still a young special discipline. No other medical field aims for a need of such close cooperation between the disciplines and players. For this reason, this book addresses large parts of the neurological rehabilitation network.

Neurorehabilitation has changed significantly over the past 30 years as a result of a steady increase in knowledge in the areas of motor learning, neuroplasticity, and the efficacy of therapeutic procedures. Significant research activity, particularly in the last two decades, has challenged existing treatment approaches and introduced new ones. One of these modern therapeutic approaches, Functional Electrical Stimulation (FES), is presented comprehensively in this book with its many possible applications in a wide variety of diseases. These range from the treatment of sensorimotor disorders to forms of therapy in the neck area for improving swallowing and speech. Neurourological application areas are also discussed.

This book reveals therapeutic possibilities to the professional audience on how various neurological diseases can be treated in a target-oriented, evident way. The importance of FES is underlined by a steadily growing body of evidence.

This fascinating therapeutic progress has been made possible by global research activity in this field. The further development of medical technology for user-friendly electrical stimulation devices tailored to patient needs has also led to an improved range of products. The added value of this development can be seen particularly in individualizable and adaptable multichannel therapy devices for electrical stimulation which in many cases also enable patient-directed movement triggering.

In their contributions, the authors expressly refrain from naming and describing commercially available medical devices for functional electrical stimulation. Instead, they describe the therapeutic requirements for the patient and thus the requirements that are placed on the medical devices to be adequately used for the respective applications.

The aim of the book is to provide the reader with therapeutic instructions for treatment as well as relevant background information on the mode of action of FES. It is not intended to be another book on electrotherapy, but a first comprehensive standard work on FES and its great importance in the context of therapy in neurorehabilitation.

All authors contributing to this book are scientifically active and clinical experts in the field of neurorehabilitation, FES, or electromedical engineering.

We have deliberately focused on the treatment of structural, functional, and activity deficits in upper and lower motor neuron damage, improving mobility, sensitivity, and perception, as well as facial expression, swallowing, and oral function.

I hope this book contributes to many inspiring insights into FES with its wide range of applications in neurological patients.

Innsbruck, Austria

Thomas Schick

Acknowledgments

A book project of this kind requires many active supporters until it is successfully produced, who, in addition to the authors, have a significant influence on the success of the book. At this point, I would like to express my gratitude to these persons. In particular, I would like to thank all authors for their very carefully prepared and consistent high-quality contributions.

My appreciations and thanks go to Ms. Anja Fuchs, who has tirelessly contributed with great creativity and extraordinary skills to the successful design and implementation of the countless graphics, tables, photographs, and video sequences in all chapters as well as Ms. Andrea Weiler, (MA) and Ms. Mag. Ursula Lehner-Mayrhofer for their great commitment and many hours of translating and proofreading of various chapters.

I would also like to express my special thanks to Ms. Patricia Meier (MSc) and Ms. Maria Steinmetz (BA) for the intensive and very constructive discussions in the early and late phases of the preparation of the book concept and for proofreading my contributions.

We would like to thank our photo models Ms. Carla Greier, Ms. Franziska Lauerwald (BSc), Ms. Vera Sprenzinger (BSc), Ms. Sabrina Falgschlunger, Mr. Oliver Hinzmann, and Mr. Stefan Ossanna for their great commitment and patience as well as the therapy department of the private clinic “Sanatorium Kettenbrücke” in Innsbruck, Austria, where we created the visual content and especially their therapy director Mr. Manuel Krug. He supported us in a very cooperative and uncomplicated way by officially providing us with the therapy rooms and materials for the two photo shoots to create the countless photographs and video sequences.

Furthermore, I would like to thank the company MED-EL, department of Neurorehabilitation STIWELL in Innsbruck, for the electrical stimulation devices and the necessary accessories they provided. This support enabled the vivid and illustrative design of the whole project.

My thoughts also go to university professor DI Dr. med. Stefan Golaszewski who passed away unexpectedly while this book was in preparation. He was a passionate advocate of various forms of electrical stimulation. He made a very large contribution to the establishment of these forms of therapy through

his intensive research activities and as a dedicated physician. We will miss him and are pleased, however, that we are able to preserve and convey a part of his extensive knowledge and experience to the interested professional community through his exciting book contribution, supporting also his spirit.

Innsbruck
April 2022

Thomas Schick

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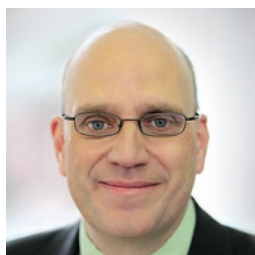
Thomas Schick, MSc gained extensive experience as a physiotherapist since 1993 and has led several rehabilitation teams at German clinics for neurorehabilitation. He also graduated as a specialist in social and health care. For more than 20 years, he has been a lecturer for various rehabilitation procedures in neurology. Among other things, he regularly teaches at the master's degree programs in neurorehabilitation and occupational therapy at the Center for Neurorehabilitation at the Danube University Krems, Austria. The main focus of his work is to convey and deepen the knowledge of FES and in particular EMG-triggered multichannel electrical stimulation. After completing his studies in neurorehabilitation with a master's degree in 2015, He joined Neurorehabilitation STIWELL, which is a department of the international company MED-EL, based in Innsbruck, Austria. Here, he is working on the development of medical products from a medical-therapeutic point of view, the implementation of training events and scientific work in the field of FES. He is member of the IFESS and published several articles in professional journals and a German-language therapeutic textbook about "Functional electrical stimulation in Neurorehabilitation" previously.



Ines Bersch-Porada, MSc, PhD is working at the Swiss Paraplegic Centre since 1991 and has been Head of the International FES Centre® since 2018. Her work is focusing on functional electrical stimulation (FES) and its implementation in the rehabilitation of people suffering from paraplegia and neuromusculoskeletal disorders.

Additionally, she teaches at the Universities of Applied Sciences in Bern and Basel. In 2012, the author obtained a Master of Science in

Neurorehabilitation Research and her PhD in Clinical Sciences at the University of Gothenburg. Her topic was focusing on upper and lower motoneuron lesions in tetraplegia—diagnostic and therapeutic implications of electrical stimulation. Apart from her clinical work, she gives lectures and organizes workshops. As a clinician, scientist, lecturer, and active member of the IFESS, she implements FES in clinical practice based on clinical study results and new technologies.



Christian Dohle, MD, MPhil is physicist, neurologist, and rehabilitation physician. Currently, he is leader of the P.A.N. Center for Post-Acute Neurorehabilitation and Head of research, both at the Fürst Donnersmarck Foundation in Berlin. Besides, he is teaching at different academic institutions, including the Charité—University Medicine Berlin and vice president of the German Society for Neurorehabilitation. His main scientific focus lies on evidence-based motor rehabilitation procedures, especially with visual stimulation (mirror therapy, virtual reality). Besides, he is working on determining factors of quality in neurorehabilitation.



Klemens Fheodoroff, MD specialist in neurology/psychiatry who achieved his diploma in Manual Medicine and Psychotherapeutic Medicine (ÖÄK). He is teaching the university course for medical managers in Graz. He is working as a senior physician in Neurorehabilitation at the Gailtal Klinik in Hermagor since 1994. Moreover, he is teaching at the Carinthia University of Applied Sciences and the Danube University Krems. Additionally, he is a member of the Scientific Advisory Board/Austrian Society for Neurological Rehabilitation (OeGNR) and the World Forum Neurorehabilitation (WFNR), especially in the special interest groups on MAC and robotics. He organized the Neurorehabilitation-Curriculum OeGNR between 2006 and 2018 and is a member of the BoNT Certification Committee of the Austrian Dystonia and Botulinum Toxin Working Group (ÖDBAG). Over 40 publications on spasticity and

BoNT, goals, ICF, and HRQoL were published including his expertise.



Stefan M. Golaszewski, MD was born in Vienna in 1964 and died unexpectedly at the end of 2020. He studied technical physics and medicine in Vienna. Between 1995 and 2001 he was working as a resident in neurology at the MR Institute of the University Hospital Innsbruck with a focus on scientific research in clinical applications for fMRI. He continued his residency in neurology from 2001 to 2002 at the Neurology Department at the Medical University of Graz and completed it between 2002 and 2004 at the Alfred Krupp Hospital in Essen and at the Department of Neurology, St. Mauritius Therapy Clinic near Düsseldorf. After that, he started working at the University Clinic of Neurology at the Paracelsus Medical University (PMU) Salzburg, where he habilitated in neurology in 2006.

From 2010, Prof. Golaszewski was medical director at the Neuroscience Institute of the PMU, where he was appointed associate university professor in 2019. Prof. Golaszewski has published a total of 150 articles in international peer-reviewed journals.



Kerstin Schwenker works in the field of Neurorehabilitation, Neuroscience, and Paraplegia Research (SCI-TReCS, Spinal Cord Injury and Tissue Regeneration Center Salzburg) at the Department of Neurology at the University Hospital Salzburg, at the Paracelsus Medical University Salzburg and at the Karl Landsteiner Institute for Neurorehabilitation and Space Neurology, Salzburg, Austria. At the Medical University of Graz, Austria, she completed the university course Clinical Trial Specialist with distinction. Until the sudden death of Dr. of medicine Stefan M. Golaszewski, university professor and engineer, in November 2020, she had been his assistant for many years. She is currently completing her extra-occupational master's degree in Study Management at the Medical University of Vienna, Austria, as well as studying human medicine at the Paracelsus

Medical University of Salzburg, Austria. In addition to her clinical and scientific work, she is also active in teaching and in the organization of congresses and workshops.



Winfried Mayr has worked at the Medical University in Vienna after he completed his studies in electrical engineering at the Vienna University of Technology in 1983. In 1992, he wrote his dissertation on “Reactivation of paralyzed muscles by FES with implants.” Subsequently, he worked on noninvasive FES applications in paraplegic rehabilitation, in space and for the elderly. He coordinated the EU project RISE with 20 partner groups, which resulted in a novel clinical method including a market-ready stimulator for denervated muscles. His current focus is on spinal cord stimulation after injury. Between 2009 and 2017, he was president of the Austrian Society for Biomedical Engineering (ÖGBMT), since then vice president and board member of the European umbrella organization EAMBES (European Alliance for Medical and Biological Engineering and Science). He is one of the founders and board member of the International FES Society (IFESS) and a section editor for FES at the Journals Artificial Organs and Frontiers in Neuroscience.



Patricia Meier, MSc, PhD student graduated as a physiotherapist in 2010 from the University of Applied Sciences for Health, Innsbruck, Austria. She continued her further qualification at the Danube University Krems, where she finished her master’s degree in neurorehabilitation with distinction in 2018. Since 2019, she is studying part-time in the PhD program for neuroscience at the Medical University of Innsbruck. She is working at the Medical University of Innsbruck, Department of Neurology, since 2011 and as a research associate (MED-EL Medical Electronics, VASCage GmbH) since 2018, focusing intensively on motor learning and rehabilitation processes and their effects on cortical reorganization. Moreover, she has been a lecturer in the field of neurorehabilitation for several years at the University of Applied Sciences for Health, Innsbruck. Within her professional career,

she has been involved in the planning and implementation of several studies and the development of guidelines (treatment pathway stroke). Apart from that she has given lectures at international congresses.



Michaela M. Pinter, MD, MAS is Full Professor for Neurorehabilitation Research at Danube University Krems, Austria, and Head of the Department of Clinical Neurosciences and Preventive Medicine as well as Head of the Center for Neurorehabilitation.

Her scientific focus is on neuromodulation as well as on restoration of neuronal functions. She actively conducts clinical studies on the modification of muscle tone and restoration of motor functions.



Carsten Kroker is a television technician and became a speech therapist in 1999. He is currently Head of Speech Therapy at the Clinic Saarbrücken (neurological acute clinic incl. stroke unit) and has his own practice in Saarbrücken, Germany. He has published various articles in professional journals and two monographs (including Aphasie—Schnell Test). He is a lecturer at several institutions, including the “interkantonale Hochschule für Heilpädagogik” (HfH) in Zürich, Switzerland. Since 2004, he has dedicated himself to electrical therapy and was co-developer of the FES treatment program for dysarthria “Dys-SAAR-thrie Therapie.”



Jan Faust, B of Health graduated in 2011 with a degree in Speech and Language Therapy (Logopedics) from HAN University of Applied Sciences in Nijmegen, the Netherlands. Since then, he has practiced as a speech therapist with a clinical focus on neurorehabilitation and holds certifications on fiberoptic endoscopic evaluation of swallowing (FEES). Since 2016, he has been practicing at Helios Hospital Krefeld, Germany, which has the status of Academic Hospital of RWTH Aachen University. The author lectures on FES in speech, voice, and swallowing disorders for health care professionals through various educating and

training institutes. Since 2020, he has been studying the MSc program in Teaching and Research Logopedics at RWTH Aachen University.



Christina A. Repitsch, BSc, MSc graduated from the Carinthia University of Applied Sciences, Austria, in 2012 with a bachelor's degree in speech therapy. Since then, she has worked as a speech therapist at the Department of Speech Therapy at the Hospital Klagenfurt as well as in independent practice. Between 2015 and 2018, she studied at the Danube University Krems and completed the course "Neurorehabilitation." She specialized her work in the treatment of facial paresis. In 2016, she founded the Facial Outpatient Clinic in cooperation with the Department of Plastic, Aesthetic and Reconstructive Surgery at the Klagenfurt Hospital. Here, the focus is on the therapeutic treatment of pre- or postoperative patients with facial nerve paresis. FES is also part of this therapeutic treatment concept. Furthermore, the author is hosting seminars on rehabilitation of facial paresis for therapists.



Berit Schneider-Stickler is otolaryngologist, phoniatician, and singer. She is Deputy Head of the Division of Phoniatics-Logopedics of the Medical University Vienna.

Her clinical focus and her research interests have been focused on voice diagnostics and voice therapy for more than two decades. She is particularly interested in neurological voice disorders like vocal fold paralysis, spasmodic dysphonia, and voice tremor. Her activities significantly contribute to the establishment of neurolaryngology in Austria.

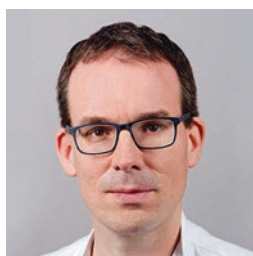
She is co-founder of the working group "Austrian Neurolaryngology" of the Austrian Society for Ear, Nose and Throat Disorders.

She is author and coauthor of many scientific papers and co-editor of two textbooks.

Since 2014, Berit Schneider-Stickler is president of the Austrian Society of Logopedics, Phoniatics, and Pedaudiology.



Birgit Tevnan, MSc is working as an occupational therapist since 2012. She studied at the University of Applied Sciences for Health Professions in Upper Austria and is working at the Neuromed Campus, Linz, in the Department of Neurological Acute Aftercare since 2013. In 2017, she achieved her master's degree at the University of Applied Sciences Vienna for Health Assisting Engineering. Her research was focusing on the review and evaluation of user-friendliness of FES medical devices in home therapy. Since 2018, the author has additionally been working as a freelancer, specializing in neurological follow-up of patients after stroke in the home-setting. In 2019, she joined the start-up Rewellio as a part-time clinical expert for the development of a therapy app for the neurological follow-up of patients with neurological disorders after stroke.



Gerd F. Volk, MD is working as a physician in the Department of Otorhinolaryngology at the Jena University Hospital since 2006. Since 2012, he is Head of the interdisciplinary Facial Nerve Center Jena, Germany, a cooperation of the departments of psychology, neurology, physiotherapy, radiology, and ENT. In addition to the interdisciplinarity, the special feature is a two-week biofeedback training for patients with peripheral facial nerve palsy with defect healing. In addition to surface EMG, constrained induced movement techniques known from “deaf training” are used for biofeedback. Already during his medical studies in Münster, Volk was working in the research group of Solon Thanos, specializing on quantification and improvement of nerve regeneration. His clinical interests are electrophysiological and imaging techniques for the assessment and visualization of the muscles and nerves of the face and larynx, the application of botulinum toxin in the head and neck region, and the functional diagnosis and therapy of peripheral nerve lesions. His scientific focus is on the development of new methods for reconstruction and rehabilitation of facial and laryngeal nerve lesions, electrical stimulation as a diagnostic and therapeutic tool, central nervous changes after cranial nerve lesions, especially of the facial and vestibular nerves, and mechanisms for their compensation.



Jürgen Pannek, MD born in Essen, Germany in 1963, studied human medicine at the Ruhr-University in Bochum, Germany from 1982 to 1988. He completed his training as a urologist at the university hospitals of Bochum and Essen. A research stay at the Johns Hopkins Hospital in Baltimore, USA, from 1996 to 1997 led to his habilitation at the Ruhr-University Bochum, Germany in 1999, where he received the extraordinary professorship for urology in 2005. From 2003 to 2007 he was Head of the Neuro-urology Department at the University of Bochum, Germany. Since 2007, he has been Head of the Neuro-urology Department at the Swiss Paraplegic Centre in Nottwil, Switzerland; therefore, in 2011 he was rehabilitated and appointed titular professor at the University of Bern, Switzerland.

In addition to additional urological qualifications (focus titles for special urological surgery, neuro-urology, and urology of women), he completed the training to become a “Certified Health Care Manager” and acquired the certificate of competence in classical homeopathy.



Jens Wöllner, MD, EMBA is Senior physician in the Department of Neuro-urology in Swiss Paraplegic Centre, Nottwil, Switzerland since 2013. In 2020, he gets his “Venia legend” at the medical school of the University of Mainz in Germany and a master’s degree in Master of Business Administration in Medical Management (EMBA), PHW Bern, Switzerland. He is medical doctor (MD) since 2008 and specialist in urology since 2009. The primary education ended in 2003 at medical school university of Mainz, Germany.



Anja Fuchs graduated in graphic and communication design from the HTL 1—Construction and Arts in Linz, Austria and now working as a multimedia designer in Innsbruck, Austria. In close cooperation with the authors and the editor, she created the photo and video content including the selection and edit of these extensive recordings. Her professional and descriptive graphic preparation of the figures and tables resulted in a uniform and clear design that runs through the entire book. She was also the responsible graphic designer for the German edition of *Functional electrical stimulation in neurorehabilitation* in the publication year 2020.

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Introduction and History of Functional Electrical Stimulation

1

Thomas Schick

Persons interested in neurorehabilitation are confronted with a wealth of technical information and scientific findings. Filtering out the most important and current information for one's own professional field from this wide range of information would require regular study of scientific literature. Also, the decision for the appropriate therapy method – depending on the problem constellation of the patient – such as functional electrical stimulation (FES), can be a challenge. This book is intended to provide valuable assistance for searching specific and therapy-relevant approaches. This makes it easier to achieve the goal of patient-centered, high-quality therapy. The main focus of this book is FES and its wide range of applications in neurological patients with various symptoms. The special nature of modern FES with its importance in the context of motor learning and its strongly task-oriented approach compared to classic methods is discussed intensively. It is not uncommon for initial difficulties to arise in the search for current literature due to the internationally very variable use of FES terms. In this chapter, the reader gets a basic overview of the numerous technical terms and their meaning.

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1.1 Introduction and Explanation of Terms

It is intended to provide a useful classification of the inconsistent terminology and reflects the opinion of the author. The most frequently used terms are described. Fig. 1.1 illustrates the terms and their predominant use for the therapeutic field in the context of electrical stimulation (ES).

Figure 1.1 is based on extensive literature research and experience of the most common usage and does not claim to represent the language choice of all actors in electrical stimulation in a universally valid way. This list is to be understood as a contribution to the improved comparability of studies and clinical applications. The classification and division of the forms of therapy is based on the structure and function level as well as the activity level of the ICF (International Classification of Functioning, Disability and Health).

In this book, the authors use the umbrella term *FES*. This was coined by the scientists Moe and Post in 1962 [1]. The older term *Functional Electrotherapy (FET)* [2] has not gained acceptance among experts (Fig. 1.2) and is now used only occasionally [3]. The term FES is probably the most commonly used term in literature [4]. Electrical stimulation is called functional if the contractions triggered by the stimulation are coordinated in a way that they compensate for a restricted or absent support function.

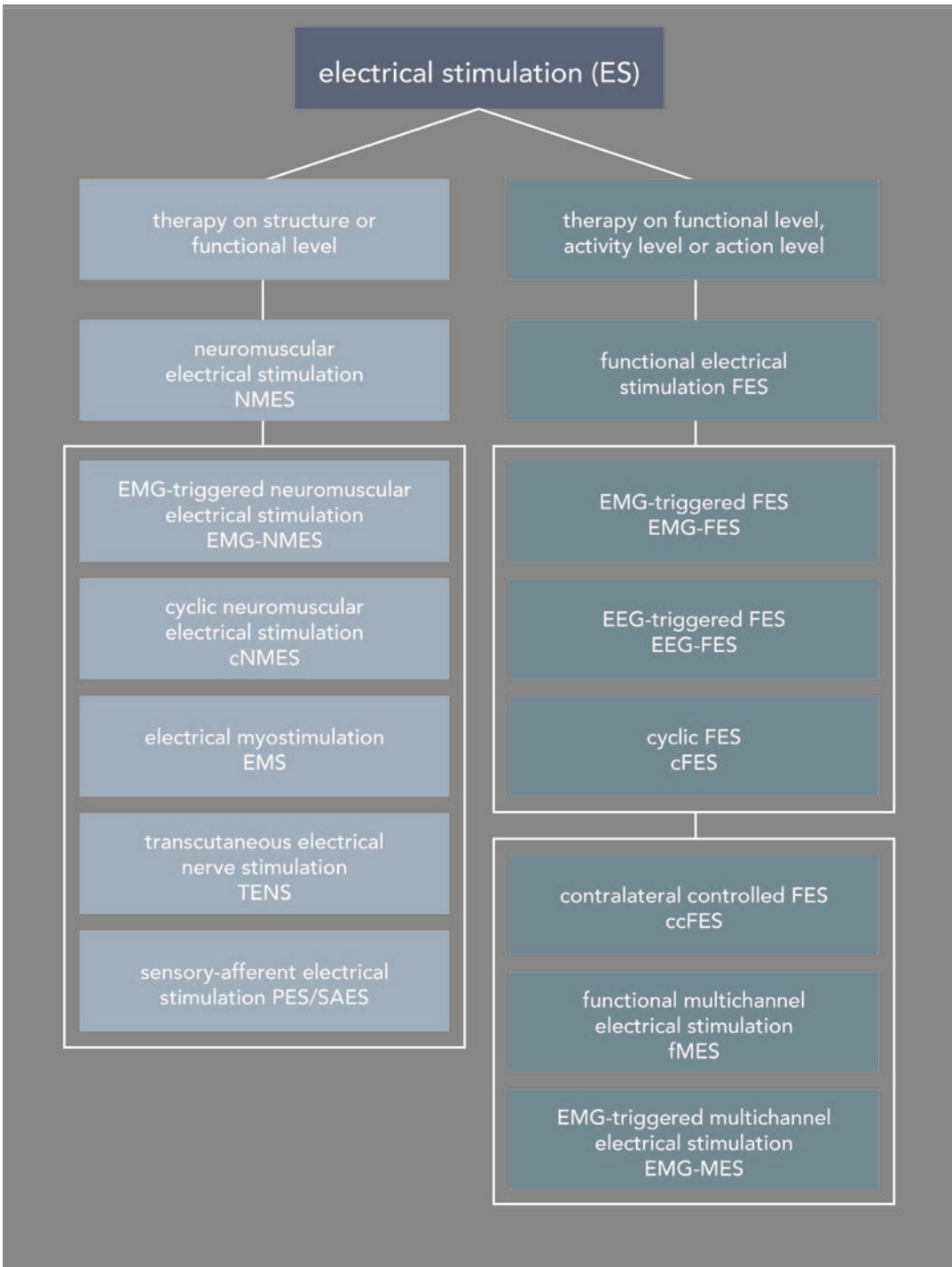


Fig. 1.1 Comparison of functional electrical stimulation (FES) and neuromuscular electrical stimulation (NMES) and their further development

Thus, FES in the proper sense does not denote muscle stimulation that triggers contractions of muscle groups or a single muscle by means of an

electrical stimulus [5]. According to another logical definition, the FES is an electrical stimulation during the execution of a voluntary movement.

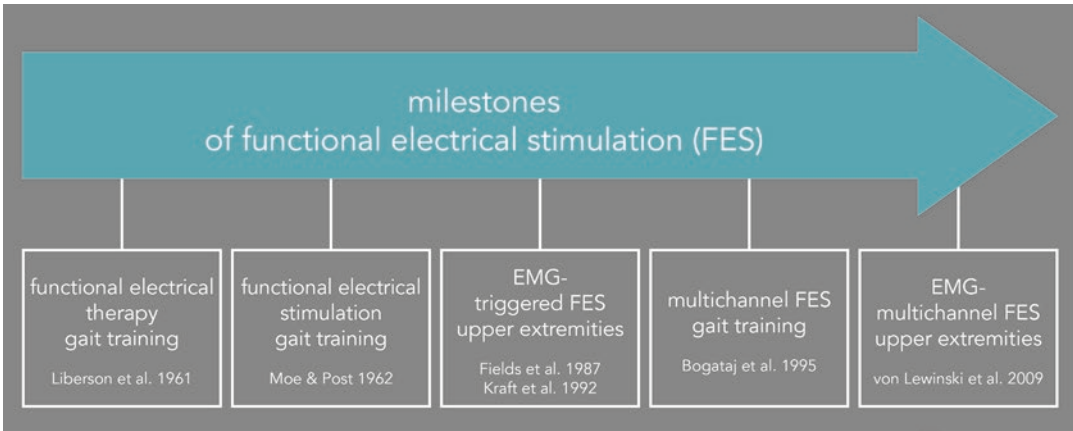


Fig. 1.2 Milestones in functional electrical stimulation

This means that every time a person wants to perform a movement, he or she receives electrical assistance from the electrical stimulation device [3]. This distinguishes FES from passive neuromuscular electrical stimulation (NMES), which is not designed for active, functional, or task-oriented patient cooperation. Some authors consider FES a sub-area of NMES [6]. The author of the contribution does not agree with this classification. NMES has a rather passive treatment approach which focuses mainly on structural and functional deficits. It is used for atrophy prophylaxis, muscle strengthening, toning or detonation of muscles, for certain forms of spasm treatment, to promote blood circulation, or to improve sensory perception. This represents a significant difference from the above-mentioned definitions.

If the stimulations are given by an electrical stimulation device at defined, temporally repeating intervals, this is referred to as cyclic neuromuscular electrical stimulation (cNMES).

Early work further specifies FES as Electromyography (EMG)-triggered FES (EMG-FES), in which impulses are triggered when a certain threshold is reached according to EMG measurement [7, 8]. EMG-triggered stimulations are mostly described in the literature as EMG-triggered neuromuscular electrical stimulation (EMG-NMES) [9]. The emphasis of the therapy with EMG-NMES is based on a cyclic movement electrically supported by the stimulation device, which is actively initiated by the patient. The conscious initiation of movement

and muscular activity of a stroke patient is the main focus of EMG-NMES. EMG-triggered stimulation devices with only one stimulation channel are usually used in these cases [10]. This form of therapy focuses on the repetitive aspect similar to cyclic stimulation. This distinguishes the EMG-NMES from EMG-triggered multichannel electrical stimulation (EMG-MES; see below), in which a task-oriented, active therapy approach is explicitly required. Switch-triggered neuromuscular electrical stimulation (sNMES) [11] is another option. This technique is used to assist stroke patients or paraplegic patients while walking, again mainly using the term FES [3]. Transcutaneous electrical nerve stimulation (TENS) is used not only in pain treatment, but also in electrical myostimulation (EMS), for example in postoperative functional paresis, in sports, but also occasionally in stroke therapy [9]. In the case of TENS, which is also designed to be passive, the minimization of muscle atrophy rather than functionality is usually the first priority apart from pain treatment. Muscle contractions in this case are amplitude-dependent, since one cannot only stimulate in the sensory-threshold area but in the motor-threshold area via neuromuscular excitation at the motor end plate [12].

Also, the term EMS is misleading since the muscle itself is not directly stimulated, but always the upstream nerve based on the corresponding stimulation parameters. Only a few studies on muscle stimulation after nerve damage in animal