1 Introduction and History of Functional Electrical Stimulation

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.

T. Schick (✉)
MED-EL, Department Neurorehabilitation
STIWELL, Innsbruck, Austria
e-mail: schick@neuro-reha.info

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.

T. Schick (ed.), *Functional Electrical Stimulation in Neurorehabilitation*,
https://doi.org/10.1007/978-3-030-90123-3_1

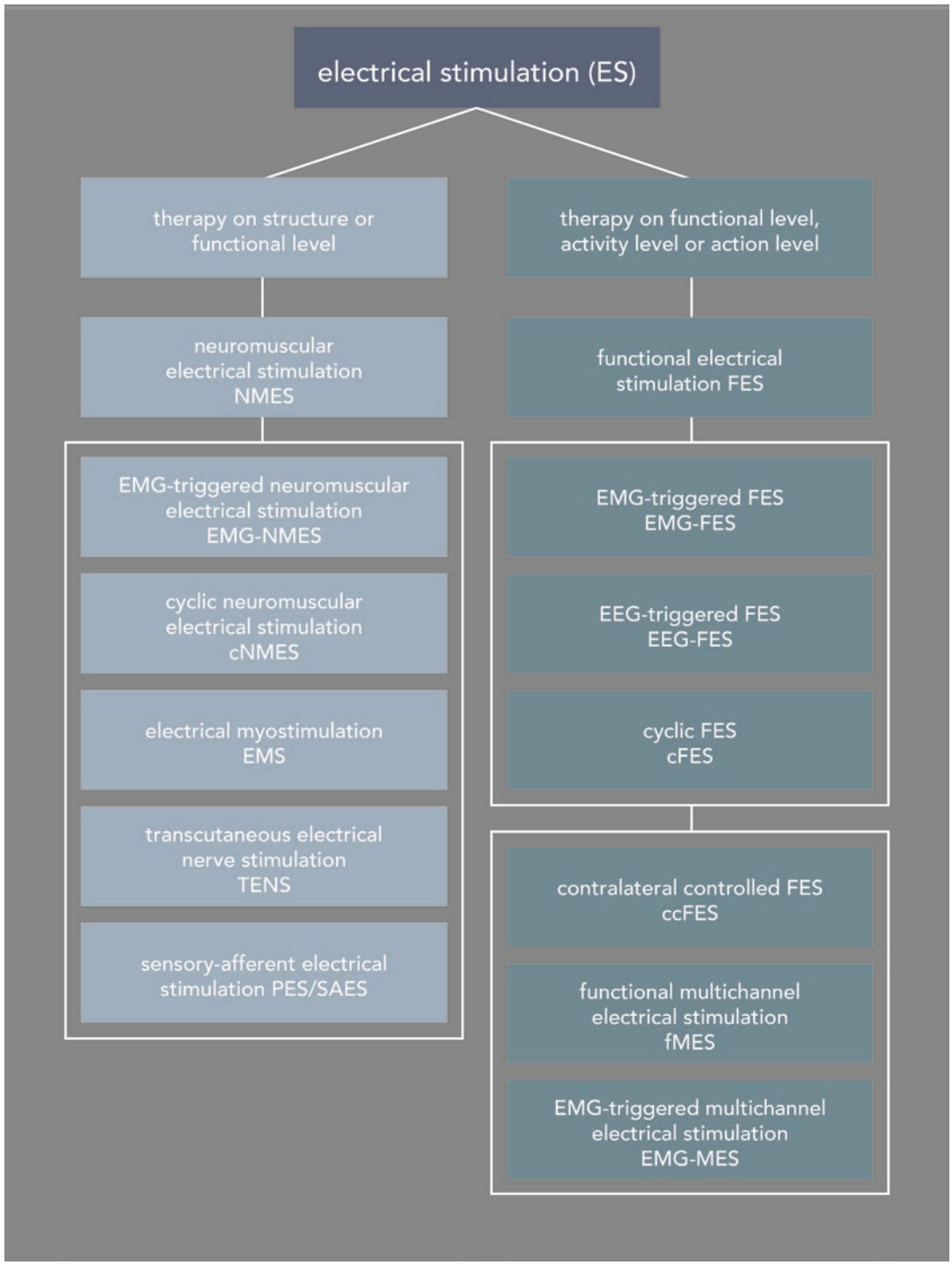

Fig. 1.1 Comparison of functional electrical stimulation (FES) and neuromuscular electrical stimulation (NMES) and their further development

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.

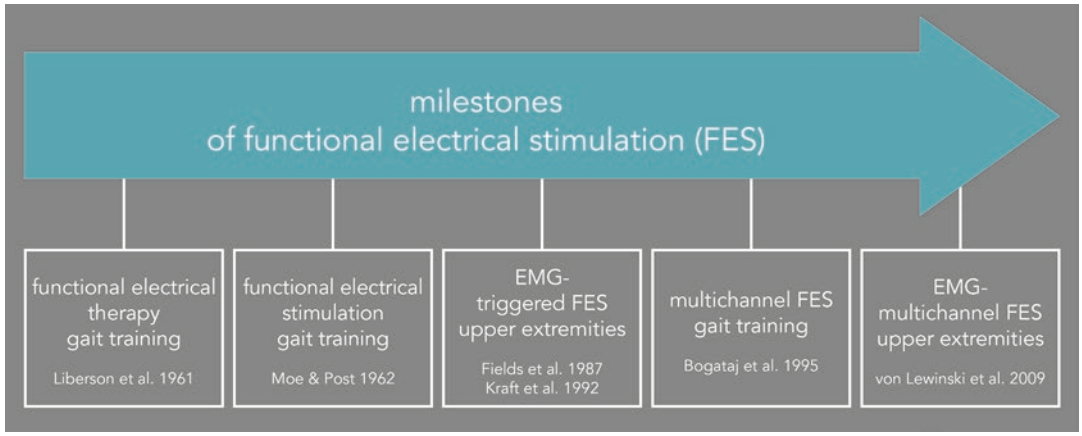

Fig. 1.2 Milestones in functional electrical stimulation

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

experiments use EMS in the study description [13]. In sports therapy, EMS is used for additional non-specific recruitment of muscles under forced activity. However, this approach significantly differs from the functional approaches required and used in neurorehabilitation.

In neurorehabilitation, peripheral or sensory-afferent electrical stimulation PES/SAES has developed further in recent years as a subform of TENS, which is characterized by the stimulation of sensitive nerve fibers aiming for a change in sensorimotor functions [14]. Both TENS and PES/SAES, as well as EMS, can be considered subsets of NMES. However, SAES can also be actively used in therapy in a task-oriented manner and with the aim of improving functionality, and can thus be assigned to FES (Chap. 9).

In electrical stimulation of denervated muscles in lower motor neuron syndrome (LMNS), FES has been established to support reinnervation even in partial denervation. Electrical stimulation is performed directly on the denervated muscle since stimulation via upstream nerves is no longer possible. Here, the term EMS would actually make sense in the early phase, but this does not correspond to the common use and indication of EMS. Also, EMS stimulation devices are not regularly designed for the treatment of denervated muscles due to their technical equipment.

Examples of the treatment of neurological patients with LMNS are described in detail below (Chap. 8). The therapeutic treatment approach of the FES considerably differs from the forms of stimulation used for damage to the first motor neuron or upper motor neuron syndrome (UMNS) in the selection of the necessary current parameters, e.g., pulse widths, frequencies, and current shapes. This treatment approach also focuses on the therapeutic goal of improving functionality and requires the active cooperation of the patient according to his possibilities, and thus justifies the name FES.

A clinically relevant form of FES in the context of motor learning in patients with UMN impairment is patient-initiated FES or EMG-FES. However, many available electrical stimulation devices have only one stimulation channel, which considerably reduces the possibilities for functional and action-oriented therapy.

For modern products with four or more stimulation channels, another specification for multichannel FES (MFES) for the treatment of UMNS is EMG-triggered multichannel electrical stimulation (EMG-MES) [15–17]. The special possibilities of using this modern method are described in detail and illustrated with practical examples in Chap. 6.

As could be seen in the previous section, it is usually difficult to identify a uniform term for electrical stimulation. The following example will illustrate this. The American Stroke Association (ASA) guideline on post-stroke care [18] recommends, among other things, the use of NMES in stroke patients with minimal functions and shoulder subluxations. According to the authors, these recommendations are based on several randomized control trials (RCTs) primarily on FES in stroke patients [19, 20]. Also, there is no uniform use of terms. This shows the urgent need to agree on international uniform definitions of the different forms of stimulation.

To simplify and improve clarity and for reasons of plausibility, the authors of this book predominantly use the designations FES, EMG-triggered electrical stimulation (EMG-ES), and EMG-triggered multichannel electrical stimulation (EMG-MES). The reason for this is mainly the emphasis on the manifold possibilities especially of EMG-MES in the context of task-oriented practice and the expected positive effects on plastic changes and synaptic reorganization in the context of motor learning.

The classical electrotherapy procedures are not described in this book, as the activity-enhancing FES therapies are preferred in neurorehabilitation.

Summary

Electrical stimulation is said to be functional if the contractions triggered by the stimulation are coordinated in a way that they support a restricted or absent function.

1.2 History of Functional Electrical Stimulation

It was a long way of acquiring knowledge and experience in the field of electrical engineering as well as human physiology and pathophysiology until the FES emerged in its differentiated form as it is available to the user in neurorehabilitation today. Records of the use of electrical shocks by citterrays or electric eels date back to the 4th millennium BC [21]. In antiquity, the Greek natural philosopher Thales first described the electrostatic charging of amber (Gr.: ἤλεκτρον/Electron), which still shapes the name of electrical therapy today [22].

Targeted attempts at electrical stimulation in humans only became public with the discovery and invention of the "Leiden bottle" by von Kleist in 1745. A kind capacitor enabled the application of electricity [23]. Early written documentation of experiments and hypotheses of effects on humans can be found in the book of the French mathematician and philosopher Louis Jallabert who, as an experimental physicist in Geneva in the middle of the eighteenth century, described the first observations of the effects of electricity on humans [24]. In the same book, interesting experimental observations in stroke patients are described by Professor de Sauvages from Montpellier in the form of a missive to his colleague Doctor Bruhier. Therein, he reports on systematic, daily electrical stimulation of patients who, following the treatment series, regained functions of the hand and arm and improved their walking and stair climbing.

In 1770, the German Johann Friedrich Hartmann published an extensive work with a detailed set of rules for electrical stimulation in various diseases. One of his focal points was the treatment of neurological patients with paralysis using electricity [25]. Only 6 years later, the German physician Gottlieb Schäffer published a book on the effects of electricity on paralyzed limbs [26]. The next milestone was set by the Italian anatomist Luigi Galvani who became the founder of electrophysiology. In 1780, he randomly discovered the simultaneous twitching of a prepared frog's leg while a spark was being passed through a nearby "electrifying machine." Galvani suspected electrical energy directly in the muscle. These observations and countless follow-up experiments with various electrical conductors as well as comprehensive records were the basis for the Italian physicist Alessandro Volta to develop his own energy source in the form of a battery at the beginning of the nineteenth century. He was the founder of the theory of electricity [27].

In the same century, the French physiologist and neurologist Guillaume-Benjamin Duchenne developed muscle stimulation; he is still considered the father of electrotherapy. Among other things, he made numerous experiments on the stimulation of facial muscles [28]. During this time, the neurologist Robert Remark from Berlin described the first specific paralysis treatments of the hand where he defined the muscle stimulation points [12].

In 1831, Michael Faraday developed the electromagnetic machine, a precursor of today's electrical therapy devices which generated alternating current by means of a rotating metal coil. The term "faradic current" has evolved at this time [29]. Since that time, the application of current in the body was also used for diagnostics. It was clinically observed that paralyzed musculature reacts only to galvanic (direct current), but not to faradic current (alternating current).

The French neuroscientist Louis Lapicque shaped the beginning of the twentieth century with the term *rheobase* as a measure of the membrane potential. Thus, the excitation threshold could be determined. The rheobase describes the current intensity at which excitation was just achieved for an infinitely long stimulus time [30]. Another parameter was the Determination of the *chronaxy* which is the shortest current flow duration for tissue excitation at double rheobase. The determined parameters were now also used for the diagnostic assessment of nerve damage. Adrian [31] produced the first curves for the assessment of healthy and damaged human muscles.

From the 1950s, portable, battery-powered electrical stimulation devices were available. The invention of the transistor in 1948 enabled the

development of such portable electrical stimulation devices. A few years later, Vladimir Liberson emphasized on the term "electrical stimulation" for the first time.

Functional electro-therapy (FET) for percussive patients with foot dorsiflexion weakness is a current-assisted functional alternative to conventional orthoses. He documented improved functional outcomes after electrical stimulation [2]. A short time later, the term was changed to *Functional Electrical Stimulation (FES)* [1] which has endured to this day. Despite encouraging reports over more than two and a half centuries, functional electrical stimulation (FES) did not become established in the rehabilitation of neurological patients until the twenty-first century. Until the turn of the millennium, it was still rarely used in patients with central paralysis, although significant studies on EMG-triggered FES in stroke patients [7, 8] and first papers on multichannel electrical stimulation to improve walking [32] had already been published in the 1980s and 1990s. Vogedes wrote in the Year 2000 "...still the treatment of central paralysis with electrical therapy is rarely performed in Germany. For many physicians and therapists, the treatment of central paralysis is still an absolute contraindication for the entire spectrum of electrical therapy" [33]. However, the same author referred to new therapeutic possibilities of EMG-triggered electrical stimulation. In 2004, Wenk writes justifying *"…the treatment of central paresis is still met with skepticism today. (...) Critics must be told in no uncertain terms that this electrical therapeutic method is only ever used in combination with recognized methods such as Bobath, Vojta or PNF. Electrical therapy can only provide a positive basis in the sense of inhibition and facilitation primarily at the spinal cord level"* [34].

This aforementioned skepticism and criticism are now outdated and overcome. Chapter 3 provides modern approaches to clarify the actual mode of FES. Bossert writes in 2014 about EMG-ES: "*...even in central paresis, the 1st motor neuron should be activated and thus movement reinitiated*" [12]. Fortunately, FES is becoming increasingly established in neurorehabilitation, due to an increase in research activities in the field of FES, but also in motor learning [35], and neuroplasticity [36] (Chap. 2). This process has been supported by the development of modern electrical stimulation devices, which no longer control impulse triggering in a purely device-driven manner, but in a patient-initiated manner, e.g., by EMG or sensor triggering.

In recent years, technological progress has provided additional impetus: User-friendly modern electrical stimulation devices with more than one stimulation channel have been developed, described, and investigated [15, 16, 32, 37, 38]. These can be used to target stimulation not only of individual muscle groups but also of entire movement sequences in patients with UMNS [4].

Functional, activity-enhancing and action-oriented electrical stimulation has thus arrived in modern neurorehabilitation and is becoming increasingly established. The many therapeutic options of FES for increasing the function and activity of a neurological patient are summarized in detail in this book. Well-founded, up-to-date knowledge from science and extensive clinical empiricism are intended to provide users, as well as criticists, with an understanding of the current data situation and the rehabilitative application possibilities. Fig. 1.2 shows the significant publications from the early FET and FES in single-channel application to the first FES with EMG triggering, MFES, and later of EMG-MES in stroke patients.

Summary

The term FES was first mentioned in the literature in 1962 and is still predominantly used today.

References

1. Moe J, Post H. Functional electrical stimulation for ambulation in hemiplegia. J Lancet. 1962;82:285–8.
2. Liberson W, Holmquest H, Scot D, Dow M. Functional electrotherapy: stimulation of the peroneal nerve synchronized with the swing phase of the gait of hemiplegic patients. Arch Phys Med Rehabil. 1961; 42:101–5.

3. Popovic M, Masani K, Micera S. Neurorehabilitation technology, 2. Aufl. Springer Science, s.l.; 2016
4. Doucet B, Lam A, Griffin L. Neuromuscular electrical stimulation for skeletal muscle function. Yale J Biol Med. 2012;85:201–15.
5. van Kerkhof P. Das Elektrotherapieskript. Muskelstimulation wwwPhysiosupportorg 12 October; 2013:S1–260.
6. Eraifej J, et al. Effectiveness of upper limb functional electrical stimulation after stroke for the improvement of activities of daily living and motor function: a systematic review and meta-analysis. Syst Rev. 2017;6(1):40.
7. Fields R, et al. Electromyographically triggered electric muscle stimulation for chronic hemiplegia. Arch Phys Med Rehabil. 1987;68:407–14.
8. Kraft G, Fitts S, Hammond M. Techniques to improve function of the arm and hand in chronic hemiplegia. Arch Phys Med Rehabil. 1992;73(3): 220–7.
9. Iruthayarajah J, et al. Evidence-based review of stroke rehabilitation. London: Evidence-Based Review of Stroke Rehabilitation; 2018.
10. Monte-Silva K, et al. Electromyogram-related neuromuscular electrical stimulation for restoring wrist and hand movement in poststroke hemiplegia: a systematic review and meta-analysis. Neurorehabil Neural Repair. 2019;33(2):96–111.
11. Coscia M, et al. Neurotechnology-aided interventions for upper limb motor rehabilitation in severe chronic stroke. Brain. 2019;142:2182–97.
12. Bossert F-P, Vogedes K. Elektrotherapie, Licht- und Strahlentherapie, 3. Aufl: Elsevier GmbH, Urban & Fischer, München; 2014.
13. Willand M, et al. Electrical muscle stimulation elevates intramuscular BDNF and GDNF mRNA following peripheral nerve injury and repair in rats. Neuroscience. 2016;15(334):93–104.
14. Golaszewski S, Frey V. Neuromodulation in der Neurorehabilitation nach Schlaganfall. Jatros Neurol Psychiartrie. 2019;3:12–8.
15. von Lewinski F, et al. Efficacy of EMG-triggered electrical arm stimulation in chronic hemiparetic stroke patients. Restor Neurol Neurosci. 2009;27(3): 189–97.
16. Kapadia N, et al. Functional electrical stimulation therapy for grasping in traumatic incomplete spinal cord injury: randomized control trial. Artif Organs. 2011;35:212–6.
17. Schick T, et al. Synergy effects of combined multichannel EMG-triggered electrical stimulation and mirror therapy in subacute stroke patients with severe or very severe arm/hand paresis. Restor Neurol Neurosci. 2017;35(3):319–32.
18. Winstein C, et al. Guidelines for adult stroke rehabilitation and recovery: a guideline for healthcare professionals from the American Heart Association/American Stroke Association. Stroke. 2016;47(6):e98–e169.
19. Alon G, Levitt A, McCarthy P. Functional electrical stimulation (FES) may modify the poor prognosis of stroke survivors with severe motor loss of the upper extremity: a preliminary study. Am J Phys Med Rehabil. 2008;87(8):627–36.
20. Hara Y, Ogawa S, Tsujiuchi K, Muraoka Y. A home-based rehabilitation program for the hemiplegic upper extremity by power-assisted functional electrical stimulation. Disabil Rehabil. 2008;30(4):296–304.
21. Moller P. Review: electric fish. Bioscience. 1991;41(11):794–6.
22. Hackmann W. Electrostatic machine. In: Bud R, editor. An historical encyclopedia. Instruments of science. New York: Garland; 1998. p. S221–4.
23. Lommel E. Ewald Georg von Kleist, Allgemeine Deutsche Biographie. Allgemeine Deutsche Biographie. 1882;16:112–3.
24. Jallabert L. Experimenta electrica usibus medicis applicata. J. R. im Hof, 312 S. Pappband der Zeit, Basel; 1750
25. Hartmann JF. Die angewandte Elektrizität bei Krankheiten des menschlichen Körpers. s.n., Hannover; 1770
26. Schäffer JG. Die Elektrische Medicin oder die Kraft und Wirkung der Elektricität in dem menschlichen Körper und dessen Krankheiten besonders bei gelähmten Gliedern aus Vernunftgründen erläutert und durch Erfahrungen bestätigt, 2. Aufl. Johann Leopold Montag, s.l. 1766
27. von Oettingen A, Galvani A, Volta A (Hrsg). Abhandlung über die Kräfte der Elektricität bei der Muskelbewegung: (Comm. Bonon. Sc. et Art. Inst. et Acad. T. 7); (1791)/von Aloisius Galvani. Untersuchungen über den Galvanismus: (1796–1800)/von Alessandro Volta, 2. Aufl. Bolognia (Hrsg), Thun/Frankfurt am Main; 1996
28. Duchenne G-B. Mécanisme de la physionomie humaine ou analyse électro-physiologique de l'expression des passions. Deuxième édition ed. Paris: Librairie J.-B. Bailliere et Fils; 1876.
29. Baker L, Bowman B, Waters R, Benton L. Funktionelle Elektrostimulation. Geschichte der Elektrostimulation. Darmstadt: Dr. Dietrich Steinkopff Verlag Gmbh & Co. KG; 1983.
30. Lapicque L. Définition experimentale de l'excitabilité. 24 Juillet. Comptes Rendus Acad Sci. 1909;67: S280.
31. Adrian E. The response of human sensory nerves to currents of short duration. J Physiol. 1919;53: 70–85.
32. Bogataj U, et al. The rehabilitation of gait in patients with hemiplegia: a comparison between conventional therapy and multichannel functional electrical stimulation therapy. Phys Ther. 1995;75(6):490–502.
33. Vogedes K. Treatment of central paralysis with electrotherapy. Z Elektrostim Elektrother. 2000; 2:24–8.
34. Wenk W. Elektrotherapie. ISSN 2627–3179. 1 Auflage. Berlin Heidelberg: Springer-Verlag; 2004.

35. Hardwick R, Rottschy C, Miall R, Eickhoff S. A quantitative meta-analysis and review of motor learning in the human brain. J Neuro-Oncol. 2013;67:283–97.
36. Taub E, et al. Technique to improve chronic motor deficit after stroke. Arch Phys Med Rehabil. 1993;74(4):347–54.
37. Tan Z, et al. The effectiveness of functional electrical stimulation based on a normal gait pattern on sub- jects with early stroke: RCT. Biomed Res Int. 2014;2014:545408. https://doi.org/10.1155/2014/545408.
38. Teasell R, Bhogal S, Foley N, Speechley M. Gait retraining post stroke. Top Stroke Rehabil. 2003;10(2):34–65.