Electrical stimulation in lower motoneuron lesions, from scientific evidence to clinical practice: a successful transition

Ines Bersch (1), Winfried Mayr (2)

(1) International FES Centre®, Swiss Paraplegic Centre, Nottwil, Switzerland; (2) Medical University of Vienna, Center for Medical Physics and Biomedical Engineering, Vienna, Austria.

This article is distributed under the terms of the Creative Commons Attribution Noncommercial License (CC BY-NC 4.0) which permits any noncommercial use, distribution, and reproduction in any medium, provided the original author(s) and source are credited.

Abstract

Long pulse stimulation in its application in everyday clinical practice still represents a challenge for many therapists and clinicians. It is often unclear how the intervention setup, in particular the parameters pulse width, frequency and amplitude, can influence muscle morphology. In addition, the cause of damage to the lower motoneuron can have multiple reasons and is not anatomically located at the same site. Given the large heterogeneity, it is essential to know the current options and limitations in order to carry out a targeted treatment. A retrospective data analysis of n=128 patients, seen at the Swiss Paraplegic Centre (SPC) in 2022, shows a broad variability in manifestation of lower motoneuron damage. Treatment examples based on different causes of lower motoneuron damage are shown and corresponding stimulation programmes are assigned, as well as the expected results in terms of stimulation duration, volume and configuration.

Key Words: long pulse stimulation; denervation; lower motoneuron damage.

Eur J Transl Myol 33 (2) 11230, 2023 doi: 10.4081/ejtm.2023.11230

Long pulse electricalstimulation and its beneficial effect on lower motoneuron (LMN) damage have long been underestimated in daily rehabilitation practice in Switzerland and worldwide.[1-3]
Underlying reasons may be the lack of knowledge about the neurophysiological changes of muscle after LMN in the acute phase after injury, the incorrect selection of stimulation parameters, namely pulse width, frequencies and amplitudes, the lack of perseverance in the application in the chronic phase after injury or the unavailability of appropriate simulators. In addition, the aetiology of the damage to the LMN may vary.[4] The lesion might directly occur in the anterior horn, as it is the case in spinal cord injury (SCI), or it might result from peripheral nerve injuries, which can affect upper or lower extremities as a result of cuts, fractures or disc herniations.
Due to the large heterogeneity of the aetiologies and the small population in the individual groups, the aim of the present observational study was to extract the number of patients, the type of LMN lesion and form of applied stimulation from data collected in SPC during 2022 and consequently to substantiate these with the scientific evidence for the clinically expected stimulation effect. In addition, a case series of six representative patients is described in specific detail to illustrate the heterogeneity in aetiology, diagnosis and treatment.

Materials and Methods

Data analysis

Data collection included a pool of 128 patients seen in the year 2022. Only those who consulted the outpatient service for the first time seeking to conduct long pulse stimulation in the domestic setting were included for data analysis. The International FES Centre® at the SPC Nottwil, Switzerland, offers evaluation and treatment for patients with neuromuscular, functional electrical stimulation (FES) as well as long pulse stimulation. If the primary evaluation confirms a need for further treatment, an individual decision is made whether this should take place in the form of an independently administered domestic treatment with regular remote monitoring or on-site in the form of a regular outpatient treatment. In the case of independent home-based treatment, a device is provided for domestic use. All patients or their guardians signed an informed consent before enrollment. The individuals, selected from the data base, were grouped in stimulation of the upper or lower extremities as well as in damage affecting the anterior horn or the peripheral nerve.

Patient cases

Patients were selected based on the following criteria: i) Outpatients consulting the International FES Centre® for

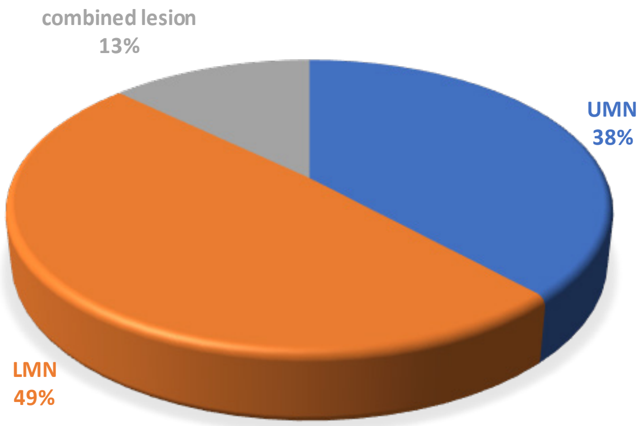

Fig 1. *Distribution of upper and lower motoneuron lesions.*

evaluation; ii) Acute, subacute or chronic damage to the LMN; iii) Muscles not responding to typical neural stimulation patterns with 300 µs duration (per phase, biphasic rectangular), frequency of 35 Hz and an amplitude of up to 120 mA

Results

From the 128 new patient cases, having been evaluated in 2022, 38% showed an upper motor neuron lesion, 49% a LMN lesion and 13% a combined lesion (Figure 1). In 57% the lower limbs and in 43% the upper limbs were affected, respectively (Figure 2). The heterogeneity of the various types of LMN is reflected in Figure 3.

Six representative patients, that conducted long pulse stimulation at home, are presented here as individual cases with their physiological background and the illustration of their functional improvement. The demographic data are provided in the related six tables.

Patients #2 and #4 had peripheral nerve lesions in the upper extremity, patient #3 in the peroneal nerve and the other three in the lumbar spine. Intervention was adapted to the individual clinical situation. Reference for application protocol was 3 minutes low frequency muscle twitching for warm-up and 30 minutes treatment with 12 to 20 Hz pulse trains of 4 s, 5 times per week. Individual deviations ranged from twice daily, 7 days per week (Patient #4), and once daily, 2 days per week (Patient #5), depending on physical condition and compatibility with daily living.

Presentation of patient cases

Case 1

The 54-year-old female patient with the meningomyocele sought for advice for prevention of pressure injuries, because with increasing age she notices accelerating redness around the buttocks at the level of the tuber ischiadicum. When unloading, this disappears, but the time until the redness diminishes becomes longer and thus also the associated immobilization time. This has a negative impact on participation in work and social life.

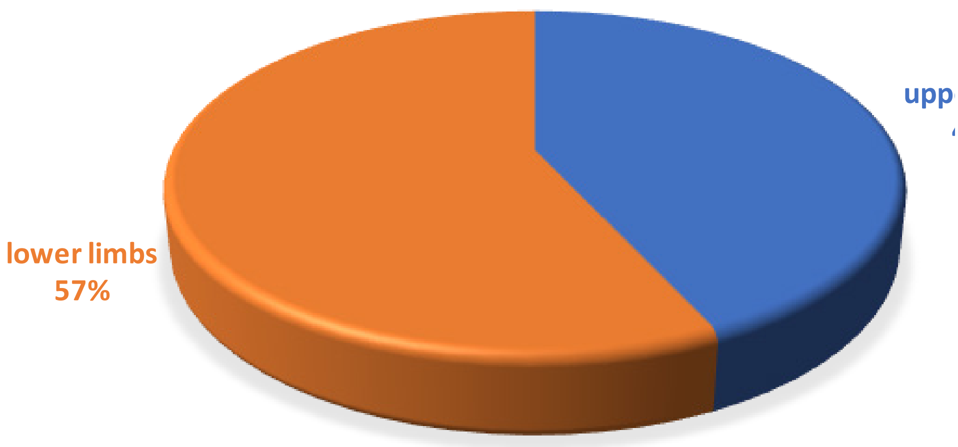

Fig 2. *Distribution in stimulation between upper and lower limbs.*

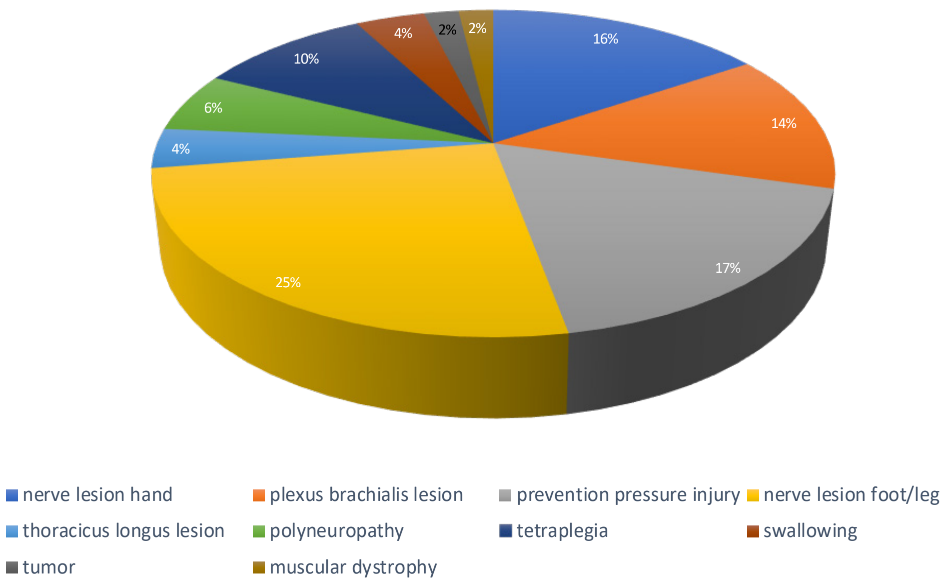

Fig 3. *Etiological heterogeneity of LMN lesions.*

The presentation at the International FES Centre® and the testing of the gluteal muscles by means of electrical nerve stimulation with short duration stimuli did not result in any contraction. Long duration pulses, delivered with 0.86 Hz, neither led to pronounced muscle twitches. Nevertheless, she received a device for self-administration in domestic setting and preformed 5 days per week training with a warm-up phase of 3 minutes low frequency pulsing followed by 30 minutes of burst stimulation. After 4 months of stimulation (Table 1, ID1),

Table 1. *Demography of patient 1.*

ID	Gender	Age	Diagnosis	Stimulation start post injury	Treatment
1	f	54	Meningomyelocele L4-S1	54 years	Stimulation of the buttocks (glutaeus muscle)

Stimulation parameters	Stimulation duration	Outcome
Warm up: 11 s bursts, 0.86 Hz, biphasic ramp-shaped pulses with impulse durations of 150 ms (75 ms per phase) and interpulse pauses of 1 s followed by 11 s breaks, 90 mA **Training phase:** biphasic symmetrical rectangular pulse shape, 20 Hz, 40 ms impulse durations (20 ms per phase) and 10ms interpulse pauses, 2 s bursts and 2 s breaks, 150 mA	6 months, 5 times a week 33 minutes (3 minutes warm up, 30 minutes training phase)	visible contractions after 4 months, subjective improved sensibility in both legs down to the calves, improved defecation

The table illustrates beside the demographic data the onset of stimulation, the anatomical location, the stimulation parameters, the volume of stimulation and the outcome. With respect to the stimulation parameters and their phases, each stimulation was started with a warm-up phase that remained unchanged. The subsequent training phase was adjusted in its frequency (Hz) in the course of the stimulation period, if required.
Abbreviations: m=male, f=female, L=lumbal, S=sacral, MRC= British; Medical Research Council Scale (manual muscle test), s=seconds, ms=milliseconds, Hz=Hertz, mA=milliampere

Eur J Transl Myol 33 (2) 11230, 2023 doi: 10.4081/ejtm.2023.11230

Table 2. *Demography of patient 2.*

ID	Gender	Age	Diagnosis	Stimulation start post injury	Treatment
2	m	16	upper plexus brachialis lesion right side	9 months	Stimulation of delta muscle in all parts, biceps brachii, serratus anterior

Stimulation parameters	Stimulation duration	Outcome
Warm up: 1 s bursts, 1.42 Hz, biphasic ramp-shaped pulses with impuls duration of 200 ms (100 ms per phase) and interpulse pauses 11 s followed by 11 s breaks, 20-30 mA **Training phase 1**: biphasic symmetrical rectangular pulse shape, 12 Hz, 65 ms impulse durations (32.5 ms per phase) and 20 ms interpulse pauses, 2 s bursts and 2 s breaks, 40 mA **Training phase 2**: biphasic symmetrical rectangular pulse shape, 20 Hz, 40 ms impulse durations (20 ms per phase) and 10 ms interpulse pauses, 2 s bursts and 2 s breaks, 40 mA	since 4 months 5 times a week every muscle 33 minutes (3 minutes warm up, 30 minutes training phase)	reanimation of biceps MRC 0 to 4, delta muscle 1 to 3, serratus anterior 0 to 1

The table illustrates beside the demographic data the onset of stimulation, the anatomical location, the stimulation parameters, the volume of stimulation and the outcome. With respect to the stimulation parameters and their phases, each stimulation was started with a warm-up phase that remained unchanged. The subsequent training phase was adjusted in its frequency (Hz) in the course of the stimulation period, if required.
Abbreviations: m=male, f=female, L=lumbal, S=sacral, MRC= British Medical Research Council Scale (manual muscle test), s=seconds, ms=milliseconds, Hz=Hertz, mA=milliampere

contraction activity was visible not only in the warm-up phase but also in the trainings phase with burst stimulation. Subjectively, sensory perception improved in both legs up to the calf. Likewise, an improvement in bowel management was reported, representing an elimination of laxatives to the present time.

Case 2

The 16-year-old patient was involved in a moped accident and was affected by an upper brachial plexus injury on the right side with paresis of the deltoid, biceps, and serratus anterior muscles. The latter was probably caused by a distension of the thoracic longus nerve in conjunction with the accident. The accident occurred at the end of March 2022. The first presentation at the International FES Centre® for the evaluation of direct muscle stimulation was at the end of August 2022. It was possible to elicit muscle contractions directly with burst stimulation (20 ms phase duration, 12 Hz) after a warm-up period with muscle twitches (150 ms per phase rectangular pulses), but not with short duration pulses (300 µs per phase). After only 4 weeks (1.9.2022-5.10.2022), improvements in voluntary control of the biceps muscle were observed. The patient was able to lift the forearm against gravity, which enabled him to make volitional hand-to-mouth movements. Motor control improvements were also seen in the deltoid muscle. The limitation to initial muscle twitch responses to long duration stimuli improved to voluntary moving the upper arm in absence of gravity counteraction (MRC force value from 1 to 2). In December 2022, the parameters could be changed to 40 ms /20 Hz stimulation bursts, leading to pronounced tetanic muscle contractions without signs of fatigue (decrease of contraction strength) over a training session of 30 minutes. Voluntary muscle function continued to improve with growing ability to move the arm against gravity (Table 2, ID 2). At the request of the referring physician, the serratus anterior muscle was also tested for response to stimulation. Consequently, the muscle is currently stimulated at 12 Hz and an intensity of 20 mA. After 4 weeks, also voluntary activation of the serratus muscle was observed. Increasing the stimulation intensity for eliciting full contraction force remained a challenge in the present case because current levels are not well tolerated. Consistent application and regular re-adjustment of the amplitude as well as the change to a

Table 3. *Demography of patient 3.*

ID	Gender	Age	Diagnosis	Stimulation start post injury	Treatment
3	m	30	lesion N. peronaeus communis right side	6 months	Stimulation of all foot extensors (M. tibialis anterior, M. extensor digitorum longus, M.extensor hallucis longus)

Stimulation parameters	Stimulation duration	Outcome
First year 100 ms, 0.5 Hz, 2 s bursts **Second year** 120 ms, 1.9 Hz, 4 s bursts **Since then** 60 ms, 7 Hz, 4 s bursts	since September 2018, 5 times a week, 30 minutes	after 1-year voluntary activity of the M. extensor digitorum longus and hallucis longus (MRC 1) after 2.5 years voluntary activity of the M. extensor digitorum longus and hallucis longus increased (MRC 3) after 3 years additional voluntary activity in M. tibialis anterior (MRC 2)

The table illustrates beside the demographic data the onset of stimulation, the anatomical location, the stimulation parameters, the volume of stimulation and the outcome. With respect to the stimulation parameters and their phases, each stimulation was started with a warm-up phase that remained unchanged. The subsequent training phase was adjusted in its frequency (Hz) in the course of the stimulation period, if required. Abbreviations: m=male, f=female, L=lumbal, S=sacral, MRC= British Medical Research Council Scale (manual muscle test), s=seconds, ms=milliseconds, Hz=Hertz, mA=milliampere

triangular instead of rectangular pulse shape helped to increase the intensity tolerance level.

Case 3

The 30 years old male patient experienced a complex knee trauma in December 2018, which resulted in damage to the common peroneal nerve followed by a surgical neurolysis. In the first six months after starting stimulation, there was no motor but sensory improvement. One year later, with consistent stimulation 5 times a week (Table 3, ID3), the extensor digitorum longus showed a voluntary value in activation of MRC 3, the extensor hallucis longus a MRC of 2, the perineal muscles of 3, and the tibialis muscle of 1. After three years of stimulation, all foot extensors except for the tibialis anterior muscle (MRC 2) have reached a MRC of 3. In everyday life, this enables the patient to walk without orthoses. Only for sport activities it is necessary to use a flexible ankle strap.

Case 4

The 42-year-old carpenter had an injury of the hand at work with damage of the ulnar nerve, which was surgically reconstructed. Clinically, the patient showed weakness in the flexion of the metacarpophalangeal joints, so that the movement could not be actively performed through a full range of 90°. Testing of the dorsal interossei muscles by long pulse stimulation showed good movement in flexion and abduction also in fingers VI and V. Subsequently, stimulation was performed 7 times a week, 2 times a day in home therapy (Table 4, ID4). After 8 weeks of stimulation, the movement could be performed voluntarily.

Case 5

The 47-year-old female patient presented in April 2022 at the International FES Centre® with the request of pain reduction in the sacrum/pelvis/sacro-iliaca joint area, especially on the right side. She clinically showed the symptom of a hypermobile sacroiliac joint on the right side, a paralysis of the foot extensors and paresis in the plantar flexors and gluteal muscles on the right side. These deficits affect the patient especially in walking and sitting. Due to the damage of the lower motor neuron, the muscle tissue appeared strongly reduced and transformed into connective and adipose tissue, proved by regular ultrasound imaging, in the course of the existing damage. Until the patient received her own stimulation device, she came to SPC for outpatient stimulation therapy twice per week from April 2022 to February 2023 (Table5, ID5). As soon as tetanic contraction in the triceps sure muscle could be accomplished the accompanying back pain declined (NRS 8/10 to 2/10). In addition, the patient reported improved stability in the terminal stance phase due to the change in elasticity of the musculature, as plausibly caused by the stimulation. The reduction in back pain was due to the change in gait pattern, as the compensatory movement of an unphysiological lowering of the stance leg side in the hip joint disappeared.

Table 4. *Demography of patient 4.*

ID	Gender	Age	Diagnosis	Stimulation start post injury	Treatment
4	m	42	lesion N. ulnaris left side after cuts, followed by nerve suture	4 months	Stimulation of the intrinsic hand muscles (Mm. interossei dorsales et palmares, Mm. lumbricales)

Stimulation parameters	Stimulation duration	Outcome
Warm up: 11 s bursts, 1.42 Hz, biphasic ramp-shaped pulses with impuls duration of 200 ms (100 ms per phase) and interpulse pauses 11 s followed by 11 s breaks, 20-30 mA **Training phase 1** (first 4 weeks): Biphasic symmetrical rectangular pulse shape, 12Hz, 65 ms impulse durations (32.5 ms per phase) and 2 ms interpulse pauses, 2 s bursts and 2 s breaks 27 mA **Training phase 2** (following 8 weeks) Biphasic symmetrical rectangular pulse shape, 20 Hz, 40 ms impulse durations (20 ms per phase) and 10 ms interpulse pauses, 2 s bursts and 2 s breaks, 30 mA	7 times a week,2 times a day, 33 minutes	3 months until recovery of function

The table illustrates beside the demographic data the onset of stimulation, the anatomical location, the stimulation parameters, the volume of stimulation and the outcome. With respect to the stimulation parameters and their phases, each stimulation was started with a warm-up phase that remained unchanged. The subsequent training phase was adjusted in its frequency (Hz) in the course of the stimulation period, if required. Abbreviations: m=male, f=female, L=lumbal, S=sacral, MRC= British Medical Research Council Scale (manual muscle test), s=seconds, ms=milliseconds, Hz=Hertz, mA=milliampere

Case 6

The 53-year-old patient presented at the International FES Centre® due to his increasing limitation in walking. He was particularly concerned about the significantly worsening terminal stance phase and the decreasing stability in the upper ankle joint. Increasingly painful pressure sores occur in the area of the proximal toe joints, as the lack of tension in the triceps surae muscle by leading the toe flexors to compensatory over-activity with an increasing and persistent flexion position. Testing with electrical stimulation revealed that the triceps surae muscle showed signs of denervation. Since July 2022, the patient has regularly stimulated his triceps surae muscle 2 to 5 times weekly, although his voluntary motor function is unchanged (MRC 3), a significant improvement occurred three months after the start of stimulation regarding stability in the mid and terminal stance phase of the right leg (Table 6, ID6). The pressure injuries disappeared. This example demonstrates that a functional improvement, in this case of walking, can also be achieved by a structural change in the musculature without an improvement in voluntary movement control and strength.

Discussion

Actual clinical opportunities

Long pulse stimulation of denervated muscles is an early treatment option in temporary and potentially chronic peripheral denervation. The best effects are accomplished as long as the muscle is intact or just slightly atrophied and not yet undergoes degenerative developments.[5-7] In cases with perspective of recovery of nerve supply, the method is capable of preserving the reinnervation target in near-normal state.[1] If denervation is permanent, long pulse stimulation of denervated muscle is the only option to maintain muscle tissue and metabolic functioning in the anatomical region.[8] This is important for prevention of pressure injuries and various degenerative developments, generally associated with disuse in the long-term. Not at least, preserving a healthy state keeps applicability of eventual future novel therapy options open, whereas heavy long-term degeneration result in definitely irreversible conditions; nevertheless, there is evidence, that even then tissue morphology and metabolic processes can be positively affected.[9] In an early state long-duration pulses with 15 to 20 ms per phase are applicable. Together with short inter-pulse

Table 5. *Demography of patient 5.*

ID	Gender	Age	Diagnosis	Stimulation start post injury	Treatment
5	f	44	radiculopathy L4/5 with chronic pain syndrome (2017) and paralysis of the foot extensors and flexors right side, as well as muscle weakness of the M. glutaeus medius	5 years	Stimulation of M. triceps surae

Stimulation parameters	Stimulation duration	Outcome
Warm up: 11 s bursts, 1.42 Hz, biphasic ramp-shaped pulses with impuls duration of 200 ms (100 ms per phase) and interpulse pauses 11 s followed by 11 s breaks, 20-30 mA **Training phase 1** (first 4 months): biphasic symmetrical rectangular pulse shape, 2 Hz, 100 ms impulse durations (50 ms per phase) and 2 ms interpulse pauses, 4 s bursts and 4 s breaks, 40 mA **Training phase 2** biphasic symmetrical rectangular pulse shape, 20 Hz, 40 ms impulse durations (20 ms per phase) and 10 ms interpulse pauses, 2 s bursts and 2 s breaks, 50 mA	since April 2022 two times a week till February 2023 since February 2023 daily 33 minutes	pain free since October 2022, no voluntary function achieved, but more stability

The table illustrates beside the demographic data the onset of stimulation, the anatomical location, the stimulation parameters, the volume of stimulation and the outcome. With respect to the stimulation parameters and their phases, each stimulation was started with a warm-up phase that remained unchanged. The subsequent training phase was adjusted in its frequency (Hz) in the course of the stimulation period, if required.
Abbreviations: m=male, f=female, L=lumbal, S=sacral, MRC= British Medical Research Council Scale (manual muscle test), s=seconds, ms=milliseconds, Hz=Hertz, mA=milliampere

pauses those allow eliciting strong fused contractions with stimulus bursts of 20 Hz or more.[10-12]

Current options and limitations

The spectrum of available stimulators is still limited. There are several handy stimulators on the market, that allow, by single twitch activation, effective conditioning of small denervated muscles in their excitability, towards reaction to shorter duration stimuli – shorter means duration per phase of 15 to 20 ms in biphasic pulses, which is a precondition to accomplish fused contractions via pulse trains with frequencies of 20 Hz or more. This is essential for building of muscle volume, force and endurance training, and functional use. Slightly lower frequencies, e.g. 30 ms per phase/approx. 15 Hz are already somehow suitable for muscle building as a compromise modality, though contraction patterns appear unfused and overlaid with some ripple.

A limitation of most available stimulators is in low deliverable maximum amplitude and minimum of inter-pulse pauses being limited to longer than the pulse itself. Currently, the “Stimulette RISE”, offered by the Viennese family enterprise Schuhfried, is the only certified medical product capable of delivering stimuli with the necessary reduced inter-pulse pauses, down to 10 ms, which are required for eliciting fused contractions, and an intensity reserve sufficient for activating larger muscles like quadriceps femoris or gluteus maximus. The device is powerful enough to even allow standing-up and stepping exercises in persons with flaccid paraplegia, when an appropriate training status has been reached.[13-15]

What remains critical, is handling and placement of electrodes. As excessive local current density can result in skin injury, care must be taken to assure full surface skin contact with evenly distributed contact pressure and so, well distributed current density. As efficient therapy requires daily home-based application, users need specific training in safe application of electrodes, including cleaning procedures for conductive polymer electrodes, as those can easily get damaged, with hidden risk of inhomogeneities in current distribution. Longstanding denervation and in particular large muscles require the use of polymer electrodes in wet foam pockets or with salt free gel as contact medium. The widely preferred hydrogel electrodes are applicable in smaller,

Table 6. *Demography of patient 6.*

ID	Gender	Age	Diagnosis	Stimulation start post injury	Treatment
6	m	53	spinal stenosis L 3/4 and L 4/5 (2021), paresis of M. triceps surae (MRC 3/5)	1 year	Stimulation of M. triceps surae

Stimulation parameters	Stimulation duration	Outcome
Warm up: 11 s bursts, 1.42 Hz, biphasic ramp-shaped pulses with impuls duration of 200 ms (100 ms per phase) and interpulse pauses 11 s followed by 11 s breaks, 20-30 mA **Training phase** Biphasic symmetrical rectangular pulse shape, 20 Hz, 40 ms impulse durations (20 ms per phase) and 10 ms interpulse pauses, 2 s bursts and 2 s breaks, 50 mA	since July 2022 two to five times a week, 33 minutes	after three months more stability in the stance phase and terminal stance phase, no improvement in voluntary activty (MRC 3)

The table illustrates beside the demographic data the onset of stimulation, the anatomical location, the stimulation parameters, the volume of stimulation and the outcome. With respect to the stimulation parameters and their phases, each stimulation was started with a warm-up phase that remained unchanged. The subsequent training phase was adjusted in its frequency (Hz) in the course of the stimulation period, if required.
Abbreviations: m=male, f=female, L=lumbal, S=sacral, MRC= British Medical Research Council Scale (manual muscle test), s=seconds, ms=milliseconds, Hz=Hertz, mA=milliampere

well conditioned muscles with better skin trophism and lower charge transfer levels..
Biphasic rectangular pulses are first choice and most effective in eliciting muscle contractions. For cases, where intact sensory nerves or motor nerves are unintentionally co-activated, ramp-shaped pulse forms can shift activation thresholds of neurons higher than those of muscle fibers, based on accommodation effects in the nerve fiber membrane with a higher excitability.[10] This can help avoiding or reducing unpleasant sensation, or unwanted neuromuscular activation of adjacent muscles. In case of partly denervation of a muscle, which is seen in practice rather often, accommodating pulses can be useful for recruiting the denervated fiber population with some selectivity. This is useful for estimating the degree of denervation in single muscles as well as for focused conditioning of the denervated fiber population.
In conclusion, there is great heterogeneity in the clinical presentation of the LMN lesions. The selection and composition of the individual stimulation parameters and the stimulation volume are crucial for the expected outcomes. Changes in the degenerated musculature can still be expected even in long-standing chronic state (more than 20 years after denervation). Changes in the degenerated musculature can still be expected even in long-standing chronic state (more than 20 years after denervation). However, a timely approach is preferable since degeneration in the damaged muscle is not yet so advanced and maintenance of tissue health is easier with a minimum of daily training effort..

List of acronyms

FES - functional electrical stimulation
LMN - lower motoneuron
MRC - manual muscle test by British Medical Research Council Scale
NRS - numeric rating scale
SCI - spinal cord injury
SPC - Swiss Paraplegic Centre

Contributions of Authors

The authors equally contributed to designing and implementation of the typescript. Both Authors read and approved the final edited typescript.

Acknowledgments

The authors would like to thank Kathrin Schafer for preparing the data, Marie Alberty for her professional support and Susanne Opel and Ursula Gföller for the daily implementation of the stimulation in clinical practice, as well as all patients who carry out the treatment with motivation and satisfaction.

Funding

None

Conflict of Interest

The authors disclose no conflicts of research and publication interest or any specific endorsements of the products referenced in this manuscript.

Ethical Publication Statement

We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

Corresponding Author

Ines Bersch, International FES Centre®, Swiss Paraplegic Centre Nottwil, Guido A. Zäch Strasse 1, 6207 Nottwil, Switzerland. Tel.: +41 41 9394206
ORCHID iD: 0000-0001-5519-5893
E-mail: ines.bersch@paraplegie.ch

E-mail and ORCID iD of co-author

Winfried Mayr: winfried.mayr@meduniwien.ac.at
ORCHID iD: 0000-0001-9648-3649

References

1. Bersch I, Fridén J. Electrical stimulation alters muscle morphological properties in denervated upper limb muscles. Ebiomedicine. 2021;74:103737. doi:10.1016/j.ebiom.2021.103737, PMID: 34896792, PMCID: PMC8671101
2. Chandrasekaran S, Davis J, Bersch I, Goldberg G, Gorgey AS. Electrical stimulation and denervated muscles after spinal cord injury. Neural Regen Res. 2020 Aug;15(8):1397–1407. doi:10.4103/1673-5374.274326. PMID: 31997798, PMCID: PMC7059583
3. Bersch I, Fridén J. Upper and lower motor neuron lesions in tetraplegia: implications for surgical nerve transfer to restore hand function. J Appl Physiol. 2020;129(5):1214–1219. doi:10.1152/japplphysiol.00529.2020 PMID: 32969783
4. Kern H, Hofer C, Mödlin M, Forstner C, Richter WM. Functional Electrical Stimulation (FES) of Long-Term Denervated Muscles in Humans: Clinical Observations and Laboratory Findings. Basic Appl Myol. 2002;6(12):291–299.
5. Kern H, Carraro U. Home-Based Functional Electrical Stimulation of Human Permanent Denervated Muscles: A Narrative Review on Diagnostics, Managements, Results and Byproducts Revisited 2020. Diagnostics. 2020;10(8):529. doi: 10.3390/diagnostics10080529 PMID: 32751308
6. Kern H, Stramare R, Martino L, Zanato R, Gargiulo P, Carraro U. Permanent LMN denervation of human skeletal muscle and recovery by h-b FES: management and monitoring. Europ J Transl Myology. 2010;20(3):91–104. doi: 10.4081/bam.2010.3.91
7. Carraro U, Boncompagni S, Gobbo V, Rossini K, Zampieri S, Mosole S, Ravara B, Nori A, Stramare R, Ambrosio F, Piccione F, Masiero S, Vindigni V, Gargiulo P, Protasi F, Kern H, Pond A, Marcante A. Persistent muscle fiber regeneration in long term denervation. Past, present, future. Europ J Transl Myol. 2014;25(2):77–92. doi:10.4081/bam.2015.2.77 PMID: 25844146
8. Mandl T, Meyerspeer M, Reichel M, Kern H, Hofer C, Mayr W, Moser E. Functional Electrical Stimulation of Long-term Denervated, Degenerated Human Skeletal Muscle: Estimating Activation Using T2-Parameter Magnetic Resonance Imaging Methods. Artif Organs. 2008;32(8):604–608. doi:10.1111/j.1525-1594.2008. 00609.x, PMID: 18782129
9. Alberty M, Mayr W, Bersch I. Electrical Stimulation for Preventing Skin Injuries in Denervated Gluteal Muscles—Promising Perspectives from a Case Series and Narrative Review. Diagnostics. 2023;13(2):219. doi:org/10.3390/diagnostics13020219, PMID: 36673029, PMCID: PMC9857944
10. Mayr W, Hofer C, Bijak M, Rafolt D, Unger E, Reichel M, Sauermann S, Lanmueller H, Kern H. Functional Electrical Stimulation (FES) of Denervated Muscles: Existing and Prospective Technological Solutions. Basic Appl Myol. 2003 Feb 14;6:287–290.
11. Kern H, Salmons S, Mayr W, Rossini K, Carraro U. Recovery of long-term denervated human muscles induced by electrical stimulation. Muscle Nerve. 2005 Jan;31(1):98–101.doi: 10.1002/mus.20149
12. Boncompagni S, Kern H, Rossini K, Hofer C, Mayr W, Carraro U, Protasi F. Structural differentiation of skeletal muscle fibers in the absence of innervation in humans. Proc Natl Acad Sci U S A. 2007. Dec 4;104(49):19339–19344.doi: 10.1073/pnas.0709061104, PMID: 18042706, PMCID: PMC2148291
13. Albertin G, Hofer C, Zampieri S, Vogelauer M, Löfler S, Ravara B, Guidolin D, Fede C, Incendi D, Porzionato A, Caro RD, Baba A, Marcante A, Piccione F, Gargiulo P, Pond A, Carraro U, Kern H. In complete SCI patients, long-term functional electrical stimulation of permanent denervated muscles increases epidermis thickness. Neurol Res. 2018 Apr;40(4):277–282. doi: 10.1080/01616412.2018.1436877 PMID: 29447083
14. Kern H, Boncompagni S, Rossini K, Mayr W, Fanò G, Zanin ME, Podhorska-Okolow M, Protasi F, Carraro U. Long-term denervation in humans causes degeneration of both contractile and excitation-contraction coupling apparatus, which is reversible by functional electrical stimulation (FES): a role for myofiber regeneration? J.

Neuropathol. Exp. Neurol. 2004 Sep;63(9):919–931.doi: 10.1093/jnen/63.9.919, PMID: 15453091

15. Kern H, Carraro U, Adami N, Hofer C, Loefler S, Vogelauer M, Mayr W, Rupp R, Zampieri S. One year of home-based daily FES in complete lower motor neuron paraplegia: recovery of tetanic contractility drives the structural improvements of denervated muscle. Neurol Res. 2010 Feb;32(1):5–12.doi: 10.1179/174313209x385644, PMID: 20092690.

Disclaimer

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article or claim that may be made by its manufacturer is not guaranteed or endorsed by the publisher.

Submission: January 31, 2022
Revision received: April 28, 2022
Accepted for publication: April 28, 2022