journal of clinical practice
ISSN 2220-3095
2025 Vol 16 №2

Multi-Channel Functional Electrostimulation: The Method of Restoring the Walking Function in Patients with a Past History of Acute Cerebrovascular Event

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ABSTRACT

Multi-channel functional electrostimulation (MFES) represents a promising method for the rehabilitation of post-stroke patients, aimed at restoring the walking function in various periods after an acute cerebrovascular event. The review systematizes the modern concepts of using the MFES in patients with the consequences of cerebral stroke, analyzing the technical parameters of stimulation, the methodical approaches to conducting the procedures and the clinical efficiency of the method. The analysis of literature data demonstrates significant variability of MFES protocols: the stimulation frequency varies from 20 to 100 Hz, the duration of the procedure ranges from 15 to 60 minutes, the treatment course can last from 3 to 30 weeks. The main targets of stimulation are the four groups of muscles in the lower limbs — the anterior tibial muscle, the plantar flexors, the quadriceps muscle of thigh and the group of muscles on the posterior surface of thigh. The synchronization of stimulation with the walking cycle is conducted predominantly by means of contact sensors, accelerometers and electromyographic signals; modern developments include the inertial systems and the machine learning algorithms. The review presents a combined analysis of the technical aspects of MFES from the point of view of staging of motor learning and individualization of the stimulation parameters. Special attention was paid to the integration of MFES with the robotic devices, including the exoskeletons, which represents a new trend in rehabilitation. Along with the absence of the unified criteria for choosing the stimulation parameters, it is worth noting that there is a necessity of differentiated approach depending on the type of motor disorders, on the duration of the disease and on the cognitive capabilities of the patient. The analysis presented justifies the necessity of developing personalized MFES protocols and arranging a large-scale research for optimizing the stimulation parameters in the rehabilitation of post-stroke patients.

Keywords: *multichannel functional electrical stimulation; stroke rehabilitation; gait; motor recovery.*

For citation:

Skvortsov DV, Klimov LV, Lobunko DA, Ivanova GE. Multi-Channel Functional Electrostimulation: The Method of Restoring the Walking Function in Patients with a Past History of Acute Cerebrovascular Event. *Journal of Clinical Practice*. 2025;16(2):69–81. doi: 10.17816/clinpract684717 EDN: JCFLTU

Submitted 16.06.2025 Accepted 18.06.2025 Published online 06.07.2025

BACKGROUND

Currently, one of the main objectives of early rehabilitation among the patients after an acute cerebrovascular event (CVA) is restoring the functions of walking without assistance [1, 2].

It is known that, already at the early stage after the CVA, hemiparesis typically develops, which is associated with gait abnormalities caused by the developing asymmetry both in the spatial and the timing parameters of the step cycle, which significantly restricts the ability of unassisted walking, also affecting the balance control, leading to the increased risk of falling [3, 4].

According to the data from the research on the biomechanics of walking, the gait parameters in patients with a past episode of stroke show typical impairment patterns of this function [5–8]. The patients after a cerebral stroke have lower walking speed with their gait being asymmetrical by many parameters, the stance phase on the paretic side is significantly shorter than the one on the contralateral side. Significantly less is the amplitude of motions in

Многоканальная функциональная электростимуляция: метод восстановления функции ходьбы у пациентов, перенёсших острое нарушение мозгового кровообращения

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АННОТАЦИЯ

Многоканальная функциональная электростимуляция (МФЭС) представляет собой перспективный метод реабилитации постинсультных больных, направленный на восстановление функции ходьбы в различные периоды после острого нарушения мозгового кровообращения. Обзор систематизирует современные представления о применении МФЭС у пациентов с последствиями церебрального инсульта, анализируя технические параметры стимуляции, методические подходы к проведению процедур и клиническую эффективность метода. Анализ литературных данных демонстрирует значительную вариабельность протоколов МФЭС: частота стимуляции варьирует от 20 до 100 Гц, длительность процедур составляет от 15 до 60 минут, курс лечения может продолжаться от 3 до 30 недель. Основными мишенями воздействия являются четыре группы мышц нижних конечностей — передняя большеберцовая мышца, подошвенные сгибатели, четырёхглавая мышца бедра и группа мышц задней поверхности бедра. Синхронизация стимуляции с циклом ходьбы осуществляется преимущественно посредством контактных датчиков, акселерометров и электромиографических сигналов; современные разработки включают инерциальные системы навигации и алгоритмы машинного обучения. В обзоре представлен комплексный анализ технических аспектов МФЭС с позиций этапности двигательного обучения и индивидуализации параметров стимуляции. Особое внимание уделено интеграции МФЭС с робототехническими устройствами, включая экзоскелеты, что представляет новое направление в реабилитации. Наряду с отсутствием единых критериев выбора параметров стимуляции следует отметить необходимость дифференцированного подхода в зависимости от типа двигательных нарушений, периода заболевания и когнитивных возможностей пациента. Представленный анализ обосновывает необходимость разработки персонализированных протоколов МФЭС и проведения масштабных исследований для оптимизации параметров стимуляции в реабилитации постинсультных больных.

Ключевые слова: *функциональная электростимуляция; реабилитация; инсульт; ходьба.*

Для цитирования:

Скворцов Д.В., Климов Л.В., Лобунько Д.А., Иванова Г.Е. Многоканальная функциональная электростимуляция: метод восстановления функции ходьбы у пациентов, перенёсших острое нарушение мозгового кровообращения. *Клиническая практика.* 2025;16(2):69–81. doi: 10.17816/clinpract684717 EDN: JCFLTU

Поступила 16.06.2025 Принята 18.06.2025 Опубликована online 06.07.2025

the joints on the paretic side [5–7]. Electromyographic (EMG) examinations of the muscles in the lower limbs in hemiparetic patients show the changes in the electric activity of muscles, which manifests by the absence or by the decrease in the amplitudes and by the presence of pre-term or delayed muscle activity peaks [8].

One of the variants of restoring the walking function in general and of achieving the walking symmetry in particular is the method of repeated teaching the motor skills, for which, the high-intensity repeating specific training sessions are necessary at the early period of rehabilitation after the CVA [9]. One of the promising methods of restoring the walking function is

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the method of functional electrostimulation of muscles (FES)[1]. Specifically, this context of fulfilling a certain functional task, as it was initially described by the authors of the method — J.H. Moe and H.W. Post [10], makes this field topical in modern rehabilitation. In particular, FES is used for reproducing the example of automatic activation of muscles in the lower limbs during the process of restoring the walking function [11], and specifically for this purpose, the artificial external excitation of muscles with electric current is used.

The mechanism of FES efficiency, nevertheless, remains unclear. For example, in the research by G.F. Santos et al. [12], it was found that FES improves walking in patients with a foot drop syndrome, with this, the basis of this effect is not evident.

The MFES method was assessed as promising in terms of restoring the walking function, beginning from the early rehabilitation period after the cerebral stroke and up to the onset of the residual neurological deficit period. Thus, at the early recovery period, when the pathological gait is still at the development phase, the use of MFES, evidently can be associated with higher efficiency.

The aim of this research is exploring the possibilities of MFES for restoring the walking functions in patients with a past episode of cerebral stroke.

Methodology of searching the literature sources

For searching the literature sources, the PubMed, eLibrary and Google Scholar databases were used. The search with a depth of up to 10 years was using the following key words and their combinations: “stroke”, “CVA”, “rehabilitation”, “walking”, “multi-channel functional electrostimulation”, “stroke”, “rehabilitation”, “gait”, “multichannel functional electrical stimulation”. The inclusion criteria for the analysis were the following: the analytical reviews, the clinical and experimental research, the recommendations from the scientific communities, the full texts of articles in Russian or in English.

Exclusion criteria: clinical cases; research works devoted to the foot drop syndrome; the ones where stimulation was applied to only one muscle; the use of implanted stimulation systems; other methods of walking, except the common one or the static position; stimulation with using the training devices (exercise bicycle and others); research works employing the survey method; the ones where stimulation was used as the experimental variable; the research works with multi-channel constant stimulation; multi-channel stimulation in healthy test subjects.

NUMBER OF CHANNELS AND THE MUSCLES STIMULATED

FES was first used for compensating the foot drop syndrome in rehabilitation after a cerebrovascular stroke by V.T. Liberson et al. [13] in 1961. The authors have obtained positive results of correcting the foot drop symptom in patients after the CVA. Later on, multiple research works have demonstrated that FES is an effective method of improving the motor function [14], of increasing the walking speed [15] and of decreasing the degree of intensity for spasticity after a cerebrovascular stroke. With this, it is known that single- or double-channel FES in a sufficiently effective way stimulates the dorsal flexing of the ankle joint, which is accompanied by the decreased flexing amplitude in the knee joint along with the plantar flexion of the ankle joint at the second half of the stance phase, at the beginning of the swing phase [11], decreasing the repulsive momentum generated at the end of the stance phase. The application of multi-channel FES can compensate and provide the insufficient momentum force. In particular, a number of research works reported the positive results of using MFES in early rehabilitation of individuals after the CVA in a context of affecting the balance control and mobility. In the research works by the groups headed by Z. Tan [16] and T. Yan [17], it was demonstrated that using the four-channel FES for the main flexors-extensor muscles of thigh and shin can improve the motor function, the balance, the ability to walk, as well as the ability to perform everyday activities in CVA patients at the early rehabilitation period.

In the research on the effects of FES of the anterior tibial muscle, an effect of increasing the walking speed and frequency was described [14], with this, the FES of the anterior tibial muscle, of the long peroneal muscle, of the quadriceps and the *hamstring* muscles, was to a significant extent increasing the efficiency and the speed of walking [18], while the involvement of the femoral abductor stimulation into the process has stabilized the positioning of the coxofemoral joint itself and to a significant extent has increased the ability of unassisted walking, contributing to re-gaining the balance [19].

[1] Decree issued by the Ministry of Health of Russia dated July 31, 2020, No. 788n «Concerning the approval of the Procedure of organizing the medical rehabilitation of adults». Access mode: https://www.garant.ru/products/ipo/prime/doc/74581688/?ysclid=mc8qui3cc6321811374

Upon taking off the table the separate topic of stimulation in cases of foot drop syndrome, in other cases the muscles used for FES are the main flexors-extensors of the shin and the thigh. When training the walking motions using FES, the main target muscles are the groups represented in table 1 [17, 20–25].

OPTIMAL TIMING PARAMETERS OF FUNCTIONAL ELECTROSTIMULATION

The main MFES parameters may include the following: the duration of a single procedure, the number of procedures per weeks and the total course duration. The conducted research works describe various timing parameters of the procedure. For example, the possibility of using the stimulation lasting from 15–30 minutes [26] to 30–45 minutes [17, 27] was studied. In general, it is worth noting that the optimal timing of FES, for example, in case of correcting the foot drop symptom in CVA patients, can vary extensively. In particular, S.K. Sabut et al. [15] report the positive results of daily usage of the device with sessions lasting 20–30 minutes. Some research works describe the gradual increase of session duration (from 15 minutes during the first week to 30–45 minutes in the following weeks [14]), which can contribute to better adaptation of patients to electric stimulation and can decrease the risk of muscular fatigue at the initial stages of rehabilitation, at the same time, the stimulation device itself is claimed to be the means of prosthetic replacement for the function.

Regarding the frequency of training, the majority of FES protocols recommend arranging the sessions not less than 5 times a week [17, 28], though no justification is provided by the authors. In the research by Z. Hong et al. [29] with arranging the FES training sessions among the patients at the chronic stage of stroke, the sessions lasted 20 minutes 3 times a week for 7 weeks with good clinical effect. In the systematic review published in 2024 [30], the authors came to the conclusion that less long training sessions are more effective than the long-lasting ones.

Thus, the practice of using FES most frequently includes the so-called standard protocols, which are used regardless of the stroke period, namely: from 3 to 5 training sessions a week with the duration from 30 to 60 minutes depending on the patient status with a total course of 3–12 weeks for the purpose of improving the walking parameters, such as speed and balance, as well as for the correction of spasticity [14, 31]. If necessary, the FES duration can reach up to 6 months for achieving the stable effect with sessions performed daily or several times a week [25]. It was noted that the early initiation of FES and its long-term application are of fundamental importance for achieving the optimal results.

Currently, a trend can be seen towards combining the MFES itself with other technologies of training to walk (treadmill sessions, motorized exercise bicycle training sessions etc.) for increasing the functionality of the process [32, 33].

MODES OF FUNCTIONAL ELECTROSTIMULATION

Currently, the stimulation models known as the variable-frequency trains (VFT), have a number of benefits comparing to the traditional constant-frequency trains (CFT). In particular, it was noted that the VFT enhance the isometric [34] and non-isometric [35] parameters of the muscles, as

Table 1

Muscles of the lower limb and their combinations used for functional electrostimulation

Source	Stimulated muscles
Allen, 2018 [20]; Aout, 2023 [21]	The anterior tibial muscle has the fundamental importance for performing the dorsal flexion of the ankle joint at the swing phase
Allen, 2018 [20]; Aout, 2023 [21]	Plantar flexors of the ankle joint are stimulated at the second half of the stance phase to improve the repulsion and frontal motion when walking
Hakansson, 2011 [22]	Isolated stimulation of only the anterior tibial and gastrocnemial muscle
Tenniglo, 2018 [23]	Stimulation of only the posterior group of thigh muscles
Purohit, 2024 [24]	The quadriceps muscle is being selectively stimulated for the purpose of improving the stability of the lower limb
Shin, 2022 [25]	The abductor muscle of the thigh and the gluteus maximus muscle for supporting the vertical position of the body when walking
Yan, 2005 [17]	Four muscles simultaneously (main flexors-extensors) — anterior tibial, medial gastrocnemial, whole posterior group of thigh muscles and the quadriceps muscle of thigh

https://doi.org/10.17816/clinpract684717

journal of clinical practice ISSN 2220-3095 2025 Vol 16 №2

shown in the healthy quadriceps muscles of the thigh comparing to the CFT of similar frequency, especially when the muscles are tired. Besides providing the improved performance of skeletal muscles, the VFT are considered a more physiologically justified stimulation pattern comparing to the CFT [36].

The difficulties of predicting the effect of FES have multiple factors, which are difficult to take into account in the real-life settings: thus, for example, the mode of muscles working can significantly change at various motion phases, the response to FES can also be different. For more precise exposure, mathematical models are being developed that operate the data sets accessible as of today [12], nevertheless, the information currently available is insufficient and the research must be continued.

The main FES parameters in the published articles were summarized in table 2 [10, 11, 14–18, 20, 22–24, 26–28, 31–33, 37–41]. The analysis of stimulation parameters has revealed a wide variability of FES protocols used by various investigators for various forms and clinical stages of stroke. The stimulation frequency varies from 30 to 100 Hz with the predominance of the 30–40 Hz range in the majority of research works. It is important to note that only 8 of 22 research works state the current force. The average procedure duration is approximately 30 minutes with the marginal values from 15 to 60 minutes. Notably, the multiplicity of the procedures varies from 2 to 7 a week (with a mean of 5 sessions) and the total course duration — from 3 to 30 weeks, more often 4–6 weeks.

The synchronization of FES with the walking cycle represents a critically important aspect of the effective usage of the methods. The analysis of literature data shows a variety of synchronization methods applied in various researches. Thus, the most widespread is the usage of contact switches located in the shoes of the patient [14, 18, 21, 22, 37]. Contact sensors determine the step cycle, then the algorithm supposes the presence of the needed delay before switching on one or another channel, however, contact sensors are temperamental, they have a certain activation threshold, bouncing and other technical drawbacks. More modern systems use the data from the accelerometers [27, 38] or more complex inertial systems [11], which allows for increasing the accuracy of determining the step cycle. Some research works employ the synchronization based on the EMG-activity of the contralateral limb [16] or of the paretic limb itself [32], as well as manual activation [10, 17]. Modern developments include the integration of inertial sensors (inertial measurement unit, IMU) with the algorithms of machine learning [39], which potentially can provide a more adaptive and personalized synchronization of stimulation with the individual features of the pathological gait in a patient.

EXTERNAL ACCESSORIES FOR THE MOTION ORGANIZATION

The complete correction of known disorders when walking using FES is not possible for the majority of patients, which is why, during the course of stimulation, as well as in everyday life, the patients continue to receive aid with special technical means that not just assist the movement, but also organize it. Such technical means include both the simple ortheses for supporting the normal positioning of the ankle joint [40] and much more sophisticated training equipment along with walking imitators, the robotic devices and neuroprostheses [41]. As of today, the hybrid set including the exoskeleton combined with FES is estimated as one of the most promising technologies for restoring the walking function. In a number of research works, it was noted that using FES causes the rapid onset of muscular fatigue [42], which, in turn, decreases the ability of the muscles to maintain or produce the contraction force and significantly decreases the training session time. Based on this, attempts were made to combine FES with passive orthesis [43], which was used to dampen the consequences of muscular fatigue, but these devices failed to provide an additional torsional moment required, in particular, for the knee joints. Autonomous exoskeletons [44, 45] can compensate this and other moments: in this combination, the supportive robotic aid decreases the general operating cycle of muscle contractions induced by FES, also delaying the onset of muscular fatigue during the course of physical exercises with high torsional moment, such as the “sit-stand”. Besides, active muscle contractions induced by FES, promote to the neuroplasticity that restore the lost functioning of the limb, unlike the electrically driven exoskeletons, which provide only passive motions [46].

Exoskeletons with integrated FES have appeared on the Russian medical market at the beginning of 2020s. The topic of integration was discussed previously [47], which lead to the increase in the number of such devices offered at the national medical market and allowed for arranging a research on the combination of FES when moving with the aid of the exoskeleton among the patients after a cerebral stroke [48, 49]. The authors have revealed a positive effect for the immediate and early rehabilitation periods, however, so far the experience of using such devices is significantly limited.

Table 2

Stimulation parameters

Frequency	Frequency, Hz	Single impulse duration	Session duration, min	Current, mA	Number of sessions per week	Course duration, weeks	Synchronization method
Hakansson, 2011 [22]	30	300 msec	30	-	3	12	Contact switches
Tenniglo, 2018 [23]	40	125–475	-	-	3	5	Contact switches
Nam, 2019 [37]	80	300	15	-	5	4	Contact switches
Kojović, 2009 [27]	50	400 μsec	45	12–38	5	4	Accelerometer/ contact switches
Kesar, 2010 [11]	30	300 μsec	20–30	Not provided	3–5	4	Gyroscope / Goniometer Contact switches
Yang, 2009 [18]	40	250 μsec	20	Not provided	5	4	Contact switches
Sabut, 2010 [14]	40	300 μsec	First week: 15 Following weeks: 30–45	20–60	5	12	Contact switches
Sabut, 2011 [15]	35	280 μsec	60	-	5	12	Contact switches
Tan, 2014 [16]	30	200 μsec	30	Not provided	5	3	EMG in the contralateral limb
Yan, 2005 [17]	30	300 μsec	60	20–30	5	3	Manual trigger at the swing phase
Bloemendaal, 2016 [26]	35	350 μsec	30	10–50	5	4	Contact switches (force)
Lee, 2013 [32]	Not provided	50 μsec	30	Not provided	5	4	EMG-activity
Alon, 2011 [33]	50	250 μsec	30	Not provided	3	8	Synchrodrive
Sharif, 2017 [31]	40	Not provided	20–30	Not provided	5	6	-
Dantas, 2023 [38]	-	-	30	-	2	6	Accelerometer
Purohit, 2024 [24]	20–45	450 msec	45	30–55	-	-	-
Allen, 2018 [20]	Not provided	Not provided	30	Not provided	3	6	Contact switches
Ji, 2022 [39]	30–45	200–350 μsec	25	25–70	4	5	Inertial + machine learning
Moe, 1962 [10]	30	0.1–0.5 msec	15	Not provided	5	6	Manual trigger at the swing phase
Cheng, 2010 [28]	40	200–300 μsec	30	Not provided	3	4	-
Kluding, 2013 [40]	30–50	200 μsec	30	Not provided	2	30	Contact switches
Thrasher, 2006 [41]	35	300 μsec	15–30	18–110	2–5	12–18	Manual trigger at the swing phase
Bao, 2020 [42]	30	0.3	45	15	5	8	Contact switches

https://doi.org/10.17816/clinpract684717

journal of clinical practice ISSN 2220-3095 2025 Vol 16 №2

Due to the fact that the main function of the exoskeleton is the decrease of the excessive monotonous loading and easing the hard work of the nursing medical staff [50], the usage of additional methods of increasing the training efficiency is deemed justified. In a later research work by M.T. Dantas et al. [38], it was noted that FES, undoubtedly, positively contributes to the training among the post-stroke patients using the exoskeleton and proposes an adaptive stimulation algorithm with taking into consideration the motion amplitude developed.

THE STAGING OF TEACHING THE MOTOR SKILLS

The process of teaching the motor skills can and must be analyzed stagewise [51]. Even though, in practice, the transition from one stage of learning the motor skills to another is smooth and it is not always clearly understandable at which specific stage the patient is currently, three phases can be isolated — the initial, the associative and the autonomous.

At the initial stage of learning the motor skills, or at the so-called cognitive stage, in order to master a specific motor task, various strategies are employed for selecting the optimal motion variant. The support from the rehabilitation therapist at this stage is extremely important and, depending on the degree of deficit in a patient, it can be implemented either in the form of physical or the verbal feedback [52].

When transitioning to the associative stage of learning, the patient demonstrates a sharper skill of the motion trained. The motor training task is done with lesser variability, until the optimal strategy could be finally found [53]. From this moment, the specialist shall restrain from manual support, but the target feedback is still important. This feedback should be provided with a delay relative to the motor task to avoid overlapping with the inner feedback for the motion control [54]. After the motion strategy is defined, the training sessions can be modified a little.

The autonomous stage suggests mainly the automatic motor skill, the task should be repeatedly modified until the moment of the patient being capable of doing it in any type of environment conditions. At the autonomous stage of motor learning, the program is already automated: this means that the motion can be done in the almost optimal manner, not requiring significant attention or concentration [53]. At this stage, it is possible to more precisely focus on the separate components of motion to preserve them. Variations of exercises, as well as the inclusion of higher difficulty elements, are now necessary for supporting the motivation of the patient [52].

THE EFFICIENCY OF FUNCTIONAL ELECTROSTIMULATION AND THE TECHNICAL ASPECTS

In a randomized research by Z. Tan et al. [16], the efficient rehabilitation cycle lasted for 3 weeks, while the improvements could persist within at least 3 months upon the end of the course. Special attention is attracted by the time of the onset of the possible positive FES effect, for example, the increase of the walking speed. It was noted that the gradual increase of this parameter occurs when using FES within the first 18 weeks, but later on no changes could be observed [40].

In the accessible literature, researchers do not emphasize in any manner the clinical form of stroke and which time period exactly after the CVA is the best to initiate training. In a research by T.M. Kesar et al. [11], it was reported that FES is used to restore the lost or abnormal motions. Nevertheless, the most effective FES is considered the one that was initiated at the subacute stage of stroke, usually within several weeks or months after a cerebrovascular accident, for this period has the fundamental importance for the maximal restoration of motor activity and for functional improvement [31]. Arranging the FES in 6 months from the moment of disease onset is also considered as effective, for the sessions allow for preserving or improving the walking function and mobility, though the speed of developing the functional changes is already not so high [21]. According to the data from the review by Z. Hong et al. [29], FES also remains effective in patients at the chronic stage of stroke. It was shown that the quality of walking could be improved along with its symmetry when using the stimulation of the anterior tibial muscle and of the triceps muscle of the calf in patients with insufficient motion control in the ankle joint. In one of the recent systematic reviews, the authors make a cautious conclusion that FES can be more effective for patients exactly at the chronic phase [30]. Similar conclusion was drawn up in the research by M.J. Nam et al. [37]: based on the proprietary data, the authors recommend FES for patients at the chronic stage of stroke.

Among the technical aspects of arranging the FES, the importance of correct positioning of electrodes at the stimulated muscles was noted: in order to fulfill this task, it is necessary not only to have the knowledge of functional anatomy, but also the possibility of individual approach in each specific case. At the present moment, there is a general rule for the positioning of electrodes: the electrodes are first placed above the nerve(s) innervating the stimulated muscle, after which stimulation is undertaken. If the resulting motion is desirable, the positioning remains. In case of the negative result, the electrodes should be repositioned (usually by not more than several centimeters) and the test should be repeated until achieving the desired motion, with this, the patient should have the motivation for conducting the FES [55]. The majority of manufacturers of such an equipment provide the stereotypical schemes of electrode positioning without taking into account the places were the nerves originate, but recommending that the main belly of the muscle is positioned between the electrodes. In this case, the property used for the applied stimulation is the direct excitation of muscle fibers.

DISCUSSION

The majority of research works on FES is still focused on the single-channel stimulation for compensating the foot drop syndrome [20–22], with this, the multi-channel stimulation in various forms is recognized as more effective, however, it is much less frequently applied. There are various variants of it, but the main ones include four groups of flexors-extensors of the lower limb: the quadriceps muscle of thigh (or its separate head), the posterior group of thigh muscles (or separate muscles), the anterior tibial muscle and one or both gastrocnemial muscles. Our analysis has shown that the clinical reports on using the MFES in patients after an episode of cerebral stroke were quite few. There are only single ones that are modern. With this, there are publications submitted over the last years which are of technical or experimental nature and fall outside the ranges of the inclusion criteria for this review.

The duration of the FES session significantly varies (from 15 to 60 minutes), with the absence of justification for this or that duration provided by the authors. In fact, the spread of the parameter values, where the minimal value is 4 times less than the maximal one, speaks for itself. The FES parameters were also not matching the physical stamina of the patients. It is evident that this or that duration should be manageable for the whole test group, but this is all that could be suggested taking into consideration that the patients with similar clinical form and the degree of hemiparesis can show various exercise tolerance and, probably, require different timings of FES sessions. Our suggestion is that the specialists involved into performing the FES sessions commonly remain within the frames of treatment schemes approved, in which the session time is some kind of a constant not anticipating any individual approach.

The number of procedures per week is also subject to variability, mainly within the range from 3 to 5. This aspect is also presented as a constant with no discussion, why this or that number is used. Evidently, it is related to the organizational aspects of the rehabilitation process, not to the physiological justification. The trend of arranging 5 sessions a week, as it is set in the research works by J.S. Cheng [28] and T. Yan [17], can be resulting from the reference to the number of work days and not the optimal stimulation mode. For the first case (3 days a week) they come every other day (Monday, Wednesday, Friday), while for the second one (5 days a week) — all the work days. Thus, even this parameter is not in fact related to the clinical form or to the status of the patient.

The duration of FES course varies with a factor of eight — from 3 to 24 weeks, with this, the number of authors report that the longer the course is, the higher is its efficiency [23]. The objective criteria for the duration of a certain course were also not provided by the authors. It can be agreed that the changes in the walking function as a result of cerebral stroke by no means can be restored in all the cases. The remaining stable abnormalities require supporting activities for the life term, and in this context, the long-term courses can be surely justified. But it seems that the judicious balance here will depend on very numerous factors, including the system of organizing the rehabilitation therapy, and it is still not the object of research.

As for the modes of used FES, the majority of research works use constant frequency. This aspect is also not supported by any explanations: the authors just state the name of the equipment used. And here, the most important role is played by two circumstances. The first one that the stimulation devices with constant frequency are technically much simpler and more available for use [56]. These reasons are already enough to have the overwhelming dominance in the research works. Second off — the methods with variable frequency are not just incomparably more complex: the experience of their application is very limited, while the criteria for controlling the new variable (the frequency) are even less clear, with the effect of decreased spasticity — the one of the essential ones — is reported for the stimulation with constant frequency current [57]. Besides, it is known that various muscles, even at the normal conditions, have various sensitivity and response to changing the frequency at various activity phases [58], and we have even less understanding of the various conditions of muscles in patients after a cerebral stroke, depending on its specific form. Besides, it is necessary to note that applying the data for healthy muscles to the muscles with pathological neuromuscular regulation is still not possible. Another essential moment is that the

https://doi.org/10.17816/clinpract684717

journal of clinical practice ISSN 2220-3095 2025 Vol 16 №2

pathological locomotion itself results in changes in the functions of the muscles [56], due to which, the cause and effect can not always be clearly differentiated.

The analysis of published research data demonstrates significant variability in the parameters of electric stimulation. The stimulation frequency in the majority of research works varies from 30 to 50 Hz [16, 17, 22, 27], though separate articles describe both the lower (20–45 Hz [24]) and significantly higher (80 Hz [37]) frequencies. The 30–50 Hz frequency has a certain physiological justification [58], however, for patients after a cerebrovascular stroke presenting with hemiparesis, the status of the muscles changes from the immediate to the residual period. What frequency for which type of muscle impairment and at what phase would be the best, remains disputable.

The duration of impulses also significantly differs — from 50 μsec [32] to 450 μsec [24], with the most commonly used range being the 200–350 μsec. The impulse duration has a number of justified criteria [58], but what needs to be taken as guidance when determining this parameter for each specific muscle in the given patient remains unclear. With other factors being equal, the longer impulse carries more energy, but this is probably and so far the only evident criterion to be used to achieve the required response from the muscle.

The current amplitude, where provided, usually varies from 10–12 to 60–70 mA with an individual adjustment for each patient. Oftentimes, the amplitude is not reported in the research at all, and this is not a mistake made by the authors. The thing is that this parameter is too much related to many other factors, among which are the following: the surface area of the electrodes employed, the stimulated muscle itself and its status, the thickness of subcutaneous-fatty tissue, some technical features of the stimulating channel etc. Thus, even when the current amplitude is mentioned, this can only serve as the guiding point.

It is important to note the absence of unified criteria for choosing the stimulation parameters for specific groups of patients. The majority of protocols are developed empirically, without the clear justification of selecting these or those parameters. S. Chen et al. [30] in their research note the urgent need for studying the specific features of operating with FES with various adjustments of stimulation frequency and other parameters.

The topic of synchronizing FES with walking is technically the most complex. The method of contact switches, which is used in the majority of cases, is the result of permissible simplification. The contact sensors themselves are used for various types and constructions, but they operate in harsh conditions of the body weight affecting them and, with this, they need to have a low activation threshold and a short (within milliseconds) hysteresis (returning to initial conditions upon the removal of the load). These issues fall outside the frames of solely medical field, however, in the current century, new methods were proposed for detecting the step cycle phase, in particular, the inertial sensors, which at the present moment have almost completely replaced the contact sensors in the autonomous systems for the correction of foot drop. Synchrodrives can be used only as a part of robotic devices with walking imitation, which limits their usage. The methods for initiating a pack of stimulating impulses based on the EMG-activity detection is another new method. From the methodical point of view, it can be deemed adequate only for the muscles which have no phasic activity impairments. In other cases, this method is inapplicable. How precisely the EMG-signal can detect the time parameters of synchronization, also remains disputable. In one of the research works [16] this method was used in the modification that employed the unaffected side for initiating the FES on the paretic one. Such a variant can not be considered as good or applicable for the reason that the EMG-activity on the unaffected side is not compensatory modified, but also the step cycles themselves have substantial reciprocal shifts [7] i.e. the shifting of step cycles relative to each other is present, which may reach the values of 10–30% of the step cycle. Thus, the error of “detecting” the step cycle becomes unacceptable. Nevertheless, the synchronization based on the EMG-activity can be a very reasonable choice for voluntary movements, but it is already out of the frames of the walking function. The manual option of activating FES might as well have only the historical value due to its extreme inaccuracy.

There is no doubt that, in cases of significantly impaired walking biomechanics, its feasible correction may be required. The matter if it is possible to achieve the decrease in the degree of motor disorders by this, remains unexplored and requires further research activities. At what degree and for which clinical cases the exoskeleton or other devices with integrated stimulation system could be useful, the results of further research works will show.

The staging of rehabilitation can serve the purpose of the individual estimation of the current status of the patient and its dynamic changes, with this in mind and with all the other factors being equal, it gives ground for using the MFES method from the first days of starting to teach the patient to move without assistance.

It could be stated that there is no existing all-purpose MFES protocol fitting all the patients with a history of cerebrovascular stroke. The differentiated approach is necessary, the one taking into account several key factors, the most important of which are the following.

Type of motor disorder. For the patients with predominant decrease of muscle strength without pronounced spasticity, the effective stimulation could be the one having the parameters aimed at strengthening the muscles and at improving their stamina (low frequency — 20–30 Hz, longer sessions). In patients with significant spasticity, the more effective could be the mode with high stimulation frequency (more than 50 Hz) [15, 57].

Rehabilitation period after a cerebrovascular stroke. At the immediate and the early period of rehabilitation, MFES can contribute to the prevention of developing pathological motor stereotypes and could be a valuable addition to the traditional methods of rehabilitation. At the residual stage, MFES can be especially useful for overcoming the rehabilitation plateau and for improving the functional capabilities [30].

Cognitive abilities of the patient. For patients with cognitive disorders, the more preferable could be the systems with automatic synchronization, not requiring the active participation of the patient in the stimulation process. For patients with intact cognitive functions, the more effective systems could be the ones with biological feedback, requiring the active participation of the patient [52].

CONCLUSION

Multi-channel functional electrostimulation is considered an effective method of restoring the walking function in patients after a cerebrovascular stroke, however, the existing application protocols are characterized by the significant variability of parameters without the clear physiological justification. It was found that the recommended duration of procedures varies from 15 to 60 minutes, the stimulation frequency — from 20 to 80 Hz, while the course duration — from 3 to 24 weeks, with the choice of specific parameters having a predominantly empirical pattern and depending on the organizational factors, not on the clinical status of the patient. A necessity was demonstrated for developing a differentiated approach to the application of MFES with taking into consideration the type of motor disorder, the period of rehabilitation after a cerebrovascular stroke and the cognitive capabilities of the patient. The optimal technical parameters of stimulation were defined: 30–50 Hz frequency, 200–300 μsec impulse duration with individual adjustment of amplitude and obligatory synchronization with the step cycle in the paretic limb. Modern trends of improving the method include the integration of MFES and of the robotic devices and systems with biological feedback, which opens new possibilities for personalized rehabilitation. The obtained results justify the necessity of arranging large-scale clinical research for the standardization of MFES protocols and for compiling the scientifically justified recommendations on its use in various clinical situations.

ADDITIONAL INFORMATION

Author contributions. *D.V. Skvortsov:* research concept development, literature search and analysis, writing the original draft; *L.V. Klimov:* literature search, data analysis, editing, and results interpretation; *D.A. Lobunko:* literature search, text editing, and data visualization; *G.E. Ivanova:* project supervision and organizational support. The authors made a substantial contribution to the conception of the work, acquisition, analysis, interpretation of data for the work, drafting and revising the work, final approval of the version to be published and agree to be accountable for all aspects of the work.

Funding sources. The work was carried out as part of the R&D project “NeuroStim 2024” [LOS1] Reg. No. EGISU R&D 124031100047-5.

Disclosure of interests. The authors have no relationships, activities or interests for the last three years related with for-profit or not-for-profit third parties whose interests may be affected by the content of the article.

Statement of originality. The authors did not use previously published information (text, illustrations, data) while conducting this work.

Data availability statement. The editorial policy regarding data sharing does not apply to this work, data can be published as open access.

Generative AI. Generative AI technologies were not used for this article creation.

Provenance and peer-review. This paper was submitted to the journal on an initiative basis and reviewed according to the usual procedure. Two external reviewers and the scientific editor of the publication participated in the review.

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https://doi.org/10.17816/clinpract684717