ACTA FACULTATIS
MEDICAE NAISSENSIS

UDC: 617.57-085.84:616.8-009.11
DOI: 10.5937/afmnai40-39107

Review article

Functional Electrical Stimulation of the Upper Extremities of Persons with Quadriplegia

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SUMMARY

Introduction. Traumatic injury to the cervical segment of the spinal cord causes disability and quadriplegia. Upper extremity mobility and restoration of hand function for people with quadriplegia is a priority. With coordinated electrical stimulation of peripheral muscles and nerves, known as functional electrical stimulation (FES), this is possible. Upper limb stimulators are designed to increase the physical function and are controlled by users through preserved, uncoupled and limited voluntary movements.
Aim. By reviewing the available literature, the aim of the paper was to prove the importance of FES in motor control and functional ability of the upper limbs of people with quadriplegia.
Material and method. Using the keywords "quadriplegia", "FES", "upper extremity", "functional ability", "motor control" and "traumatic injury", the three authors searched the databases PubMed, EMBASE, SciELO, BMC, Academia according to pre-established criteria. Edu, Web of Science and Science & Technology (November 2021 – March 2022). Potential papers were selected using the Jovell and Navarro-Rubio classification of study design. Papers older than five years, papers that were not available in their entirety, or in English, were excluded. Fifty-seven papers were classified, and six were included in the research.
Results. Functional electrical stimulators improved the functional ability of the upper extremities shortly after application. They cause neurophysiological changes in the central nervous system and cortical reorganization depending on the synchronization of the voluntary command and the successful execution of the planned task. Sensory stimulation is important in the preservation of neurological function because by synchronizing the voluntary command and successfully executing the planned task, neuroplasticity is stimulated.
Conclusion. With the emergence of more research and analysis of the obtained results, we can expect the creation of new programs to improve the recovery process of the upper extremities, a greater degree of independence in daily life activities, and a better quality of life for people with quadriplegia.

Keywords: **upper extremity, quadriplegia, rehabilitation, electrical stimulation therapy**

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INTRODUCTION

Quadriplegia is the most common neurological category that occurs after a traumatic injury to the cervical part of the spinal cord and causes significant disability. The residual strength of partially paralyzed muscles is an important determinant of independence in the functioning of these individuals. Any improvement in the function of the upper extremities can make a significant difference in their daily activities, and advances in rehabilitation technologies make this possible (1).

Impairment of hand and hand function is directly related to the loss of levels of functional independence, so the recovery of upper extremity movements is essential for rehabilitation. Tendon transfers, orthoses, and neuromuscular electrical stimulation (NMES) have been used to improve sensory and motor deficits (2). NMES is the application of electrical stimulation in movement rehabilitation that produces contraction of innervated paralyzed muscles, increases strength, creates movement, and increases participation in voluntary activities (3).

Functional electrical stimulation (FES) is a subtype of neuromuscular stimulation in which coordinated electrical stimulation of peripheral muscles and nerves helps to establish functional and purposeful movements (3, 4). The system consists of an electrical stimulator, stimulation electrodes, sensors for stimulation control and orthoses to perform the desired movement. The stimulator generates electrical discharges that produce muscle contraction and stimulation is possible through a stimulation channel consisting of a cathode and an anode. Orthoses create movement when stimulation alone is not enough because they save energy and reduce muscle fatigue (3).

Stimulation is obtained by means of fully or partially implanted electrodes on the surface of the body or near the target nerves. This system is interactively managed by the user, control and management unit. FES is powered by a battery that uses information from users and sensors, transforms them into commands and transmits radio frequency signals to the stimulator. Control is achieved by means of a breath switch, myoelectric signals or a voice recognition sensor, which achieves palmar, lateral and lumbar grip (3, 4).

The most widely used FES capture systems are Rebersek and Vodovnik (The Wireless Hand Rehabilitation System-NESS H200), FESMate system (NEC Medical Systems - FESMate), Freehand system and bionic glove, and to achieve COMPEX Motion, Belgrade system and MyndMove. With the advancement of rehabilitation engineering, FES has been upgraded to a functional electrical stimulation therapy (FEST) system in which the user tries to perform a functional motor task, FES produces movement and generates correct sensory feedback, and physiotherapist ensures quality and correctness of movement. By integrating FES with the brain-computer interface (BCI) neuroprosthesis, it is possible to conduct brain signals into control commands with the simultaneous presence of motor command and sensory information, so FES stimulated by changes in the nervous system produces movements that lead to the restoration of voluntary movement (3).

Functional electrical stimulation is a promising intervention in improving motor control and functional ability of the upper extremities in people with quadriplegia (4 - 6). It causes neurophysiological changes in the central nervous system and cortical reorganization that depends on the ability to synchronize the voluntary command and the successful execution of the intended task (7). Reaching and grasping movements assisted by neuromuscular electrical stimulation can produce motor patterns and are used for functional motor training (2).

Evidence suggests that intensive training with the FES system, focused on a specific task, improves hand function and to date, several high-quality randomized controlled trials have been conducted that confirm this (8).

The aim of this paper is to review the available literature to examine the evidence on the importance of functional electrical stimulation on motor control and functional ability of the upper extremities in people with quadriplegia.

MATERIAL AND METHOD

This paper is a systematic review of the literature which includes original professional and scientific papers and abstracts published in electronic databases PubMed, EMBASE, SciELO, BMC, Academia Edu, Web of Science and Science & Technology and concern the importance of functional electrical stimulation in improving the function of the upper extremities in people with quadriplegia. Searching for the keywords "electrostimulation therapy", "functional ability", "motor control", "traumatic injury", "upper extremity" and "quadriplegia", the three authors reviewed 57 papers from November 2021 to March 2022. Initial data selection was based on the title and abstract selected and evaluated by the authors using the Jovell and Navarro-Rubio classification for studio design. All misunderstandings were resolved through discussion. The selection of papers is shown in the flow diagram of the reviewed literature (Chart 1).

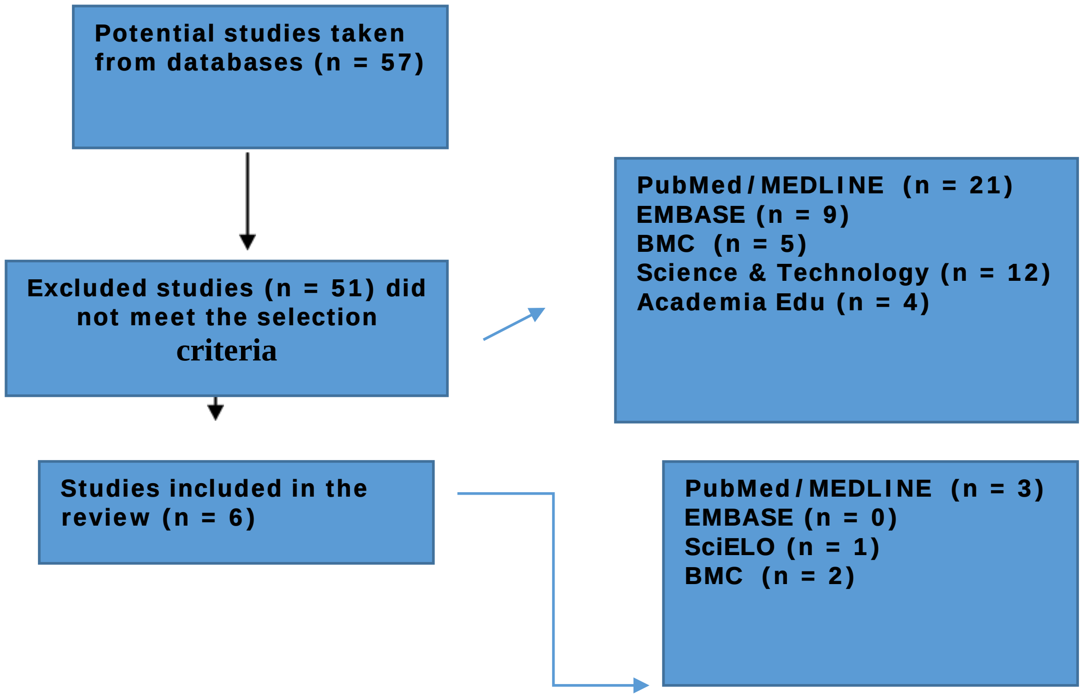

Chart 1. *Flow chart of literature review selection*

The criteria for inclusion in the research were papers published in their entirety in English, in the period from January 2017 to January 2022 (five-year period), which investigated the use of FES in integration with other systems, in adults, with complete and partial traumatic injury of the cervical segment of the spinal cord (level C4-C7) in the subacute and chronic phase of rehabilitation. Randomized controlled trials, clinical trials, systematic reviews, and case reports were considered. All papers had to be thematically related to the title of the research. The research excluded papers that were published before 2017, papers that were not published in their entirety and papers that were not written in English. Papers that are not thematically closely related to the title of the research have not been considered.

RESULTS

A review of titles and abstracts excluded irrelevant papers and then evaluated all potentially relevant papers to determine if they met the inclusion criteria. The search resulted in six studies (four clinical and two case studies) that met the established criteria. Data extraction (subject characteristics, type of FES used, outcome measures) and methodological assessment of the quality of the selected studies were then undertaken using the Jovell and Navarro-Rubio classification system for study design.

This system rates evidence from meta-analyses and large randomized controlled trials (RCTs) as "good" (evidence level I and II), small RCTs (evidence level III), non-randomized controlled trials (evidence level IV) and non-randomized controlled retrospective studies (level of evidence V) as "good and correct". The evidence from cohort studies and case-control studies is “fair” (levels of evidence VI and VII) and from uncontrolled studies and case reports “poor” (levels of evidence VIII and IX) (9) (Table 1).

Applying this classification system, one prospective clinical study had methodological score IV, one clinical study methodological score V, two clinical studies had methodological score VI and two case studies had methodological score VII (Table 2).

The age of the participants in the included studies was between 19 and 58 years, the neurological level of the injury was C3-C7, and the time since the injury was six months to three years (Table 3).

The outcome measures of the International Classification of Functioning, Disability and Health (ICF - International Classification of Functioning, Disability and Health) were used: Graded Redefined Assessment of Strength, Sensitivity and Prehension (GRASSP), grip strength test for measurement of specific functions (Grasp and Release Test-GRT), Action Research Arm Test (ARAT), functional independence test (The Functional Independence Measure-FIM), myometric grip of the functional activity of the

Table 1. *Jovell and Navarro-Rubio study design classification (1995)*

Level of evidence	Level of evidence	Type of study desig
I	Good	meta-analysis of RCI
II	Good	RCI large sample
III	Good to correct	RCI of small samples
IV	Good to correct	Non-randomized controlled prospective trials
V	Good to correct	Non-randomized controlled prospective trials
VI	Poor	Real cohort studies
VII	Poor	Case-control studies
VIII	Poor	Uncontrolled clinical series-descriptive studies
IX	Poor	Case reports

Abbreviation: Randomized controlled research (RCI)

Table 2. *Classification of included studies*

No.	Author	Name of study	Study desin	Level of evidence
1.	Cacho et al.	Reach and palmar grasp in tetraplegics with neuromuscular electrical stimulation	A series of cases	IV
2.	Jovanović et al.	KITE-BCI: A brain-computer interface system for functional electrical stimulation therapy	Clinical trial	V
3.	Ajiboye et al.	Restoration of reaching and grasping movements through brain-controlled muscle stimulation in a person with tetraplegia: a proof-of-concept demonstration	Clinical trial	VI
4.	Likitlersuang et al.	EEG-controlled functional electrical stimulation therapy with automated grasp selection	Case report	VI
5.	Bockbrader et al.	Clinically significant gains in skillful grasp coordination by an individual with tetraplegia using an implanted brain-computer interface with forearm transcutaneous muscle stimulation	Case report	VII
6.	Thorsen et al.	Myoelectrically controlled FES to enhance tenodesis grip in people with cervical spinal cord lesion	Clinical trial	VII

Table 3. *Study characteristics*

No.	Author	Aim of the study	Intervention	Participiants	Time of injury	Age	Level of injuries
1.	Cacho et al.	Assessment of NMES-assisted movement strategy in reaching and capturing objects of different weights	Microcomputer-controlled NMES	4	7 - 9 years	31	C5-C6
2.	Jovanović et al.	Difference in stimulation latency triggered by BCI and therapist iBCI	Integrated brain-computer interface (BCI) and FES	8	1 - 24 months	46	C4-C5
3.	Ajiboye et al.	iBCI control of paralyzed arm with control of virtual 3D arm resuscitated through	implanted FES iBCI and percutaneous FES	1	8 years	53	C4
4.	Likitlersuang et al.	Evaluation of a FES system designed for voluntary movement through the use of a brain-computer interface (BCI) and a computer vision module (CV).	Integrated BCI-CV-FES system	1	1 years	45	C6
5.	Bockbrader et al.	Demonstration of motor speed control, coordinated capture and transmission of the BCI-FES facility	BCI-FES	1	Not registere d	27	C5
6.	Thorsen et al.	Usability and need for MeCFES as an auxiliary device of MeCFES	MeCFES	27	7 months	36	C5-C7

Abbreviation: * functional electrical stimulation (FES), ** brain-computer interface (BCI), *** intracortical brain-computer interface (iBCI), **** computer vision modules (CV) -form of computer module, ***** neuromuscular electrical stimulation (NMES), ****** myoelectric controlled functional electrical stimulation (MeCFES)

upper extremities (The Capabilities of the Upper Extremity Test-CUE-T), quadriplegia index - short form (The Quadriplegia Index of Function Short Form-QIF-SF), spinal cord independence test (The Spinal Cord Independence Measure-SCIM), monitoring of activities of daily living (Activities of daily living -ADL), Individually Prioritized Problem Assessment (IPPA) and the evaluation of user satisfaction with assistive technology (The Quebec User Evaluation of Satisfaction with Assistive Technology-QUEST).

A prospective clinical trial by Cacho et al. (2) conducted in order to assess the movement, reaching and grasping of various objects with the help of neuromuscular electrical stimulation included four male participants (injury level C5-C6) aged 31 years. During the ten-week intervention with electrical stimulation, ten sessions of strengthening the muscles of the dominant hand (20 minutes) and ten sessions of functional reaching and grasping training (30 minutes) were applied. Two participants (injury level C6) adapted movements with reduced wrist flexion during extension. The third participant (injury level C5) improved wrist extension, opening and palming the cylinder, while the fourth (injury level C7) increased the flexor phase and contributed to wrist flexion and finger extension in the hand opening phase and wrist extension and finger flexion in the closures (2).

The first concrete evidence of the restorative effects of electrical stimulation therapy was given by Popović, emphasizing the effectiveness of the Bionic Glove system (fingerless gloves equipped with a wrist position sensor and an electrical stimulator in which surface electrodes stimulate stretching and bending (3). Six months after use, this system improved the function of the upper extremities, increased grip, strength and range of motion in the chronic phase in individuals with incomplete spinal cord injury (level of injury C4–C7) (10).

The combined integration of FES and BCI as a therapeutic intervention is significant in restoring voluntary movement because the FES system produces a lateral grip and opens the hand, and the BCI (implemented as a brain switch) is activated by imagined movements, which leads to a unique increase in the power of electroencephalographic activity (11,12).

Jovanović, Popović, Marquez-Chin (13) integrated BCI and FES to monitor the motor rehabilitation of the upper extremities in five participants (injury level C4-C5) in the subacute phase and three participants (injury level C4) in the chronic phase. Performance carried out with one hand during 40 sessions resulted in successful activation of the total number of signaled movements in both groups (74.46% and 79.08%) and improved motor strategy of the upper extremities (13).

Two years after the implantation of FES and BCI neuroprostheses for the restoration and coordinated grasping, Ajiboyea et al. (14) analyzed the ability of the cortical control of the paralyzed arm to perform single-joint movements of the arm and hand into functional multi-joint movements. In 53 year-old participants (injury level C4), the application of intracortical microelectrodes in the area of the motor cortex and 36 implanted percutaneous electrodes in the area of the upper arm and forearm stimulated the muscles of the hand, elbow and shoulder. Cortical command of single-joint and coordinated multi-joint movements for point-to-point targets using virtual and FES-animated hands was successfully performed with 80 - 100% accuracy. Progress in reaching and grasping led to independent voluntary movements (participant successfully drank coffee 11 times out of 12 attempts 463 days after implantation and ate food 717 days) (14).

Using electrocorticographic signals (EcoG) in lateral and palmar grips, the FES system can allow a person with a C6 injury to select an ECoG activity (right, left, or wrist flexion). The system classifies the randomly selected signal and initiates the movement preset by the neuroprosthesis. Correct classification of ECoG signals can trigger predetermined hand movements (15).

Likitlersuang et al. (16) assessed voluntary movement attempts by implementing a Compex Motion stimulator, integrating a BCI and computer module (CV) system. COMPEX Motion is a four-channel stimulator with surface electrodes and stimulation of reaching and grasping in which bimanual tasks and fine manipulation of finger movements are facilitated by programming the duration of amplitude and frequency (3). In participants with a level of C6 injury, attempts of voluntary movements and repeated different functional grasps when choosing one of eight objects resulted in a classification accuracy of 87.5% and an average latency to initiate the movement of 5.3 ± 9.4 seconds. Repeated simultaneous movement attempts and sensory feedback result in FES that produce neuroplastic changes and influence the restoration of voluntary motor function (16).

By examining motor control, speed, coordinated grasping and transfer from one object to another, Bockbrader et al. (17) observed skillful coordinated grasping and significant improvement in upper extremity function tests in 27-year-old participants (injury level C5). After BCI and FES implantation, the following improved: grip strength (2.9 kg), ARAT cup, cylinders, ball, rod and blocks, GRT can, fork, wedge, weight and tape, GRASSP strength and grip (unscrewing lids, pouring from bottles, carrying pegs), QIF-SF and SCIM-SR feeding, grooming and toileting activities. These skills facilitated manipulation of household objects and contributed to participation in adapted social play (17).

Thorsen et al. (18) applied myoelectric controlled functional electrical stimulation (MeCFES) to 27 participants (injury level C5-C7) in 12 sessions of 2 h each to perform self-selected priority activities that include tenodesis grip. The IPPA score of 4.6 (STD: 3.5, effect size: 1.3) showed the relief of problematic tasks and significant improvement of hand function in all subjects, and fourteen of them considered this system useful and expressed the need for such a neuroprosthesis (18).

CONCLUSION

By searching the literature, our research confirmed that functional electrical stimulation is important in the rehabilitation of people with quadriplegia because it encourages neuroplasticity, restores motor functions, strengthens hand muscles and improves the function of the hand and fingers through functional training of reaching and grasping.

The integration of brain-computer interface technology with functional electrical stimulation therapy in the motor rehabilitation of the upper extremities induces the appearance of voluntary movements and independence in activities of daily living.

With the emergence of an increasing number of researches and the analysis of the obtained results, we can expect the creation of new programs that will speed up the recovery process of the upper extremities, a greater degree of independence in the activities of daily life, and thus a better quality of life for these patients.

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Article info
Received: July 12, 2022
Revised: November 27, 2022
Accepted: December 1, 2022
Online first: May 18, 2023

Review article

Funkcionalna električna stimulacija gornjih ekstremiteta osoba s kvadriplegijom

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SAŽETAK

Uvod. Traumatska povreda cervikalnog segmenta kičmene moždine uzrokuje onesposobljenje i kvadriplegiju. Mobilnost gornjih ekstremiteta i obnavljanje funkcije šake su prioriteti oporavka, a funkcionalni električni stimulatori (*Functional electrical stimulation* – FES) to i omogućavaju. Funkcionalni električni stimulatori za gornje ekstremitete dizajnirani su u cilju povećanja fizičke funkcije kod ovih osoba.
Cilj. Pregledom dostupne literature, objavljene u relevantnim elektronskim bazama biomedicinskih podataka, cilj rada bio je naći dokaze o značaju funkcionalnih električnih stimulatora u funkciji gornjih ekstremiteta i motoričkoj kontroli osoba s kvadriplegijom.
Metode. Korišćenjem ključnih reči „kvadriplegija", „FES", „gornji ekstremitet", „funkcionalna sposobnost", „motorna kontrola" i „traumatska povreda" tri autora su prema unaprijed utvrđenim pravilima pregledala dostupne radove objavljene od 2017. do 2022. godine. Nakon isključenja radova starijih od pet godina, radova čiji pun tekst nije bio dostupan i onih koji nisu pisani na engleskom jeziku, selektovano je 57 radova, od kojih je šest odabrano za istraživanje.
Rezultati. Funkcionalni električni stimulatori poboljšavaju funkcionalnu sposobnost gornjih ekstremiteta neposredno po primjeni i nakon nje. Izazivaju neurofiziološke promjene u centralnom nervnom sistemu i kortikalnu reorganizaciju, koja zavisi od sinhronizacije dobrovoljne komande i uspješnog izvršenja predviđenog zadatka. U cilju očuvanja neurološke funkcije bitna je senzorna stimulacija, jer je neuroplastičost podstaknuta sinhronizacijom dobrovoljne komande i uspješnim izvršenjem predviđenog zadatka.
Zaključak. S obzirom na pojavu sve većeg broja istraživanja i analizu dobijenih rezultata, može se očekivati kreiranje novih programa koji će ubrzati proces oporavka gornjih ekstremiteta, veći stepen samostalnosti u aktivnostima dnevnog života, a samim tim i bolji kvalitet života osoba s kvadriplegijom.

***Ključne riječi*: gornji ekstremitet, kvadriplegija, rehabilitacija, terapija električnom stimulacijom**