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Review Article

Functional Electrical Stimulation Cycling: A Comprehensive Review of Contemporary Evidence and Recent Advancements

A. Brammatha[1,2]*, MK Franklin Shaju[3] and Kannabiran B[4]

[1]*Ph.D. Scholar, RVS College of Physiotherapy, The Tamil Nadu Dr. M. G. R. Medical University, Chennai, India*

[2]*Professor, KMCH College of Physiotherapy, Coimbatore, The Tamil Nadu Dr. M. G. R. Medical University, Chennai, India*

[3]*Principal and Ph.D. Guide, RVS College of Physiotherapy. The Tamil Nadu Dr. M. G. R. Medical University, Chennai, India*

[4]*Professor and Co Guide, RVS College of Physiotherapy. The Tamil Nadu Dr. M. G. R. Medical University, Chennai, India*

***Corresponding Author:** A. Brammatha, Professor, KMCH College of Physiotherapy, Coimbatore, Affiliated to The Tamil Nadu Dr. M. G. R. Medical University, Chennai, India.

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Abstract

Therapeutic Functional Electrical Stimulation Cycling (FESC) involves the application of Functional Electrical Stimulation (FES) that is synchronized with the cycling motion, thus facilitating a harmonized activation of the lower limb musculature that mirrors the cyclical movements associated with locomotion. Electrical impulses are transmitted through electrodes strategically placed on the epidermis over the designated muscle groups.

Post-stroke lower limb impairments often manifest as muscle weakness, irregular muscle coactivation, and compromised joint torque coupling during gait and posture, which can diminish the flexibility of the cortical motor network, ultimately resulting in restricted motor behavior and impaired walking functionality. The repetitive characteristics of the cycling exercise are believed to foster motor learning while enhancing muscle strength, endurance, and coordination. In terms of functional outcomes, FES cycling has demonstrated benefits in enhancing overall mobility and daily living activities. Clinical trials have reported improvements in gait speed, symmetry and balance which can translate to better performance in tasks such as walking and standing. This paper reviews the evidences for lower limb FES cycling in stroke population, mechanisms of action, implications for clinical practice and technological advancements.

Keywords: Functional Electrical Stimulation Cycling; FESC; FES; Lower Limb Cycling; Stroke; Hemiplegia; Physiotherapy

Abbreviations

FES: Functional Electrical Stimulation; FESC: Functional Electrical Stimulation Cycling

Introduction

Stroke poses a significant burden in Asia, with an estimated 9.5-10.6 million strokes anticipated annually in the region due to varying levels of stroke care resources and epidemiological transitions [1].

In India, stroke significantly contributes to the burden of disability-adjusted life years (DALYs), with prevalence rates ranging from 44.29 to 559 per 100,000 individuals and an incidence rate of 119-145 per 100,000, indicating a higher disability burden compared to high-income nations [2-4].

Lower limb impairments significantly impact post-stroke mobility by affecting balance control, gait characteristics and energy absorption capacity during walking [5]. Lower limb impairments post-stroke impact mobility by affecting basic voluntary movement characteristics and daily activity capacity, with lesion location influencing enduring impairment and walking limitations differently [6,7]. Though recovery of walking occurs, but still many experiences abnormal gait patterns [8-10]. Lower limb impairments post-stroke lead to reduced joint movement, altered timing, and increased instability during weight transfer, impacting mobility, balance, and fall risk in individuals post-stroke [11,12].

Fall risk also increases as reactive balance control strategies during walking are impaired leading to difficulties in reducing forward momentum due to inadequate recovery responses [13]. Also, Lower limb muscle problems contribute to temporal gait asymmetry post-stroke, particularly at the ankle around the stance-to-swing transition period, which leads temporal gait asymmetry after stroke and can persist into later stages of recovery [14]. Lower-limb motor coordination deficits are observed in both paretic (61%) and non-paretic (17%) lower limb altering muscle synergies, reducing activation patterns and affecting motor control during both static and dynamic tasks [15]. Lower limb impairments post-stroke lead to decreased muscle perception accuracy, disruption in intra-limb coordination and dynamic balance which has impact on post-stroke gait performance [16]. So, to put together lower limb impairments post-stroke lead to biomechanical issues and gait maladaptation's interfering with mobility through multi-factorial associations.

Therapeutic FES cycling

Functional electrical stimulation (FES) represents a rehabilitative strategy that utilizes electrical currents to stimulate musculature that may exhibit weakness or paralysis [17]. The use of FES for rehabilitative objectives in clinical environments can be traced back to the 1960s, when Liberson., *et al*. (1961) employed an FES apparatus to stimulate the peroneal nerve to rectify foot drop via a foot switch; a single-channel electrical stimulation device was utilized to stimulate the common peroneal nerve through a surface electrode, resulting in ankle dorsiflexion during the swing phase of ambulation [18]. The two predominant applications of FES include functional replacement (as an orthotic device) and functional retraining (as a therapeutic device). In its therapeutic context (FES therapy), FES serves as a short-term intervention. The anticipated outcome is that patients will be able to voluntarily execute the trained activities independently post-FES training [19]. Recent advancements in scientific research and technology have yielded a variety of methods for stroke rehabilitation, among which functional electrical stimulation (FES) is frequently employed. Based on their operational mechanisms, FES systems can be classified into two principal categories: Open-loop FES and Closed-loop FES systems. In open-loop configurations, FES is primarily administered by a Physiotherapist utilizing preprogrammed patterns that are not modifiable by patient feedback to trigger muscle activation [20].

The integration of FES with a bicycle, commonly referred to as Functional Electrical Stimulation Cycling, (FESC) aims to assist individuals experiencing paralysis or muscle weakness to engage in cycling activities. In certain instances, FES is required to elicit movement in completely paralyzed limbs; in other scenarios, it may enhance the strength of weak muscle contractions, thereby facilitating the cycling process [21].

Types of FES cycles

There exist two primary categories of FES cycles. One variant allows the individual to remain in their wheelchair while positioning their feet on the pedals. The alternative is designated as a recumbent bike, predominantly utilized by patients who have achieved some level of recovery. The recumbent bike necessitates the individual to transfer onto the cycle's seating area. In both types of FES cycling, small pads known as electrode pads are strategically placed over the leg muscles. These electrodes deliver electrical currents that stimulate muscle contractions to aid in the pedaling motion. As the muscle fibers affected by paralysis are inactive, they must first undergo a retraining process to enhance functional performance. FES cycling actively engages the lower limb muscles, especially the quadriceps and hamstrings. Additionally, as the therapy is conducted while seated, it demands less balance capability, so it could be used in acute rehabilitation. FES not only activates the nerve fibers directed toward the muscles but may also influence higher brain centers, potentially facilitating the reorganization of neuromuscular activity. Therefore, the utilization of FES on the compromised leg muscles during cycling emerges as a promising therapeutic approach for the rehabilitation of stroke survivors. FES cycling systems are recognized as vital applications of FES that have demonstrated safety and efficacy in rehabilitative contexts. These systems adjust the current and pulse width of the FES in accordance with the feedback signal [22].

Therapeutic effects of FESC

Therapeutic FES cycling, a novel approach in acute stroke management, has gained attention for its potential benefits. For instance, one study highlights its efficacy in improving functional outcomes when applied early in the stroke recovery phase [23]. Additionally, FES cycling has been associated with favorable changes in biomarkers indicative of neuronal health, suggesting a mechanism for its therapeutic effects.

A meta-analysis indicated that transcranial direct current stimulation (tDCS) and functional electrical stimulation (FES) effectively augmented strength generation in stroke-affected individuals [24]. Balance training, when paired with weight shift-activated electrical stimulation, has been shown to significantly enhance balance, lower extremity motor performance and activities of daily living among stroke patients. The integration of FES with conventional balance therapy was reported to yield superior results in balance enhancement for stroke survivors [25]. Research demonstrates that Functional Electrical Stimulation (FES) cycling can substantially diminish cadence inaccuracies and enhance muscular coordination, thereby yielding improved outcomes in rehabilitation [26]. Investigations concentrating on FES-enhanced active cycling training have revealed potential advantages regarding ambulation and various limb parameters, including muscle strength and endurance, which are imperative for daily functions subsequent to a stroke [27]. Moreover, FES cycling is associated with increased oxygen uptake (VO), power output, and aerobic capacity [28]. Additionally, the integration of FES with alternative modalities, such as exoskeleton technology, has exhibited potential for augmented therapeutic effects [29]. Overall, FES cycling embodies a comprehensive strategy for stroke rehabilitation, fostering active engagement and facilitating functional recovery.

FESC and brain plasticity

Functional Electrical Stimulation (FESC) acts to influence cortical excitability, a concept that relates to the brain's sensitivity to stimuli. This alteration can result in enhanced communication between the brain and the musculature, thereby facilitating recovery and adaptation post stroke. The stimulation delivered by FES promotes the establishment of new neural connections, which are crucial for brain plasticity, as they enable the brain to reorganize and adjust to modifications in motor function following injury. This phenomenon is substantiated by a recent functional MRI study that indicated FES-induced movements activated a significantly larger region within the sensorimotor areas [30]. When Functional Electrical Stimulation (FES) is applied concurrently with voluntary movements, it amplifies the brain's capacity for learning and adaptation [31]. This synergistic method has the potential to strengthen motor pathways and could enhance overall motor control. These advancements also could be attributed to the increased sensory input transmitted to the brain due to FES Therapy [32].

Specific neural connections formed by FESC

FESC enhances the interconnections within motor pathways that govern voluntary movement. This encompasses the reinforcement of connections between the primary motor cortex and the spinal cord, which is essential for the execution of movements. Additionally, the stimulation may facilitate the reorganization of the corticospinal tract, a pathway that is crucial for voluntary motor control. Enhanced connectivity within this tract can result in improved muscle activation and coordination. FES promotes the development of connections that augment sensory-motor integration [33]. Furthermore, FES influences interhemispheric connections, which are the pathways that link the left and right cerebral hemispheres. These connections can yield enhanced coordination and balance during movement. This implies that the brain becomes more proficient at processing sensory information and converting it into suitable motor responses, thereby improving overall movement quality. The specific neural connections established through FESC contribute to the comprehensive enhancement of brain plasticity, facilitating recovery and functional advancement in individuals' post-stroke [34].

FESC equipment setup

The FES-cycling apparatus comprises components such as stimulators, sensors, and feedback mechanisms designed to optimize stimulation strategies and monitor cycling performance in real-time. Motorized FES cycling uniquely amalgamates neuromuscular electrical stimulation with motor control, thereby enabling simultaneous tracking of intended cadence and torque through adaptive control systems. The incorporation of FES with sensor systems for measuring joint angles, such as those of the hip, knee, and ankle, can significantly enhance the rehabilitation of ambulation in stroke patients by integrating FES with electromyography and various sensor modalities [35,36].

FESC dosage and parameters

Pulse frequency

The frequency of electrical pulses is crucial. Studies indicate that pulse frequencies typically range from 15 to 50 Hz. Higher frequencies may enhance muscle activation and improve neural connectivity by promoting more effective muscle contractions during therapy.

Pulse duration

The duration of each pulse also plays a role. For surface electrodes, pulse durations generally range from 280 to 400 microseconds. Adjusting this parameter can influence the strength of muscle contractions and the associated neural responses, potentially enhancing connectivity.

Current amplitude

Typically, stimulation intensity is set to produce visible muscle contractions modulated based on patient comfort and muscle response. Current amplitudes in studies ranged from 4 mA to 85 mA. Higher amplitudes may lead to stronger muscle contractions, which can stimulate greater neural activation and connectivity. Higher current amplitudes in FES stimulate neural pathways which lead to stronger muscle contractions, thereby promote neural plasticity, which is essential for recovery and improvement in motor function after a stroke, The Intensity is often adjusted incrementally to achieve effective muscle activation without causing patient discomfort.

Electrode type

The type of electrodes used can affect the efficacy of FES. Most studies utilized surface electrodes, while a few employed implanted electrodes. The choice of electrode type can influence the quality of stimulation and, consequently, the neural connectivity outcomes.

Individual variability

The optimal current amplitude may vary among individuals based on factors such as muscle condition, spasticity, and personal comfort levels. Therefore, tailoring the amplitude to each patient's needs is essential for maximizing therapeutic effects.

Treatment duration

The duration of each FES cycling session varies from 15 to 60 minutes per session, as in various research studies the length of each FES cycling session varies. For individuals who have significant impairments, shorter sessions of 15 minutes may be used initially. The number of sessions can be gradually increased as tolerated and according to progression or recovery goals. Most studies and clinical guidelines suggest a frequency of FES cycling sessions ranging from 3 to 5 times per week.

Muscles stimulated

FES Cycling focuses on enhances activities related to knee extension, along with weight bearing activities, through targeting the quadriceps muscles. The electrodes are usually positioned over two major components of the quadriceps muscle group, namely vastus lateralis and vastus medialis. Stimulation of the hamstrings is also done, as they are required not only for knee flexion but also for hip extension. These actions are pertinent to the cycling movement, as well as functional mobility. The electrodes are positioned over the biceps femoris and semitendinosus muscles to ease knee flexion and assist cycling motions. Some studies have used stimulation over the gastrocnemius and soleus muscles, which are important in the propulsive phase of cycling and walking.

Hip flexors, for example, iliopsoas, and extensors such as gluteus maximus, participate in stability and movement adjustment at the hip joint during cycling. The iliopsoas and gluteus maximus muscles are also responsible for hip flexion and extension, thus they are stimulated by the electrodes in order to achieve better cycling performance. Dosage and the stimulation parameters get required adjustments for each particular patient that corresponds with their stage of condition and recovery. Adjustments are guided by the level of muscle strength, spasticity, tolerance, and general well-being of the patient which are crucial for greatest cycling efficiency. Keeping track of how the patients respond to the changes, and modifying parameters of stimulation is essential. Always during therapy, adjustments and feedback would be needed to optimize muscle activation, address discomfort and enhance functional outcomes [37,38].

Evidence pertaining to the FESC on lower limb motor function

In the pursuit of evidence-based knowledge, the highest tier of evidence, encompassing Systematic Reviews and Meta-analyses, is regarded as the preeminent standard for healthcare decision-making, as these studies are recognized for incorporating the most robust available evidence to address health-related research inquiries. A systematic review amalgamates the findings from existing studies on a specific health issue, providing answers to a designated research question by systematically gathering and appraising all relevant research evidence that aligns with the established selection criteria of the reviewer. Systematic reviews focusing on functional electrical stimulation (FES) cycling for rehabilitation following a stroke elucidate its prospective advantages, particularly in the enhancement of motor functionality and activity levels among individuals who have experienced a stroke. Galvão *et al.,* in their meta-analysis found that FES cycling combined with exercise programs significantly enhances trunk control and walking distance in early subacute stroke patients [40]. Frazao., *et al.,* conducted an examination of Randomized Controlled Trials pertaining to FES-cycling, scrutinizing the clinical and physiological ramifications of functional electrical stimulation cycling. Their findings indicated that FES-cycling exercise serves as a more profound stimulus modality compared to other therapeutic interventions, yielding clinically significant improvements across various clinical outcomes. FES-cycling exercise has been shown to enhance cardiorespiratory fitness, although its efficacy is intricately linked to the duration of the exercise regimen, necessitating a span of over eight weeks to improve oxygen consumption capacity [41]. Fang., *et al*., in their Bayesian network meta-analysis, assessed the effectiveness and hierarchical ranking of five electrical stimulation methodologies. When juxtaposed with a regimen employing only routine comprehensive rehabilitation therapy (RT), comprehensive treatment modalities that integrate electrical stimulation techniques exhibited notable superiority in addressing lower limb dysfunction subsequent to a stroke. They identified FES as the predominant electrical stimulation method utilized for the remediation of lower limb dysfunction, grounded in the fundamental principle of simultaneous or intermittent application of electrical stimulation alongside functional tasks, from which various FES-oriented rehabilitation therapies have emerged. Transcranial Direct Current Stimulation (tDCS) represents the singular electrical stimulation technique whose application site is cranial, with its underlying mechanism potentially exerting both short-term and long-term effects on cortical excitability and neuroplasticity [42]. Barclay., *et al*. conducted a review assessing the impact of lower limb active-passive trainer cycling, with or without the incorporation of functional electrical stimulation, on spasticity, cardiovascular fitness, functionality, and quality of life among individuals with neurological conditions, revealing that active-passive trainer interventions yielded superior enhancements in walking endurance for stroke patients. Nevertheless, the implications for other outcomes and within different conditions remain ambiguous. Furthermore, it remains uncertain whether functional electrical stimulation-assisted cycling confers greater advantages than active-passive trainer cycling conducted in isolation [43]. Mahmoudi., *et al*., investigated the influence of lower extremity FES on balance enhancement in stroke patients, asserting that the combination of FES with therapeutic exercise facilitates more effective recovery compared to exercise therapy alone. They also highlighted that the tibialis anterior muscle plays a pivotal role in balance improvement among stroke survivors, suggesting that the strengthening of this muscle in conjunction with other muscle groups may yield more pronounced results [44]. Another systematic review by Ambrosini., *et al.,* suggested a slight trend towards improved walking speed and muscle strength, although no significant differences were found, emphasizing the need for higher-quality studies [45]. Additionally, Shariat *et al*. published a meta-analysis evaluating the effects of cycling, both with and without FES, on lower limb dysfunction in post-stroke patients, concluding that cycling exerts a favorable impact on walking speed and overall walking ability. Also, functional electrical stimulation combined with cycling had positive effects on balance beyond cycling alone [46]. The integration of these findings as depicted in table 1 highlights the effectiveness of cycling as a flexible rehabilitation approach, indicating that both FEST and traditional cycling can play key roles in stroke recovery programs. There exists a moderate to strong level of evidence suggesting that FES-cycling results in greater physiological effects with a significant clinical difference. In summary, while FES cycling holds potential, additional research is needed due to differences in clinical presentations, methods, equipment, and rehabilitation environments.

Systematic reviews and meta-analysis on effects of FESC for post stroke lower limb recovery					
Author/ Year	**Research topic**	**Number of Studies**	**Review Question**	**Outcome measures**	**Conclusion**
Galvão., *et al*. 2024[40].	To evaluate the efficacy and effectiveness of cycling utilizing Functional Electrical Stimulation Therapy (FEST) to enhance motor function and lower limb activity in individuals recovering from stroke	5 RCT s 187 participants	To explore the impact of cycling through FEST, either in conjunction with exercise regimens or in isolation, on motor function and activity levels in post-stroke individuals during the subacute phase.	Motricity Index, Trunk Impairment Scale, Berg Balance Scale, walking speed, Walking distance, Six Minute Walk Test Activities of daily living	Evidence has substantiated the superiority of cycling with FEST in combination with exercise programs for improvements in trunk control and walking distance when compared to isolated exercise programs during the early subacute phase following stroke
Frazão, Murillo., *et al*. 2024 [41].	To scrutinize the existing literature concerning the physiological and clinical ramifications of FES-cycling	52 studies: 19 on physiological effects and 33 on clinical effects of FES-cycling	To determine the impact on various health outcomes, including cardiorespiratory fitness, muscle mass, and overall physical fitness in different populations	VO2 difference Clinical Measures related to cardiorespiratory fitness, leg and total body lean mass, power, and physical fitness in intensive care	Variables associated with metabolic, cardiocirculatory, ventilatory, and peripheral muscle oxygen extraction exhibited statistically significant and clinically relevant differences favoring FES-cycling, with a moderate-to-high level of certainty in the evidence. They concluded FES-cycling therapy as a more robust approach..
Fang., *et al*. 2023[42].	To compare the treatment effect of five electrical stimulation methods commonly used in the treatment of stroke patients with lower limb dysfunction.	33 trials with a final total of 2246 subjects	Will routine comprehensive rehabilitation therapy (RT), along different electrical stimulation schemes (RT+FES, RT+NMES, RT +TENS, RT+TEAS, RT+tDCS) on lower limb dysfunction show significant changes on the outcome measures	FuglMeyer Assessment for Lower Extremity (FMA-LE), Modified Barthel Index (MBI), Berg Balance Scale (BBS), 10m Maximal Walking Speed (10mMWS), and Composite Spasticity Scale (CSS).	The integrative treatment protocols that incorporate electrical stimulation techniques have demonstrated notable advantages in addressing lower limb dysfunction subsequent to a stroke

Barclay., *et al*. 2022 [43].	To conduct a comprehensive review of the literature examining the implications of lower limb Active Passive Training (APT) cycling, with or without the application of functional electrical stimulation (FES), on parameters such as spasticity, cardiovascular fitness, functionality, and quality of life in individuals with neurological disorders.	12 articles 423 participants	To examine the evidence for lower limb APTs, with and without neuromuscular stimulation, and to determine their effects in relation to common issues such as spasticity, cardiovascular fitness, function and quality of life in people with neurological conditions.	Spasticity, Cardiovascular fitness, Function and Quality of life.	Evidence exists for lower limb APTs, both with and without neuromuscular stimulation, aimed at elucidating their effects concerning prevalent issues such as spasticity, cardiovascular fitness, functional capability, and quality of life among individuals presenting with neurological conditions. APT interventions appear to enhance walking endurance in individuals with neurological conditions; however, the implications for additional outcomes remain ambiguous.
Mahmoudi., *et a*l. 2021 [44].	To systematically evaluate the impact of functional electrical stimulation (FES) on balance in comparison to conventional therapy alone in post-stroke patients.	Nine papers chronic phase (n = 5) and in subacute phase (n = 4) participants 255	Significant advancements in balance were observed, particularly utilizing the Berg Balance Scale and the Timed Up and Go Scale, when FES was utilized in conjunction with conventional therapy.	Berg Balance Scale and Timed Up and Go Scale	FES was found to confer greater benefits in balance enhancement among stroke patients when integrated with standard balance therapy.
Ambrosini., *et al*. 2020 [45].	Does cycling induced by functional electrical stimulation facilitate motor recovery during the subacute phase following stroke?	7 RCTs 273 participants	To investigate the effects of cycling combined with functional electrical stimulation on parameters such as walking, muscle power and tone, balance, and activities of daily living in individuals recovering from subacute stroke	Barthel index, Modified Rankin scale, Health related QOL, Hospital Anxiety Depression score,	Cycling training with functional electrical stimulation cannot be advocated as superior to standard care in subacute stroke survivors. It is imperative to ascertain the optimal training parameters and to assess the long-term effects
Shariat A., *et al*. 2019[46].	The effects of cycling with and without functional electrical stimulation on lower limb dysfunction in patients post-stroke	14 trials 680 patients	To quantify the effectiveness of various cycling protocols, both with and without functional electrical stimulation, on functional mobility subsequent to a stroke.	2-, 6-, 10-, or 50-meter walking, Timed "Up & Go"-Test (TUG), Berg Balance Scale (BBS), Postural Assessment Scale for Stroke Patients	Cycling positively influences walking speed, walking capability, and balance; moreover, improvements in balance were augmented when functional electrical stimulation was incorporated into cycling training.

Table 1: Systematic reviews and Meta analysis studies on effects of FESC for Post stroke lower limb recovery.

Abbreviations: FESC: Functional Electrical Stimulation Cycling

Recent technology based FES cycling

Although FES itself is not new the way it's delivered has advanced greatly. Studies have highlighted the importance of real-time control systems in FES cycling, showcasing reduced angle trajectory errors and improved fatigue resistance in stroke patients. Control algorithms designed for functional electrical stimulation (FES) cycling have been developed to address a variety of functional impairments, which dynamically modulate the intensity of FES delivered to the leg musculature, as well as the electric current supplied to a motor. The algorithm independently does transitions among assistive, uncontrolled, and resistive modes to accommodate fluctuations in functional impairment, based on the difference between the intended and actual cadence, thereby exhibiting enhanced cadence regulation and reduced error in individuals recovering from a stroke. The advancement of FES cycling systems, Integrated Telerehabilitation and Closed-loop Fuzzy Based Control Systems, show potential in optimizing therapy outcomes. However, additional research and development must be conducted. Furthermore, patterning for FES cycling stimulation is made more efficient by the development of AI-based techniques, proving the advancement of human-in-the-loop AI technology. Rather than manually crafting and tuning rehabilitation devices, the processes can be automated, streamlining stimulation and improving the performance of cycling for the patient's needs [47].

FESC in other neurological population

Functional Electrical Stimulation (FES) cycling machines help for rehabilitation of patients with spinal cord injuries and also for mobility. These machines use FES system to stimulate and restore muscle motor function. Motorized FES cycling is the only method that produces neuromuscular electrical stimulation and permits control from the patient. The patient's desired cadence and torque are monitored with the use of adaptive controllers. Motorized FES cycling uniquely combines neuromuscular electrical stimulation with motor control, allowing for simultaneous tracking of desired cadence and torque through adaptive controllers. By integrating FES with electromyography and various sensors, FES cycling systems offer safe and effective rehabilitation, showcasing potential for further advancements in the field. FES-cycling leads to a substantial increase in oxygen uptake, energy expenditure, minute ventilation and arterial-mixed venous oxygen content difference compared to traditional cycling and neuromuscular electrical stimulation (NMES). Additionally, FES cycling can help individuals with spinal cord injuries train in both aerobic and anaerobic zones, as indicated by changes in respiratory exchange ratio (RER) and ventilation ratios during training sessions. Recent empirical evidence suggests that Functional Electrical Stimulation (FES) cycling significantly enhances the muscular health of the lower extremities in adults afflicted with Spinal Cord Injury (SCI) and may also contribute to an augmentation in power output as well as improvements in aerobic fitness [48]. FES-assisted cycling in individuals with cerebral palsy has shown higher cycling cadences compared to traditional cycling, highlighting its potential to enhance exercise intensity for improved cardiorespiratory fitness [49]. Individuals with Multiple Sclerosis (PW MS) face a higher risk of diseases linked to insufficient physical activity (PA). The process of deconditioning may accelerate the progression of secondary complications associated with multiple sclerosis. Cycling may provide a suitable lower limb exercise intervention for People with Multiple Sclerosis with mobility impairment. A Systematic review on nine studies found that FES cycling training could reduce Cardiovascular risk alongside trends for a reduction in spasticity post training, however the low quality of the literature precludes any definitive conclusions [50]. Most FES research conducted on other neurological population has focused on walking therapies, although cycling therapies have also been explored. These findings collectively demonstrate that FES Cycling therapy has distinct advantages over traditional cycling methods.

Discussion

Cycling and walking share similarities as rhythmic activities that involve alternating contraction and relaxation of major lower limb muscle groups and utilize comparable sensory-motor control mechanisms. Lower limb active passive trainers (APTs) facilitate cycling from either a seated or supine posture. Participants receive visual feedback regarding their cycling speed, distance traveled, power output, and cycling symmetry, which may enhance motivation, promote motor learning and control and yield improved rehabilitation outcomes. The parameters of speed, resistance, and exercise modality (active, active-assisted, or passive) can be tailored to the user's functional capacity, thereby accommodating individuals with significant disabilities. Further advancements in FES cycling systems, such as integrated telerehabilitation, real-time control systems in FES cycling and closed-loop fuzzy-based control systems, hold promise for optimizing therapy outcomes and customizing treatments for different patient populations, emphasizing the need for ongoing research and development in this field.

Speculation into future developments

Motorized FES-cycling would be advised for lower-limb rehabilitation in individuals with limited mobility who otherwise would be unable to participate in physical activity, as stationary cycling minimizes the risk of falls compared to walking with support. Nevertheless, the complex and unpredictable nature of muscle dynamics creates significant obstacles in developing closed-loop FES feedback control systems. Additionally, FESC accelerates muscle fatigue onset. Consequently, there is a need for innovative control designs to enhance the efficiency of hybrid cycling machines. These improvements could include incorporating recreational aspects, utilizing various sensor inputs, implementing novel control strategies to boost cycling performance, employing inertial measurement units (IMUs) for gait and posture analysis, and regulating electrical stimulation delivery. On-going research efforts focus on amalgamation of man and machine in terms of controlling limbs to follow a desired (force/position) trajectory through either a motorized exoskeleton. In the future, it will be important to combine functional outcome measures with assessments that provide insights into underlying neuroplastic mechanisms, such as motor-evoked potentials, to evaluate changes in the motor pathway. Research should prioritize long-term outcomes, optimal stimulation protocols, and the integration of FES cycling with alternative rehabilitation methodologies. Additionally, examining the effects of FES cycling across various stroke subtypes and severities will assist in customizing interventions for diverse patient populations. Future investigations should also focus examining optimal parameters for FES cycling, including stimulation intensity, frequency, and duration, alongside its long-term implications for stroke recovery.

Conclusion

Functional Electrical Stimulation (FES) cycling has emerged as a pivotal therapy for individuals with paralysis or neurological disorders, with the objective of restoring motor function and enhancing cardiovascular health. Its proven effectiveness in facilitating motor recovery, improving functional outcomes, and yielding secondary health benefits highlights its potential as a complementary modality within stroke rehabilitation initiatives.

Conflict of Interest

There are no conflicts of interest.

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