

Functional Electrical Stimulation for Foot Drop in Multiple Sclerosis

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Abstract

Functional electrical stimulation is an effective treatment strategy for the management of foot drop in various neurologic conditions, as demonstrated in improvements in gait performance, mobility, physiologic cost, perceived walking ability, balance, fall frequency, and quality of life. In this article, we review the current literature on the effects of functional electrical stimulation for foot drop in persons with multiple sclerosis.

Keywords

Multiple sclerosis, gait, foot drop, functional electrical stimulation, review

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Multiple sclerosis (MS) is a chronic, progressive disease of the central nervous system, believed to be caused by an autoimmune process, and resulting in demyelination and axonal loss in the brain, spinal cord, and optic nerves. MS affects approximately 400,000 individuals in the US alone and 2.5 million people worldwide. A decline in neurologic function, most notably in coordination, strength, tone, cognition, vision, sensation, and volitional control of bowel/bladder are hallmark characteristics of the disease, leading to reduced quality of life (QoL) and decreased participation in activities. Of primary concern to the MS population is impaired mobility, as it is the most visible disability and because of its profound impact on daily life.^{1,2}

Gait disturbance is present in a large number of persons with MS (pwMS) and has been identified as one of the most disabling features of this neurologic disease. Compared with healthy controls, pwMS demonstrate decreased walking speed, decreased stride length, increased cadence, reduced active lower extremity range of motion (ROM), and increased variability in gait parameters.^{3–9}

One of the more common gait pattern abnormalities demonstrated by pwMS is foot drop, caused by weakness of muscles responsible for ankle dorsiflexion and spasticity of the ankle plantarflexors. The ability to clear the foot by maintaining active dorsiflexion during the swing phase of the gait cycle is compromised in individuals with foot drop. Therefore, foot drop causes decreased gait efficiency and gait instability, leading to unwanted stumbles and falls. As a result, pwMS develop compensatory strategies including pelvic obliquity, hip hiking, and hip abduction with circumducted gait pattern to preserve foot clearance.

Treatment modalities to address foot drop include stretching, exercise, rehabilitation, orthotics, and assistive devices. The goals of treatment regardless of the intervention are to improve gait efficiency and safety, and overall improve the gait pattern to reduce musculoskeletal stress from altered biomechanics. The standard of care for foot drop has been the use of an ankle-foot orthosis (AFO). A more recently developed alternative to the AFO is functional electrical stimulation (FES).

Functional Electrical Stimulation for Foot Drop

The term FES refers to applying electrical current to a peripheral nerve via transcutaneous, percutaneous, or implanted electrodes, which in turn triggers muscles contractions with the goal of improving balance and gait. In the case of the FES application to foot drop, the electrical stimulation is applied to the common peroneal nerve, recruiting muscles controlled by both the deep and superficial peroneal nerves, and resulting in dorsiflexion and eversion of the ankle. The stimulation is synchronized with the gait cycle, so that it occurs during the swing phase of gait, and stops during the stance phase. FES devices generally include a power source (usually batteries), a stimulation unit, electrodes, and a mechanism to turn the stimulation on and off depending on the phase of the gait cycle. Various designs have been developed: wired versus wireless; tilt sensor on the leg versus heel switch. Commercially available FES systems for foot drop include the Odstock Dropped Foot Stimulator (ODFS®, Odstock Medical Limited, Salisbury, UK), the WalkAide® system (Innovative Neurotronics Inc., Austin, TX, US), the Bioness NESS L300® Foot Drop System (Bioness Inc., Valencia, CA, US), and the MyGait® system (Ottobock, Duderstadt, Germany). A majority of the published research in MS has focused on the ODFS and WalkAide devices. To date, only one head-to-head trial of

Table 1: Studies of Functional Electrical Stimulation for the Management of Foot Drop in Persons with Multiple Sclerosis

Authors	Total Number/ MS	Type of Study	Follow-Up	Outcome Measures	Effect	Results
Taylor et al., 1999 ¹¹	29/18	Questionnaire to current and past ODFS users	Return rate 64 % current users, 43 % past users	1. Questionnaire developed for the study	N/A	Perceived benefits: reduction in effort of walking, increased level of confidence with walking Reasons for discontinuing FES use: decrease in mobility, no longer necessary Problems encountered: unreliable equipment, difficulty with electrode positioning, and increase in perceived spasticity
Taylor et al., 1999 ¹	15/1/21	Retrospective study	18 weeks	1. Walking speed 2. PCI	Orthotic	Increased walking speed by 16 % Reduced PCI by 24 % No carry-over effects (improvement not maintained without device after 18 weeks)
Paul et al., 2008 ²⁰	24/12 (MS and healthy controls)	Observational study	Single evaluation	1. PWS for 5 minutes around 10 m elliptical course 2. Oxygen uptake, PCI 3. Walking distance	Orthotic	Increased PWS by 14 % (but significantly lower speed than controls) Reduced physiologic cost of walking by 12 % When walking at matched speeds, increase in energy requirement for pwMS compared with controls Similar oxygen requirements than controls when walking at PWS
Sheffler et al., 2009 ²¹	11/11	Observational study	Single evaluation	1. T25FW 2. Floor, Carpet, Up and Go, Obstacle, and Stair components of MEFAP	Orthotic	No statistically significant difference on T25FW Statistically significant improvement in performance on Stair component of MEFAP Trend toward statistical significance for obstacle course performance
Sheffler et al., 2009 ²	4/4	Case series	Single point in time (3 test conditions: no device, AFO, and FES)	1. Spatiotemporal parameters: 10mWT stride length, cadence, double support time 2. Gait kinematics	Orthotic	In FES trials, increased ankle dorsiflexion at initial contact No enhancement in spatiotemporal parameters with FES In AFO trials, no significant enhancement in walking speed, stride length, cadence, double support time, and variable effects on kinematic parameters
Barrett et al., 2010 ¹³	4/1/20	Retrospective study	18 weeks	1. PIADS—reflects degree of perceived benefit to QOL 2. 10mWT	Orthotic	Orthotic effect on walking speed with FES No training effect on walking speed Positive effect on Competence, Adaptability, Self-esteem portions of PIADS questionnaire → improved QOL No significant correlation between changes in PIADS questionnaire and walking speed
Stein et al., 2010 ¹⁴	73/31	Observational study	3 and 11 months	1. Walking speed: 10mWT, 4MWT on figure-8 course 2. PCI 3. Device usage	Orthotic	3 months Orthotic and training effect on 10mWT Training effect on 4MWT Training effect on PCI, no orthotic effect 11 months Walking speed on 4 MWT showed orthotic and training effect not as robust as nonprogressive pts Similar trend with 10mWT Plateau in gait speed with tendency to decrease speed PCI—less consistent, did not show decreasing trend in time Usage—patients with progressive conditions used FES more frequently
Everaert et al., 2010 ²³	36/24	Observational study	3, 6, and 12 months	1. Electrophysiologic measures: MEP, MVC, MMW 2. Walking speed 3. 4MWT 4. PCI	Training	Increased MVC and MEP Increase in walking speed Statistically significant improved 4MWT Decreasing PCI, indicating less effort required after FES use (not statistically significant)

Table 1: Cont.

Authors	Total Number/ MS	Type of Study	Follow-Up	Outcome Measures	Effect	Results
Taylor et al., 2013 ⁴	126/39	Retrospective medical record review	100 days onward (representative of habitual use of FES)	1. 10mWT 2. FWC 3. Device usage (based on attendance at follow-up)	Orthotic training	Median time use in MS 4 years improved 10mWT (29 % faster) with FES over the 100 days onward period (continuing orthotic effect, but no training effect) 12 pwMS demonstrated improvements in speed of which 7 improved FWC without FES Mean treatment cost ~US\$4680 US per patient and QALY of US\$23,295 US
Scott et al., 2013 ⁵	12/12	Observational study	4 visits before habitual use (visits separated by 3 days, but <14 days)	1. Gait kinematics 2. 10mWT 3. 6MWT	Orthotic	Orthotic effect on gait kinematics (ankle dorsiflexion at IC, knee flexion at IC, and peak knee flexion during swing) Orthotic effect on 10mWT, but not on 6MWT
Miller et al., 2014 ⁷	20/20	Observational study	Single evaluation (established ODFS users for at least 6 months)	1. 5MWT around elliptical 9.5 meter course 2. Gas analysis	Orthotic	Significant orthotic effect in walking speed No significant difference in energy cost of walking between groups Increase in oxygen uptake in FES use
van der Linden et al., 2014 ⁸	33/22	Observational study (MS and healthy controls)	Single evaluation	1. Gait kinematics 2. GPS—index of overall gait pathology	Orthotic	pwMS achieved similar walking speed compared with controls walking at slower speed, but with shorter stride length, increased cadence Orthotic effect of FES on walking speed Improved gait kinematics as a result of increased clearance during swing Improved GPS, indicating more normal gait pattern
van der Linden et al., 2014 ⁸	9/9	Observational study	12 weeks	1. Walking performance—10mWT, 2MWT (16.5m course) 2. Gait kinematics 3. Step count 4. Self-reported measures—MSIS-29, FSS, MSWS-12	Orthotic Total orthotic	Orthotic benefit on 10mWT, 2MWT Total orthotic effect on walking performance Improvement in gait kinematics (peak dorsiflexion)→orthotic benefit + total orthotic effect on ankle angle at IC, peak dorsiflexion, stride length, walking speed, knee flexion in swing, hip ROM No significant changes in self-reported walking performance (MSWS-12), impact of MS on daily living (MSIS-29), fatigue (FSS), or step count after 12 weeks
Bulley et al., 2014 ⁵	10/10	Phenomenologic study (AFO versus FES users)	Focus groups	1. Exploration of experiences in efficacy of assistive walking devices (FES and AFO)	N/A	Positive remarks of both devices assistive devices: reduced fatigue, improved gait, reduced trips/falls, assistance on hills/stairs, increased participation in life, greater confidence, less stress, less mental effort a. AFO users: improved balance/stability b. FES users: increased walking distance, fitness, and physical activity Negative remarks of both devices: described as cumbersome and uncomfortable; practical and psychologic barriers a. AFO users: lack of normal gait pattern (rigid device) b. FES users: application challenges, limitations in design and financial restrictions
Downing et al., 2014 ¹⁶	19/19	Observational study	2 weeks	1. T25FW 2. MSWS-12 3. MSIS-2	Orthotic training	Orthotic and training benefits on T25FW Improvement in MSWS-12 Improvement in MSIS-29

4MWT = 4-minute walk test; 6MWT = 6-minute walk test; 10mWT = 10-meter walk test; AFO = ankle foot orthosis; COPM = Canadian Occupational Performance Measure; FES = functional electrical stimulation; FSS = fatigue severity score; FWC = functional walking category; GPS = gait profile score; IC = initial contact; mEFAP = modified Emory Functional Ambulation Profile; MEP = motor-evoked potential; MMW = maximum motor wave; MSIS-29 = multiple sclerosis impact scale; MSWS-12 = MS walking scale (MSWS); MVC = maximum voluntary contraction; ODFS = Odstock Dropped Foot Stimulator; PCI = physiologic cost index; PIADS = psychosocial impact of assistive device scale; PWS = preferred walking speed; pwMS = persons with multiple sclerosis; QALY = quality of adjusted life years; QoL = quality of life; ROGA = Rivermead observational gait analysis; ROM = range of motion; T25FW = timed 25 foot walk.

Table 2: Randomized Trials of Functional Electrical Stimulation for the Management of Foot Drop in Persons with Multiple Sclerosis

Authors	Total n/MS	Type of Study	Follow-Up	Outcome Measures	Effect	Results
Barrett et al., 2009 ²²	44/44	Randomized controlled trial (FES versus exercise)	18 weeks	1. 10mWT 2. 3MWT 3. PCI	Orthotic training	No improvement on 10mWT or 3MWT in FES group (tested without FES), but improvement in exercise group Orthotic effect on 10mWT and 3MWT No significant change in PCI with FES or exercise (no significant training or orthotic effect for energy expenditure)
Esnouf et al., 2010 ¹²	64/64	Randomized controlled trial (FES versus exercise)	18 weeks	1. COPM 2. Falls diary	Training	Improvements in performance and satisfaction greater in FES group on COPM scores Statistically significant decrease in number of falls in FES group FES users demonstrated higher satisfaction scores in being able to walk longer distances FES perceived as effective in reducing trips, increasing walking distance
Taylor et al., 2014 ⁶	28/28	Randomized crossover trial (Group 1: FES for 1st 6 weeks, gluteal stimulation added at week 6, then exercise added on weeks 12–24 Group 2: Exercise weeks 1–12, FES added at 12 weeks followed by gluteal stimulation from 18th week on)	12 weeks, 24 weeks	1. 10mWT 2. ROGA score 3. MSIS-29 4. Falls diary	Orthotic training	Orthotic effect on 10mWT, but no significant training effect Improved ROGA score Improved MSIS-29 Reduction in falls

3MWT = 3-minute walk test; 10mWT = 10-meter walk test; COPM = Canadian Occupational Performance Measure; FES = functional electrical stimulation; MSIS-29 = multiple sclerosis impact scale; PCI = physiologic cost index; ROGA = Rivermead observational gait analysis.

these two devices on energy cost and walking speed in pwMS has been conducted.⁷ All of these systems provide transcutaneous stimulation via surface electrodes on the skin. From this point on, we will use the term, *FES*, when referring to transcutaneous FES for foot drop.

In 1960, Liberson et al.¹⁹ investigated the immediate benefits of using electrical stimulation to produce ankle dorsiflexion during the swing phase of the gait cycle in hemiplegic patients. The investigators found an immediate, positive effect on walking performance once the device was turned on, commonly referred to as the *orthotic* effect. The *orthotic* benefit, or “on-off” effect of FES on gait, has been well-documented in the MS population.^{3–9,13,14,16,20–24} More recently, the term *training*, or therapeutic, effect has been applied to changes in walking performance after regular, prolonged FES use when gait is evaluated without the device.¹⁴ We will refer to this type of effect as *training effect* throughout this article. Ultimately, the training effect reflects an improvement in motor ability of the affected limb over time without the assistance of FES. Additionally, the *total orthotic* effect of FES (defined as the change in walking speed with FES at follow-up assessment compared with walking speed at baseline without FES⁸) has been reported in pwMS.^{8,16,24}

One potential explanation for the training effect of FES is the promotion of neuroplasticity with repetitive daily stimulation, producing a cumulative effect over time.^{23,25} Everaert et al.²³ observed the effects of using FES

for several months in both nonprogressive and progressive disorders of the central nervous system and found a significant increase in motor voluntary contraction and motor end plate potential. The large increase in electrophysiologic parameters observed suggests strengthening of the residual corticospinal pathways and activation of motor-related areas of the cortex, regardless of the neurologic condition.²³ However, evaluating the long-term training effects of FES (or any assistive device) in the MS population is complicated by the progressive accumulation of disability over time compared with nonprogressive conditions such as stroke.¹⁴ Therefore, data supporting the training effect of peroneal nerve stimulation has been mainly explored in the stroke population.

A review of the pertinent literature on the effects of FES for foot drop in individuals in MS was conducted. Evidence pertaining to the efficacy of FES on various outcome measures is presented in this review article and summarized in *Tables 1, 2, and 3*.

Functional Electrical Stimulation on Gait Effects Gait Speed

A majority of studies investigating the effects of FES for foot drop in MS have focused on changes in spatiotemporal parameters of gait, primarily gait speed (maximal [fast] or self-selected [preferred/comfortable]), as it is closely related to gait efficiency and quality.^{3–5,7,9,13,16,18,20,22} Walking performance is usually assessed with short tests at self-selected or fast pace (10-meter walk test [10mWT] or Timed 25-foot walk [T25FW]) or with

Table 3: Studies of Functional Electrical Stimulation for Foot Drop in Multiple Sclerosis by Type of Effect Assessed

Type of Effect	Type of Study	Authors
Orthotic	Observational/ retrospective	Taylor et al., 1999 ⁴
		Paul et al., 2008 ²⁰
		Sheffler et al., 2009 ²¹
		Sheffler et al., 2009 ³
		Barrett and Taylor, 2010 ¹³
		Stein et al., 2010 ¹⁴
		Taylor et al., 2013 ²⁴
		Scott et al., 2013 ⁵
		Miller et al., 2014 ⁷
		van der Linden et al., 2014 ⁸
RCT	RCT	van der Linden et al., 2014 ⁹
		Downing et al., 2014 ¹⁶
		Barrett et al., 2009 ²²
Training	Observational/ retrospective	Taylor et al., 2014 ⁶
		Barrett and Taylor, 2010 ¹³
		Stein et al., 2010 ¹⁴
		Everaert et al., 2010 ²³
		Taylor et al., 2013 ²⁴
		van der Linden et al., 2014 ⁸
		Downing et al., 2014 ¹⁶
RCT	RCT	Barrett et al., 2009 ²²
		Esnouf et al., 2010 ¹²
		Taylor et al., 2014 ⁶
		Taylor et al., 2013 ²⁴
Total orthotic	Observational/ retrospective	Van der Linden et al., 2014 ⁸
		Downing et al., 2014 ¹⁶
		None
RCT	RCT	None

RCT = randomized controlled trial.

longer “endurance” tests (6-minute walk test [6MWT] and, occasionally, the 2-minute walk test [2MWT]) in studies of FES in pwMS and other conditions. Investigators have suggested that longer walking tests are a more accurate reflection of walking performance, and better demonstrate the benefits of peripheral nerve stimulation (PNS) devices.²¹

In a retrospective study of long-term FES use in various neurologic conditions, a significant orthotic benefit was seen in pwMS, as their fast walking speed increased by 16 % when measured at the third follow-up assessment at 4.5 months.⁴ Another study showed that preferred walking speed increased by 14 % with FES.²⁰ Contrasting with the aforementioned studies, Sheffler et al.²¹ found that FES did not increase walking speed in 11 pwMS. The only significant finding was an orthotic effect during the Stair component of the modified Emory Functional Ambulation Profile (mEFAP) and a trend towards statistical significance in the mEFAP Obstacle Course, suggesting that the effects of FES were more noticeable in more challenging conditions than walking on a flat surface. The authors note that the distance walked and duration of device-usage could be factors influencing efficacy.²¹

However, the positive orthotic effects of FES on gait speed in MS have been repeatedly observed in further studies.^{5-9,13,14,16,18,22,24} Stein et al.¹⁴ observed both the acute and long-term effects of peroneal nerve stimulation in

both nonprogressive and progressive neurologic conditions. Both groups showed improved gait speed when the device was “On” versus “Off,” lending support to the benefits of FES on walking. In the progressive group, which consisted of primarily MS patients, the magnitude of increase in walking speed was 2.3 % at baseline, and 5.7 % 3 months after using the device. Additionally, a head-to-head trial comparing two FES systems in pwMS demonstrated an orthotic benefit on walking speed for both devices, compared with nonstimulated conditions, which remains consistent with previous studies.⁷ More recently, a 2-week observational study showed that the application of FES led to both a statistically and clinically significant improvement in T25FW at baseline and post-intervention.¹⁶ The orthotic effect was manifested in an 18.3 % improvement in performance, both at baseline and after 2 weeks of FES use, suggesting that the orthotic benefits of FES can occur prior to habituation.

The training effect of FES on walking speed has also been documented in pwMS, although not as robust as in other populations such as stroke.^{8,14,23} A 12-week study showed a total orthotic effect of FES (difference in walking speed with FES at 12 weeks and without FES at baseline) on walking performance with improvement of 12.1 % and 9.8 % on the 10mWT and 2MWT, respectively.⁸ Stein et al.¹⁴ as mentioned earlier, focused on the long-term training benefit of FES in both nonprogressive and progressive conditions. At 3 months in pwMS, the authors observed, using a 4-minute figure-8 walk test, a mean walking speed improvement compared with baseline of 12.6 % with FES “On” compared with 9.1 % in FES “Off”, as well as improvement on the 10mWT. At the 11-month follow-up, a training effect on walking speed during the figure-8 walking performance and on the 10mWT was observed, although pwMS demonstrated a plateau in gait speed compared with their nonprogressive counterparts. Even though this study demonstrated the training effects of FES use up to 11 months, the authors caution that the results were based on short distance tests such as the 10mWT and the 4-minute figure-8 test, and suggest that longer walking tests are needed to offer a more accurate measure of efficacy.¹⁴

One of the difficulties in comparing the results of longer (“endurance”) walking tests between studies is the lack of consistency in the time over which the walking distance is being assessed. Barrett et al.²² found that the 6-minute walk test (6MWT) proved to be challenging for MS patients due to fatigue. They reduced the time to 3 minutes, but acknowledged that the validity and reliability of the 3-minute walk test were not established.²² Recently, Scott et al.⁵ reported no benefit even on the 6MWT with acute application of FES in 12 pwMS who had no prior exposure to FES. Compared with prior research, the participants in this study were not habitual users of FES, postulating that an extended period of FES use might be needed to observe a clinically significant difference in mobility.⁵

Overall, a majority of the studies observing the effects on walking performance have reported orthotic effects,^{4-9,13,14,16,20,22,24} and in some cases a total orthotic benefit after weeks of FES device use^{8,24} with one study noticing this benefit only after 2 weeks.¹⁶ Training effects have been consistently reproduced in nonprogressive neurologic conditions, such as stroke and spinal cord injury populations. This has not been the case in MS patients, and this difference has been attributed in part to the progressive course of MS. One publication, comparing stroke and MS patients, found that a training effect was present only in the stroke

patient group.¹⁴ However, in 9 pwMS (four with relapsing-remitting, four with primary progressive, and one with secondary progressive disease), a training effect was observed on walking performance tests, such as the 10mWT and 2MWT after device use for 12 weeks.⁸

Energetic Cost of Walking and Gait Efficiency

One objective parameter of gait efficiency that has been commonly studied with FES is the physiologic cost index (PCI), an indirect measure of the amount of effort required for walking, based on the premise that as skeletal muscles are activated, energy requirements increase and lead to an increase in oxygen uptake that is proportional to the increase in heart rate.²⁰ The PCI is calculated using the following formula: $PCI = \frac{\text{change in heart rate from resting to steady speed of walking (beats/minute)}}{\text{walking speed (m/minute)}}$ and is expressed in beats/m.⁴ A more direct parameter for measuring energetic cost is oxygen uptake, or percentage of oxygen expired, by means of a gas analysis system.

In a retrospective study of 21 pwMS, an orthotic benefit was seen on PCI with a reduction of 24%.⁴ However, only 38% of MS users achieved a significant carry-over effect defined as greater than 10% decrease in PCI compared with their stroke counterparts. Subsequently, Paul et al.²⁰ also demonstrated a statistically significant reduction in the physiologic cost of walking (12% reduction in PCI) in pwMS with FES use. However, at preferred walking speeds, no statistically significant difference between the pwMS and control subjects in oxygen uptake was found. The authors concluded that pwMS were self-selecting their walking speed so that the oxygen requirement for walking was at optimal level.²⁰ Furthermore, they observed that pwMS had a less-efficient gait pattern compared with controls and demonstrated a significantly higher physiologic cost of walking at slower speeds.

Contrasting with these positive findings, Barrett et al.,²² when comparing FES use to an exercise intervention over 18 weeks, found no significant change in PCI with either intervention. Furthermore, no significant orthotic or training effect was demonstrated on energy expenditure measured by PCI. In a long-term evaluation of 31 participants with progressive neurologic disorders including MS, there were no immediate changes in PCI between FES "Off" versus FES "On" conditions at 3-month follow-up.¹⁴ However, a significant decrease in PCI over time of -3.0% with FES "Off" and -8.7% with FES "On" was observed. At 11 months, PCI results were less consistent and, in fact, the investigators noted that as gait speed tended to plateau and even decline with time, a corresponding increase in PCI was seen.¹⁴ A comparison study of two FES systems found no significant difference between devices in energy cost of walking based on measurement of oxygen uptake.⁷ However, an increase in oxygen uptake was demonstrated with both FES devices compared with unassisted conditions, which correlated with increased walking speed leading to higher energy requirements. In this study, the energy efficiency of walking was not assessed.

Gait Kinematics

Evidence of the positive effect of FES on gait kinematics has also been substantiated in several studies of pwMS.^{3,5,8,9} Specifically, the most commonly assessed kinematic parameters include peak pelvic obliquity during swing, peak contralateral hip abduction during stance, peak knee flex/hip flex during swing, ankle dorsiflexion at initial contact, and peak ankle internal rotation during swing. An immediate improvement, or

orthotic benefit, in ankle dorsiflexion at the time of initial contact with FES has been consistently reported in pwMS.^{3,5,8,9} In a case series of five pwMS, comparing FES use to no device, three of the five subjects demonstrated enhanced dorsiflexion at initial contact, and two subjects exhibited significant improvement of knee flexion during swing phase.³ The latter finding has been hypothesized to be a result of a flexion withdrawal reflex triggered by the stimulation, and similar observations have been subsequently reported by other investigators.^{5,9}

A recent study on the acute application of FES in 12 MS patients demonstrated increased ankle dorsiflexion at initial contact, knee flexion at initial contact, and peak knee flexion during swing during gait analysis trials.⁵ Improved walking performance was also noted with FES during completion of the 10mWT. However, no difference was seen between FES and no FES on the 6MWT. van der Linden et al.⁹ also reported a similar orthotic effect on gait kinematics and walking speed. In 22 pwMS who were new FES users, FES resulted in improved walking speed and longer stride length as well as increased dorsiflexion at initial contact and increased knee flexion during swing, for a net result of increased foot clearance during the swing phase of the gait cycle.⁹ In the same study, deviation from normal gait pattern was assessed by calculating the Gait Profile Score (derived from kinematics of the ankle, knee, hip, and pelvis), which demonstrated a trend toward more normal values during the FES-assisted gait trials. Additionally, van der Linden et al.⁸ investigated the training and total orthotic effect after 12 weeks of FES use in 9 pwMS. Large effect sizes were observed for ankle kinematics, and for perceived exertion during the 2MWT, suggesting a training effect, but these changes did not reach statistical significance.⁸

User Satisfaction and Perceived Benefits of Functional Electrical Stimulation

Patient satisfaction, and especially perceived improvements in gait performance, with electrical stimulation devices for the correction of drop foot have been reported in a number of studies.^{8,11,13,15,16,22} In several reports, FES was perceived by pwMS as an effective device to improve walking distance and reduce the risk for falls.^{12,13} Further, a reduction in the effort of walking and an increase in level of confidence during gait were reported by 18 MS patients who used FES.¹¹

Barrett et al.¹³ sought to identify correlations between changes in QoL scores and objective gait parameters in patients with progressive and nonprogressive neurologic conditions after 18 weeks of FES use. A positive effect was seen in three areas of psychological well-being (Competence, Adaptability, and Self-esteem) of the Psychosocial Impact of Assistive Device Scale (PIADS)²⁶ questionnaire in 20 pwMS. Although a significant training effect was demonstrated on walking speed in both groups, there was no correlation between subjective and objective measurements. The authors note that the positive benefits of FES on QoL may "extend beyond objective changes in walking performance."¹³ Van der Linden et al.⁸ observed no significant improvement, after 12 weeks of FES use in nine pwMS, on self-reported measures of the physical and psychological impact of MS (Multiple Sclerosis Impact Scale-29 [MSIS-29]),²⁷ impact of MS on walking [MS Walking Scale-12 (MSWS-12)],²⁸ or fatigue [Fatigue Severity Score],²⁹ despite significant improvements on walking tests as described above. Conversely, a recently published study on 19 pwMS found significant improvements on the MSWS-12 and MSIS-29 after FES use for only 2 weeks.¹⁶

In a qualitative comparison study describing the experiences of pwMS using an AFO versus FES, both groups cited a reduction in fatigue, trips, and falls, improvement in gait, an increase in activity participation, greater confidence, less stress, and less mental effort.¹⁵ FES users reported an increase in walking distance and physical activity, while the AFO group cited improved balance and stability. Common limitations to both devices were related to practical concerns affecting comfort and application such as the device being described as “cumbersome” and difficult to don, and restrictions in clothing choice and footwear. Psychological and social barriers, such as reluctance to rely on a device, and self-acceptance of the necessity of this type of mobility aide were also reported. Sheffler et al.²¹ reported that participants who preferred FES over AFO cited increased active ROM, enhanced balance, and decreased spasticity as positive aspects of FES.

Implications for Clinical Practice

Preserving or enhancing walking and mobility is a priority for pwMS,¹ and FES for foot drop has generated considerable interest in the MS community. Overall, the growing body of evidence reported above suggests that FES for foot drop has beneficial orthotic and training effects on various quantitative measures of gait and walking in patients with MS. However, not all studies report statistically significant changes, and the clinical significance of the benefits observed is not consistently ascertained. Patient-reported data also suggest perceived benefits from FES, although these effects are not always reflected on standardized measures of symptom severity and functional status. Further, most studies have methodological limitations, such as a low sample size or the absence of a control group. These methodological factors are particularly important in a disease characterized by the heterogeneity of clinical presentations between patients, and by frequent spontaneous fluctuations of symptom severity and functional performance within patients.

Several questions relevant to clinical decision-making remain unanswered:

How do the Effects of Functional Electrical Stimulation Compare with those of the Standard of Care?

The most obvious difference is that FES is an “active” device, promoting muscle contraction, while the AFO is a “passive” device, immobilizing the ankle/foot. Drawing from this distinction, one can hypothesize that FES has a beneficial trophic effect on muscles and other soft tissue, while the AFO may promote muscle atrophy and loss of active ROM. FES may also be superior to the AFO when climbing stairs or walking on uneven terrain.

The benefits of AFOs in post-stroke patients have been extensively studied, showing improvement in spatiotemporal parameters such as gait velocity, gait kinematics, static balance, and physiologic expenditure. However, reports from AFO users cite drawbacks such as restriction in ankle/foot movement, rigidity, less natural gait pattern, increased discomfort, and cosmetic appearance.^{10,15,16} In pwMS, the evidence to support the use of AFOs is limited.¹⁰ Fifteen pwMS were observed performing the T25FW and certain portions of the mEFAP with an AFO versus no device. No statistical difference was seen in ambulation times and functional tasks of mobility.

Two large randomized controlled trials of FES for foot drop versus AFO in stroke survivors were published, and both concluded that the FES was noninferior to the AFO, in terms of walking/gait outcomes.^{30,31} However,

these findings cannot be directly applied to pwMS, owing to marked pathophysiologic and clinical differences between these populations. The studies from Bulley et al.¹⁵ and Sheffler et al.¹⁰ mentioned above shed some light on the qualitative differences between FES and AFO perceived by MS patients and warrant further investigation.

One concern is that the cost of FES devices is generally higher than that of an AFO and includes ongoing expenses for batteries and electrodes. In addition, FES devices are generally not covered by health insurance for MS in the US. One study in the UK evaluated the long-term cost-effectiveness of FES for foot drop in individuals with various neurologic conditions (including 39 MS patients).²⁴ The authors found that the average treatment cost was US\$4,680 per patient and the mean cost per quality adjusted life years (QALY) was US\$23,295. We are not aware of a similar analysis for AFO use in MS. A related concern (which applies to devices in general) is the rate of long-term adherence, but these data are difficult to collect systematically in real life. In general, a low dropout rate is reported in studies of FES for foot drop in MS.^{11,14} A deterioration in mobility is one of the reasons cited for discontinuation of FES use in MS,¹¹ reflecting the challenges posed by the progressive nature of the disease.

No major safety concerns have emerged with FES devices or AFOs. This is an area where experience in other conditions can be more confidently applied to the MS population. Skin irritation (and potentially skin burn) under the electrodes is a potential side effect of FES. Other problems reported encountered by FES users include difficulty with electrode positioning and equipment failure.¹¹

Who are the Best Candidates for Functional Electrical Stimulation?

Mobility devices must be tailored to the individual’s characteristics and needs, and FES is no exception to this general rule. There are few contraindications to the use of FES devices, such as the presence of an implanted pacemaker or defibrillator, a cancerous skin lesion on the leg, or contraindications to limb movement (e.g. fracture, dislocation). A past history of seizures invites caution in prescribing FES, and often constitutes an exclusion criterion in clinical trials. Peripheral nerve damage is likely to impede effective electrical stimulation. The absence of dorsiflexion ROM beyond the neutral position, and the presence of medial-lateral ankle instability, can compromise the effectiveness of FES. Decreased hand dexterity or other upper extremity impairment may limit a patient’s ability to properly position the stimulation cuff, although improvements in the design of the cuff have simplified its handling. Severe cognitive impairment may impede a patient’s ability to properly and safely apply and use the FES device. Sensory loss in the lower extremity may compromise the patient’s ability to detect skin irritation, making it essential to visually check the skin under the electrodes daily.

One of the most challenging tasks is to predict the functional response to FES. O’Dell et al.³² reporting on the outcomes of FES at 30 and 42 weeks in a relatively large group of stroke survivors (n=74 at 30 weeks and 69 at 42 weeks), classified some of the participants as “FES responders” based on gait speed, and identified a set of predictors of responder status, such as younger age, faster baseline gait speed and performance on the Timed Up and Go test, and better balance. To our knowledge, this type of information is not available for pwMS.

Additionally, the relative merits of various FES systems have not been well studied. One of the main differences between systems is the use of a tilt sensor versus a heel switch. Everaert et al.²³ found that patients preferred the tilt sensor feature since it was already incorporated into the system and did not necessitate an external heel sensor. However, variability in the active flexion of the knee at the onset of swing phase could make a heel switch more effective. To address difficulties in correctly positioning the electrodes, one recent study examined the effects of an automated, self-optimizing, array-based FES stimulator for foot drop and was found to have a comparable effect on gait speed compared with setup by a clinician using the patient's own stimulator with two conventional electrodes.³³ However, challenges associated with electrode placement could also be a result of the daily variations in muscle tone experienced by those affected by upper motor neuron lesions.¹¹ One way to alleviate the electrode placement problem is to implant the electrodes. We are aware of two commercially available FES systems using an implanted electrode: the STIMuSTEP® (Finetech Medical Co., Hertfordshire, UK), and the ActiGait® (OttoBock Healthcare Products GmbH, Vienna, Austria).

The progression of disability over time in MS poses a particular challenge in determining appropriate treatment strategies for the management of dropped foot compared with nonprogressive, single-event neurologic disorders, such as stroke and spinal cord injury. Indeed, in pwMS, discontinuation of mobility device use was attributed to an increase in perceived spasticity and mobility deterioration.¹¹ Increased fatigue may also influence the ability to utilize FES for gait impairment.²¹ Although Stein et al.¹⁴ demonstrated the long-term orthotic and training benefits of FES, the observed plateau in gait speed with a trend toward a decline and concomitant increase in energy expenditure cannot be ignored. The initial gains made earlier in terms of speed and PCI in pwMS may be reversed in the long term due to disease progression. However, this applies to the use of all mobility devices in MS, and should not necessarily prevent their use, as the disease course varies greatly between patients and is quite

unpredictable. The goal of the comprehensive management of MS is to help preserve or optimize function for as long as possible.

Although the benefits of FES for pwMS have been demonstrated in terms of immediate orthotic and total orthotic effects, the training effect seen in stroke patients may not be as pronounced in the MS population due to the progressive course of the disease. However, MS patients with more stable disease presentation could potentially exhibit a training effect in one or more walking performance outcomes or self-reported measures.

Finally, foot drop is rarely the only gait disturbance observed in pwMS. In particular, hip and knee flexor weakness are prevalent with MS, and are not directly addressed with peroneal nerve FES, although there are anecdotal reports of improved knee flexion, possibly through a reflex mechanism.³ One manufacturer proposes to add a thigh cuff as an attempt to address the concern regarding proximal lower extremity weakness (Bioness L300 Plus® system, Bioness Inc., Valencia, CA, US). However, this increases the cost of the device, and the potential gain in efficacy has not yet been demonstrated in clinical studies, to our knowledge. Additionally, the effects of stimulating the gluteal muscles on hip stability were recently investigated, and could be further explored as a means of addressing concomitant proximal muscle weakness.⁶

Conclusion

FES for foot drop is an option to consider in the array of interventions to improve walking in individuals with MS. As clinical experience with FES increases, and as the body of evidence to guide clinical decision-making grows, the criteria to determine the best candidates for FES will be better defined. In addition, ongoing technologic advances will hopefully improve the efficacy and user-friendliness of the devices. Technologies such as FES are not meant to replace other treatments for walking limitations, but rather to complement them in order to optimize functional outcomes. In our experience, it is essential to involve a physical therapist in the decision-making process, and in training the patient to use the device appropriately and to its maximum potential. ■

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