

Using Wearable Sensors and Video Analysis to Improve Functional Electrical Stimulation Prescription in Individuals With Multiple Sclerosis: A Case Series

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ABSTRACT

BACKGROUND: A growing body of evidence supports the use of functional electrical stimulation (FES) in people with multiple sclerosis (MS). However, prescription remains an imprecise process with no well-established guidelines for assessing the immediate or long-term effects to ensure maximum benefit. The purpose of this case series was to assess the potential benefits of using wearable sensors and video analysis to provide immediate feedback on gait performance to improve FES prescription in people with MS.

METHODS: Three adults (2 women, 1 man; age range, 39-62 years) with MS with varying levels of lower extremity motor function and gait impairment were enrolled. During a single visit, participants performed a series of 10-m walks under various FES and non-FES conditions while using wearable motion sensors. Additionally, 2D video analysis was used to assess alterations in knee angles during swing and stance phases.

RESULTS: All participants demonstrated improvements in a variety of gait variables, including a clinically meaningful (> 0.1 m/s) increase in gait speed during 1 or more of the FES conditions when compared with the no-device and/or prescribed ankle foot orthosis conditions. There were additional improvements associated with multichannel stimulation of the lower leg and thigh for certain gait variables.

CONCLUSIONS: Data from the wearable sensors and video analysis were advantageous in helping researchers determine the most appropriate FES prescription for each participant. This case series demonstrates the potential clinical usefulness of these technologies in prescribing FES for people with MS.

Int J MS Care. 2026;28(2):83-88. doi:10.7224/1537-2073.2025-050

Gait impairment is common in people with multiple sclerosis (MS), with up to 75% of individuals reporting difficulty walking.^{1,2} Specific gait impairments may include foot drop, poor toe clearance, circumduction, knee instability, and genu recurvatum during stance. Spatiotemporal gait changes may include reduced speed, decreased step length, increased base of support, and increased double support time when compared with age-matched individuals without MS.^{3,4} To address these gait impairments, individuals with MS are frequently prescribed lower extremity orthoses such as plastic or carbon fiber ankle-foot orthoses (AFOs) or functional electrical stimulation (FES). FES most commonly involves stimulation of the common fibular nerve to reduce foot drop. Several systematic reviews and a meta-analysis of FES have demonstrated improvements in walking speed, energy cost, fatigue, and pain.⁵⁻⁷ Individuals also report improved device acceptance and self-efficacy when using FES compared with traditional AFOs.⁸ These findings support the use of FES in people with MS, but it is costly and often not covered for this population by insurance providers in the United States.

Despite a growing body of evidence supporting the use of FES in people with MS, FES prescription remains a highly individualized and subjective process. The Association of Chartered Physiotherapists in Neurology has a guideline for FES prescription to help identify appropriate candidates.⁹ However, there are no well-established guidelines for quantifying its immediate (orthotic) and/or long-term (therapeutic) effects to ensure maximum benefit. In the current clinical environment, it is common to prescribe FES or an AFO during a single visit or after a trial of the device. Unfortunately, this approach often relies solely on a brief observational assessment by the health care professional and the user's subjective experience to determine whether gait improved. This approach can be unreliable and may lead to an inappropriate prescription, with the potential for discontinuation due to limited benefit and usability. This can have a significant financial impact, as patients often pay out of pocket for these devices. When prescribing FES or an AFO, it would be beneficial

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TABLE 1. Participant Characteristics

	Participant 1	Participant 2	Participant 3
Age	39	51	62
Sex	Female	Female	Male
Involved LE	Right	Right	Left
EDSS	6.0	3.5	6.5
MSWS-12	78%	62%	93%
BMI	36.2	26.6	28.0
Walking aid	SPC	ND	4WW
Orthosis	Anterior carbon	None	Posterior carbon
MAS (knee/ankle)	3/2	0/0	1+/1+
Vibration sensation ^a	Intact	Decreased	Decreased
Dorsiflexion strength	2	3+	3+
Knee extension strength	3+	4	4
Knee flexion strength	4	4	4
Hip flexion strength	3	3+	2+

4WW, 4-wheeled walker; BMI, body mass index; EDSS, Expanded Disability Status Scale; LE, lower extremity; MAS, Modified Ashworth Scale; MSWS, Multiple Sclerosis Walking Scale; ND, no device; SPC, single-point cane.

^aTested at first metatarsal phalangeal joint with 128-Hz tuning fork.

to quickly and easily assess kinematic and spatiotemporal gait variables to optimize the device use during a single visit. This has required a costly and time-consuming gait lab, but advances in wearable sensors and video gait analysis may now allow clinicians to measure key gait variables with acceptable accuracy in clinical settings.^{10,11}

The purpose of this case series was to describe the use of commercially available wearable sensors and video analysis to assess the immediate effects of FES on individuals with MS to improve FES prescription. To our knowledge, this series is the first to describe the effects of combining ankle dorsiflexor stimulation with thigh muscle stimulation in people with MS using a commercially available device.

METHODS

Participants

Participants were recruited by a local physiatrist based on the inclusion and exclusion criteria and their willingness to participate in an FES trial. All participants had a diagnosis of relapsing-remitting or secondary progressive MS; an Expanded Disability Status Scale (EDSS) score of 6.5 or less; and 1 or more of the following gait deficits: foot drop, lower extremity circumduction, hip hiking or vaulting, abnormal knee flexion during swing phase, or excessive knee flexion or hyperextension in stance phase. Exclusion criteria included a diagnosis of a neurological condition other than MS, cognitive or communication deficits that would limit their ability to participate safely, significant pain or deformity of the lower extremities that could impact walking ability, significant plantar flexion contracture that would prevent the ankle from achieving at least a neutral position, and significant lower extremity spasticity (Modified Ashworth Scale [MAS] > 2 at ankle). The University of Dayton Institutional Review Board approved the study, and all participants signed informed consent

prior to participation. **TABLE 1** presents the clinical characteristics of each participant.

Participant 1 was a 39-year-old woman with a 4-year disease duration. She ambulated household and short community distances primarily using a single-point cane and an anterior shell carbon fiber AFO (ToeOFF; Allard USA) on the right lower extremity. Her primary gait impairments were slow walking speed, poor right toe clearance, right genu recurvatum during stance, right lower extremity circumduction, hip hike, and decreased knee flexion during swing. Additionally, this individual fatigued easily with walking. She felt that her AFO provided some support for her foot drop, but she was frustrated by her inability to flex her knee when walking. Another concern for this individual was her inability to use her AFO with sandals. She demonstrated a prominent extension synergy in her right lower extremity during ambulation. She took oral baclofen and received regular botulinum toxin injections to her right ankle plantar flexors and knee extensors to treat her muscle spasticity and decrease her gait deviations.

Participant 2 was a 51-year-old woman with a 22-year disease duration. She ambulated community distances without an assistive device. She had previously used an FES device (Walkaide; AxioBionics) on her right lower extremity, but stated it was no longer functional and would like to explore a commercially available alternative. Her primary gait impairments included slow walking speed, reduced toe clearance, decreased knee flexion during swing, and increased knee flexion during stance. She expressed a desire to walk faster with a reduction in perceived effort.

Participant 3 was a 62-year-old man with a 34-year disease duration. He had bilateral lower extremity impairment, with his left side being more affected. He walked household and short community distances using a 4-wheeled walker and posterior

strut carbon AFO (WalkOn; Ottobock) on the left. His primary gait deficits were slow walking speed, short steps with poor toe clearance and intermittent left toe catching, decreased knee flexion during swing, and excessive knee flexion during stance. His motivation to try FES was that he was bothered by his hip flexion weakness and the frequency of his left toe catching during the swing phase, despite using his carbon fiber AFO. In addition, he quickly became fatigued during ambulation.

Procedures

Participants were evaluated during a single session that lasted 60 to 90 minutes in the research laboratory at the University of Dayton in Ohio. After collecting demographic and anthropometric data, a clinical examination was performed to assess strength, reflexes, muscle spasticity using MAS, coordination, and proprioception, and to score the EDSS for each participant. The participants also completed the 12-Item MS Walking Scale.

Walking Trials

Participants performed 2 recorded 10-m walks at a comfortable self-selected walking pace using their normal walking aid (cane, walker, or no assistive device) under the following conditions as deemed appropriate: (1) with no AFO, (2) with prescribed AFO, (3) FES on the lower leg only, or (4) a combination of FES on the lower leg and thigh. Prior to recording each FES condition, participants performed several 10-m walks during which FES intensity and timing were adjusted to optimize the response and allow for a brief familiarization. The clinical presentation of each participant determined which thigh muscles to stimulate (quadriceps or hamstrings) and during which gait phase (swing or stance). The intensity and timing of stimulation were also adjusted during the familiarization trials.

FES Device

The Bioness L300 Plus system (Bioness Neuromodulation Ltd) was used to provide FES to the lower leg and the thigh. The lower leg stimulator triggers the common fibular nerve to cause contraction of the ankle dorsiflexors and ankle evertors during the swing (and sometimes stance) phase. The thigh cuff stimulator targets either the quadriceps or the hamstrings during the swing or stance phases, but cannot stimulate both simultaneously. The lower leg unit uses a triaxial gyroscope and accelerometer to detect events in the gait cycle and is wirelessly synchronized with the thigh cuff stimulator, enabling electrical stimulation to be delivered at the appropriate point in the gait cycle.

Wearable Sensors

Prior to each testing session, 4 commercially available inertial motion sensors (IMUs; Opal V2R; APDM) were attached to the participant's sternum, posterior waist at the level of L5/S1, and the dorsum of both feet. This sensor configuration allowed us to capture gait speed (m/s), cadence (step/min), stride length (m), foot clearance (cm), foot strike angle (°), and circumduction (cm). Each IMU was equipped with a triaxial accelerometer, gyroscope, and magnetometer, and was wirelessly synchronized with a laptop via APDM Mobility Lab software (APDM Wearable Technologies

PRACTICE POINTS



Using wearable sensors and video analysis may be helpful in the prescription of functional electrical stimulation for improving gait in individuals with multiple sclerosis.

Functional electrical stimulation of both the ankle dorsiflexors and the thigh muscles during gait may offer an added benefit over stimulation of the ankle dorsiflexors alone. ■

Inc). The values for the 2 walking trials under each condition were averaged for each gait variable.

Video Analysis

A video camera (Sony ZV-1; Sony Corp) with a recording setting of 60 frames per second was placed on a tripod at the midpoint of a 10-m walkway to capture a sagittal view of the lower extremity at the height of the knee joint. Free, open-source video analysis software (Kinovea version 2023.1) was used to measure the maximum knee extension angle during stance and the maximum knee flexion angle during swing. The values for the 2 walking trials under each condition were averaged for each measure.

RESULTS

Participant 1

The main gait impairments observed in participant 1 included reduced walking speed, pronounced right genu recurvatum during the stance phase, insufficient right toe clearance, right lower extremity circumduction, and markedly decreased knee flexion during the swing phase. Gait was evaluated under 5 conditions, 4 in which the orthotic or FES was applied to the right lower extremity: (1) no device, (2) prescribed anterior shell carbon AFO, (3) FES of dorsiflexors during swing, (4) FES of dorsiflexors and hamstrings during swing, and (5) FES of dorsiflexors during swing and hamstrings during stance. The greatest combination of improvements in gait parameters occurred with FES of the dorsiflexors during swing and the hamstrings during stance. Compared with the no-device condition, this resulted in a 0.12-m/s increase in gait speed, a 0.13-cm increase in toe clearance, an 18° improvement in foot strike angle, a 7.3° reduction in knee genu recurvatum, an 8.4-cm decrease in circumduction, and 6.6° more knee flexion during swing. Compared with the participant's prescribed AFO condition, this resulted in a 0.01-

TABLE 2. Participant 1

Parameter	No device	AFO	FES DF swing	FES DF swing + ham stance	FES DF swing + ham swing	Normative values ^a
Gait speed, m/s	0.18	0.29	0.26	0.30	<u>0.32</u> ^b	1.04-1.64
Cadence, steps/min	43.1	53.6	50.5	52.8	<u>55.3</u>	103-133
Stride length, m	0.61	0.66	0.63	<u>0.68</u>	0.67	1.11-1.66
Foot clearance, cm	0.16	N/A ^c	<u>1.11</u>	0.29	0.18	0.37-2.4
Foot strike angle	-6.96°	4.66°	11°	<u>11.35</u> °	11.1°	16.5-33.2
Circumduction, cm	18.1	12.35	<u>9.1</u>	9.73	10.01	1.97-6.13
Knee flex midstance ^d	-3.85°	-7.15°	0.55°	<u>3.55</u> °	-0.8°	0-5
Max knee flex swing	5.5°	4.45°	11.1°	12.1°	<u>13.9</u> °	50-70

AFO, ankle-foot orthosis; DF, dorsiflexion; FES, functional electrical stimulation; ham, hamstring; max, maximum.

^aProvided by APDM software.

^bUnderlined values designate the best or most normal value for each gait variable.

^cNot available due to error in device recording.

^dNegative value indicates hyperextension.

TABLE 3. Participant 2

Parameter	No device	FES DF swing	FES DF swing + ham swing	FES DF swing + quad stance	Normative values ^a
Gait speed, m/s	0.8	<u>0.91</u> ^b	<u>0.91</u>	0.83	1.04-1.64
Cadence, steps/min	98.6	99.7	<u>100.2</u>	96.9	103-133
Stride length, m	0.95	1.07	<u>1.09</u>	1.03	1.11-1.66
Foot clearance, cm	0.36	0.57	<u>0.89</u>	0.52	0.37-2.4
Foot strike angle	12.0°	21.9°	<u>22.1</u> °	20.6°	16.5-33.2
Circumduction, cm	<u>2.62</u>	3.67	2.94	3.42	1.97-6.13
Knee flex midstance	21.2°	20.9°	<u>16.6</u> °	21.9°	0-5
Max knee flex swing	46.8°	49.4°	46.2°	<u>49.5</u> °	50-70

DF, dorsiflexion; FES, functional electrical stimulation; ham, hamstring; max, maximum; quad, quadricep.

^aProvided by APDM software.

^bUnderlined values designate the best or most normal value for each gait variable.

TABLE 4. Participant 3

Parameter	AFO	FES DF swing	FES DF swing + ham swing	FES DF swing + quad stance	Normative values ^a
Gait speed, m/s	0.37	<u>0.49</u> ^b	0.45	0.43	1.04-1.64
Cadence, steps/min	67.4	<u>74.3</u>	72.5	70.4	103-133
Stride length, m	0.67	<u>0.78</u>	0.76	0.72	1.11-1.66
Foot clearance, cm	0.03	0.46	0.53	<u>0.95</u>	0.37-2.4
Foot strike angle	3.77°	12.7°	12.7°	<u>15.3</u> °	16.5-33.2
Circumduction, cm	4.21	2.08	1.51	<u>1.15</u>	1.97-6.13
Knee flex midstance	23.1°	29.4°	27.1°	<u>18.8</u> °	0-5
Max knee flex swing	19.1°	34.5°	<u>39.1</u> °	33.8°	50-70

AFO, ankle-foot orthosis; DF, dorsiflexion; FES, functional electrical stimulation; ham, hamstring; max, maximum; quad, quadricep.

^aProvided by APDM software.

^bUnderlined values designate the best or most normal value for each gait variable.

m/s increase in gait speed, a 6.7° increase in foot strike angle, a 10.7° reduction in knee genu recurvatum, a 2.6-cm decrease in circumduction, and 7.6° more knee flexion during swing (TABLE 2).

Participant 2

The primary gait impairments in participant 2 were decreased walking speed, poor toe clearance, and excessive knee flexion during stance. Gait was assessed using (1) no device, (2) FES of dorsiflexors during swing, (4) FES of dorsiflexors and hamstrings during swing, and (5) FES of dorsiflexors during swing and quadriceps during stance; the orthotic or FES was applied to the right lower extremity. The condition that provided the most significant improvements in the most gait parameters was the combined FES stimulation of the dorsiflexors and hamstrings during swing. Compared with the no-device condition, this resulted in a 0.11-m/s increase in gait speed, a 0.53-cm increase in toe clearance, and a 4.6° decrease in knee flexion during midstance. The participant also reported a decreased perceived effort required to advance her right leg during walking (TABLE 3).

Participant 3

The primary gait impairments in participant 3 were decreased walking speed, inadequate toe clearance with short steps, reduced left knee flexion during swing, and excessive left knee flexion during stance. Gait was evaluated using (1) prescribed AFO, (2) FES of dorsiflexors during swing, (3) FES of dorsiflexors and hamstrings during swing, and (4) FES of dorsiflexors during swing and quadriceps during stance. The participant experienced varying levels of improvement. Utilizing FES for the dorsiflexors during swing resulted in an increase in gait speed of 0.12 m/s, an increase in toe clearance of 0.43 cm, and an increase in stride length of 0.11 m. When using FES for the dorsiflexors during swing and the quadriceps during stance, there was a smaller improvement in gait speed of 0.06 m/s, a greater increase in toe clearance of 0.92 cm, a smaller increase in stride length of 0.05 m, and a 4.2° reduction in knee flexion during stance (TABLE 4). Although both conditions offered different benefits, the participant preferred lower leg stimulation due to its ease of application, lower cost, and greater improvement in gait speed.

DISCUSSION

This case series demonstrates the potential benefits of using wearable sensors and video analysis to enhance the prescription of FES for people with MS. Each of the participants was able to achieve a clinically meaningful improvement in gait speed (ie, greater than 0.10 m/s) as well as improvements in other important gait variables such as toe clearance and knee position during stance and swing.¹²

The data obtained from the sensors and video provided immediate feedback, which was instrumental in determining the most effective FES conditions. This was particularly important when assessing the effects of stimulating the thigh muscles. Currently, the Bioness L300 Plus system allows for stimulation of the quadriceps or the hamstrings, but not both simultaneously. Consequently, it is necessary to decide which thigh muscle group to stimulate during specific phases of

the gait cycle to achieve optimal benefit, a choice that is not always straightforward. Because the quadriceps and hamstring muscles influence knee and hip motion, it can be difficult to predict how these joints will respond to stimulation during the gait cycle. This complexity is more pronounced in individuals with MS, who may experience abnormalities in tone, coordination, strength, sensation, and range of motion. As a result, the process typically involves some trial and error, with wearable sensors providing valuable immediate and objective feedback to identify the best approach.

Our case series highlights the clinical utility of combining sensor data with 2D video analysis to gather multiple kinematic and spatiotemporal variables, allowing a more comprehensive understanding of gait under each condition. This breadth of data may help clinicians determine which variables are most relevant to improving each individual's gait. For example, when a person has significant genu recurvatum during stance, as Participant 1 did at baseline, the addition of 2D video analysis enabled us to select the FES condition that normalized her knee flexion during stance while simultaneously assessing the extent to which FES affected the sensor-collected spatiotemporal and kinematic variables. In addition, providing sensor and 2D video analysis data to third-party payers was objective evidence of the benefits of FES. For Participant 1, this led to insurance approval and reimbursement for both a lower leg and a thigh cuff, marking the first time this device had received approval from this insurance provider for a person with MS in the state.

To our knowledge, this is the first case series to describe the potential advantages of individuals with MS utilizing a commercially available FES device on the lower leg and thigh to improve gait. A prior case study using surgically implanted multichannel electrodes in the hip flexors and dorsiflexors improved short-distance walking in a person with MS who exhibited minimal volitional movement and stepping capacity.¹³ In comparison, our case series involved stimulation of dorsiflexors and either the quadriceps or hamstrings using surface electrodes.

The body of literature supporting the use of FES in people with MS continues to grow. A recent systematic review found that FES may offer greater improvements in gait speed, kinematics, and perceived exertion than AFOs.⁵ However, it is important to note that the FES studies included in this review focused solely on stimulation of the ankle dorsiflexors. Our results suggest that using FES to stimulate multiple muscle groups may offer additional benefits; this warrants further investigation and is particularly relevant given the recent availability of commercial options. Using multichannel FES increases the cost and complexity of application, so any additional benefits should be carefully weighed against these factors. This was true for Participant 3, who preferred the simplicity of using only the lower leg FES despite the additional benefits of using the thigh stimulator.

Some limitations of this work should be acknowledged. This was an exploratory case series in which participants were selected because they were likely to benefit from FES; therefore, these findings are not generalizable. The outcomes were measured during a single FES exposure, with no long-term

follow-up, to determine whether the immediate orthotic effects were maintained and whether there were any therapeutic effects. We also did not determine whether the same FES prescription decision would have been made without the sensor and video data. However, some of the improvements in gait measured by the sensors were not obvious during visual observation. From a clinical feasibility perspective, the cost of wearable sensors continues to improve. However, most sensors are still several thousand dollars each and can require a software subscription, which may act as a barrier for some clinicians. The sensors that we used were easy to use, could be placed on the participant in less than 5 minutes, and did not require a software subscription. The video analysis required setting up a tripod at a standard height and distance from the participant, then removing the memory card and using the software on a computer. This took approximately 10 minutes and could be more challenging in a true clinical environment. Phone- or tablet-based video analysis apps may be faster and easier alternatives, but they may require a subscription and must comply with the Health Insurance Portability and Accountability Act.

CONCLUSIONS

Given the varied nature of motor and gait impairments in people with MS and their different responses to FES, it is important to use an individualized approach when prescribing FES. Recent advancements in wearable sensors that demonstrate acceptable accuracy and reliability may enable clinicians to measure a number of gait variables quickly and easily,^{10,11} allowing for a more objective evaluation of FES responses in clinical practice. This case series demonstrates the feasibility of using wearable sensors and video analysis to assess the effects of multichannel FES across a range of gait variables. We are hopeful that our efforts may lead to improvements in FES prescription in individuals with MS and other neurological disorders. ■

Acknowledgments: The authors wish to thank Nick Padgett, PT, DPT, OCS, and Robert Campbell, PT, MSPT, of Bioness Medical Inc, who provided the FES equipment, clinical expertise, and adjustment of stimulation parameters during the trials.

Financial Disclosures: The authors have disclosed no relevant conflicts of interest.

Prior Presentation: This work was presented in poster form at the American Physical Therapy Association's Combined Sections Meeting, held February 13-15, 2025, in Houston, Texas.

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