Control of Stroke-Related Genu Recurvatum With Prolonged Timing of Dorsiflexor Functional Electrical Stimulation: A Case Study

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Background and Purpose: Abnormal knee hyperextension during the stance phase (genu recurvatum) is a common gait abnormality in persons with hemiparesis due to stroke. While ankle-foot orthoses (AFOs) are often used to prevent genu recurvatum by maintaining ankle dorsiflexion during the stance phase, AFOs reduce ankle joint mobility. Functional electrical stimulation (FES) is an alternative to the use of AFO for producing appropriately timed ankle dorsiflexion and with prolonged timing may also have value for reducing genu recurvatum.

Case Description: A 51-year-old man with chronic stroke was the subject of this case study. The patient had excessive plantarflexion during stance phase (ie, dynamic equinus foot), with associated genu recurvatum.

Intervention: Evaluation included clinical examination, instrumented gait analysis, 10-meter walk test, and 6-minute walk test. The patient underwent a trial of botulinum toxin to the plantarflexor muscles that was not effective for controlling the genu recurvatum. A subsequent trial with surface FES to elicit dorsiflexion during gait was effective, and he subsequently received an implanted FES system.

Outcomes: Stimulation-induced contraction of the dorsiflexors during terminal swing phase resulted in improved ankle dorsiflexion at initial contact. Moreover, extension of stimulation into the loading phase ensured tibial advancement, which limited knee hyperextension. The patient was reevaluated 12 months following implantation with continued positive outcomes.

Discussion: This case study illustrates the potential value of prolonged timing of dorsiflexor FES to manage genu recurvatum attributed to a dynamic equinus foot in a stroke survivor.

Key words: *drop foot, functional electrical stimulation, gait, genu recurvatum, rehabilitation, stroke*

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INTRODUCTION

 \sum enu recurvatum, abnormal knee hyperextension during
the stance phase,¹⁻³ is a common gait abnormality in per-
sons with hamingrasis due to stroke $\frac{1.2}{1.2}$ From a higmachanical sons with hemiparesis due to stroke.^{1,2} From a biomechanical point of view, it is characterized by a ground reaction force vector anterior to the knee joint center.^{1,3,4} Different causal mechanisms that may lead to genu recurvatum have been proposed in the literature, including (i) weakness of quadriceps, hamstrings, or buttock muscles; (ii) spasticity of quadriceps; (iii) limited ankle dorsiflexion during the stance phase; and (iv) proprioceptive disorders.¹ Depending on the identified or suspected cause, different types of treatment have been proposed such as medical therapy (eg, intramuscular injection of botulinum A toxin into triceps surae⁵), orthotic devices (eg, ankle-foot orthoses $[AFOs]$, 6 knee-ankle-foot orthoses⁴), rehabilitation techniques (eg, feedback electrogoniometric devices or multichannel electrical stimulation¹) or surgical procedures (eg, aponeurotic calf muscle lengthening¹).

When the main cause of genu recurvatum is associated with limited ankle dorsiflexion during the stance phase, tibial advancement is often not achieved.⁷ Poor muscle timing may result in failure to flex the knee during early stance, consequently the tibia is driven posteriorly resulting in genu recurvatum. In situations such as this, AFOs have been shown to be an efficient intervention, correcting both the ankle dorsiflexion at initial contact and the posterior tibial inclination during the stance phase.3,4,6,8 However, the use of AFOs has been associated with reduced ankle joint mobility and poor muscle activation.⁹

Functional electrical stimulation (FES) applied to the peroneal nerve has been proposed as an alternative to AFO for the treatment for impaired ankle dorsiflexion (ie, foot drop).⁹ Unlike AFOs, FES preserves ankle joint mobility and muscle activity. The typical use of FES is to generate a stimulation-induced contraction of the dorsiflexors during the swing phase to reduce foot drop. Several studies have demonstrated the improvement of ankle kinematics, $10,11$ spatiotemporal parameters, $10,11$ gait symmetry, $11,12$ obstacle avoidance, 13 and balance control¹⁴ using FES. Moreover, it has been shown that in persons with stroke who have spasticity, FES can induce a small but statistically significant reduction of the spasticity of the quadriceps muscles.¹⁵

Despite the value of FES for promoting more normal ankle dorsiflexion, the potential benefits of FES on the mechanics of proximal joints such as knee remains unclear. In a recent

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randomized controlled trial, 10 23 stroke survivors were implanted with a 2-channel peroneal nerve stimulator (Finetech Medical Ltd, Welwyn Garden City, UK) and kinematic parameters were assessed at baseline (ie, without FES) and 26 weeks after implantation (ie, with FES). The results did not show significant difference between the 2 conditions (ie, without FES vs with FES) on the hip and knee kinematics. However, the mean knee flexion angle at initial contact slightly increased by 3◦ suggesting a potential effect of FES on knee mechanics. An improvement of the knee flexion during swing phase was also reported in a case study and may be explained by improved ankle plantar flexion at push-off.¹¹

The aim of this case study was to report and discuss the use of FES in a stroke survivor presenting with genu recurvatum due to limited ankle dorsiflexion during the stance phase (ie, dynamic equinus foot). The main assumptions were that by extending the time of dorsiflexor stimulation past the swing phase, into the initial contact and loading phases (ie, 0%-10% of the stance phase⁷), tibial advancement could be restored preventing knee hyperextension during midstance. This protocol was approved by the National Ethics Committee of Luxembourg and the patient gave his informed consent before participation.

CASE DESCRIPTION

The subject of this case study was a 51-year-old male construction worker who had experienced a right hemispheric infarction 11 months earlier. He presented at our rehabilitation center complaining of a recurrent left knee pain during walking. The patient did not use any assistive device during walking and declined the use of a passive orthotic device. The patient reported no history of left knee pathology prior to his stroke. The dynamic equinus foot was characterized by the ability to perform voluntary dorsiflexion during the clinical examination, but an inability to achieve dorsiflexion during the swing phase of gait. The patient described the genu recurvatum as painful, and he reported that the pain prevented him from walking more than few steps and therefore limited his ability to work.

Initial Clinical Examination

The patient had good muscle strength (ie, 4/5) of the lower extremity muscles based on manual muscle test grades tested while seated (see Table 1). He had slight spasticity based on resistance to passive stretch while at rest (Table 1: 1/5 on the modified Ashworth scale¹⁶) and no observable proprioceptive dysfunction. During observational gait analysis, the patient presented with plantarflexion during the stance phase of walking and an appreciable genu recurvatum. Specific patient characteristics are given in Table 1. Based on this assessment, the clinical interpretation was that the genu recurvatum was attributable to the dynamic equinus foot⁷ as a consequence of walking with a limited ankle dorsiflexion for an extended period thereby overstretching the ligamentous and capsular structures that support the posterior aspect of the knee joint.

INTERVENTION

Treatment

As a first treatment strategy, the decision was made to target the spasticity in the plantarflexors as this was thought to contribute to the dynamic equinus foot and the associated genu recurvatum. Intramuscular botulinum toxin (Botox; Allergan, Irvine, California) injections were made into gastrocnemius medialis (50 units) and soleus (150 units) muscles. Three sessions of injections were performed each separated by 6 months. However, after the third session of injections (December 2009), the patient was not satisfied with the results, and it was concluded that the treatment had been ineffective for correcting the genu recurvatum.

As a second treatment strategy, surface FES (WalkAide, Innovative Neurotronics, Austin, Texas) was provided with the patient's agreement (January 2010). The goal was to

^bModified Ashworth scale.¹⁶

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restore and promote dorsiflexion to achieve heel strike at initial contact, along with tibial advancement during midstance to correct the dynamic equinus foot and improve the control of the knee. The surface FES system was effective for restoring a heel strike at initial contact and thus corrected the genu recurvatum. However, the location of the housing that contained the peroneal electrodes (around the proximal shank near the proximal head of the fibula) interfered with the patient's ability to kneel during work.

A third treatment strategy, an implanted FES system, was established with the goal of incorporating FES in a manner that would also promote professional reintegration. This patient was included in an observational study conducted in our rehabilitation center to perform a 3-year follow-up of stroke survivors implanted with this FES device. He was the only patient presenting with an appreciable and painful genu recurvatum. As part of the study of the implanted FES system, the patient underwent a second clinical examination and instrumented gait analysis session prior to implantation.

Pre- and Postimplantation Clinical Examination and Instrumented Gait Assessment

One month prior to the implantation (M−1), the patient underwent a clinical examination and clinical gait analysis (CGA), which was repeated 12 months following implantation (M+12). Both M−1 and M+12 measurements followed the same procedure. The clinical examination was performed to assess the passive range of motion of each joint (measured with a manual goniometer in the supine position), muscles strength (using the Medical Research Council score¹⁷), and dorsiflexor muscle spasticity (using the modified Ashworth scale¹⁶); both the M−1 and M+12 clinical examinations were performed by the same physician. The CGA was performed using a motion capture system to compute 3-dimensional kinematics, kinetics, and ground reaction forces. The CGA system consisted of 7 optoelectronic cameras (BTS Bioengineering, Garbagnate Milanese, Italy) sampled at 250 Hz and 2 force plates (AMTI, Watertown, Massachusetts) sampled at 1000 Hz.

The motion capture procedures were based on the Davis-Kadaba model¹⁸ and are composed of 17 cutaneous markers placed on both pelvis and lower limbs. During the data capture for the CGA, the patient walked at a self-selected speed along a 10-m straight walkway; 5 gait cycles were recorded. When necessary, data were interpolated using a cubic spline interpolation, filtered using a 4th-order low-pass Butterworth filter—cutoff frequency of 6 Hz for kinematic data and 20 Hz for kinetic data. Data were then normalized to a 0 to 100% gait cycle and averaged over the 5 recorded gait cycles. Kinetic data were normalized to the product of body weight (BW) and lower limb's length (LL). Similarly, ground reaction forces were normalized to BW. Third, gait spatiotemporal parameters were evaluated during CGA and completed by a 10-m walk test (10MWT)—performed at maximum speed—and a 6-min walk test (6MWT)—performed at self-selected speed.¹⁹ All measurements were performed the same day in our rehabilitation center.

For this study, only mean sagittal kinematics and kinetics computed from M−1 and M+12 CGA were compared to the gait parameters of the normative data of our gait laboratory. These normative data were defined by recording the gait of 10 women (37 \pm 14 years, 1.67 \pm 0.06 m, 64.06 \pm 8.56 kg) and 10 men (35 \pm 13 years, 1.80 \pm 0.09 m, 77.95 \pm 10.54 kg) walking at a 0.96 ± 0.11 m/s in the same conditions as the patient. To evaluate the quantitative differences between the patient's kinematics and kinetics and the normative data, a measure of goodness of fit was performed. The root mean square error (RMSE) was thus used to indicate how well the mean kinematics and kinetics obtained from the patient's data followed the normative data parameters. The difference was obtained by computing the RMSE between the mean curve of each parameter and the associated normative mean curve over both the stance phase and the swing phase.

Implanted FES Treatment

The patient underwent surgery to implant the FES system (Actigait, Ottobock, Duderstadt, Germany) in September 2011 (ie, 33 months after stroke). A detailed description of the implanted FES system has been published previously (see Burridge et al²⁰ and Ernst et al²¹). Briefly, the system is composed of implanted and external components. The implanted component is made of 4 distinct electrodes, embedded in a cuff, which surrounds the motor branch of the common peroneal nerve. The cuff is surgically placed proximal to the knee joint but distal to the separation of the sensory and motor nerve branches. In this sense, the system can only act on dorsiflexors (ie, tibialis anterior, extensor hallucis longus, extensor digitorum longus, and peroneus tertius) and eversors (ie, peroneus longus and peroneus brevis), respectively, through the superficial and deep peroneal branches. The stimulus parameters delivered by each electrode can be individually activated and adjusted in terms of impulse duration. This allows balancing of the dorsiflexor and everter muscle responses to adjust the foot obliquity in the frontal plane. These adjustments are conducted in a seated position and refined during gait. The external components of the system are the control unit and the heel switch. The control unit allows the patient to switch the system on or off and to modulate the intensity of the stimulation. The heel switch is a wireless device that is sensitive to pressure; it is positioned under the foot using a dedicated sock. The heel switch detects the heel lift and heel strike events that are used to define the stimulation onsets and offsets.

The implanted FES system was activated 3 weeks after the implant surgery. Between surgery and activation, a knee immobilizer splint (Zimmer, Warsaw, Indiana) was used to avoid excessive knee flexion that could cause the displacement of the cuff and delay its attachment. After activation, the patient followed a 1-month education program (ie, 1-hour sessions, 4 times per week) in our center to learn how to use the system in an optimal manner. This program included a progressive increase of the stimulation intensity and duration to avoid muscular fatigue and pain. Subsequently, the patient participated in a 3-month gait rehabilitation program, composed of 1-hour sessions, 3 times per week. The gait training program focused on the optimal use of the FES device, gait symmetry, and knee control (ie, quadriceps strengthening with eccentric contraction exercises such as going down stairs, and knee flexion management with exercises such as flexed knee gait). Stimulation parameters were adjusted by a physician and a research engineer of the gait laboratory of our rehabilitation center when specific problems were experienced. By 12 months after implantation $(M+12)$, the final stimulation parameters were as follows: a pulse rate $= 20$ Hz, a pulse duration = $89.25 \mu s$, and a current of 1.2 mA. A bipolar square waveform was used for stimulation. Moreover, a ramp time of 0.2 ms was applied to gradually increase and decrease the stimulation intensity. Thus, the stimulation remained active and efficient for an extra time ≤0.2 ms after initial contact, corresponding roughly to the loading response phase (Figure 1).

Figure 1. Comparison with normative data of the sagittal joint kinematics and kinetics and of the proximal/distal and antero/posterior ground reaction forces obtained before implantation (M−1) and 12 months after implantation (M+12 without and with FES). All data are measured during clinical gait analysis on the paretic side and time-normalized in stance and swing. Net joint moments (newton meters; N*m) are reported normalized to body weight times leg length (BW*LL). Ground reaction forces were normalized to body weight. Stimulation profile (in terms of stimulation intensity) is also given during the entire gait cycle. Mean and standard deviation of the 5 recorded trials are reported for each parameter.

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OUTCOMES

Clinical Examination

The clinical examinations performed during both M−1 and $M+12$ assessments (Table 1) did not show clear differences in terms of muscle strength and spasticity. However, (1) the passive knee hyperextension, measured in the supine position, increased by 5° , and (2) the passive ankle dorsiflexion in knee extended position decreased by 5◦ while its value in knee flexed position increased by 5◦.

Kinematics

Figure 1 gives the sagittal kinematics computed from M−1 and M+12 (with and without the use of FES) CGA during both the stance phase and the swing phase. The RMSEs of these parameters are given in Figure 2. The accompanying video illustrates the appearance of the subject's gait without and with FES at the $M+12$ time point (see Video, Supplemental Digital Content 1, [http://links.lww.com/JNPT/A135\)](http://links.lww.com/JNPT/A135).

During the stance phase, with the use of the implanted FES system the foot, ankle, knee, and hip sagittal kinematic patterns were improved and better fit the normative data (RMSE decreased by 65%, 64%, 41%, and 32%, respectively). More specifically, foot tilt (ie, the angle between the foot and the ground in the sagittal plan) and ankle dorsiflexion increased, respectively, by 24.07◦ and 22.66◦ at initial contact and were accompanied by a mean increase of knee flexion of 41.25◦ during midstance (ie, 17%-50% of the stance phase).

Figure 2. Root mean square errors (RMSEs) during the stance and swing phases for sagittal kinematics and kinetics parameters (F/E means flexion/extension) obtained before implantation (M−1) and 12 months after implantation (M+12 without and with FES) compared to normative data. Net joint moment (newton meters; N*m) are reported normalized to body weight times leg length (BW*LL). Ground reaction forces (A/P and P/D, respectively, mean anterior/posterior and proximal/distal) are reported in body weight (BW).

Hip sagittal kinematics was also improved under stimulation as the hip remains flexed until terminal stance (ie, until 50% of the stance phase). Conversely, joint kinematics obtained after implantation but with the FES system turned off were not improved relative to the baseline data (eg, foot and hip kinematics) or were degraded (i.e., ankle and knee kinematics).

During the swing phase, with the use of the implanted FES system, the foot and ankle sagittal kinematic patterns were improved and better fit the normative data (RMSE decreased, respectively, by 6% and 72%). In particular, the mean ankle dorsiflexion increased by 10.64◦ during terminal swing (ie, 67%-100% of the swing phase). Hip kinematics remained almost unchanged (the absolute variation of RMSE was $\langle 1^\circ \rangle$), but the peak knee flexion decreased by 9.53◦. As with the stance phase measures, joints kinematics obtained after implantation but with the FES system turned off were not improved relative to the baseline (eg, foot and hip kinematics) or were degraded (ie, ankle and knee kinematics).

Kinetics and Ground Reaction Forces

Figure 1 gives the sagittal kinetics and ground reaction forces computed from M−1 and M+12 (with and without the use of FES) CGA during the stance phase. The RMSEs of these parameters are given in Figure 2.

During the stance phase, ankle, knee, and hip sagittal kinetics were improved and better fit the normative data after implantation with the use of FES (RMSEs decreased, respectively, by 92%, 52%, and 66%). Specifically, the ankle plantarflexion moment increased by 400% at the peak and the knee extension moment was restored during midstance (ie, 17%-50% of the stance phase). Hip sagittal kinetics was also improved and tended to the normative data. However, joints kinetics obtained after implantation but without the use of FES were not improved regarding the baseline (eg, ankle kinetics), slightly improved (ie, hip kinetics), or degraded (ie, knee kinematics).

During the stance phase, both proximal/distal and anterior/posterior ground reaction forces were improved and better fit the normative data after implantation with the use of FES (RMSE decreased, respectively, by 63% and 50%). The main improvements were during preswing (i.e., 83%-100% of the swing phase) with a clear recovery of propulsion (ie, the posterior ground reaction force increased by 150% at the peak force).

Spatiotemporal Parameters

A sample of spatiotemporal parameters, obtained during CGA, of the paretic and nonparetic limb at M−1 and M+12 (with and without the use of FES) and the results of the 10MWT and 6MWT are given in Table 2.

Comparing the M−1 and M+12 values shows that without the use of FES, an increase of 40 m was observed during the 6MWT, while the time to perform the 10MWT decreased by 0.10 s. No clear change was observed on both spatial and temporal parameters during CGA except an increase of 0.06 m/s of the walking speed. Conversely, with the use of FES an increase of 140 m was observed during the 6MWT (ie, 100 m more than without the use of FES), and the time to perform the 10 MWT decreased by 2.10 s (ie, 2.00 s more than without the

Table 2. Mean and Standard Deviation (When Available) of the Spatial and Temporal Parameters Obtained During Clinical Gait Analysis (CGA), 10-Meter Walk Test at Maximum Speed (10MWT), and 6-Minute Walk Test at Self-Selected Speed (6MWT)a

use of FES). While walking speed showed the same increase of 0.06 m/s with and without the use of FES, when FES was used, the ratio between the step length of paretic side and nonparetic side moved closer to 1, indicating an improvement of the gait symmetry.

DISCUSSION

with FES).

The goal of this case study was to assess the potential of FES to manage a genu recurvatum attributed to dynamic equinus foot in a person with chronic stroke. The hypothesized benefit was based on 2 assumptions: (1) that the FES would improve ankle dorsiflexion at initial contact by generating stimulation-induced contraction of the dorsiflexors during the swing phase and (2) that extension of stimulation into the loading phase should ensure a tibial advancement and thus reduce knee hyperextension. As expected, by generating a stimulation-induced contraction of the dorsiflexors during the swing phase, the results obtained with the use of FES support the first assumption by showing a clear increase of the foot tilt angle and ankle dorsiflexion and heel strike at initial contact. These results are consistent with the literature, where FES is recognized as an efficient tool to increase ankle dorsiflexion during the swing phase and thus ensure a better foot positioning in preparation for initial contact.^{9,10} The level of foot tilt angle depends on the intensity of stimulation and passive range of motion of the patient. In our outcomes, there was no modification of the proximal limb kinematics, suggesting that the effect was localized to the ankle and knee joints.

The outcomes of this case study support the value of extending the dorsiflexor stimulation duration into the loading phase to maintain ankle dorsiflexion during the stance phase. Indeed, once the foot is in contact with the ground, ankle dorsiflexion generates tibial advancement bringing the knee joint center anterior to the ground reaction force vector. While the stimulation stops after the loading phase, the knee remains flexed during the entirety of midstance. This observation supports the assumption that knee hyperextension was the result of inability to control the posterior alignment of the tibia.⁷ However, because of the considerable passive knee moment, FES could not avoid knee hyperextension during

terminal stance. Consequently, the passive knee hyperextension still tends to increase, even after having started the FES treatment.

To our knowledge, this is the first report of extending the period of dorsiflexor stimulation duration into the loading phase. This may be because most of the previous FES studies were focused on correction of foot drop during swing phase. While Springer et $al¹²$ had previously suggested the use of FES to enhance the control of the knee during the stance phase, their focus was on genu recurvatum related to the weakness of quadriceps or hamstrings. For that reason, the authors proposed the use of a dual-channel FES to provide stimulation both to the ankle dorsiflexors and to the quadriceps or hamstrings, with the proximal stimulation activated during stance phase. The approach we used allows similar results to be achieved with a single stimulator and avoid the need to coordinate the timing of multiple stimulators.

Beyond the validation of our 2 initial assumptions, the outcomes show an increase of ankle plantarflexion moment and the antero/posterior ground reaction force, demonstrating an improvement of the ankle push-off. The restoration of an efficient ankle push-off has previously been reported and associated with the reduction of a compensatory movement strategy.^{11,22} In our case study, the underlying mechanism may be related to the improvement in ankle kinematics, by restoring a heel strike at initial contact and increasing the plantarflexion during preswing. The quality of gait was also improved with a better gait symmetry illustrated by a similar step length of both the paretic and nonparetic sides, as has been reported by others.11,12 These results are confirmed by the 10MWT and the 6MWT, suggesting a global improvement in walking ability. Indeed, both walking speed $(+0.54 \text{ m/s})$ and 6-minute-walk distance $(+140 \text{ m})$ were increased and exceeded the minimum clinically important differences estimated at 0.16 m/s^{23} and 50 m, respectively, for meaningful change. 24

Limitations

While the outcomes of our case study are encouraging, this is a single-case study for which the outcomes may not be generalizable and which has some limitations. First, both FES and rehabilitation were performed, and therefore rehabilitation could have contributed to the observed improvements. Indeed, since the rehabilitation program focused on knee control during stance, it may have contributed to limit the knee hyperextension. For that, quadriceps strengthening exercises were used in addition to constrained knee flexed gait exercises to return the patient knee to a sufficient level of stability and strength. However, most of the assessments performed after implantation but without the use of FES demonstrate that ankle and knee kinematics were not improved despite participation in a gait rehabilitation program. Only the distance performed during the 6MWT demonstrated a meaningful change of 40 m. 24 Second and more important from the perspective of neurologic physical therapist practice is given that the patient had good muscle strength on manual muscle testing, it is possible that similar results could have been obtained with a motor learning rehabilitation program that focused on activating the muscles at the appropriate time in the gait cycle. Finally, it must be noted that the patient was a good responder and had characteristics that may have contributed to the positive outcome. The patient had few residual motor limitations following his stroke and consisted primarily of the dynamic equinus foot and slight plantarflexors spasticity. The lower limb muscles had good muscle strength, and joint passive range of motion was near normal. Despite these limitations, for this individual the FES as applied in this case study was associated with improved walking function, and less stress on the knee joint as the result of improved gait mechanics.

SUMMARY

This case study illustrates positive outcomes related to the management of genu recurvatum with FES applied to the peroneal nerve in a person with chronic stroke. The novel aspect of the stimulation was that, in addition to activating the dorsiflexor muscles during the swing phase, the stimulation continued into the loading phase. This prolonged dorsiflexor stimulation period resulted in improved heel strike and promoted knee flexion with advancement of the tibia over the base of support through the loading phase. Further investigations with larger numbers of subjects are warranted to identify the characteristics of individuals who might benefit from this approach.

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