The effect of Functional Electric Stimulation in stroke patients’ motor control – a case report

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Abstract. Functional Electric Stimulation (FES) has been studied as a therapeutic resource to reduce spasticity in hemiplegic patients, however there are no studies about the effects of FES in motor control of these patients during functional tasks like balance maintenance. Muscular activation of gastrocnemius medialis and semitendinosus was investigated in both limbs of a hemiparetic patient during self-disturbed quiet stance before and after FES on tibialis anterior, by surface electromyography. The instant of maximum activation peak of GM and ST were calculated immediately after a motor self-disturbance, in order to observe muscular synergy between these two muscles, and possible balance strategies used (ankle or hip strategy). At the preserved limb there occurred distal-proximal synergy (GM followed by ST), expected for small perturbations; however, at spastic limb there was inversion of this synergy (proximal-distal) after FES. It is possible that intervention of electricity had inhibited synergical pathways due to antidromic effect, making it difficult to use ankle strategy in the spastic limb.

1. Introduction
Stroke is a disease with vascular origin, in which there occurs a focal perturbation of encephalic function, due to ischemia or bleeding on encephalic nervous tissues. It is the second principal cause of death in the world, and among the survivors, there is a large ratio of disabled people that need constant support from their families and from social and health institutions [1].

Hemiplegia is the most prevalent sequel in patients that suffered stroke [2], which is commonly characterized by spasticity, motor control deterioration and consequently changes in gait pattern [3]. Usual motor alterations are decrease of triple flexion of lower limb [4], reduction on dorsiflexion range of motion, equinus foot, and knee hyperextension [5]. Thus, these subjects have higher energy expenditure in walking [6] and also balance deficit [4].

The main factor that contributes to these alterations is spasticity [7], due to loss of central inhibition of the muscle stretch reflex by injury to upper motor neurons, which predominates in extensor muscles at the lower limbs [2].

Spasticity reduces the ability to regulate voluntary movement. The reason that this occurs is that patients with stroke sequel have their reciprocal inhibition (RI) decreased [8], because the predominance of hypertonic muscles blocks the interaction between synergistic and antagonistic muscle groups, resulting in a static fixation of the joint – in this case, the equine foot – instead of dynamic stability during motor tasks [9].
At post-stroke rehabilitation, neuromuscular facilitation is commonly used, which emphasizes the inhibition of abnormal reflex patterns and tone normalization before training standing and gait [10]. Therefore, a possible treatment would be interfering in the mechanism that modulates RI and presynaptic inhibition [11]. It is known that FES has the immediate effect of increasing RI of stimulated muscles’ antagonists [12], so it is possible that, by stimulating the dorsiflexor muscles, a decrease in spasticity of plantar flexors can be caused, favoring a more efficient pattern of muscle activation in spastic hemiplegic patients.

Since 1961, when Liberson et al. [13] described a method of FES on hemiplegics’ fibular nerve, induce RI in spastic muscles by FES has been studied by several researches [14,15], and all of them found significant results such as increase of RI and, consequently, spasticity decrease in these patients. However, it is important to highlight that, with the exception of Alfieri’s research [14], none of them measured the duration of RI on the spastic muscles. On the other hand, Alfieri showed that there was a reduction of spasticity after FES with duration of effect ranging from 10 minutes to 3 hours, with an average of 1 hour; but this was measured by the Ashworth Scale, which is subjective and unreliable to measure spasticity objectively.

Moreover, most of the cited studies has evaluated spasticity of plantar flexors in a static manner, but did not assess how these muscles behaved in functional motor tasks such as balance and gait.

With this background, we found that FES can be a useful therapeutic approach in reducing the spasticity of hemiplegic patients, but it is necessary to study the effects of FES in motor control during functional tasks such as maintaining balance.

2. Materials and methods

The present study investigated muscle activation of the lower limb in hemiparetic patients during self-disturbed stance before and after FES of tibialis anterior, by surface electromyography. However, we used kinematic variables to enable the division of the electromyography signal in two phases: disturbance and post-disturbance. The post-disturbance, when the subject is recovering from the perturbation, is the phase of interest in this study.

The research was developed in the Laboratório de Movimento of the Instituto de Medicina Física e Reabilitação of the Hospital das Clínicas of the Faculdade de Medicina da Universidade de São Paulo (IMREA – HC / FMUSP). The laboratory has advanced technological resources such as (1) Imaging System, (2) Power Platforms System and (3) Surface Electromyography System. These systems are integrated with the Acquisition and Processing System of the collected data.

2.1. Subject selection

We assessed a male volunteer, aged 51, who was in a rehabilitation program in the model of Light Hemiplegia in the Estação Especial da Lapa unit of IMREA.

Inclusion criteria were: diagnosis of chronic stroke (more than one year of injury), level of spasticity in lower limbs = 2 (Modified Ashworth), level of dorsiflexion muscle strength ≥ 3, and the presence of functional ambulation without aids or orthoses.

Exclusion criteria were: age above 60 years, previous use of FES as a treatment, botulinum toxin injection in the plantar flexor muscles in the last six months, orthopedic disorder or equinus foot deformity, cognitive disorders, other neurological disorders, and hemodynamic instability.

The volunteer was included in the study after he agreed to participate in the research and signed the INFORMED CONSENT FOR RESEARCH PARTICIPATION, making him aware of the procedures related to the collection of data. Additionally, all of his doubts were clarified as to the procedures to be performed. Participation was voluntary and unpaid.
The experimental methods used were non-invasive and pose no hazard to the health of the volunteer. We did not use any type of substance, and no medical/therapeutic treatment was prescribed.

2.2. Subject Preparation
After the explanations of testing procedures, the individual wore appropriate clothing (swimsuit or shorts), and then he was properly prepared for the attachment of reflective markers at specific anatomical points, defined by the anthropometric model of Dempster (1995) [16]. This was necessary because through these markers, body segments were determined in order to calculate the total center of mass (COM) using the Ortho Trak 6.2 software [16], which was subsequently utilized for the separation of task intervals by the method of Costa et al. [17].

To capture the electromyography signal, after the abrasion of the skin with alcohol, surface electrodes were fixed on the following locations: the gastrocnemius medialis muscles (at 32% of the distance between the medial popliteal fossa and the medial side of the Achilles tendon), the semitendinosus (at 50% of the distance between the medial epicondyle and the ischial tuberosity), and the tibialis tuberosity (ground electrode). These points were chosen following the recommendations of SENIAM [18] and Sacco [19].

2.3. Experimental protocol
The experimental sequence of this study was composed of the following stages: (1) system calibration, (2) execution of the task, (3) intervention using the FES, and (4) post-intervention biomechanical analysis, every 45 minutes during a period of 3 hours.

The task consisted of the recovery of balance after a self-perturbation caused by the subject. The volunteer was instructed to position himself standing on the force platform, so the axis of mediolateral movement was represented by the $x$ coordinate, and the anteroposterior by $y$, in relation to the axis of reference adopted on the laboratory platform. The initial position was 60° of trunk flexion (relative to the ground) with arms resting on the back of a chair - to avoid possible falls, since the subject had a deficit of balance - and feet comfortably parallel to the body (Figure 1).

![Figure 1: Schematic representation of the task: the volunteer’s initial position (60° of trunk flexion) and final position (already in the upright posture).](image-url)
Data collection began after an initial sound stimulus, when the volunteer was asked to make a sudden extension of the trunk to the upright position (Figure 1), causing him a motor disturbance. Afterwards, he was told to keep his eyes open and fixed on the horizon and stay in the upright quiet position for 60 seconds, when the second sound stimulus indicated the end of the first data collection. After 1 minute of rest, the second collection was performed, and then the third, respecting the same resting interval. Of these three collections, the first was considered the task’s adjustment period and was discarded. The second was chosen as valid for analysis, but in cases when the subject had made some unwanted movement like shaking his head or arms, we used the third collection. This task has been used in other experiments with the intention of causing a motor disturbance, and was described in more details by Castro [20,21] and Costa [17].

The intervention with FES was initiated immediately after the initial biomechanical analysis. For this, the volunteer was positioned in a chair with his feet flat on the floor, with hip ischial support, keeping the hip, knee, and ankle in 90°.

For the motor point mapping, two adhesive electrodes were used: the first, with 5 cm of diameter, was used as the reference electrode; the second, with 3.2 cm of diameter, was used to map the motor point. It was considered an indication of proper motor point placement when there was muscle stimulation with FES, gradually increasing the amplitude and causing a pure dorsiflexion. After locating the motor point, two electrodes of the same size (5 cm) were applied for electrical stimulation.

Electrical stimulation parameters were: frequency = 20 Hz [22], pulse width = 300US, ramp-up = 2s, ramp down = 2s, contraction time = 6s, rest time = 10s, and the intensity was regulated until the occurrence of a minimum degree of dorsiflexion contraction (TA action) without joint movement [14]. The application time was 40 minutes.

After the intervention with FES, the volunteers were re-evaluated by the biomechanical system according to the procedures described above, and these were repeated four more times with time intervals of 45 minutes, totaling a period of 3 hours after FES application.

Thus, each subject was analyzed in six trials, ordered from 1 to 6, namely: trial 1 - prior to FES, trial 2 - immediately after FES, trial 3 - 45 minutes after FES, trial 4 - 1 hour and 30 minutes after FES, trial 5 - 2 hours and 15 minutes after FES, and trial 6 - 3 hours after FES.

2.4. Acquisition and processing of data

After pre-processing of the raw data by Evart software [23], the system provides the files with kinematic and EMG data. OrthoTrak 6.2 software [16] integrates the signals from the cameras and creates a three-dimensional model of the studied subject by photogrammetry, after manual processing by a program operator.

Before processing the EMG signals, it was necessary to determine the following intervals performed by the volunteer: disturbance interval (when the subject performed trunk extension for upright posture) and post-disturbance interval (when he reached the upright position and kept oscillating to maintain postural control). For the division of these intervals, a pre-processing of kinematic data was carried out.

2.4.1. Pre-processing of data. For pre-processing of data, kinematic and EMG variables captured by the software Evart were used.
The imaging system generates a raw data file with information of markers fixed on the subject during the movement of self-perturbation, with the coordinates of the joints, the COM and the centers of mass of each segment at coordinates $x$, $y$ and $z$. This file can be read in an Excel spreadsheet and has the extension *.TRBCoord. Another file with extension *.xls contains the values of the electromyography signals of ST and GM muscles of both legs during the collection interval [16].

In order to identify the end of self-disturbance, a criterion was established to select the task intervals, and these were calculated by a mathematical routine created in Matlab, which also provides the frame in which each interval began.

The criteria used were, in this order: a) speed of center of mass position vector, b) speed in $z$, and c) acceleration of center of mass position vector. Both the criteria and the equations used for calculation can be observed in detail in the study of Costa [17].

2.4.2. Electromyography signal processing. After the *.xls file was created, the linear envelope of the EMG signal was generated by the Excel software, and the first peak time of gastrocnemius medialis (GM) and semitendinosus (ST) muscles was calculated in the post-disturbance interval by the same software.

3. Results and discussion

The instant of maximum peaks of GM and ST muscles activation allows us to observe the synergism between these two muscles in an attempt to maintain balance after a motor disturbance, and possible strategies used to keep balance (ankle or hip strategy) on each trial (1-6), and are shown in Figure 2.
Figure 2: Instant of maximum peaks of the gastrocnemius medialis (GM) and semitendinosus (ST) muscles at trials 1 (prior to FES), 2 (immediately after FES), 3 (45min after FES), 4 (1h30min after FES), 5 (2h15min after FES), and 6 (3h after FES), in the preserved limb (A) and spastic limb (B).

One can observe that in the preserved limb (Figure 2A), there is a proximal-distal synergy (ankle strategy), in which activation of the GM occurs followed by ST activation for all trials, as expected for small perturbations [24]. In the spastic limb (Figure 2B), this pattern occurs only in the first trial (prior to FES); but in all trials after the completion of the FES (with the exception of trial 4) this pattern is reversed, and proximal-distal activation occurs. This synergistic pattern is related to the hip strategy, which relates to major disturbance of balance [24]. One can imagine that after the use of FES the spastic member showed greater difficulty in maintaining balance, since the same task was considered a major disturbance.

In 1986, DiFabio [25] performed a study with EMG in hemiparetic subjects and found latencies in distal muscles of their paretic limb that were longer than the contralateral limb, and he commented that patients with hemiparesis become fixed on stereotyped patterns of movement, showing a loss of flexibility and adaptability, as well as delayed responses and disruption of synergistic muscle coordination of the hemiparetic side, therefore they need to activate the proximal muscles before the distal muscles.

It is possible that FES did not cause an effective RI in the study subject’s GM muscle, or it may even have caused an opposite effect to that which was expected: the action potential propagated by the motoneurons can also have passed along collateral axons making synapse with spinal inhibitory interneurons called Renshaw cells. Antidromic activation of these interneurons, in turn, inhibits the activity of agonists and synergistic hyperactive motoneurons [26]. Thus, instead of facilitating the synergy between GM and ST, there may be an inhibition of these synergistic pathways leading to a proximal-distal synergy in the spastic limb.

Another plausible hypothesis is that, due to spasticity, the subject presented greater weight-bearing at the preserved limb (despite having been instructed to distribute his weight equally between both legs), and therefore, this member had responded to self-disturbance of balance with little assistance of the spastic limb.

However, this research is a case report, so we cannot discard the possibility of measurement error or a non-sensitive method to detect changes caused in the synergy of GM and ST by RI.
More studies are needed, with a larger sample of subjects to verify the effectiveness of the RI by FES in the synergy of hemiplegic patients, and even different methodologies to detect its effect.

4. Conclusion
Spastic hemiplegic stroke patients present altered proximal-distal synergy in the spastic limb during maintenance of the balance after a motor self-disturbance. FES is a useful tool in reducing the spasticity of GM by RI, but there is the possibility that the antidromic effect, caused by an electrical intervention, can inhibit certain muscle synergies such as the one that is used in the ankle strategy of balance, so it can be more difficult to maintain balance after a disturbance.

Therefore, further studies are needed with larger samples of subjects and different methodologies in order to determine the benefit or harm caused by FES in these patients’ motor control.

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