Hemiplegia means paralysis of half of the body. It commonly occurs following “stroke”, which is due to impedance of blood supply to the brain, hence also termed as “cerebrovascular accident” (CVA). As a consequence of this, the brain tissues suffer from ischemic damage resulting in several symptoms, such as mere weakness, numbness to complete loss of power (paralysis). In order to restore or improve the lost functional movement of the body of the stroke-affected and hemiplegic subjects, a method called functional electrical stimulation (FES) has often been employed as the measure of rehabilitation. FES makes use of low levels of electrical current to activate the nerves and then the muscles, affected. The response of the body to this electrically triggered nervous stimulation could be recorded through different bio-signals. In our work, we measured the accelerometers of hemiplegic patient in two states; with FES and without FES. The nonlinear and nonstationary walking-function-related accelerometers are analyzed using recurrence plots (RP), which helps to visualize the dynamic behavior of the signals. The RPs of electromyography (EMG) signals with stimulation showed distinct periodicity and rhythm when compared to that without stimulation. In addition, we extracted recurrence quantification analysis (RQA) parameters from RP to quantify the obtained information from the RP. Lower values were observed for most of the RQA parameters with FES than obtained without FES. This also confirmed the fact that FES is very useful in bringing more order, rhythm and better control in the physical activities of hemiplegic people.

Keywords: FES; recurrence quantification analysis; hemiplegia; recurrence plot; walking-function-related accelerometer.
1. Introduction

Disruption of blood supply to the brain due to any cause is clinically referred to as stroke. Such disruptions happen chiefly due to either cerebral thrombosis or rupture of the cerebral vessels. Stroke resulting from the blockage of blood vessel is known as “ischemic stroke” and that due to rupture of the blood vessel is called “hemorrhagic stroke”. These lead to the deprivation of oxygen and essential nutrients to the brain tissues and finally these are damaged leading to the progress of the stroke. The reason behind these blood vessel damages could be attributed to several factors, such as long-standing high blood pressure, high cholesterol, diabetes, arrhythmias and other cardiovascular diseases, excess tobacco use, lack of proper exercise, and unhealthy dietary habits.

Globally, 15 million people suffer stroke attacks, out of which, five million die and another five million suffer permanent disability, such as hemiplegia, quadriplegia or paraplegia. Stroke is the third leading cause of death in the developing countries after coronary heart disease (the leading cause) and cancer (the second leading cause). In United States, stroke is the third leading cause of death and the first leading cause for major long-term disability. In USA, every three minutes, a stroke-related death occurs. Moreover, the treatment of stroke is quite expensive.

All these statistics about stroke emphasizes the importance of prevention of stroke and fast possible recovery/rehabilitation of a person of a stroke victim.

The prognosis of the hemiplegic patients is grave. There might be permanent motor damage, disorders in memory, learning, speech and language, somatosensory deficiencies, loss of pain perceptions and disturbances in vision. Functional problems like sleep disturbances, depression, incontinence and deglutition can also occur to hemiplegics. Once stroke results in hemiplegia related deficits in body functions, next step is to take adequate steps to recover the patient back to normal.

1.1. Functional electrical stimulation (FES)

Functional electrical stimulation (FES) or neuromuscular electrical stimulation (NMES) is the method by which electricity is used to stimulate or control a part of the body. In hemiplegic and stroke affected people, using FES, electric current is applied to stimulate special nerves, muscles or muscle groups in order to restore the body functions of a person with nervous system impairment. This electric stimulation produces contraction in the affected or paralyzed muscles.

Stimulation wave form for the FES in this study has been depicted in Fig. 1, below. This is an approximate square wave with six controlling variables. They are the carrier frequency, amplitude, inter-pulse, burst frequency, burst width and amount of burst.

The carrier frequency is adjustable from 1 KHz to 10 KHz and the burst frequency is adjustable from 10 Hz to 100 Hz. The amplitude of the burst frequency signal can be adjusted up to tens of volts range, required to generate enough current required for stimulation. The importance of the inter-pulse duration is that it...
reduces the phase charge required to stimulate the peripheral nerve. The purpose of using a pre-modulated waveform for FES is that it lowers skin impedance thus causing lesser discomfort to the patient on whom FES is applied. Nihonmedix Corp. developed the electric stimulation device used by us.

Fagri et al. (1994) found that FES has a beneficial effect on subluxation, pain, functioning and range of motion of arm in patients affected by shoulder pain after stroke. Chantraine et al. (1999) found that long term (24 month) controlled application of FES in hemiplegic stroke patients helped in reducing the severity of subluxation and pain. Functional electrical stimulation is beneficial in the case of recovering back from impairments caused by spinal cord injury (SCI), head injury, stroke, cerebral palsy, multiple sclerosis or some other neurological abnormalities. Alon et al. (2007) showed that FES might improve upper extremity functional use in patients with mild to moderate paresis. Abidin et al. (2010a) studied FES prototype on the small muscles of hands and found quite effective if applied at the early stage of motor loss.

However, it may be noted that it is not always possible to recover a hemiplegic person back to normalcy by employing FES. In some cases, it can only provide partial recovery. Recovery depends on the intactness of the nerve endings supplying a particular muscle or groups of muscles. Also, it cannot repair the damaged spinal cord. Functional electrical stimulation is of no use if the target muscles are completely damaged.

The FES system is comprised of (i) an electronic stimulator, (ii) a control unit, (iii) leads, (iv) electrodes, and several output channels, which are activated to produce the desired functions. Electrodes again could be external (on the skin surface) or surgically implanted depending on the requirement.
Imaging and neurophysiological studies have proved that FES benefits by improving the lost power/movement, function and skill to the stroke patients. However, for obtaining the required results, we have to fix parameters like (i) timing, (ii) intensity, (iii) frequency and (iv) duration of FES. We should be able to measure quantitatively these effects, produced by FES. We must also know whether these results are temporary (just produced in the presence of FES) or long-lasting (whether the effects can sustain even in the absence of FES for long duration).

1.2. Walking-function-related accelerometer

The evaluation of improvement in walking due to FES is an important issue in restoration of walking. The widely used gait evaluation criteria include motion analysis based asymmetry, walking speed, or surface EMG based muscle activity linear estimates, muscular or joint pathological evaluation. However, recently, researchers showed that, human gait changes in long-range fluctuation, and unexpected correlations of stride interval were reported. Furthermore, the impaired gait, and effect of therapeutic intervention was more complex for evaluation. So it may not be possible for the conventional evaluation criteria to reflect the nonlinear nature of human gait and FES-induced gait restoration process.

A 38 year old female, who had a major neuro-muscular dysfunction on left lower-limb, resulting in an asymmetric hemiplegic gait participated in this study. Without FES support, on a treadmill she was able to walk with a highest speed of 0.4 km/hr with left cane support. Due to the poor activation effect of stimulation to tibialis anterior muscle for ankle flexion, and hamstring for knee flexion, a flexor reflex was activated by stimulating peroneal common nerve at an empirically determined moment during walking. The stimulation timing can be at first denoted by the subject through a button and then can be automatically detected by a gait phase detection system. Figure 2 shows the subject trying to walk with FES, with accelerometers fixed on her ankles.

After the experiment goal and procedure were explained to the subject, a written consent was obtained from the subject before participating in this experiment. The entire experiment was monitored by an experienced medical doctor.

1.3. Relevant works

In this section, we have showcased relevant researches on FES and EMG applications. Sabut et al. (2010a) have studied the effect of FES in managing “foot drop” in stroke subjects by analyzing surface EMG (sEMG) signals taken from the tibialis anterior (TA) muscle. They measured temporal and spectral parameters of EMG signals. They observed an increase in parameters of mean-absolute-value (MAV) and root-mean-square (RMS). They also found an improvement in the amplitude and median frequency of sEMG power spectrum during application of FES. This improvement denotes an improvement in muscle strength.
In another study, Sabut et al. (2010b) analyzed the effect of sEMG signals with and without FES of stroke patients with foot drop to evaluate the improvement brought by FES on the effort and speed of walking and on the metabolic responses by spectral and temporal analysis. Application of FES resulted in an increase in muscle strength of the patient. This improved muscle strength was indicated by a significant improvement in the value of mean-absolute-value, mean root-mean-square and median frequency of TA muscle EMG signal. Improvements were also found in the cardiorespiratory responses like oxygen consumption, heart rate etc. while walking with FES device. They proved that FES is very useful in rehabilitation program to improve muscle strength, walking ability and metabolic responses of stroke patients with foot drop.

Another work of Sabut et al. (2010c) measured gait parameters, physiological cost index, ankle range of motion, spasticity of calf muscles, Fugl-Meyer scores etc. and found that FES was helpful in the rehabilitation of stroke patients with spastic foot drop impairment.

Hara (2008) had given an overview of clinical and therapeutical applications of FES. The author (Hara, 2010) showed the benefits of providing EMG triggered FES to stroke patients by performing spectroscopy studies of physiological parameters.

Functional electrical stimulation has been tested on small muscles of hands by Abidin et al. (2011). The authors developed a light-weight, portable, low cost, user friendly FES prototype, which has been tested in paralytic patients in eliciting flexion and extension movements of the wrist joint abreast relevant muscle functions in the hand. The said device is a single channel, battery-powered device and is simple to use transcutaneously. The prototype has been tested in normal and
diseased (hemiplegic) subjects and found effective in inducing motor function of hand muscles for both flexor and extensor groups.

It may be noted that all these works used either typical physiological parameters or temporal or spectral parameters for analysis. Physiological parameter extraction generally requires invasive tests. The complete information of the EMG signal which is nonlinear in nature, cannot be captured by time and frequency domain analysis. Thus, the most suited method to analyze EMG signals is to use nonlinear techniques, detailed below.

2. Device Used

Accelerometer used was GYROCUBE3A, (O-Navi products, 3-axis accelerometer, 3-axis gyro). Two such sensors were fixed at the left and right ankle, such that the \( y \)-axis was along the proximal longitudinal direction of lower legs, and \( z \)-axis perpendicular to the sagittal plane.

Data was sampled using A/D converter (NI USB-6218, National Instruments products) at 1600 Hz. These digital data were recorded on a note book computer by using the LabVIEW7.1 software (National Instruments). Figure 3 shows typical accelerometer signals without and with FES for left and right axis sides. Figure 3(a) is the signal with FES applied and Fig. 3(b) without FES. In both figures, the \( y \)-axis is the magnitude of accelerometer signal measured in millivolts, while \( x \)-axis is the sample number value against which the signal is measured. The \( x \)-axis parameter is thus equivalent to the time parameter against which the corresponding accelerometer signal value is measured.

Both accelerometer signals (with and without FES) have closely packed small irregular spikes and have a lot of variations. The minimum accelerometer value without FES never comes below 2.38 mV, while for the “with FES” case, below 2.36 mV. When this DC level difference is excluded, it is difficult to distinguish between the 2 states just by visually examining the figures.

![Accelerometer signals](image-url)
Accelerometer signal with and without FES can be analyzed by time-domain and frequency domain methods. In the following section, related works have been described to understand the importance of accelerometer and FES in the neuromuscular study, relevant with the stroke patients.

3. Methodology

Physiological signals which are nonlinear, nonstationary and irregular can be analyzed effectively using nonlinear techniques.\(^{30-32}\) Nonlinear techniques involve parameters and methods like correlation dimension, Hurst exponent, Lyapunov exponent, fractal dimension, entropy related parameters, phase space plots, recurrence plots, recurrence quantification analysis, self-similarity and interdependencies.\(^{33,49-52}\)

In this work, the methods used are recurrence plots (RP) and recurrence quantification analysis (RQA). These methods come under the broad area of nonlinear data analysis.

**Recurrence Plots**

Recurrence plot was proposed by Eckmann et al. (1987).\(^{34}\) It is a 2D graphical plot which can show the recurrences of states. Recurrence is said to have occurred when the distance between two states “\(i\)” and “\(j\)” falls below a threshold value “\(\varepsilon\)”. It is then able to extract the hidden periodicities in a signal in time domain which is not easily noticeable or measurable. It can measure the nonstationarity of time-series signal. Let \(x_i\) be the \(i\)th point on the orbit in an \(m\)-dimensional space. Whenever \(x_j\) is sufficiently close to \(x_i\), a dot is placed at \((i, j)\). The plots are symmetric along the diagonal \(i = j\) because if \(x_i\) is close to \(x_j\), then \(x_j\) is close to \(x_i\). Thus recurrence plot is an array of dots in an \(N \times N\) square. It can also be viewed as an \(N \times N\) matrix of black and white dots in time related space. A black dot in recurrence plot indicates that recurrence has occurred.

**Recurrence Quantification Analysis (RQA)**

Recurrence quantification analysis is used to quantify RP by measuring the number and duration of recurrences in a dynamical system. For the nonstationary input data signal, RQA gives parameters which are measures of complexity and nonlinearity. Zbilut et al. (2002)\(^{35}\) has found that RQA helps in detecting changes and measuring complexity and randomness in nonstationary cardiac signals, which cannot be easily detected by traditional methods. Without making any initial assumptions whether the input signal is linear or nonlinear or stationary, RQA method has the ability to analyze linear as well as nonlinear signals. There are many works which employ RQA. Many features are defined for RQA. The details of RQA features used in our work are:

(i) **Recurrence Rate (RR)**: Recurrence Rate is a parameter which gives indication about the density of recurrence points present in a RP. As described
earlier, a black dot indicates that recurrence has occurred. Recurrence Rate is defined as:

\[ RR = \frac{1}{N^2} \sum_{i,j=1}^{N} R_{i,j}, \]  

(1)

where, \( R_{i,j} \) is the representation of RP, \( N \) is the total number of states considered.

(ii) **Determinism (DET):** Determinism is the fraction of recurrence points, which form the diagonal line in recurrence plot. It is defined as

\[ DET = \frac{\sum_{\ell=\ell_{\text{min}}}^{\ell_{\text{max}}} \ell P(\ell)}{\sum_{i,j=1}^{N} R(i,j)}, \]  

(2)

where, \( P(\ell) \) is the frequency distribution of the lengths \( \ell \) of the diagonal lines (proportion of diagonal lines of length \( \ell \) over the total diagonal lines), \( \ell_{\text{min}} \) is the length of the minimum diagonal line. States of the system which have similar time evolution fall in the diagonal line of the RP. Determinism is a measure of predictability and determinism of the system.

(iii) **Mean diagonal line length (L):** \( \langle L \rangle \) is an indicator of the mean prediction time of the system. It is defined as

\[ \langle L \rangle = \frac{\sum_{\ell=\ell_{\text{min}}}^{\ell_{\text{max}}} \ell P(\ell)}{\sum_{i,j=1}^{N} P(\ell)}, \]  

(3)

This parameter is a measure of the inverse of divergence of the system.

(iv) **Longest diagonal line** \( L_{\text{max}} \): \( L_{\text{max}} \) is length of the longest diagonal line in RP. It is defined as

\[ L_{\text{max}} = \max(\{l_i; i = 1 \ldots N\}) \]  

(4)

(v) **Entropy (ENTR):** The complexity of the recurrence system is given by Entropy. It is a measure of the average information contained in the line-segment distribution. It is given by,

\[ \text{ENTR} = -\sum_{\ell=\ell_{\text{min}}}^{\ell_{\text{max}}} p(\ell) \ln p(\ell) \]  

(5)

(vi) **Laminarity (LAM):** This is the fraction of recurrence points, which form the vertical lines. It is an indicator of the number of laminar states in the system.

\[ \text{LAM} = \frac{\sum_{v=v_{\text{min}}}^{v_{\text{max}}} v P(v)}{\sum_{i,j=1}^{N} P(v)} \]  

(6)

Here \( P(v) \) is histogram of the length \( v \) of the vertical lines.

(vii) **Trapping time (TT):** This is related to the average length of the vertical lines. It is the average time the system remains in one state or changes its state very slowly.
(viii) **Longest vertical line** $V_{\text{max}}$: $V_{\text{max}}$ is the length of the longest vertical line in RP.

It is defined as

$$V_{\text{max}} = \max \{ v_i; i = 1 \ldots N_v \}$$ (7)

(ix) **Transitivity** (Trans): The expression is given by,

$$C = \frac{\sum_{i,j,k=1}^{N} R_{i,j}^{\text{ref}} R_{j,k}^{\text{ref}} R_{k,i}^{\text{ref}}}{\sum_{i,j,k=1}^{N} R_{i,j}^{\text{ref}} R_{j,k}^{\text{ref}} R_{k,i}^{\text{ref}}}$$ (8)

There are so many previous works on RP and RQA.

Cortical function at different sleep stages were quantified using RP-based features, extracted from EEG signals. They showed that different sleep stages have unique recurrence plots. Also different sleep behavior and stages were characterized in patients having sleep apnea syndrome using RQA features extracted from their EEGs. In another work, depth of anesthesia was determined by studying RQA features of EEG signal and feeding it to ANN to classify responses to incision with an accuracy of 87.76%.

Many works had shown that for epileptic patients, pre-ictal, inter-ictal and ictal stages have different RQA measures. The effect of seizures on EEG signal was studied using RQA measures and RP showed pronounced rhythmicity during seizures. They predicted start of seizure by these 7 RQA measures extracted. Acharya et al. (2011) has used RQA for the automated identification of epileptic EEG signals.

4. Results

The RPs with FES and without FES are given in Fig. 3 and the listing of RQA features with and without FES are given in Table 1.

The RP of the hemiplegic without FES looks random and the dots in the plot are more scattered. With FES applied, it can be seen that RP is more periodic and...
rhythmic than what is obtained without FES. This shows that FES helps in bringing more rhythm to the movements of a hemiplegic person.

Table 1 shows the range of values for nine RQA features, which are clinically significant with their \( p \)-values less than 0.0001. It can be seen that all the RQA values except the RR parameter are high for the hemiplegic subjects with no FES applied. The lower the RQA values are, the more orderly are the body functions. This shows that when FES is applied to hemiplegic people, they get more control in their body movements.

5. Discussion

We have selected nine statistically significant (with \( p \)-value less than 0.0001) RQA parameters to evaluate the effect of application of FES on hemiplegic people.

Of these nine, the mean value of eight parameters showed significant decrease on application of FES indicating that FES helps hemiplegic persons to have better control over their motor functions. In this regard it is worth mentioning that, Yan et al. (2006)\(^{44}\) studied how FES can contribute to the improvement of motor and walking ability of people recovering after a stroke (acute enough to have resulted in cerebral infarction and hemorrhage). From the electromyograph, they measured the parameters of composite spasticity scale (CSS) and maximum isometric voluntary contraction (MIVC) of the ankle dorsi-flexors and plantar-flexors. Their work confirmed that FES improves the motor and walking ability of patients affected by acute stroke.

Rodrik et al. (2006)\(^{45}\) studied the nonlinear behavior of surface myoelectrical activity of biceps muscle during simulated contraction in two postures. Using Lyapunov exponents, they evaluated and could clearly understand the difference in chaos between these two postures.

Arjunan et al. (2007)\(^{46}\) used fractal theory and fractal dimension to study the nonlinear properties of surface electromyograph and did the classification of subtle hand actions. They identified a new feature called bias, which comes under the section fractal dimension which was found very useful in modeling muscle activity and classification of hand gesture.
Liu et al. (2004)\textsuperscript{17} used RQA to analyze EMG signals during dynamic exercise. They found that increase in RQA parameters to be a good indicator of fatigue. Their work showed the usefulness of recurrence analysis in charting the efficacy of a specific exercise therapy program in reducing low back pain by elevating the fatigue threshold.

Wenwei et al. (2009)\textsuperscript{48} analyzed the effect of stimulation on a hemiplegic subject with a severe neuro muscular impairment on left lower-limb which had resulted in an asymmetric gait. They studied accelerometer signals from the subject with and without FES using nonlinear parameters of Hurst Exponent, Fractal Dimension, Embedding Dimension and Recurrence plot. Their results showed that hemiplegic subject can get a better control and rhythm over its body movements with FES.

Similar to the work of Yan et al. (2006)\textsuperscript{44} and Hara (2010),\textsuperscript{28} there are many previous works which showed the benefits of FES in immediately trying to recover the patient after stroke and in rehabilitating a stroke patient. These works studied physiological signals, mainly EMG signals and the evaluation parameters for measuring the improvement of the patient were physiological parameters. The measurement of physiological parameters required the expertise in medical field. Sabut et al. (2010) handled temporal and spectral measures of EMG in addition to physiological parameters. The time-domain and frequency domain analysis could indicate correctly the improvements brought by FES, but cannot completely convey all the information since EMG signal is a nonlinear signal. The best suited analysis method is to employ nonlinear techniques to EMG signal.

Rodrik et al. (2006) used the nonlinear parameters of Lyapunov exponents for studying EMG activity. Arjunan (2007) used nonlinear technique of fractal theory and the parameters of fractal dimension and bias value to classify subtle hand actions from EMG signals. Liu et al. (2004) used recurrence quantification analysis (RQA) as a good indicator of fatigue during dynamic exercise by analyzing EMG signals.

In our work, we analyzed accelerometer signals of hemiplegic and post-stroke patients with FES using RP and RQA methods. Our results agree with these previous studies that nonlinear techniques can be used to analyze walking function related accelerometer signals effectively and can evaluate any modifications of accelerometer signal caused by an external activity. We evaluated the modification of EMG in the presence and absence of FES. Ours is the first and only work which uses RQA which can clearly discriminate an EMG signal with FES to an EMG signal without FES in the case of hemiplegic and stroke affected persons. This can be very useful for recovering and rehabilitating post-stroke and hemiplegic patients. Unlike earlier works which used one or two nonlinear parameters for analysis, we used nine significant parameters of RQA. These parameters can together indicate even the minute changes of EMG signal. This work can be extended by giving these significant RQA parameters as input to a classifier for automation.
6. Conclusion

Functional electrical stimulation is the process of giving electrical stimulation to muscles that are deprived of nervous control with an objective of providing improved muscular control and functioning. In this work, we analyzed the effect of giving FES to hemiplegic and stroke-affected subjects. Electromyography of hemiplegic subjects obtained with and without FES is analyzed using nonlinear techniques of RPs and RQA. Our results show smaller values for most of the RQA parameters in the presence of FES and more periodicity for RPs. It showed that FES equips hemiplegic subjects with better control over their motor functions. The future work can be the automated discrimination of different levels of the effect of FES on post-stroke and hemiplegic patients and its benefits in long-term rehabilitation using these large number of significant nonlinear RQA parameters.

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References

