

New Concept for FES-Induced Movements

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Abstract. Functional Electrical Stimulation (FES) had become a viable option for movement restoration, therapy and rehabilitation in neurologically impaired subjects. Although the number of such subjects increase globally but only few orthosis devices combine with the technique are available and are costly. A factor resulting to this could be stringent requirement for such devices to have passed clinical acceptance. In that regard a new approach which utilize the patient wheelchair as support and also a novel control system to synchronize the stimulation such that the movement is accomplished safely was proposed. It is expected to improve well-being, social integration, independence, cost, and healthcare delivery.

1. Introduction

Over the years, electrical stimulation have been used for alleviation of pains, healing of wounds and training of skeletal muscles. Functional Electrical Stimulation (FES) which is the application of electric current with certain behaviors in order to regain functional abilities lost due to trauma ailment or tragedy.

FES has numerous applications some of which include: in remedy of loss in urine control, in hearing restoration, in viewing disorders and in alleviating or solving problems of moving the parts of the body. In human body joint movements suitable FES signals are applied to the appropriate muscles via electrodes mounted on them. It could be internal or external which are technically known as implant or surface mount respectively [1, 2]. FES is currently used as assistant to facilitate the restoration of movement, rehabilitation and for therapy.



Most of existing control systems for the lower limb FES applications were open loop. Enhancement of performance and safety makes the closed loop worth exploring [3-5]. Additional reasons are due to few available FES devices and significant rise in number of patients (www.cms.gov/medicare-coverage-database/details/ Decision Memo for Neuromuscular Electrical Stimulation (NMES) for Spinal Cord Injury (CAG-00153R))[6]. Fatigue is the incapacitation of muscles to generate enough contraction and may be as results activities engaged or sickness (either of nervous system or metabolism [7-12]. Muscles that are artificially stimulated fatigue at higher rates [9, 13-19], giving rise to a significant factor due to the nonlinear nature of the neuromuscular plant [20, 21] and difficulty when applying FES. Others are delay in response of nervous systems, spasm, tremors etc. Fatigue could be reduced with closed loop control systems [22, 23] with acceptable limit of adaptation ability and robustness [24, 25]. Using feedback with predictive control can also be used [26, 27] for the task. Retuning the controller for each individual and evaluations on the extents of stability add up to the challenges. And finding solutions is strongly linked to leading to passage of clinical trials, which eventually could facilitate the availability of more devices [22, 28-33]. A novel hybrid sliding mode wavelet neural network controller would be explored due to robustness showed by the sliding mode control technique as shown in literature. Due to the performance of wavelet neural networks [34-37], it is expected that it could be harnessed suppression of major shortcoming associated with the sliding mode control technique and also improved robustness and adaptation, hence the possibility of reducing the retuning burden as well as smoothening the switching process of the controller which worsen the issue of fatigue.

A new approach for the FES-assisted sit-to-stand movement would be proposed for paraplegics. The wheelchair would be made in such a way that it become the support for the subject. New approach for modelling the FES systems using characteristics modelling as well as a novel control scheme using sliding mode-wavelet networks would be explored. Also, emphasis will be given on stability and adaptability. The work is expected to be both simulation and real experimentation depending on circumstances. The MATLAB/SIMULINK software and most likely SOLID WORKS software as well would be utilized.

2. Review of relevant literature

2.1. Review on control of FES-induced movements

The linear, intelligent and nonlinear control schemes have been proposed for operation FES-Induced movements in the lower limb.

Abbas and Chizek [38], Jaime et al. [39], Masani et al. [40], Kim et al.[41, 42], Vette et al. [43-45], and Same et al. [46] proposed the Proportional Integral Derivative (PID) control for upright standing in paraplegic and “Von Hippel-Lidau syndrome” subjects. Matjacic and Bajd [47, 48], utilized the Linear Quadratic Regulator (LQR) method, while Hunt et al. [49, 50], went further to implement the Linear Quadratic Gaussian (LQG), the LQG with polynomial equation [51], and the pole placement [52-54], and finally the H-infinity control was developed for improvements [55-57]. Although experimentally tested some observations include: the need for improved sensing, retuning needs, tests conducted with patients having less complex neural ailment, complexity of implementation of the LQ and H-infinity based controls and that of stability. Standing is dominated by stance phase of gait is less complicated compared to the swing phase whose dynamics is associated with more variations. Imagine applying the schemes for swing phase, other movements or subject with significant level of spasm, tremor or of fatigue. Hence, the remarks by Lynch et al that the linear methods may not be suitable for FES control [58-60], had gained high weight.

Studies on intelligent control comprises of the works of Arifin et al. using fuzzy logic for movements (walking restoration) [61-67]. Same type controller was proposed by Davoodi and Andrews [68] rowing exercise. Combination genetic algorithms and fuzzy logic was applied for control of “sit-to-stand” movements, same technique was proposed for modelling and control of knee joint swinging by

Huq and Tokhi [69, 70] and Ibrahim et al. [71-75]. Artificial neural networks and fuzzy logic were combined for sit-to-stand control by Hussain et al. [76] and Massoud [77]. Chang et al. [78, 79], utilized Artificial Neural Networks(ANN)-PID for FES-induced gait control. ANN was used by Abbas et al. [80-87] and Graupe and Kordylewski [88] for movement restoration and for therapeutic exercise in the works of Chen et al. [89] and Hussain et al. [90]. Fuzzy logic together with sliding mode control techniques were proposed by Erfanian et al. for standing [91], swinging of knee joint [92, 93] and for cycling [94]. Although some studies were simulations but others are were tested with both healthy and unhealthy subjects. Results were encouraging and portray the likelihood of passing clinical tests. Observations were complexity, higher tuning timing, required retuning and higher computational time. An unstable controller is worthless and therefore this make analysis on stability important but that was very challenging when using intelligent control due to absence of mathematical model [70].

Works on nonlinear control include that of Jezernik et al. [95, 96], Mohammed et al. [97], Schauer et al. [98] and Lynch et al. [58, 99], proposed varieties of sliding mode controllers for knee joint movement. And for standing by Jezernik et al. [100]. Better results were observed but high switching is a treat to fatigue and similar properties of nervous disorder subjects. Gain-scheduling was proposed by Previdi et al. [101, 102], study was successful but identifying suitable variables for scheduling was very difficult. Negard et al. [103] and Schauer et al. [104] proposed the back-stepping control method for movements of knee joint. Results indicates that the accuracy of plant model is proportional to level of improvements. The adaptive control approach was proposed in research conducted by Ferrarin et al. [105] and Crago et al. [106] (ANN-based) explore the adaptive control technique for knee joint. Apart from enhancements observed the method also shows the tendency of improving systems with periodic properties.

The unsuitability of the linear control techniques makes the intelligent and nonlinear techniques viable options, but the nonlinear becomes more suitable when stability become the focus. Stability is an essential property of control systems.

2.2. Sliding mode control (SMC)

SMC is a branch of variable structure control (VSC) systems and is classified as robust control method. Robust control are purposely developed to reduce the problem of differences in actual plant model to that used during the controller or control system design. VSC and SMC systems originated from the works of Emelyanov and colleagues, which include Utkins and Itkins of the then Soviet Union (Now Russia) in the 1950s. Later other researchers in control systems became highly interested due its potentials. Basically, VSC/SMC technique uses a control law with high switching capability that makes the plant/system follow a particular pattern by forcing its trajectory of the states to propagate in a defined sequence determined by the designer due to the particular surface chosen. It also regulate the plant state trajectory confined within the predefined surface. The structure of the control system keep varying due to the fact that the gain when operating above the surface is different from it operates below [107].

2.3. Wavelet networks (WNs)

WNs techniques are at their early stages for systems identification and control systems applications. They are formed by merger of wavelet and neural networks (sigmoid functions based) [36, 108, 109]. Wavelet analysis are used for removal of noise in signals, signal compressions, signal suppression, detection of discontinuities, detection changes in signals over long duration, detection of similarities in signals and pure frequency identification [110]. Works on wavelet begins with short time Fourier Transform with Gaussian windows by Denis Gabor in the year 1946. Jean Morlet in 1982 developed for application in geophysics where the modulation aspect was modified with an algorithm that directly dilates the fixed function. In 1984 Alex Grossman and co-researchers further the wavelet algorithm by incorporating coherent states of quantum Physics and linking it with the frame theory.

Wavelet was taken to next level again through the work of Yves Meyer in 1985, where the mathematical basics for the theory of wavelet was first developed, as a result of incorporating harmonics analysis to the one in existence, which eventually lead to the foundation orthonormal wavelets in 1986. It was taken to a greater heights by other reasearchers such as S. Mallat, I daubaches, R. Coffmant, A. Cohen [111, 112].

ANNs are mathematical models design to mimic the operation of the human central nervous system. The inputs are synonymous to the dendrites in the human nervous system while the output, weights and neuron are similar to the axon, synapse and soma respectively. Basically, it is made up of the input, hidden and output layers. The input and output layers of course are the points where signals are sent into and obtained or received from the network respectively while the processing is done in the hidden layer.

The system learns as a result of gradual adjustments of the weights due to the series of inputs and outputs supplied to it. Applications include engineering, finance, medical, science, management and operational research to mention just a few. System identification is another area where the artificial neural networks is receiving attention and yielding resounding results [113, 114]. Artificial neural networks are well known for detection of patterns, learning capabilities, processing of signals, identification of both linear and nonlinear systems, fault detection and control systems designs [115].

2.4. Why sliding mode wavelet networks

A distinguishing characteristic of the sliding mode control (SMC) technique is its complete insensitivity to system parameter uncertainties and perturbations hitting the system originating from other sources during operation while gliding along the surface. And also the surface could be varied in order to make the dynamics of the follow a particular pattern, this is achieved through high rate switching on the surface [107] which could lead to phenomenon known as chattering (a well-known shortcoming of the SMC). The rate at which fatigue is reached worsen as switching frequency is increased [116, 117] . Hence, this chattering effect might negatively affect the control scheme. Wavelet networks (WNs) utilize a combination of wavelet analysis and neural networks (with sigmoid functions) and are currently new or not very popular for control application. Wavelet transformation or analysis was outstanding in noise removal capability, while the artificial neural networks is well known for achieving adaptation due to its intelligence and both are good in nonlinear systems, apart from other desirable characteristics. These makes the WN rich in lowering switching rate, accuracy, reduced computational times and memory requirement in closed loop systems [34, 36, 108]. Therefore, these desirable could be explored to lower the switching rate of the SMC as well as that of the overall closed loop and hence improving or reducing the rate at which the muscle fatigue during FES induced movements. Review on literature showed that SMC is promising most especially when it is made hybrid. The hybrids form are intelligent based, so the problem of mathematical model still exist. In the current application the intelligence (WNs) component was intended be used for smoothening the switching surface. The sandwich from all indication could result in improving fatigue and the control system that can possibly lead to clinical acceptance when successfully implemented.

3. Methodology

3.1. Method description

The research would be conducted in stages: modelling of plant, controller design, analysis (stability, robustness and adaptation ability) and experimentation.

Simulation studies would be conducted by using existing knee joint model developed by Ferrarin and Pedotti, (2000) [118]. Disturbances models proposed by Lynch et al., [30, 58-60] would be used in analysis. The control system would be developed using SIMULINK/MATLAB software. Both

swinging knee joint and the sit-to-stand models would be implemented using SIMULINK/MATLAB and SOLIDWORKS softwares.

The experiments will be conducted in two stages, the free knee joint swinging test and the sit-to-stand movement test.

In the first case the paraplegic subject would be seated comfortably on a suitable chair such that the leg the test will be conducted on hangs freely. Two stimulating electrodes, positive and negative would be placed on the quadriceps muscle after application of the conductive gel. Effort will be made to place the electrodes where full extension would be achieved. In order to eradicate the effect of muscle changes in positions underneath the skin, the cathode will be fixed over the rectus femoris muscle while the anode would be immediately above the patella. The goniometer would be fixed at the knee joint which serves as the feedback transducer for the resulting angular position of the thigh during stimulation. In the second aspect it would be for sit-to-stand restoration which is achieved with the help of wheelchair support. Stimulating electrodes as well as goniometers will be placed at appropriate positions.

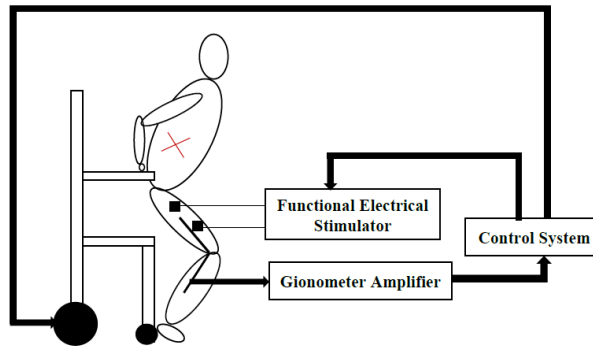


Figure 1 Demonstration of the concept

The wheelchair will be made such that it can conveniently support the patient and the wheels receive signal from the controller to lock or unlock the wheels depending on action being executed. Stimulation would be received by the desired muscles using surface electrodes and goniometers are used to measure angular position of the joints involved. After signals were collected they will be passed through the amplifier for boosting and then the analog to digital converter before finally reaching the controller. The controller generates signal that appropriately modulate the stimulator depending on feedback received from the goniometers. The controller would be initially implemented on PC after which it would be transferred to a microprocessor when implementing the project. Figure 1 is an illustration of process.

The control system performs two basic functions: First, is to synchronize the initiation of the movement (in sit-to-stand which is not present in free knee joint swinging). Secondly it regulates the stimulation pulse width depending on the angular knee position (feedback measurement) and the targeted position at a particular instant.

3.2. Proposed sliding mode wavelet networks controller

The Sliding Mode-Wavelet Networks Controller (SMWNC) would be achieved by exploring the robustness capability of the sliding mode technique, noise suppression capability of wavelet networks and the adaptive as well as intelligent abilities of the neural networks. The nature of our plant; that is the neuromuscular being highly nonlinear and associated with so many disturbances. Although, the SMC is robust, it is associated with high switching rate, that was a treat to fatigue related the FES activated movements. Noise suppression or smoothening or reducing the rate of switching but still maintaining the control objectives and the capabilities to improve the adaptation capability of the

overall control system using the WNs which is desirable for the application. The WNs would be used to smoothen switching on the sliding mode surface. The sandwich from all indication could result in improving fatigue, tremor, spasm and sensor error suppression as well as improved capability for making it suitable for different subjects and scenarios and finally the control system that can possibly lead to clinical acceptance after implementation.

4. Expected research outcome

Revelations of novel approach, controller and model and new findings regarding adaptation ability, robustness and stability for restoration of sit-to-stand manoeuvre using FES in mainly paraplegics. Potential application of the study would be mainly aiding in restoration of movements, others are for therapy and rehabilitation for spinal cord injury subjects as well as those with other forms of nervous system disorders. Automated, efficient and clinically acceptable alternative way to restore movements in spinal cord injury subject will emerge, which will provide solutions to the existing problems associated with open loop system. It can also be harnessed for prevention of complications and also for eradicating other mobility issues due to the failure of the nervous system. It would make the subjects more independent and hence lessen burden on others, improve integration with society. Reduce cost of management which could originate from the individual relatives or government and emergence of improved healthcare delivery.

5. Conclusion

FES was promising for movement restoration, therapy and rehabilitation for neural disorder patients whose number increase globally with no corresponding rise FES orthosis devices. It may be due to strict clinical requirement. A new approach was proposed that use the patient chair for support and a novel controller to facilitate efficient stimulation. Feedback, cost-effective and acceptable alternative way to restore movements in spinal cord injury subjects will emerge, which will provide solutions to the existing problems associated with closed loop lower limb control systems. It can also be harnessed for prevention of complications and also for eradicating other mobility issues due to the failure of the nervous system.

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