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A Robust and Intelligent RISE-based Control for Human Lower Limb Tracking via Neuromuscular Electrical Stimulation

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Abstract. Spinal Cord Injury (SCI) leads to partial or total paralysis due to traumatic or non-traumatic causes. One possibility of motor rehabilitation is through neuromuscular electrical stimulation. This paper presents the application of a control technique named robust integral of the sign of the error (RISE) for a closed-loop electrical stimulation system. In the literature, this controller presents good tracking results without any fine-tuning method. However, the trial and error approach aggravates muscle fatigue. We provide a robust and intelligent approach using this controller. Experimental results with two healthy individuals are provided. The control performance can be improved via the proposed procedure, which provide a fast recovery in the best performance for SCI patients, in the way that a better tuning will avoid premature fatigue and other problems during rehabilitation.

Keywords. Knee joint, electrical stimulation, RISE controller, spinal cord injury, improved genetic algorithm.

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1 Introduction

In the last few years, several studies have been carried out showing that Neuromuscular Electrical Stimulation (NMES) produces good rehabilitation treatments of spinal cord injured patients. Damages to the spinal cord may be occasioned by traumatic causes like road accidents, or, nontraumatic ones such as diseases. Notwithstanding, the problem itself, Spinal Cord Injury (SCI), causes some issues as total or partial paralysis; muscle's atrophies; and lost of movements.

The application of NMES for SCI rehabilitation is one of the most frequent methods, which provides many health and social benefits for its patients, such as offering higher expectation and quality of life; the maintenance and recovery of muscles strength; and by allowing social reinsertion. NMES is a technique based on the use of equipment that generates electrical current for muscle stimulation at the motor level, where the strength of muscle contraction is controlled by manipulating pulse frequency, amplitude or duration.

The present study investigated a continuous and robust control technique for uncertain nonlinear systems named robust integral of the sign of the error (RISE) developed by [6]. In the literature one can find several application of this controller to knee joint control (for instance, check [2, 4, 5], and references within), however, the motivation of this paper emerges from the lack of intelligent techniques to adjust the RISE controller parameters, wherein the aforementioned researches authors did not inform how they tuned the controller or that was used an empiric approach (pretrial tests). Nevertheless, in daily routines of NMES application to SCI patients, exist several problems as muscular fatigue, due to incomplete tetanus and even from the electrical stimulus application itself, which would be increased by applying a "trial and error" method to tune the controller.

To overcome the previously mentioned problem, this paper proposes a robust and intelligent approach using the RISE controller, which could be used in rehabilitation of SCI patients via NMES/FES. We hypothesize that using an empirical approach to clinical procedures would present a large amount of poor performance, while a more adequate tuning will avoid premature fatigue and other problems on SCI patients during rehabilitation. In [1] our group presented simulation results using this approach and assuming a nonlinear mathematical model from the knee joint with parameters of three paraplegics and one healthy patient. In this paper, rather than a mathematical model, the proposed methodology is validated with 2 healthy male individuals using Neural Networks (NNs) black-box modeling.

The following sections are organized as: Section 2 introduces the new approach and its theoretical background. Section 3 presents materials and methods, such as instrumentation, analyzed individuals and experimental set-up. Section 4 presents results and its discussion. Finally, the conclusions are presented in Section 5.

2 Proposed Approach and Theoretical Background

Fig. 1 illustrates the proposed approach, where at the first session a patient has no data and a stimulation session is made on the attempt to acquire information on the relationship between delivered Pulse Width (PW) and reached angular position. Secondly, the acquired data is appropriately treated to pass through an identification step via NNs. Therefore, a simulation process is made to efficiently tune the RISE controller for the identified model. At final, the rehabilitation procedure is retaken with fine-tuned gains for a better control-stimulation session, aiming to prevent premature fatigue and other problems of SCI patients that would be present by not choosing an appropriate gains combination.

In future sessions, all data (control and identification) from previous rehabilitation sessions are used for training a neural network model in an offline scheme, where before each next section, all data from a patient is combined to a single dataset and used to better map its relationship with electrical stimulus. Thus, the same optimization process using the trained model provides fine-tuned gain parameters to be afterward applied to the rehabilitation procedure.

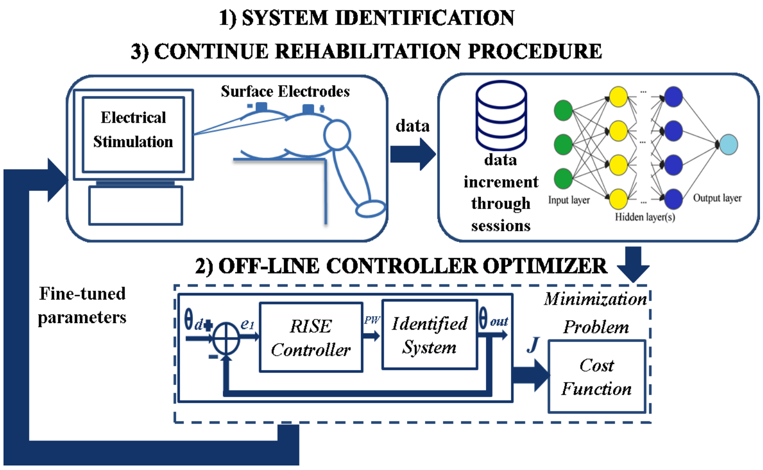

Figure 1: Robust and intelligent control-based approach for human lower limb rehabilitation.

The construction of NN models is essentially based on the quality of measured data about the system. Fundamentally, an operator F from an input space $\mathbb{U}$ to an output space $\mathbb{Y}$ expresses the model of the system to be identified, where the goal is to find a function $\hat{F}$ that approximates F to a specific requirement. By the Stone-Weierstrass theorem, there exists a continuous and bounded function F, that can be uniformly approximated as closely as desired by a polynomial function $\hat{F}$. Further, according to the universal approximation theorem, there exists a combination of hyperparameters of an NN that allows it to identify and learn any nonlinear function [3]. The following subsections describe the remaining components: the RISE control method and an Improved Genetic Algorithm (IGA) for the optimization procedure.

2.1 RISE Control Development

The RISE control technique has been proposed as a continuous-time and high gain feedback control approach for uncertain nonlinear systems, which even in spite of bounded smooth external disturbances and bounded modeling uncertainties, the control law can guarantee asymptotic tracking. To achieve the stated control objective, a position tracking error denoted by $e_1(t) \in \mathbb{R}$, is defined as

$$e_1(t) = \theta_d(t) - \theta(t), \tag{1}$$

where $\theta_d(t)$ is the desired angular trajectory assumed to have bounded continuous time derivatives, and $\theta(t)$ the actual position. Additionally, filtered tracking errors $e_2(t) \in \mathbb{R}$ and $r(t) \in \mathbb{R}$ are defined as

$$e_2(t) = \dot{e}_1(t) + \alpha_1 e_1(t), \tag{2}$$

$$r(t) = \dot{e}_2(t) + \alpha_2 e_2(t), \tag{3}$$

where $\alpha_1, \alpha_2 \in \mathbb{R}$ denote positive and adjustable control gains. Authors in [2,4,5], proved semi-global asymptotic stability for an uncertain nonlinear muscle model with the RISE control law defined as

$$u(t) = (k_s + 1)e_2(t) - (k_s + 1)e_2(0) + \int [(k_s + 1)\alpha_2 e_2(\tau) + \beta sgn(e_2(\tau))]d\tau, \tag{4}$$

where $k_s, \beta \in \mathbb{R}$ are also positive and adjustable control gains, and $sgn(\cdot)$ denotes the standard signum function.

2.2 Improved Genetic Algorithm (IGA)

The proposed IGA to better optimize the gains parameters of the RISE controller was introduced in [1], given pages limitation, it will be summarized here. One should refer to the indicated paper for more information about the algorithm. Initially, a preprocessing step is applied to initiate the search efficiently by bounding gain limits. In the second step, a construction phase using a simple fast genetic algorithm is made to generate a good set of solutions, such that, at final, an improvement of this population using a complete genetic algorithm is done. At final, a set of solutions containing gains values and the cost function are provided by the algorithm.

3 Materials and Methods

3.1 Instrumentation and Analyzed Individuals

The test platform used for conducting the experiments at the Instrumentation and Biomedical Engineering Laboratory ("Laboratório de Instrumentação e Engenharia Biomédica - LIEB") at UNESP - Ilha Solteira, is composed of a NI myRIO controller (National Instruments®) to operate in real time; a current-based neuromuscular electrical stimulator; an instrumented chair composed by an electrogoniometer (Lynx®), a gyroscope LPR510AL (ST Microelectronics®), two triaxial accelerometers MMA7341 (Freescale®); and two user interfaces developed in the LabVIEW® student version edition, one for identification and the other for controlling.

Two smooth references were used for tracking purposes, a sine wave ranging from 10° to 40°, and the second one is a 40° step wave. The control law in Eq. (4) was used to vary the PW in real time while the current amplitude was fixed at 80 mA and the stimulus frequency in 50 Hz. Further, surface electrodes with rectangular self-adhesive CARCI 50 mm x 90 mm settings are used in this study.

Two healthy individuals (male, aged 24 and 28) participated in the study. The study with volunteers was authorized through a research ethics committee involving human beings (CAAE: 79219317.2.1001.5402) at São Paulo State University (UNESP), and before the participation, written informed consent was obtained from both individuals.

3.2 Experimental setup

Initially, a muscle analysis is made to determine the motor point, in order to guarantee proper positioning of the surface electrodes. Secondly, a few open loop tests are performed applying a step-type signal during four seconds, in the interest of determining a bounded PW band ρ_{min} and ρ_{max} concerning to $\theta_{min} = 10°$ and $\theta_{max} = 40°$.

Thereafter, an stimulation test is carried out consisting on one minute of randomly selected PW in the predetermined range per individual. Hence, the identification data is fed into a feedforward NN with one hidden layer, aiming to map the relationship between PW and the angular position. The number of neurons varied from 10 to 1000; hyperbolic tangent activation is used in each neuron from the hidden layer and the output layer is composed of one neuron with linear activation, which gives the estimated output.

Therefore, using the estimated model, an optimization procedure is performed based on the IGA to find the best gains combination for both reference trajectories. The simulation system was developed using the Matlab/Simulink® platform, which contains both sine and step trajectories, a saturation block bounding control signal from 0 μs to ρ_{max} μs for each patient, the RISE controller block, and the identified neural network block for each individual.

Lastly, using empiric gains and then the gains encountered in the previous step, the controlling procedure is experimentally implemented for both trajectories. During the experiments, subjects were instructed to relax, to not influence the leg motion voluntarily and allow the stimulation to control it. Further, during electrical stimulation sessions, the patient could deactivate the stimulation pulses using a stop button, under any displeasure situations.

4 Results and Discussion

Both individuals, from now on labeled as H1 and H2, participated in three sessions. The first session took more time and an additional stimulation than the following others due to the identification test of one minute, and the training/optimization time made to find the best gains combination. Table 1 presents the Root Mean Squared Error between desired and acquired angle (RMSE) from H1 and H2 in experimental results comparing both empiric and IGA tuning approaches. Figure 2 shows control results from the last session for both individuals.

As one can notice in Table 1 and in Figure 2, results for both individuals using an empirical tuning provided poor tracking performances in most of the sessions, while with

Table 1: RMSE on experimental results for individuals H1 and H2.

Session	**H1**				**H2**			
	Sine		**Step**		**Sine**		**Step**	
	Empiric	IGA	Empiric	IGA	Empiric	IGA	Empiric	IGA
1st	7.49°	5.83°	5.92°	6.16°	5.21°	5.05°	9.76°	6.21°
2nd	6.37°	3.62°	6.74°	4.40°	11.7°	3.63°	11.82°	5.45°
3rd	6.38°	3.56°	6.88°	4.42°	4.88°	3.56°	6.42°	4.89°

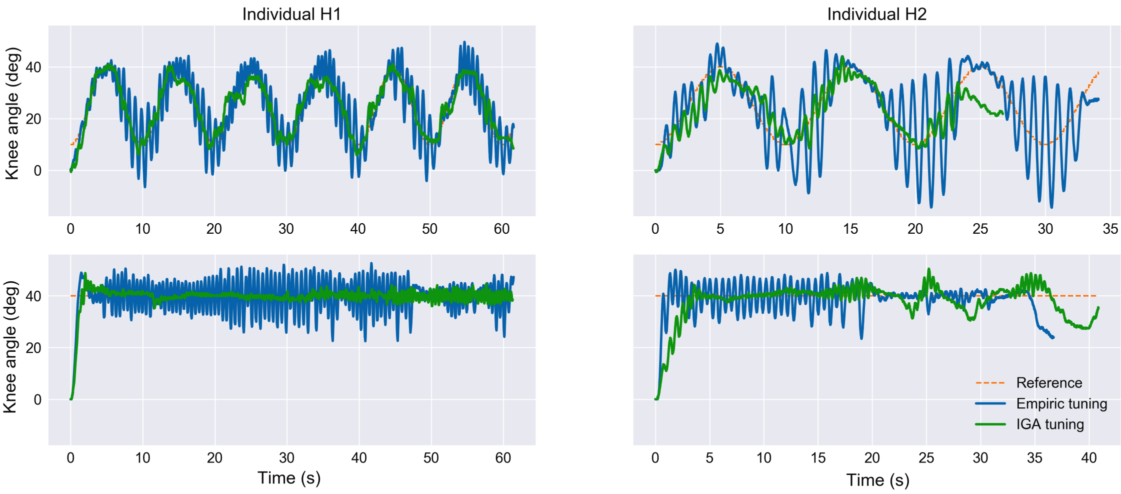

Figure 2: Experimental results for H1 and H2 on sessions one and five respectively.

an appropriate choice of gains, using the proposed methodology, the lower limb presented better tracking results. In all stimulation sessions, even the ones with poor performances, the control-stimulated lower limb tried robustly to track the reference angle during 60 seconds for H1 and in average 40 seconds for H2, while the literature presents results between 8 to 45 seconds of stimulation. Additionally, for both individuals and trajectories, tracking results in all sessions presented a RMSE less than or equal to 6°, representing very satisfactory tracking results. Furthermore, the RMSE tended to decrease using fine-tuned gains as sessions passed by and comparing results for both empirical and IGA tuning approaches, the difference is discrepant in favor of the IGA tuning, showing that the proposed approach could provide good rehabilitation treatments for SCI patients that continuously go on sessions of NMES/FES.

5 Conclusion

On the purpose of proposing an improvement to human lower limb tracking control of SCI patients via NMES/FES, this paper introduced a robust and intelligent approach consisting of an identification step that uses past rehabilitation data, the RISE control method to guarantee the system's stability and an IGA to tune the controller efficiently. Experimental data were acquired from two healthy individuals, and as hypothesized and proven in results, the use of an empirical approach on clinical procedures would present a large amount of poor performance while with an appropriate choice of gains the RISE controller can better compensate the tracking performance.

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