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A fuzzy-genetic model for estimating forces from electromyographical activity of antagonistic muscles due to planar lower arm movements: The effect of nonlinear muscle properties

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ABSTRACT

The aim of this paper is to create a model for mapping the surface electromyogram (EMG) signals to the force that generated by human arm muscles. Because the parameters of each person's muscle are individual, the model of the muscle must have two characteristics: (1) The model must be adjustable for each subject. (2) The relationship between the input and output of model must be affected by the force–length and the force–velocity behaviors are proven through Hill's experiments. Hill's model is a kinematic mechanistic model with three elements, i.e. one contractile component and two nonlinear spring elements.

In this research, fuzzy systems are applied to improve the muscle model. The advantages of using fuzzy system are as follows: they are robust to noise, they prove an adjustable nonlinear mapping, and are able to model the uncertainties of the muscle.

Three fuzzy coefficients have been added to the relationships of force–length (active and passive) and force–velocity existing in Hill's model. Then, a genetic algorithm (GA) has been used as a biological search method that can adjust the parameters of the model in order to achieve the optimal possible fit.

Finally, the accuracy of the fuzzy genetic implementation Hill-based muscle model (FGIHM) is invested as following: the FGIHM results have 12.4% RMS error (in worse case) in comparison to the experimental data recorded from three healthy male subjects. Moreover, the FGIHM active force–length relationship which is the key characteristics of muscles has been compared to virtual muscle (VM) and Zajac muscle model. The sensitivity of the FGIHM has been evaluated by adding a white noise with zero mean to the input and FGIHM has proved to have lower sensitivity to input noise than the traditional Hill's muscle model.

1. Introduction

Modeling of the force generated by the muscles using the electromyogram (EMG) signal has considerable applications in various scientific fields. Typical use cases of this method are designing and developing of functional electrical stimulation (FES) systems to assist the disabled (Hoshimiya et al., 1989; Riener et al., 2000; Thorsen et al., 2001; Yu et al., 2002), bio-mimetic robots (Yoshida et al., 2006), fabricating artificial muscles in comparison with the bio-muscles (Artificial Muscle Research Institute, 2010), interacting of human and computer systems (Kazerooni, 1990; Fukuda et al., 1998), modeling of the human muscle–skeletal system (Tahara et al., 2005, 2006; Arimoto, 2006; Karniel and Inbar, 1997; Kim et al., 2007), rehabiliting and tele-rehabiliting (Jack et al., 2001; Bouzit et al., 2002; Loureiro et al., 2003; Mulas et al., 2005; Dovat et al., 2006; Kawasaki et al., 2007), designing and controlling of prostheses (Tsuji et al., 2000), etc.

Skeletal muscle dynamics are very complex and highly nonlinear. Muscles produce force nonlinearly based on a neural drive, the length of the muscle, and the velocity at which the muscle is moving (Zajac, 1989).

The main difficulty in modeling the human muscle is that the muscle force cannot noninvasively be measured in vivo. In other

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words, we are trying to model a system with no direct access to its output. Instead, in this paper, EMG and joint angle were recorded, and then an inverse dynamics method is used to calculate the muscle's force, length and velocity of muscle contraction according to the joint angle.

The practical muscle model suggested by Nobel Laureate A.V. Hill in 1938 (Winters and Stark, 1985; Hill, 1938) is widely accepted and used by biomedical engineers and other researchers in this field. Hill's early experiments illustrate three important behaviors of muscles:

(1) *Passive force–length behavior*: If the length of a non-activated muscle is changed, the muscle resists to this change like a spring.
(2) *Active force–length behavior*: The muscle generates the maximum force in response to activation when it is at resting length.
(3) *Force–velocity behavior*: The force generated by the muscle depends on contraction velocity.

Hill modeled these relationships with a spring, a damper and a force source.

Hill's mechanical model is the simplest and the most comprehensible model for human muscles. Such model cannot be used for real time purpose and it is reported by Winters and Stark. They showed that a system consisting of two antagonistic Hill muscle models and one hinge-like joint required at least eight state variables (Winters and Stark, 1985, 1987). The mentioned model can be difficult to modify because of high-order differential state equations.

Brown and Loeb (1999) and Brown and Loeb (2000a,b) did an elaborate set of physiological experiments that contributed to the development of virtual muscle (VM). VM is a Hill-style model that is similar to a model of muscle that is suggested by Zajac (1989). VM is widely accepted by biologists but it is extremely complex.

O'Brien developed a fuzzy muscle model to improve the limitations of Hill model (O'Brien, 2008). He used the fuzzy theory to model the input/output of muscle. He has named it: the fuzzy logic implemented Hill-based muscle model (FLIHI). FLIHI implements the passive force–length behavior, the active force–length behavior, and the force–velocity behavior of the muscle in fuzzy logic rather than high-order dynamic differential state equations. In order to adapt the model with experimental data, he suggested the use of neuro-fuzzy systems. However, this approach involves a more complicated model (due to the number of fitting parameters) and thus requires higher data processing speed. In this paper, we use genetic algorithm (GA) for finding appropriate membership functions' parameters instead of the neuro-fuzzy methods.

Another well known, popular muscle model is the Zajac's (Zajac, 1989). Zajac has established muscle properties by fitting curves to the Hill muscle model. In comparison with Hill's model, Zajac's muscle model is completely arithmetic with no differential equations. Although it is a popular model for the researchers in this field, and it shows the muscle's behavior in a simple way (Zajac, 1989), we have shown (Nowshiravan Rahatabad et al., 2009) that his model has two major problems. Firstly, the model does not have sufficient adjustable parameters. Secondly, in the case of any changes in the muscle's configuration, the model will not be able to follow the behavior properly. These drawbacks may come from the inflexibility of Zajac's model parameters. A complex biological system (similar to human muscles) can rarely be described by some stiff mathematical equations. Zajac's model is extended in this study because it is simple, arithmetic and widely used by other researches in this field. We have added three fuzzy coefficients for scaling the amplitudes in both force–length (active and passive) and force–velocity relationships. Each coefficient is related to the muscle's length and the velocity of contraction. A genetic algorithm is then used to adjust these coefficients according to the training data for each subject. In other words, the genetic algorithm changes the fuzzy coefficient parameters in order to reach the best EMG-force mapping.

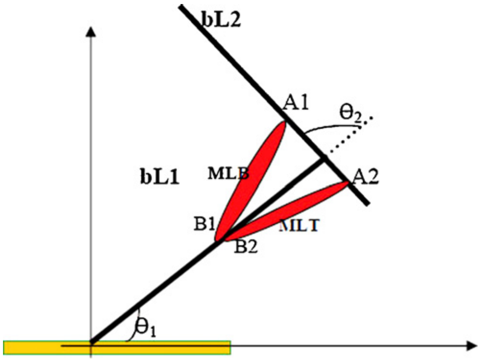

Fig. 1. The two-link arm model with biceps and triceps muscles. Where MLB: length of biceps muscle; MLT: length of triceps muscle; bL1: arm bone; bL2: forearm bone; (θ_1, θ_2) are the angle of the shoulder and elbow joints, respectively.

The benefits of FGIHM in comparison to the Hill's and Zajac's models are:

1. The user can adopt the number of adjustable parameters through choosing the number of input/output membership functions. By increasing the number of input/output membership functions, the parameters will be increased.
2. Because fuzzy systems are used, the model is robust to the noise polluted EMG signals (O'Brien, 2008). In Section 3 of this paper, FGIHM is compared with Hill's and Zajac's muscle models in terms of robustness.
3. FGIHM can also completely simulate the behaviors of Hill's and Zajac's models by choosing fuzzy coefficients equal to one in all states.
4. The genetic algorithm helps FGIHM to achieve the optimal fitting for each individuals.

Furthermore, the benefits of FGIHM in comparison to fuzzy muscle model as FLIHI are:

1. FLIHI uses gray box modeling and maintains the main components of Hill's model. These components are active force–velocity, passive force–length and active force–length; their existence has been documented by Hill and has been accepted by most researchers.
2. FGIHM and FLIHI utilize fuzzy inference system, but FGIHM approach is more understandable due to the direct use of mechanistic processes of Zajac equations in the model.

In this paper, a model for mapping the surface electromyogram (EMG) signals to the output force of muscles is proposed. In order to evaluate the model's accuracy, experimental data has been recorded from three healthy male subjects. Also, the robustness of the proposed model has been invested by adding noise to the input of the fuzzy genetic implementation of Hill-based muscle model (FGIHM) and compared with the non-fuzzy models.

2. Methods

In this section, musculo-skeletal redundant arm model was established. This model consists of two serial links with two antagonistic muscles to simply a human arm elbow movement (Fig. 1). This arm is modeled in the horizontal plane with fix shoulder joint angel to reduce the degree of freedom. EMG and elbow joint angel are recorded from the muscles and joint, then fuzzy genetic algorithm is introduced to the Hill muscle model.