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Human Arm's Muscle Force Estimation Model Based on Fuzzy Theory

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Abstract. Muscle force estimation, is important in order to understand human control strategies, rehabilitation, motion analysis and human-machinery interfacing. To estimate the force, bio-signals analysis is used. Bio-signals enable signal recognition and analysis of muscle action and it is used to estimate muscle force.

In this work, a method to estimate human muscle force is proposed. This model, which is based on Fuzzy Logic Theorem, is fast and easy to implement. Fuzzy Model process a raw of rectified smoothed electromyography (RSEMG) signal and extract muscle force. Our model is a general one, it can use for any muscles. To prove that, we used biceps brachii muscle of the left and right arms and two different arm muscles as validation. Our results, demonstrate that the new model improves the accuracy of muscle force estimation. This model can efficiently extract muscle force features from (EMG) signals. Our results showed that algorithmic regression exceeds 99%. The mean square error (MSE) results for Fuzzy Model was very small (MSE equal to $1.11x10^{-08}$).

Introduction

EMG is a time-varying bio-potential waveform technique that is used to estimate the electrical activity generated by muscles. In 1666, Francesco Redi performed the first experiments to record EMG signals. In 1792, Luigi Galvani found that electricity could initiate muscle contractions. The first experiment to record the electric flux during muscle contraction was carried out in 1890 [1]. Over the past 50 years, researchers have begun to use EMG more widely to study muscles.

In recent years, interest has been expressed in introducing interfaces that recognize a user's body movements and change them into machine commands. Artificial methods are radical approaches to analyze and characterize the behavior of biological systems. Artificial algorithms, such as, Neural Network and Fuzzy have produced new approaches in this field. Fuzzy logic provides mathematical strength to the emulation of certain perceptual and linguistic attributes associated with human cognition. The two important methods of Fuzzy Inference [2] are Mamadni's Fuzzy Method and Takagi-Sugeno Method (known as the TS method). In general, Fuzzy Logic is capable of working with highly varying and non-linear conditions better than other techniques [3].

In the past, physicists and mechanical engineers used simulation procedures to create a model to replicate human muscles. In 1938, Hill created his model that simulates human muscles (known as Hill-type model). Researchers used his model to estimate the muscular force generated by humans [4-9]. Unfortunately, the Hill-type model is a complex one. It has many parameters that configuring carefully. Many variables included in the Hill-type model need to be measured by other experiments that use a lot of equipment, such as, cameras and video processing techniques to measure the speed of muscular movement and contractions.

Muscle force estimation processes start by taking the EMG recorded signal of any muscle in the human body. Subsequently, this signal is manipulated by many signal-processing techniques to extract usable information. These processes can be described as filtering, smoothing and rectifying. Subsequently, the output signal is used to extract the neural activation signal. This signal is used as an input to estimate muscle force by using a model, such as, the Hill-type.

In this work, we have created a new and easy model that converts a RSEMG signal into muscle force. Our model takes the RSEMG signal, convert it into muscle force without the complexity of converting the signal into an active one and then estimate its magnitude. The researcher used human arms in dynamic motion to predict the flow of EMG signals from the biceps brachii muscles of each. Fuzzy Model was validated by training on two arm muscles. The researcher used a Hill-type model to develop the researcher's model and training it.

The remainder of this paper is organized as follows. This section closes by listing the related work of other researchers. Section III, introduces the theory and algorithm that was used to create the research model. Section IV, describes the experiment and lists the configuration of the parameters that were used. The experiment section closes with the results and observations. Finally, the paper ends with a summary and conclusion.

Related Work

Using EMG signals to estimate muscle force is a well-known procedure, which has been used in many studies. For example, Guimaraes [10] estimated the muscular force of a cat by using EMG signals and a geometric model. The author used a video camera (60Hz) and planar to calculate fiber lengths and velocity. Unfortunately, the method that the author used was not effective and it needed an extended run to obtain results. It also needed a lot of equipment. Buchanan [5] used the same method to estimate muscle forces and joint moments based on Hill-type model. The author's work was complex because of the need to convert the signal into neural and then into forces activation. The author used many mathematical equations, which needed many variables. Our Fuzzy Model, however, does not need any variables for the conversion process. Mobasser [11] is one of the first researchers who used multi-layered perception, ANN (MLPANN), to estimate activation force. He used MLPANN with a radial basis function (RBF) method to estimate the upper arm muscle force involved in elbow joint movement using an activation EMG signal, joint angle and angular velocity as input data. The current researcher used RSEMGS and time as the only input for the estimation process. Vilimek [7] used different muscle models, such as, the Hill-type and EMG-driven models, using mathematical equations and muscle activation from EMG signals to estimate musculo-tendinous forces. Oyoug [12], [13] used EMG signals to estimate muscular force and joint torque by two methods: simulated annealing (SA) and a genetic algorithm (GA). Their methods, however, were manipulated by EMG signals. Unfortunately, as with the previous works, their methods needed much mathematics and equipment to calculate joint torque.

The Proposed Muscle Force Estimation Method

The method is divided into two parts. The first part involves EMG signal recording, analyzing and force estimation. The second part, Fuzzy Model construction and testing. The researcher used the data that was gathered from the first part to validate and teach the model algorithm.

EMG Signal Processing

An EMG signal, is a very complex one that needs four different processing stages to extract force estimations. Information from an EMG signal was passed through a high-pass filter (5 to 30 Hz). The output was rectified to obtain the absolute value of the signal and its shape normalized. Finally, the signal was smoothed by passing it through a low-pass filter (3 to 10 HZ). After the completion of these processes, the output is known as the RSEMGS (e (t)) and is used as the input for the force estimation process. When muscle fiber is activated, it generates a response. This response is called neural activation p(t), which can be represented as second order differential system [9]. There is a non-linear relationship between frequency and force; therefore, a transform neural activation p(t) to nonlinear activation force a(t) should be considered [4]. Subsequently, the output of the last stage, which is known as a non-linear activation force can be used as an input for any muscle force estimation model, such as, a Hill-type model. The Hill-type model depends on the relation between muscle length and velocity. Muscles generate force when they are activated. This is represented by a force-length curve. Fiber velocity is calculated with time. Fiber length is estimated using Runge-Kutta forward integration. The calculation ends when all data of a(t) ceases. Parameters of muscle-tendon were adopted from Delp [14], and other parameters are calculated depending on [5], [6], [7].

Fuzz Procedure

The Fuzzy Inference System includes four steps: (1) fuzzification of the input variables, (2) evaluation of the output for each rule, (3) aggregation of the rule's outputs and (4) defuzzification. Fuzzy Inference Systems are categorized into linguistic and precise models. In the Takagi–Sugeno (TS) Fuzzy Inference System, a fuzzy rule is constituted by a weighted linear combination of crisp inputs rather than a fuzzy set. The researcher's Fuzzy Model will base on the TS method with a polynomial rule in order to estimate the muscle force from the RSEMG signal. Moreover, it used the force estimated by the Hill-type model for training. The model is constructed of five network layers. These layers operate as follows. Layer 1 generates fuzzy membership values for input variable. Layer 2 multiplies the incoming signals from the previous layer and estimates the firing strength of each rule. Layer 3 computes the normalized firing strength. Layer 4 calculates the contribution of the rule in the model's output based on first-order Takagi–Sugeno rules. Layer 5 calculates the weighted global output of the system. One important point that the researcher desired to demonstrate was that after teaching Fuzzy Model, the model only needs the RSEMG signal to calculate the estimated force.

The Experiment

This work was conducted on a healthy male of height 170 cm and weight 80 kg. The researcher used an ME6000 bio-monitor device on the biceps brachii muscle of the left and right arms to construct the research models. The researcher used two muscles to validate the models. Moreover, using three channels and three surface electrodes for each channel as shown in Fig. 1, to record the EMG signal. The names of these muscles and their descriptions can be shown in table1.

Table 1. Muscles name and their descriptions

Muscle Name	Description	Symbol
Biceps brachii	The biceps is located on the upper arm between the shoulder and the elbow. Its main function is flexes the elbow and supinates the forearm	M1
Thenar eminence	It's a group of muscles in the palm of the hand at the base of the thumb. It's controls movement of the thumb.	M4
Hypothenar eminence	It's a group of three muscles of the palm that control the motion of the little finger.	M5

The researcher used the motion of the arm to produce an EMG signal to obtain a pulse. The pulse was used to estimate the RSEMGS (e (t)). This signal was passed through a high-pass filter (25 Hz). Then, the output signal was rectified to obtain its absolute value. The signal was smoothed and normalized by using the low-pass filter with 9Hz.

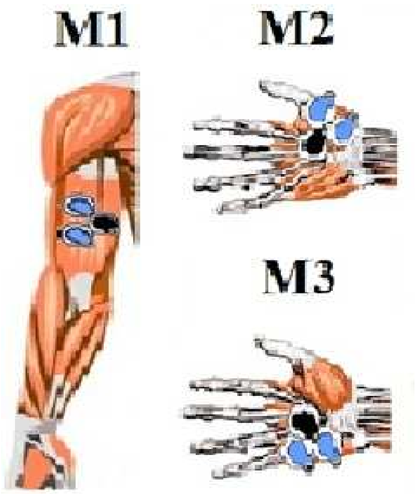

Fig. 1. Electrodes position on arm muscles.

Subsequently, the researcher used MATLAB to construct a Fuzzy Model to estimate muscle force. Unfortunately, Fuzzy Model needs data for learning and testing. The learning process is important in order to construct the weights that each node uses. The data should consist of input and output data lists. To construct such a file, the researcher needed to use C programming language for the Hill-Model. Unfortunately, to obtain the neural activation signal p(t) and muscle activation a(t) from RSEMGS the researcher would need to configure many of variables. It was hard to predict the optimal values for these variables and parameters. In order to obtain these values, the researcher use C programming language with the RSEMGS as an input with all combinations of p(t) signals and the second equations parameters. The data was fed into the Hill-type Model that had been programmed in C language also. The output of this stage represented the data that was needed to teach Fuzzy Model to estimate the force. The whole process is shown in Fig. 2, how the EMG signals taken from the arm muscles pass through multiple processes to produce the RSEMG. This signal is used in Fuzzy Logic Model to estimate the muscle force.

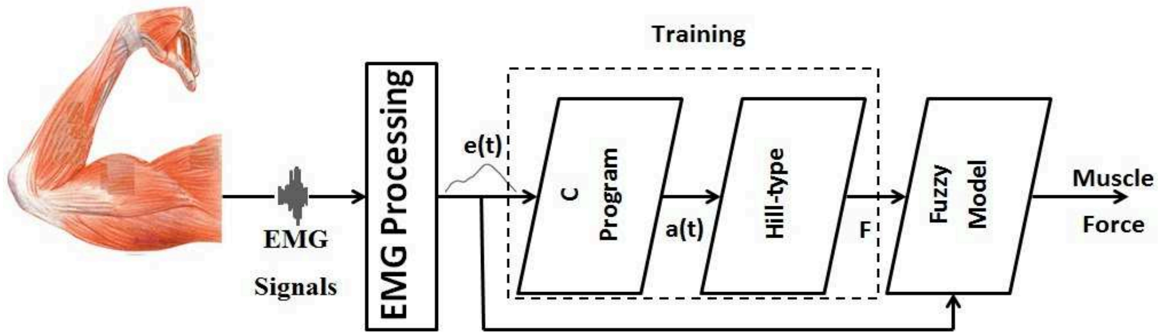

Fig. 2. Flowchart of our method

In the proposed Fuzzy Model, the researcher used different membership functions, i.e. Gaussian and Generalized Bell. Fuzzy rules define the first-order Sugeno Fuzzy Model. For the Fuzzy Inference System, the researcher used two membership functions each consisting of three nodes.

The researcher used the output from Hill-type Model to train process the Fuzzy Model to estimate the force as a function of time. Different number of nodes and layers, and different types of function were examined for the model. The configuration of the research model, the number of inputs, nodes, epochs, hidden layers and type functions that were used is shown in table 2.

Table 2. The configuration parameters

	Fuzzy
Number of inputs	2
Epochs	5000
Membership	2
Nodes	3 in each member
Function	Gaussian, Generalized bell

Results and Discussion

In this section, an explanation is given for the muscle force that was predicted from results that were collected through the research model for the M1 muscle of the left and right arms. The model will then be used to predict the force for two other arm muscles. This procedure was adopted to prove that the research model is a general purpose one and can be used for any muscle in the body. Two performance metrics were used: regression and the mean square error (MSE). The results were divided into two sections: model performance, validation of Fuzzy Model using other muscles.

Fig. 3a shows the input RSEMGS signal that was extracted from the EMG signal using the four steps discussed above. This signal was used as an input for the Hill-type Model to predict force. This force is shown in Fig. 3b. The researcher used the RSEMGS signal as an input for the Fuzzy Model. The force estimated by this model is shown in Fig.3b. In this figure, one can observe the similarity between the output of the Fuzzy Model and that of the Hill-type Model. This proves that the research model can replace all the complex steps and estimate the force without any calculation. One, however, must train the model before using it to estimate the force.

Fig. 3b demonstrates the effect of neglecting all the mathematical equations and assumptions of the variables. The research model can obtain the same results as a Hill-type Model. Moreover, there is no need for any extra equipment to calculate muscle forces. In addition, it should be noted that the research model could be ported for use with other muscle force models without changing his structure. The only additional requirement is to train the network with other data from other models.

One can also observe that there is a direct proportional relationship between muscle activation and the produced force

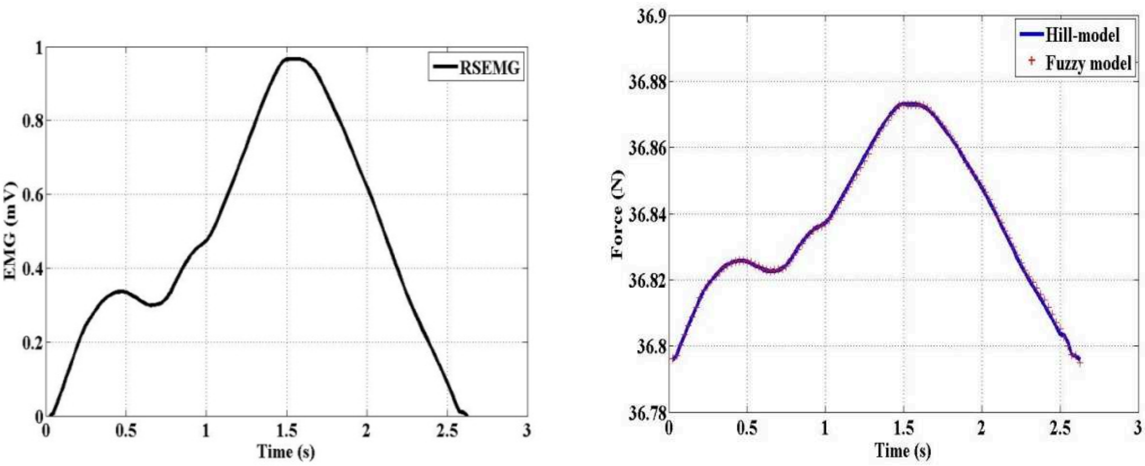

Fig.3. Right hand, M1 muscle. A: the input SREMG signals. B: the output force comparison between Hill and fuzzy model

Fig. 4 shows the same extracted muscle force. These results, however, are for the left arm. These figures show the symmetry between the two hands of our volunteer. This means that the calculation performed for one hand can be safely used on the other

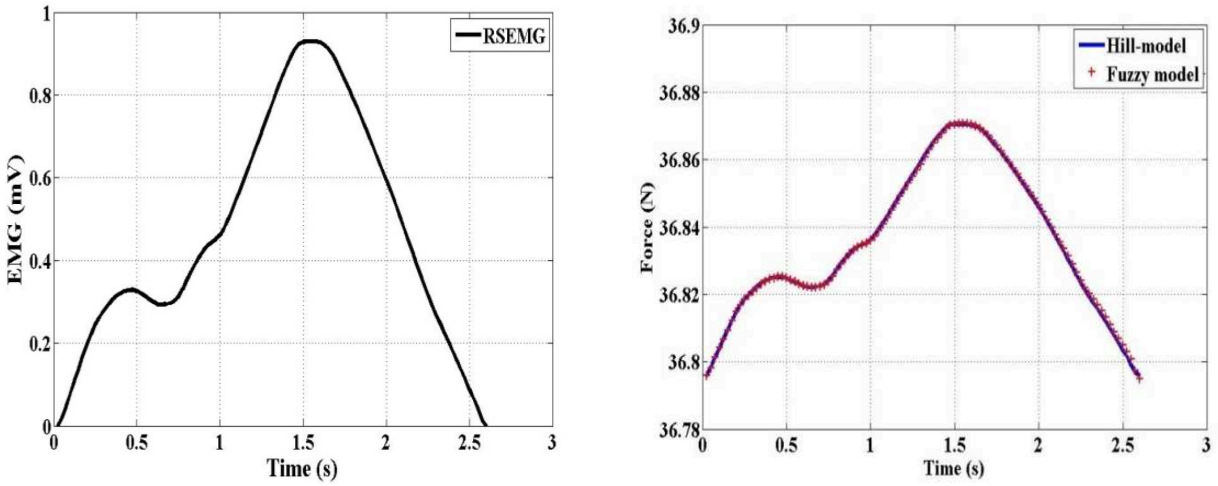

Fig. 4. Left hand, M1 muscle. A: the input SREMG signals, from the muscle. B: the output force comparison between Hill and fuzzy model

Performance of the Model

The performance measurements for the research Fuzzy Model is shown in figure 5. The researcher used the regression value of this model as its performance metric. Figure 5 shows the model's tested regression value, which as exceeds 0.999. The trained Fuzzy Model was able to predict the highly nonlinear relationship between the SREMGS and generated muscle force. This model was able to provide better-estimated results with an MSE equal to $1.11 x 10^{-08}$ and regression (R=0.99999) of this performance.

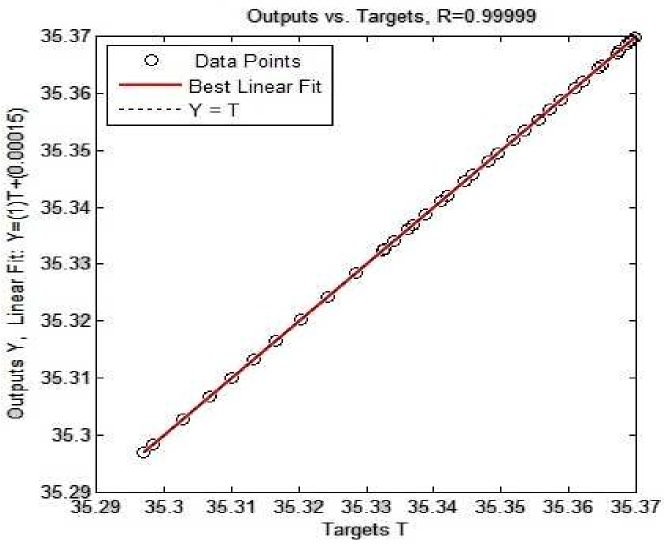

Fig. 5. Testing regression of the fuzzy model

Validation of the Research Models

To prove that the research model can be used with any human muscle, the researcher took two muscles (as in table 1) of the right arm as validation of our Fuzzy Model. Fig. 6A and Fig. 6B show the RSEMG signals from these two muscles were used as inputs to Fuzzy Model. All signals of these two muscles are obtained under the same experimental conditions; surface EMG electrodes were used to collect the EMG signals.

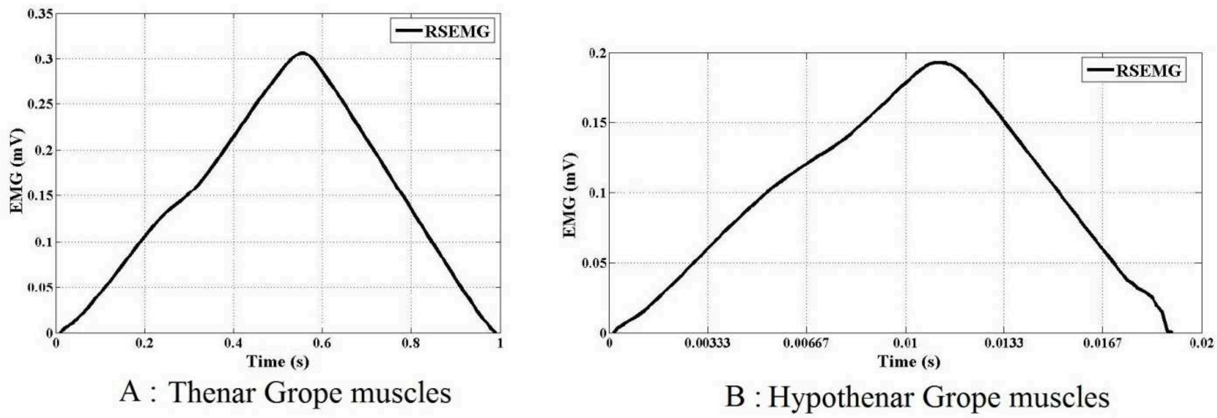

Fig. 6. RSEMG signals for the right arm muscles

The RSEMG signals of these two muscles were fed into Fuzzy Model to estimate their muscle force. This force was compared with the force obtained from Hill-type Model as shown in Fig. 7A and Fig. 7B. These figures show the comparison in muscle force between the Fuzzy and Hill-type Models for the two muscles. As one can see, the research model shows that it can be safely used for any muscle.

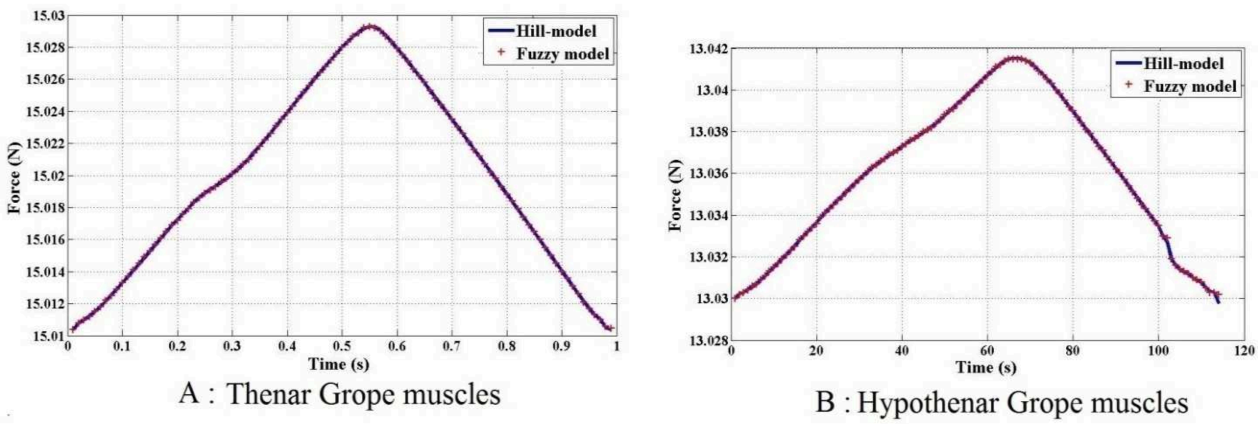

Fig. 7. Comparisons between muscle force from fuzzy model and Hill-model for five muscles

Conclusion

This paper investigated the use of Fuzzy theory for muscle force estimation. This method was based on RSEMG signals obtained from EMG ones. The researcher created Fuzzy Model, this model was used to estimate the muscle force of the human arm. The researcher Fuzzy Model based upon first-order Sugeno theory. The results demonstrated that the new model improves the accuracy of muscle force estimation. The proposed model could efficiently extract muscle force features from (EMG) signals. The research model was fast and easy to implement. To validate the model the researcher took two muscles from the humane right arm.

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