The Development of Quadriceps Muscle Model for Paraplegic

R. Jailani*, S. H. Zakaria and M.O. Tokhi

Faculty of Electrical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, MALAYSIA
Department of Automatic Control and System Engineering, University of Sheffield, UK

Abstract

This paper presents the development of paraplegic quadriceps muscle model based on Functional Electrical Stimulation (FES). A type of modeling, Artificial Neural Network (ANN) were used to investigate the impact of different stimulation frequency, pulse width, pulse duration and settling time on the movement of quadriceps muscle with paraplegia due to a spinal cord injury. 361 training data and 300 testing data set are used in the development of muscle model. Two type of learning approach which is feed-forward backpropagation and cascade-forward backpropagation are considered to develop quadriceps muscle model. The developed model then, validated with clinical data. The model of muscle presented is able to accurately predict muscle torque outputs, along with the variability of the identified parameter. In this study, the feed-forward NN muscle model is found to be the most accurate muscle model representing paraplegic quadriceps muscle model. The established model is then used to predict the behaviour of the underlying system and will be used in the future for the design and evaluation of various control strategies.

Keywords: Functional Electrical Stimulation (FES); quadriceps; spinal cord injury (SCI)

Nomenclature

| Symbol | Description |
|--------|-------------|
| \( t_k \) | target output |
| \( O_k \) | Actual output |

1. Introduction

Paralyzed muscle functions can be restored by electrical activation of peripheral neuromuscular system. This technology, known as functional electrical stimulation (FES), can enable paralyzed patients to position their legs in space [1]. Functional electrical stimulation has been explored as a means of restoring lost function in the spinal cord injured (SCI). Specific training with FES can cause significant improvements of the cardiovascular and pulmonary systems, reduce atrophy of skeletal muscle, increase lower limb circulation and improve immune system function, increase bone density and also lead to psychological benefits [2].

Quadriceps refers to a group of four muscle placed on the anterior or front aspect of the thigh, which are consist of Vastus Medialis, Intermedius and Lateralis and Rectus Femoris. Ducheme, in 1866, the first investigator to study the action of the quadriceps was described the extensors of the knee as the rectus femoris, vastus lateris, and vastus medialis. [3]. Functionally, knee extension is performed with coordinated activities of the four muscle heads of the quadriceps femoris (quadriceps): the rectus femoris (RF), vastus lateralis (VL), vastus medialis oblique (VMO) and vastus intermedius (VI).
muscles [4]. The paraplegic subject lost their knee extension ability due to spinal cord injury. Nowadays, the spinal cord injury discovered using functional electrical stimulation when the researchers develop muscle model which represented the actual condition of muscle.

Many muscle models have been developed. The earliest and most popular is the Hill muscle model. Hill muscle models come with parameters that describe familiar concepts related to the sarcomere structure and they consist of successive equations based on experimental results, this makes them more preferable than those that depend on theories as it is claimed that they are more accurate [5]. This model assumes that a muscle can be represented by a nonlinear ‘contractile element’ (Ec) which exists in series and in parallel [6] with nonlinear viscoelastic elements [7]. The series element, an ‘elastic element’ (ES) represent the mechanical isometric response of the muscle and ‘contractile element’ (Ec) represent the active force generating capacity derived from chemical free energy stores. The ‘elastic element’ (Ep) joined parallel with other two series element for the resistance of passive muscle stretch [6].

Since the introduction of Hill model, various modifications have been made to increase the muscle model accuracy. Zajac et al. [8] introduced the tendon connection and accounted for the muscle fiber pennation angle in his model. Ferrarin and Pedotti [9] developed a model that is capable of relating electrical stimulus to dynamic joint torque. The optimal model is described by a simple one pole transfer function that relates the stimulus pulse width and active muscle torque that was identified by means of parametric approach that considered the family of autoregressive with exogenous input (ARX) models and using least squares method on the error between the real data and the output of the model. More complex models have been developed by researchers [10-12] to increase the model accuracy, describing the physiologically based interpretation that capture activities under microscopic and macroscopic level such as muscle fatigue, calcium dynamics and cross bridge interaction. They [10-12] introduced a muscle model composed of three parts, activation dynamics, contraction dynamics and body segmental dynamics. Activation dynamics provide the activation needed by the muscle to generate force. It is computed as a function of pulse width and frequency with first order relation and includes the effect of muscle fatigue by introducing the fitness function and a linear second order calcium dynamics [11].

Makssoud et al. [13] developed a muscle model composed of two parts, activation model and mechanical model. The activation model depends on the parameter of the stimulation intensity, pulse width and frequency whereas the mechanical model deals with the mechanical behaviour. The model developed is based on physiological operation condition through the implementation of macroscopic muscle model designed by Hexley [14] who provided an explanation of the interaction of cross bridge phenomena and thus can be linked to the microscopic muscle model introduced by Hill [15]. The drawback of Makssoud et al. [13] muscle model is that the important component of physiological based muscle model such as muscle fatigue and calcium dynamics are not accounted.

Previously, hamstrings muscle model has been developed using Adaptive Neuro-Fuzzy Inference System (ANFIS) by R. Jailani et. al [16,17]. In this paper, the hamstrings muscle model developed are reported to be more practical in FES application. Therefore, this research will develop a new quadriceps muscle model from a series of experimental data using two different ANN approaches.

2. Methodology

2.1. Data Collection

A paraplegic subject is be placed in a semi upright sitting position (45° to 60°) with the thigh hanging using thigh support to avoid any constraint on the leg movement. The isometric force output of the quadriceps muscle is recorded via a force transducer (PCE-FM200, PCE Group Company, Deutschland), which is placed aligned with the anterior aspect of the leg, 5cm proximal to the lateral malleolus. The position of the leg is recorded instantaneously using Matlab software through ADC card & serial connection. Then, the force and torque are recorded.

The electrical stimulation then is delivered via two gel surface electrode (Pals platinum, Axelgaard Mfg, Comp, USA, 50mm x 90mm). The cathode and anode are placed over the upper thigh, covering the motor point of rectus femoris and vastus lateralis, and lower aspect of thigh just above patella, respectively. A RehaStim Pro8 channels stimulator will receives stimulation pulses generated in Matlab through USB connection for application to the muscle.

From above procedure, more than 300 data are obtained from more than 200 pulses with simulation frequencies, pulse widths and pulse durations varying from 10Hz to 50Hz, 200μsec to 400μsec and 1 sec to 5sec respectively. Data preparation is important before developing any predictive model. Data preparation allows identifying unusual cases, invalid cases, erroneous variables and the incorrect data values in the dataset. If the data is prepared properly, the models will be able to give better results because of the cleaned data and at the same time, right models will be created that represent the right scenarios. In this study, 361 data points are used as training data and 300 data point are used as testing and validating data set. The data were used to develop model using Artificial Neural Network (ANN).
2.2. Artificial Neural Network

Artificial neural networks appear promise as a pattern generator for their great ability to learn and memorize complex non-linear input/output information [18]. Neural networks are computational models broadly inspired by the organization of the human brain.

The most important features of a neural network are its abilities to learn and to associate complex input and output mappings. This is done by presenting the system with a representative set of examples describing the problem, namely pairs of input and output samples; the neural network then will establish a mapping between input and output data.

After training, the neural network can be used to recognize data that is similar to any of the examples shown during the training phase. The neural network can recognize incomplete or noisy data, an important feature that is often used for prediction, diagnosis or control purposes.

Two models developed using two different learning approach namely feed-forward backpropagation algorithm and cascade forward backpropagation

1. Feed-forward Backpropagation

Feed-forward backpropagation algorithm consists of the propagation of errors beginning at the output layer, through the hidden layer, and so on, to the input layer, in a backward direction. The weights are therefore updated at each layer, beginning at the output layer. The changes in weights are proportional to the derivative of the errors with respect to the incoming weights.

![Figure 1: Multilayer neural network](image)

The weight and thresholds are determined during the network been trained to minimize the error function which is defined by the Least Mean Square algorithm (LMS). LMS defined by equation:

\[
E=\frac{1}{2} \sum_{k} (t_k-O_k)^2
\]  

2. Cascade-forward Backpropagation

Cascade-forward backpropagation model are similar to feed-forward networks, but include a weight connection from the input to each layer and from each layer to the successive layers. For example, a three layer network has connections from layer 1 to layer 2, layer 2 to layer 3, and layer 1 to layer 3. The three-layer network also has connections from the input to all three layers. The additional connections might improve the speed at which the network learns the desired relationship [19].

In both learning approach, the Levenberg-Marquardt algorithm was used as training algorithm since it is considered to be the best choice for most problems. The model developed by train the 361 training data by changing some parameter to obtain the best result, including the transfer function for hidden layer and output layer, and number of neuron. Number of neuron in hidden layer changed from 3 to 20 neuron, in order recognize the best number of neuron, thus, induce the best model of muscle. The model then, tested using 300 testing data.
3. Results

3.1. Backpropagation Neural Network

The neural network architecture of quadriceps muscle model developed in this study consists of four inputs and single output, represented by frequency, pulse width, pulse duration, settling time and torque respectively. 1000 iterations were used to train the network. Figure 2 shows the best validation performance of the network is 0.80556 at 282th iterations. This model has a single hidden layer with 7 neurons and using tan-sigmoidal (tansig) transfer function, while linear (purelin) transfer function used at the output layer. This parameter was found to be most optimum in this muscle model development.

Figure 2: Performance Error

The regression plots of the model developed showed in Figure 3, which is measure the correlation between outputs and targets. The regression value of 1 means a close relationship, while 0 a random relationship. R values obtained are almost close to 1. Therefore, Figure 3 shows the training, validation and testing data set are highly correlated with the model fitting. This means that the quadriceps model developed is highly acceptable.

After training process, 300 data points were used to test network. The actual data from experiment and the output data from ANN muscle model are showed in Figure 4. This figure shows the output data from ANN muscle model followed the actual data accurately. By referring to ANN error plot in Figure 5, the model represented is found to be very accurate since the error lies from -3.1721 to 2.0889. 98.6% of the error lies between ±2Nm. The error occurs shows the correlation between actual output data from experiment and output data from developed muscle model.

Figure 3: Regression plot

Figure 4: Output of testing data

Figure 5: ANN output error
3.2. Cascade Forward Backpropagation

The model develop using this learning approach also consist of four input and single output with same data used in feed-forward backpropagation approach. The model shows it best performance at 0.66872 at 44th iterations. The best parameter also found to be same as used in feed-forward backpropagation approach which is 7 neuron in the hidden layer and using tan-sigmoidal (tansig) transfer function, while linear (purelin) transfer function used at the output layer.

Regression, R, value shows in Figure 7 above is close to 1 for training, testing and validation. 94.93% error in this approach lies between ±2Nm, which is lower than error in feed-forward backpropagation method. This testing error shows in Figure 9.

4. Conclusion

A muscle model represent quadriceps muscle has been developed using Artificial Neural Network with two different type of learning approach which is feed-forward backpropagation and cascade-forward backpropagation. The model developed then has been validated with the experimental data. The model develop using feed-forward backpropagation is more accurate than the model developed using cascade-forward backpropagation, since the accuracy of error produced using this method is higher. Thus, it can predict more accurate result for torque muscle when tested with unknown’s data. The ANN quadriceps muscle model was found to be most accurate representing the actual muscle model. It accuracy make it possible to be used in measuring parameter in order to provide rehabilitation for paraplegic patient using functional electrical stimulation.
Acknowledgement

The authors would like to express gratefulness to the Research Management Institute, University Teknologi MARA and the government of Malaysia for the research funding. This research is carried out under research grant number 600-RMI/ST/DANA 5/3/Dst (385/2011).

References

[1] Ning Lan, Huan-Qing Feng, And Patrick E. Crago, “Neural Network Generation Of Muscle Stimulation Patterns For Control Of Arm Movements” IEEE Transactions On Rehabilitation Engineering, Vol. 2, No. 4, December 1994, Pg 213-224.

[2] Margit Göföler, Thomas Angeli, and Peter Lugner. Modeling of Artificially Activated Muscle and Application to FES Cycling. 12th International Conference on Mechanics In Medicine And Biology. Porto Myrina Palace, Lemnos, Greece, 9-13 September, 2002.

[3] Fredrick J. Lieb, and Jacquelin Perry “Quadriceps Function: An Anatomical and Mechanical Study Using Amputated Limbs”, The Journal of Bone and Joint Surgery, pg 1535-1547.

[4] Shweta Shenoy, Priyaranjan Mishra, J.S. Sandhu” Peak Torque And Iemg Activity Of Quadriceps Femoris Muscle At Three Different Knee Angles In A Collegiate Population”, J Exerc Sci Fit , Vol 9, No 1(2011).pg 40-45

[5] R. Massoud “Comparative Study of Three Human Muscle Models” 12th International Conference on Computer Modelling and Simulation (2010) pg. 213-215.

[6] R. Jailani, M. O. Tokhi, S. Gharooni, and Z. Hussain “Development of Dynamic Muscle Model with Functional Electrical Stimulation” Complexity in Engineering (2010) pg. 132-134.

[7] Jack M. Winters “Improvements within A.V. Hill Model Structure: Strengths and Limitation”. Chemical, Bio, and Material Engineering, Arizona State University. 1988.

[8] F. E. Zajac, E. L. Topp and P. J. Stevenson. 1986, A Dimensionless Musculotendon Model. Proceedings IEEE Engineering in Medicine and Biology. http://ieeexplore.ieee.org Biology Society, Dallas-Ft Worth, Texas.

[9] M. Ferrari and A. Pedotti, 2000. The relationship between electrical stimulus and joint torque: a dynamic model. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 8(3): 342-352. DOI: 10.1109/86.867876. http://ieeexplore.ieee.org.

[10] R. Riener, J. Quintern and G. Schmidt, 1996. Biomechanical Model of The Human Knee Evaluated by Neuromuscular Stimulation. Journal of Biomechanics 29(9): 1157-1167. DOI: 10.1016/0021-9290(96)00012-7, PubMed: 8872272, http://pubmed.gov.

[11] R. Riener and T. Fuhr, 1998. Patient-Driven Control of FES-Supported Standing Up: A Simulation Study. IEEE Transactions on Rehabilitation Engineering 6(2): 113-124. DOI: 10.1109/10.35296, INSPEC: 3508963, PubMed: 2789177, http://ieeexplore.ieee.org.

[12] M. Ferrari, F. Palazzo, R. Riener and J. Quintern, 2001. Model-based control of FES-induced single joint movements. IEEE Trans. on, 9(3): 245-257. DOI: 10.1109/7333.948452. http://ieeexplore.ieee.org.

[13] H. E. Makssoud, D. Guiraud and P. Poignet, 2004. Mathematical Muscle Model for Functional Electrical Stimulation Control Strategies. Proceedings of the 2004 IEEE International Conference on Robotic and Automation, April 26-May 1, 2004: 1282-1287. DOI: 10.1109/ROBOT.2004.1308001, INSPEC: 8065665, http://ieeexplore.ieee.org.

[14] A. F. Huxley, 1957. Muscle Structure and Theories of Contraction. Progress in Biophysics and Biophysical Chemistry: 255-318. Pergamon Press. http://pubmed.gov.

[15] A. V. Hill, 1938, The Heat of Shortening and The Dynamic Constants in Muscle, Proceedings of the Royal Society: 136-195.

[16] Jailani, R. Tokhi, M.O., Gharooni S.C. and Hussain, Z., (2009). A Novel Approach in Development of Dynamic Muscle Model for Paraplegic with Functional Electrical Stimulation, Journal of Engineering and Applied Science, Medwell Journals, Vol. 4, Num. 4, pp 272-276, 2009. ISSN: 1816-949x, 1818-7803.

[17] Jailani, R., Tokhi, M.O., Gharooni, S.C. and Hussain, Z., (2010). Development of dynamics muscle model with functional electrical stimulation. Proceedings of the International Conference on Complexity in Engineering (COMPENG2010), 22–24 February, Roma, Italy, pp 132-134, ISBN 978-0-7695-3974-4.

[18] Ning Lan, Huan-Qing Feng, and Patrick E. Crago “Neural Network Generation of Muscle Stimulation Patterns for Control of Arm Movements” IEEE Transactions On Rehabilitation Engineering, Vol. 2, No. 4, December 1994. pg. 213-224

[19] Sumit Goyal and Gyandera Kumar Goyal “Cascade and Feedforward Backpropagation Artificial Neural Network Models For Prediction of Sensory Quality of Instant Coffee Flavoured Sterilized Drink” Canadian Journal on Artificial Intelligence, Machine Learning and Pattern Recognition Vol. 2, No. 6, August 2011.