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Process modeling of force behavior in the automatic bovine cortical bone milling process using adaptive neuro-fuzzy inference system

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ABSTRACT: In this article, an adaptive neuro-fuzzy inference system is utilized to model the effect of important parameters in the cortical bone milling process including the rotational speed, feed rate, depth of cut and tool diameter to predict the cutting forces. To model the process force behavior, experimental tests are conducted on the fresh cow femur. Next, the results of performed experiments are used to train and test the inference system. In this model, the most influential parameters of automatic cortical bone milling process including the rotational speed, feed rate, tool diameter and depth of cut are taken as the input parameters, while the cutting forces in the feed direction, normal to the feed direction and normal to the bone surface as well as the resultant force are considered as the output. To this aim, the adaptive neuro-fuzzy inference system relies on 75% of the trained laboratory data and the remaining 25% to test the model validation. The accuracy of the obtained model is investigated using different diagrams and numerous statistical criteria. The results indicate that the adaptive neuro-fuzzy network has shown a successful performance in predicting the cutting forces of cortical bone milling process.

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1. INTRODUCTION

Orthopedic surgery has been increasingly applied to the treatment of diseases related to joints and bones due to the less inclination of society to physical activity in addition to higher sports injuries and old age [1]. The orthopedic surgery involves different machining processes on the cortical bone tissue. The cortical bone machining process in advanced surgeries using different tools helps to accurately perform orthopedic surgeries. Nowadays, different milling tools are used in knee and hip replacement, hearing and hearing aids, dentistry and vertebral column, among others. Thus, the milling process can be considered as a major means of machining to cut or create slots on bone tissue. The cutting forces generated during bone machining are of significant importance. Excessive cutting forces result in mechanical damage to the bone tissue, breaking of tools in the tissue as well as the temperature rise and the unwanted phenomenon of thermal necrosis [2, 3]. During the knee joint replacement, the thermal necrosis impedes the cell growth between the bone and prosthetic joint, hence the lack of strong bond between them [4]. The damage to bone tissue during bone milling can be reduced with the aid of modeling and optimization of milling parameters based on the mathematical model of force [3].

This article benefits from an Adaptive Neuro-Fuzzy Inference System (ANFIS) to model important parameters in the cortical bone milling for the first time to predict the cutting forces. These parameters include the tool rotational speed, feed rate, depth of cut and tool diameter. To date, this method has not been utilized to study the behavior of cutting forces and predict the magnitude of forces in the cortical bone milling. To this end, the results of experiments conducted for training and testing of fuzzy inference system are employed. In this model, the most important parameters of cortical bone milling including the tool rotational speed, feed rate, tool diameter and depth of cut are taken as inputs, while the cutting forces in the three directions of feed, normal to feed and normal to the bone surface along with the resultant force are assumed to be outputs. As another novelty, this article considers the changes in the tool diameter as one of the factors in the prediction of cutting force.

2. METHODOLOGY

To methodically conduct experimental tests in this article, the standard end mill is used for machining purposes. The end mill is constructed from High Speed Steel (HSS) at three different diameters. The geometrical parameters of the tools are similar to those of standard tools used in medical operations [5]. These tools include 4 cutting edges with a helix angle of 30°, rake angle of 5°, and relief angle of 20°. The diaphysis of cow's femur (middle section) with a length of 90 mm whose cortical bone thickness is 8–10 mm is used. The milling processes are performed using a three-axis Computer Numerical Control (CNC) milling machine produced by Tabriz Machinery Manufacturing Co. with an accuracy of 0.02 mm (Fig. 1). To measure the cutting forces

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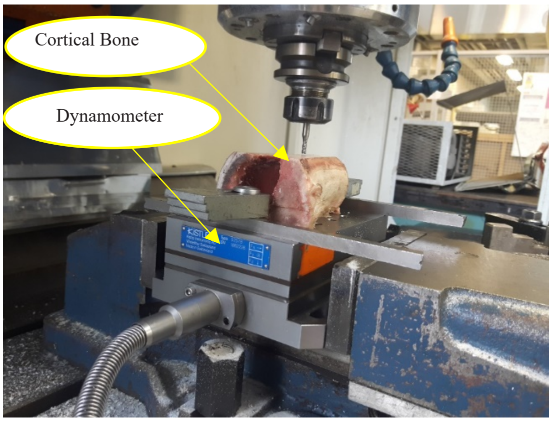

Fig. 1. Bovine femur used in the experiment

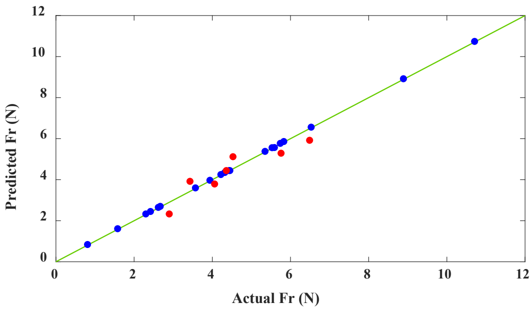

Fig. 2. Comparison between actual and predicted data by ANFIS network for modeling of F_r

created during the process, a piezoelectric dynamometer of type 9572B made by Kistler is used that could measure forces along three directions with an accuracy of 0.01 N. This apparatus is equipped with data acquisition and result analysis system and utilizes Dynoware software to examine the force outputs. Four controllable and independent factors selected in this process include tool rotational speed (V), feed rate (F), tool diameter (D) and depth of cut (d). The values of parameters are selected by considering the opinions of orthopedic experts. In this regard, 27 tests are carried out based on the experiment design and the central composite design approaches.

The ANFIS system takes advantage of fuzzy logic and neural network methods. There are 5 distinct layers in the structure of ANFIS network, making it a multilayer network. A special type of this network is the Sugeno fuzzy inference system with two inputs and one output. In summary, the first layer in the ANFIS structure performs the formation of fuzzy system and the second layer realizes the antecedent part of if-then rules. The third layer is related to the normalization of membership function and the fourth layer constitutes the consequent part of fuzzy rules. Finally, the last layer computes the network output. Accordingly, it is obvious that the first and fourth layers in the ANFIS structure are the adaptive layers in which c_i and σ_i in the first layer are known to be the parameters related to the input membership functions. In the fourth layer, r_i, q_i and p_i are adaptive parameters, also known as resultant parameters [31].

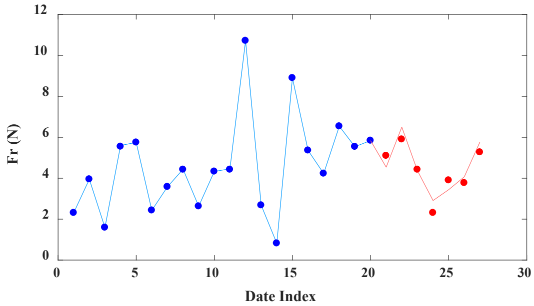

Fig. 3. Differences between actual and predicted data in two parts of training and testing for modeling of F_r

3. RESULTS AND DISCUSSION

The experimental data are randomly divided into two subsets: 75% for network training and 25% for network testing. Fig. 2 simultaneously shows the real and approximate data based on ANFIS for the resultant force. As observed, the ANFIS network exactly matches the data of the training part. Also, one notes that the obtained model successfully predicts the network test part with very high accuracy. The little discrepancy observed here could be attributed to the error in experimental data. Fig. 3 demonstrates the resultant force for real and predicted data in the training and test sections. As visible in these plots, the ANFIS network is fully consistent with the training and test data.

4. CONCLUSION

This study illustrates how the adaptive neuro-fuzzy inference system can be employed to model the cortical bone milling process based on the input (tool rotational speed, feed rate, tool diameter and depth of cut) and output (cutting forces along x, y and z directions as well as resultant force) variables. The conducted analysis showed that this system is highly competent, using which different values of cutting forces can be predicted according to the changes of input variables of bone milling process.

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