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Prediction of the wear behavior of UHMWPE using artificial neural networks

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ABSTRACT

In the present investigation, the tribological behavior of ultra-high molecular weight polyethylene (UHMWPE) was investigated under dry, distilled water and physiological saline lubricated conditions against a 316L stainless steel disc. The effect of the applied load, sliding velocity as well as the lubrication type on the coefficient of friction and the wear rate of UHMWPE were investigated. The results revealed that the highest and lowest wear rates of UHMWPE have been taken place under dry sliding and distilled water lubrication, respectively. The steady-state friction coefficient in dry sliding is about two times the value in saline, and about 3-4 times that in distilled water. An artificial neural network (ANN) model for predicting the effect of the applied load, the sliding speed and type of lubricant on wear rate and the coefficient of friction of the UHMWPE was developed. It has been observed that the experimental results coincided with ANNs results.

KEYWORDS

Ultra-high molecular weight polyethylene (UHMWPE);
Wear;
Coefficient of friction;
Lubrication;
Artificial neural networks (ANN).

INTRODUCTION

Ultra high molecular weight polyethylene (UHMWPE) can be considered as the most widely polymeric material that is used in medical applications[1-3]. UHMWPE merits attention due to their excellent properties, such as high tensile and compressive strength, non-toxic, low coefficient of friction for nonstick and self-lubricating surfaces, high sliding abrasion resistance and excellent chemical resistance. The aforementioned advantages of UHMWPE make it useful in medical applications such as total joint replacements (TJRs), heart valves, contact lenses, blood containers and in making the plate bones[1-4].

Several investigations were conducted to evaluate the tribological performance of UHMWPE under several sliding conditions[5-7]. It has been shown that wear of the UHMWPE is highly sensitive to the type of motion as well as the type of lubricant. *Wang et al.*[5] investigated the effect of plasma and brine lubricants on the friction and wear behavior of UHMWPE using the geometry of a Si_3N_4 ball sliding on a UHMWPE disc under patterns of uni-directional reciprocation and bi-directional sliding motions. The results revealed that the sliding motion pattern affected the friction coefficients lubricated with plasma, while seldom affected that lubricated with brine. The UHMWPE lubricated with plasma showed about half of the wear rate of that lubricated with brine. *Sawae et al.*[6] studied the effect of synovia constituents, serum protein and hyaluronic acid on the friction and wear of UHMWPE. They found that the wear rate in the serum protein solution was not much different from that in the diluted serum, but the friction coefficient was higher. On the other hand, hyaluronic acid could reduce the friction and wear. *Gispert, et al.*[7] found that a lubricant containing brine serum albumin could reduce the friction coefficient and keep it stable during wear testing.

The current investigation presents a study on the tribological characteristics of UHMWPE under dry sliding, physiological saline and water lubricated conditions against 316L stainless steel counterface. Wear tests were conducted under several conditions of loads and sliding speeds. Another purpose of the current investigation is to develop artificial neural network (ANN) model that is capable of predicting the wear rates and coefficient of friction of UHMWPE as a function of load, velocity and type of lubricant. The ANN provides useful data from experimental databases, which means considerable saving of cost and time. ANN is a general-purpose tool for numerical modeling that is suitable to map complex functions. The strongest reason for using neural networks is their ability to generalize when confronted with new situations. ANN does not require a priori knowledge about problems, which they are intended to solve; they are able to tolerate disruptions or discontinuities, accidental gaps or loss in the learned data set. Over the last several years, ANN have gained increasing interest in the field of materials engineering[8,9]. The growing popularity of ANN is due to their ability to model relations between investigated variables with no need to know the physical model of the phenomena. The results provided by ANNs very often exhibit better correlation with experimental data than those obtained from empirical explorations or mathematical models of the processes under investigation.

EXPERIMENTAL PROCEDURES AND ANN MODELING

Wear testing

The friction and wear properties of UHMWPE were measured using pin-on-ring wear testing machine shown schematically in Figure 1. The wear tests were conducting under lubrication of distilled water and physiological saline as well as under dry sliding conditions. UHMWPE cylindrical pin specimens having dimension of 8 diameter and length 12 mm were used. The counterface disc was made of 316 stainless steel, of nominal composition (by wt.-%) 0.08% C, 1% Si, 12% Ni, 17% Cr, 2.5% Mo and balance Fe, with a hardness of 184 VHN. The disc was polished on 1200 emery papers before each wear test. A fixed track diameter of 100 mm (ring radius) was used in all tests. Wear tests were conducted at nominal sliding velocities of 0.5, 0.75 and 1 m/s and normal loads of 100, 150 and 200 N. The sliding time varies up to 75 min. The duration of the experiment was controlled by a stopwatch.

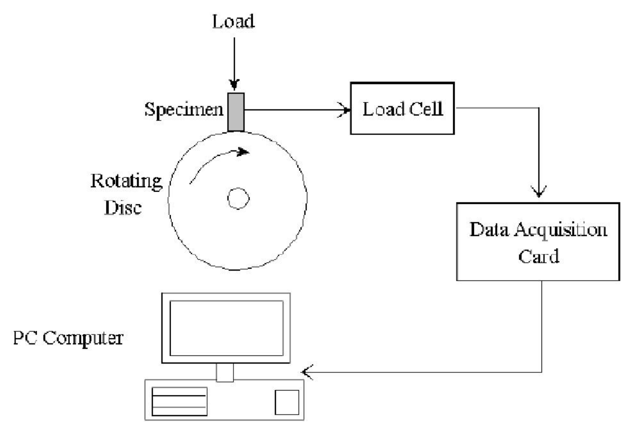

Figure 1 : Schematic diagram showing the pin-on-ring wear tester.

Wear behaviour was obtained by calculating the weight loss of the specimens before and after tests using an electronic balance with sensitivity 0.1 mg. The wear rates (the slopes of the cumulative weight loss versus sliding distance curves) of the investigated alloys were calculated by using the data after the run-in stage. Friction coefficient measurements were conducted using a transducer to measure the frictional force developed on the pin holder and caused by the ring rotation. The coefficient of friction was computed by dividing the frictional force by the normal load.

ANN modeling

In the present investigation an ANN model was developed using multilayer perceptron (MLP) network structure. The MLP network currently forms the basis for the majority of practical applications. An MLP is a network of simple neurons called perceptron. The perceptron computes a single output from multiple realvalued inputs by forming a linear combination according to its input weights and then possibly putting the output through some nonlinear activation function. Mathematically this can be written as:

$$y = \varphi\left(\sum_{i=1}^{n} \omega_i x_i + b\right) \quad (1)$$

Where ω denotes the vector of weights, x is the vector of inputs, b is the bias and φ is the activation function. A typical MLP network consists of a set of source nodes forming the input layer, one or more hidden layers of computation nodes and an output layer of nodes. The input signal propagates throught the network layer-by-layer. The signal-flow graph of an MLP network with one hidden layer is shown in Figure 2. In order to facilitate the comparisons between predicted values and the desired values for the different networks, an error evaluation was carried out using mean relative error (MRE). The MRE values were calculated by the following expression:

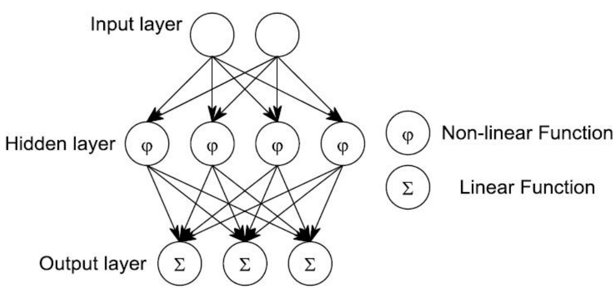

Figure 2 : Signal-flow graph of an MLP network.

In order to facilitate the comparisons between output (predicted) values and experimental (desired) values for the ANN network, an error evaluation was carried out using mean relative error (MRE). MRE values were calculated using the following equation:

$$MRE = \frac{1}{n}\left(\sum_{i=1}^{n} \frac{100\,|D_i - O_i|}{D_i}\right) \quad (2)$$

Where D_i is desired value, O_i the output (predicted) value and n the number of data. The lower the MRE, the better the network performance is.

In the present work, the ANN model were developed using Statistica neural network commercial software facilities. The input or independent variables are the applied load (P) in N, the sliding speed (V) in meters per second and the type of sliding (dry sliding, distilled water and physiological saline). The output or dependent variable is the wear rate (WR) in milligrams per meter and the coefficient of friction (COF).

RESULTS AND DISCUSSIONS

Coefficient of friction of UHMWPE

Figure 3 shows an example of the variation of friction coefficient with sliding distance, for the dry sliding and lubricating conditions, at several applied load and constant velocity of 1 m/s. In dry sliding condition (Figure 3a), the initial friction coefficient is relatively low, but it increased gradually with the sliding distance, and then reached to steady-state value. In physiological sa-

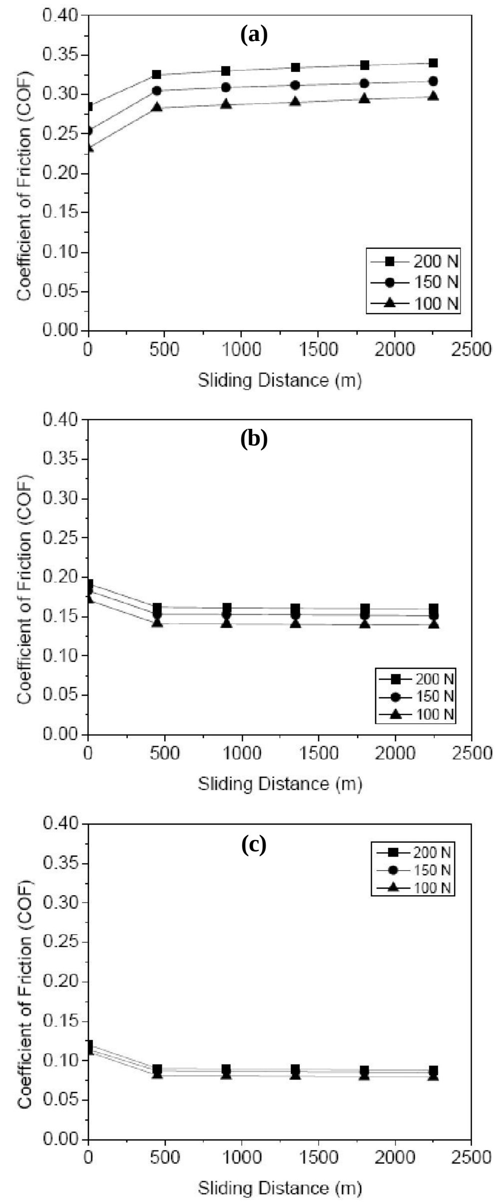

Figure 3 : Variation of friction coefficient with sliding distance at V=1(m/s) (a) (dry) (b) Under physiological saline lubricated condition (c) under distilled water lubricated condition

line and distilled water lubrication (Figure 3b and 3c, respectively), the initial friction coefficients are all higher than their stead-state friction coefficients.

The variation of the steady state friction coefficient with the applied load and sliding velocity under dry sliding and lubrication conditions is illustrated using three dimensional plots in Figure 4. It has been found that, under

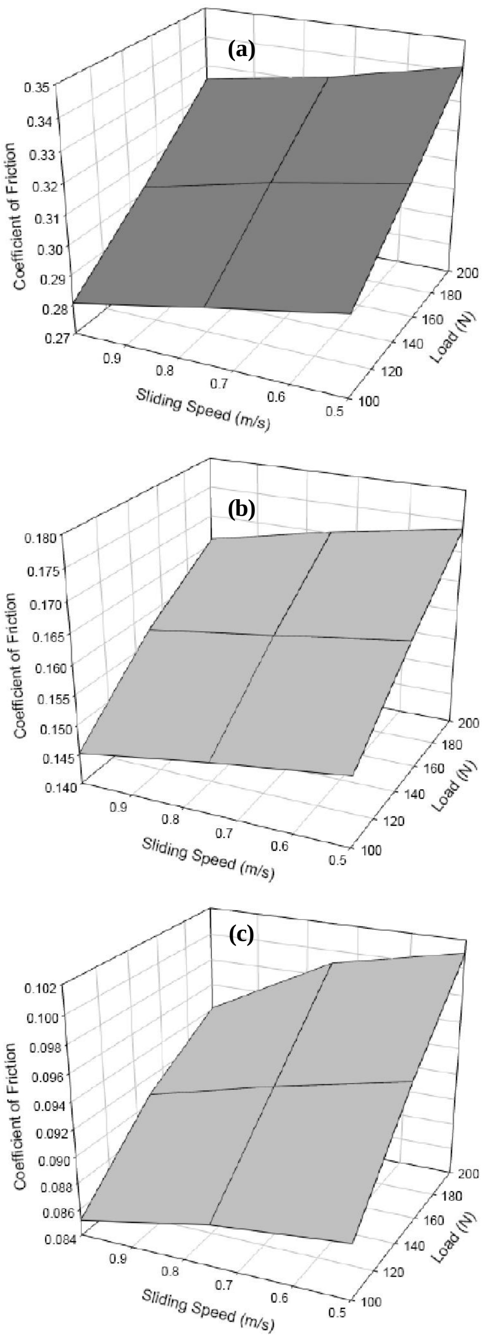

Figure 4 : Three dimension plots showing the variation of friction coefficient with both the applied load and sliding speed under dry (a), physiological saline (b) and water (c) lubricated conditions.

dry sliding and lubricating conditions, increasing the applied load and/or the sliding velocity increases the coefficient of friction. The steady-state friction coefficient in dry sliding is about two times the friction coefficient under physiological saline lubrication and about 3–4 times the friction coefficient under distilled water lubrication. For example the UHMWPE showed coefficient of friction of about 0.29, 0.15 and 0.09 at dry, physiological saline and distilled water lubrications, respectively, at applied load of 100 N and sliding speed of 0.5 m/s.

The aforementioned results indicate that the state of water absorption of UHMWPE has great effect on its friction behavior. The water absorption results in the swelling of UHMWPE and decreases the shear strength of UHMWPE, thus, reducing its friction. The friction coefficient in dry sliding increases with increasing sliding distance due to no water absorption by UHMWPE resulting from friction heat. On the other hand, the UHMWPE absorbs water in saline and distilled water, thus, the friction coefficient decreases with increasing sliding distance. After sufficient sliding distance, the water absorption rate of UHMWPE pin surfaces reaches steady state and thus the friction coefficients enter steady state. Because the states of water absorption of UHMWPE are similar at the beginning of sliding, the initial friction coefficients in dry, saline, and distilled water are approximately the same. Pure distilled water immerges the UHMWPE easily, and its water absorption should be the highest, thus, the friction coefficient is the lowest.

Wear rate of UHMWPE

The variation of the weight loss of UHMWPE with the sliding distance under dry as well as saline and distilled water lubrication is shown in Figure 5. It is clear that the weight loss of the UHMWPE increases as the sliding distance increase. Moreover, the weight loss was the highest under dry sliding condition, while was the lowest under distilled water lubricated condition. The weight loss was found to increase with increasing both the applied load and the sliding speed. Such behavior was observed under all sliding conditions.

Figure 6 shows the variation of the wear rate of the UHMWPE with the applied load at several sliding speeds. It has been observed that the wear rate increase with the increase of both the applied load and the sliding speed. However, the effect of load on the wear rate is larger than that of sliding speed. The wear rate in dry condition is the highest and equal to twice the wear rate under physiological saline lubricating condition. The lowest wear rate was observed under distilled water lubricating condition.

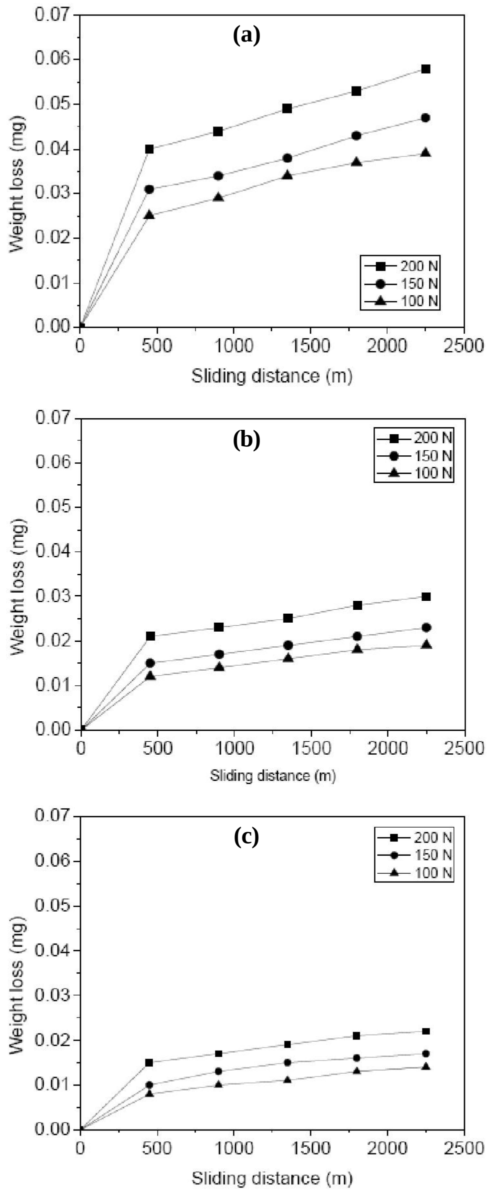

Figure 5 : Three dimension plots showing the variation of friction coefficient with both the applied load and sliding speed under dry (a), physiological saline (b) and water (c) lubricated conditions.

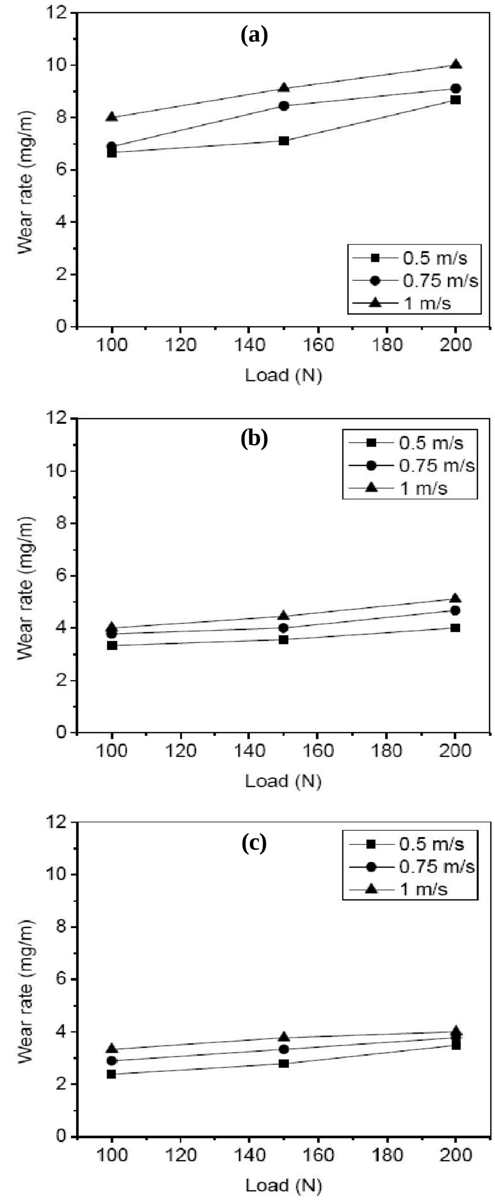

Figure 6 : Variation of wear rate with both the applied load and sliding speed under dry (a), physiological saline (b) and water (c) lubricated conditions.

ANN modeling

The wear rate and coefficient of friction data obtained from the experimental work have been preprocessed to the required format for training procedure. After the repeated training and testing procedure, the final MLP model configurations for dependence of the wear rate and the coefficient of friction of the UHMWPE on the applied pressure, sliding velocity as well as the lubrication were obtained. A comparison between the experimental and predicted data for the coefficient of friction and wear rate of UHMWPE resulted from the developed ANN model is shown in Figure 7. A prediction would be when all the plotted points were on the 45° line. The accuracy of the ANN model can be easily compared by the closeness of the data clusters to this line. It is clearly seen from Figure 7 that the experimental and predicted values developed from the ANN model are very close to each other. It has been found that the mean relative errors (MRE) for the wear rate and the coefficient of friction for the UHMWPE were 2.6% and 0.62%, respectively.

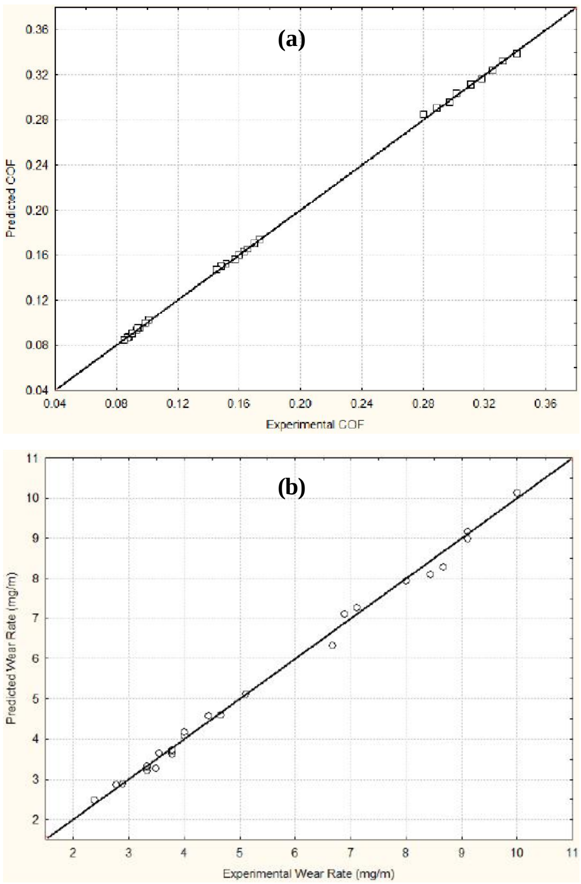

Figure 7 : Predicted values from the developed ANN model versus the experimental values of both (a) the coefficient of friction and (b) the wear rate of UHMWPE.

The calculated relative error distribution as a function of test data derived from developed ANN network is shown in Figure 8. The results revealed that the level of relative error is satisfactory. The maximum relative error for the coefficient of friction was about 1.38% and observed under the distilled water conditions. While the maximum relative error for the wear rate was about 6.7% and was observed again under the distilled water conditions. The above results indicates that the developed ANN model is capable of predicting both the wear rate and the coefficient of friction of the UHMWPE under several conditions of lubrication and sliding velocities and loads. The proposed ANN model predicts good agreement with the experimental data. Neural network modeling provides useful information from relatively small experimental databases, leading to savings in cost and time.

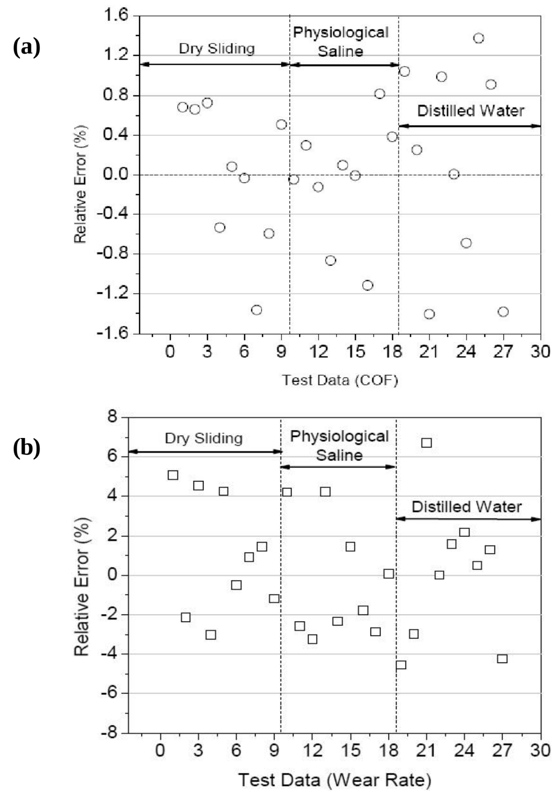

Figure 8 : Relative error distribution obtained from the developed ANN network as a function of the test (a) coefficient of friction data and (b) wear rate data.

Variation of the wear rate and the coefficient of friction of the UHMWPE with both the sliding speed and the applied loads under different lubricating conditions are shown in Figures 9 and 10, respectively. The figures show both the experimental and predicted contour lines. It is clear that both contour lines (predicted and experimental) are close to each other. Accordingly, it can be concluded that the developed ANN model is ideally suited for simulating the wear rate and the coefficient of friction of UHMWPE.

There are many parameters that control the tribological behavior of the UHMWPE such as the sliding speed and the applied load as well as the lubrication conditions. The results obtained from the present investigation indicate that ANNs could be of help to simulate the effect of these parameters on both the wear rate and the coefficient of friction. The successful prediction of the tribological behavior of the UHMWPE using the developed ANN could be of benefit to reduce the number of more complex experiments. The well-trained ANN will be of help in the material design, parameters studies and property analysis of UHMWPE.

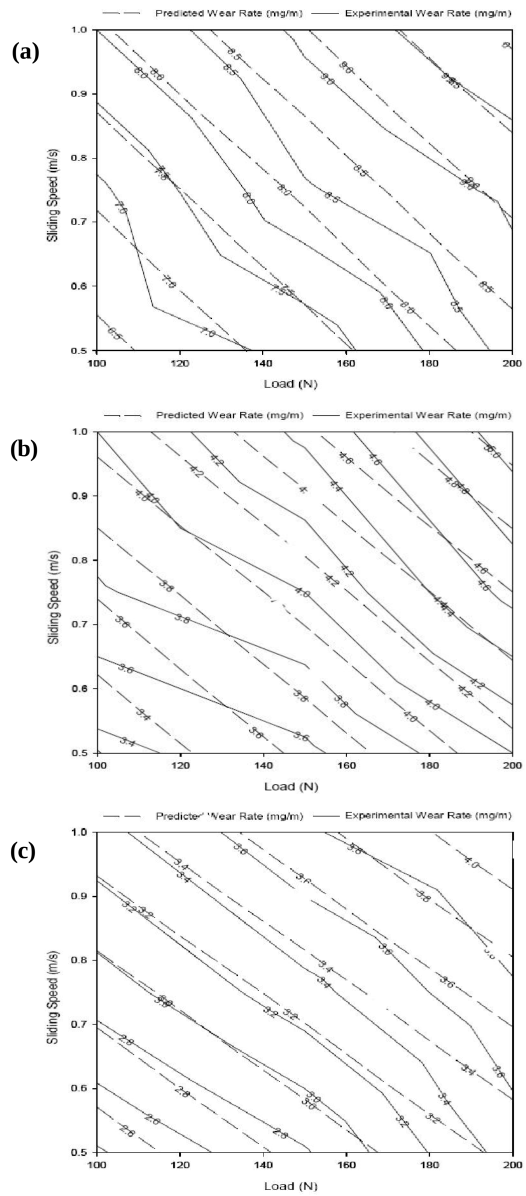

Figure 9 : Contour plot of the experimental and predicted wear rates of UHMWPE as a function of the applied load and sliding speed under (a) dry sliding, physiological saline (b) and distilled water (c) lubrication.

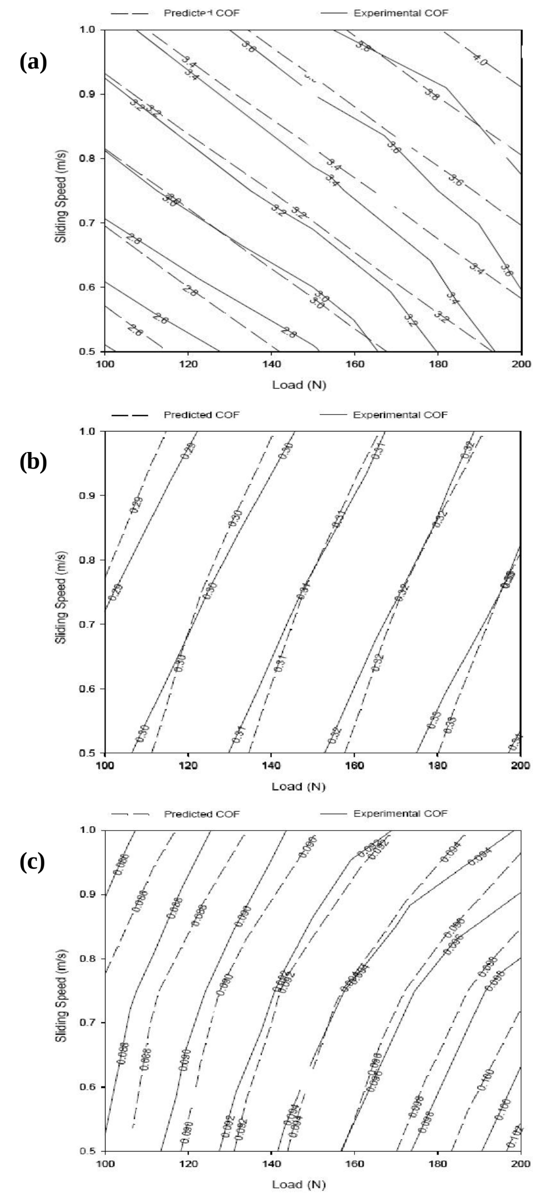

Figure 10 : Contour plot of the experimental and predicted coefficient of frictions of UHMWPE as a function of the applied load and sliding speed under (a) dry sliding, physiological saline (b) and distilled water (c) lubrication.

CONCLUSIONS

1 The steady-state friction coefficient in dry sliding is about two times the friction coefficient under physiological saline lubrication and about 3–4 times the friction coefficient under distilled water lubrication.

2 The wear rate of UHMWPE in dry condition is the highest and equal to twice the wear rate under physiological saline lubricating condition. The lowest wear rate was observed under distilled water lubricating condition.

3 Artificial neural network was used to predict the friction and wear behavior of UHMWPE under several sliding conditions of speeds and loads as well as the lubrications. The developed model showed good agreement with experimental data. The developed ANN model provides useful information about the

tribological behavior of UHMWPE, leading to savings in cost and time.

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