Journal of Korea Multimedia Society Vol. 22, No. 7, July 2019(pp. 790-803)
https://doi.org/10.9717/kmms.2019.22.7.790

Construction of Abalone Sensory Texture Evaluation System Based on BP Neural Network

Xiaochen Li†, Yuyang Zhao††, Renjie Li†††, Ning Zhang††††, Xueheng Tao†††††, Lee Eung-Joo††††††

ABSTRACT

The effects of different heat treatments on the sensory characteristics of abalones are studied in this study. In this paper, the sensory evaluation of abalone samples under different heat treatment conditions is carried out, and the evaluation results are analyzed. The three-dimensional (3D) scanning and reverse engineering are used in tooth modeling of the sensory evaluation of abalone samples under different heat treatment conditions. Besides, the chewing movement models are simplified into three modes, including the cutting mode, compressing mode and grinding mode, which are simulated using finite element simulation. The elastic modulus of the abalone samples is obtained through the compression testing using a texture analyzer to distinguish their material properties under different heat treatments and to obtain simulated mechanical parameters. Finally, taking the mechanical parameters of the finite element simulation of abalone chewing as input and sensory evaluation parameters as the output, BP neural network is established in which the sensory texture evaluation model of abalone samples is obtained. Through verification, the neural network prediction model can meet the requirements of food texture evaluation, with an average error of 9.12%.

Key words: Abalone, Heat Treatment, Sensory Evaluation, Finite Element Simulation, BP Neural Network.

1. INTRODUCTION

Abalone, a kind of edible sea snail, has been recognized as one of the most highly-valued seafood, especially in Asian countries, which can be attributed to its delicious taste and nutritional richness. China is endowed with abundant seafood resources. This paper aims to study the Haliotis discus distributed in Bohai Sea [1,2]. The Haliotis discus species has contained protein, fat, vitamins, glycogen, and many other trace elements, which has high nutritional value and is thereby widely used for healthcare [3]. The abalone aquaculture production has grown rapidly in China in recent years, which gives rise to the emergence of new products (such as ready-to-eat abalone) as consumer favorites. Characteristics, including texture, aroma, color, appearance, and size, are of great importance to evaluate the quality of ready-to-eat abalone under different heat treatments. The existing re-

※ Corresponding Author : Lee Eung-Joo, Address: 428, Sinseon-ro, Nam-gu, Busan, Korea, TEL : +82-51-629-1143, FAX : +82-, E-mail : ejlee@tu.ac.kr
Receipt date : May 29, 2019, Approval date : June 25, 2019
† Dept of Mechanical Engineering, Dalian Polytechnic University, China (E-mail : liana_chen0@sina.com)
†† Dept of Mechanical Engineering, Dalian Polytechnic University, China (E-mail : 13293637003@163.com)
††† Dept of Mechanical Engineering, Dalian Polytechnic University, China (E-mail : 949074501@qq.com)
†††† Dept of Information Communications Engineering, Tongmyong University, Korea (E-mail : jangneyong0829@hotmail.com)
††††† Dept of Mechanical Engineering, Dalian Polytechnic University, China (E-mail : taohouse@163.com)
†††††† Dept of Information Communications Engineering, Tongmyong University, Korea
※ The authors acknowledge the National Engineering Research Center of Seafood. This work is supported by Public Science and Technology Research Funds Projects of Ocean, China (no.201505029).

search on the quality evaluation of abalone meat mainly focused on the sensory evaluation, Texture profile analysis methods and the electronic sensing technology. Of them, sensory evaluation was a relatively accurate evaluation method, which could evoke measure, analyze and explain product according to responses through vision, olfaction, feeling, taste, and hearing. However, such a method was time consuming, laborious and error-prone during the evaluation process. On the other hand, the Texture profile analysis method had been used to evaluate the physical or mechanical indicators of food using a texture analyzer, which could establish the relationship between the test signal and the texture parameters to analyze the food texture. This method was fairly objective; However, its results were far removed from expectations as a result of the different instrumental structures and human masticatory organs. With the recent rapid development of electronic technology, an increasing number of researchers had applied the electronic sensing technologies, including electromyography and the piezoelectric-film sensor, in the texture analysis of food [4]. In the meantime, many kinds of bionic equipment had emerged (like the electronic tongue), which could simulate the human perception methods for testing [5]. However, these methods were expensive and complicated, which did not align with the requirements of the enterprise.

In this study, the effects of heat treatment conditions on the sensory characteristics of abalones are analyzed. Concretely, the mechanical properties of abalone are measured under different treatment conditions through the finite element simulation. Furthermore, an evaluation model is established based on the back propagation (BP) artificial network to predict the sensory hardness, springiness, and smell using the mechanical properties obtained from the finite element simulation.

2. MATERIALS AND METHODS

2.1 Materials and Sample preparation

Fresh abalones (Haliotis discus hannai Ino), 70 ± 5 g (including shell) in weight and 8±1 cm in length, are purchased from the Dalian seafood market. The abalone meat is removed from the shell and the viscera is preserved in icy water prior to the experiments [6]. All processed abalone meat is divided into 30 groups, followed by thermal treatment using a thermostat at a power of 1500 W in a water bath (HH-4 Changzhou Rui Zhibo equipment manufacture Co. Ltd.) at 60, 80, 85, 90 and 100℃ for 15, 30, 60, 120, 240 and 360 min, respectively [7]. In addition, an experiment table containing 30 sets of experiments is shown in Table 1, while meat processing in the water bath is pre-

Table 1. Factors and levels table for experimental design.

S/N	T/℃	t/min	S/N	T/℃	t/min	S/N	T/℃	t/min
1	60	15	11	80	240	21	90	60
2	60	30	12	80	360	22	90	120
3	60	60	13	85	15	23	90	240
4	60	120	14	85	30	24	90	360
5	60	240	15	85	60	25	100	15
6	60	360	16	85	120	26	100	30
7	80	15	17	85	240	27	100	60
8	80	30	18	85	360	28	100	120
9	80	60	19	90	15	29	100	240
10	80	120	20	90	30	30	100	360

Fig. 1. The thermal processing of abalone meat.

Fig. 2. The processed abalone samples.

sented in Fig. 1, and the processed abalone samples are displayed in Fig. 2.

2.2 Methods

2.2.1 Sensory Evaluation

The abalone meat used for sensory evaluation is cut into cubes at the dimension of 14×14×14 mm. Typically, a sensory evaluation team including 6 men and 5 women with good distinctions and descriptive abilities, is established to carry out the sensory evaluation according to the double-blind method in the well-ventilated and partition booths under fluorescent light. Concretely, the hardness, springiness, and chewiness of the abalone meat are evaluated using a 5-point scale. The sensory evaluation index criteria are shown in Table 2.

2.2.2 Determination of Mechanical Properties

The constitutive properties of food are generally quite complex, but most mechanical properties of food before breaking are close to the linear elasticity. On this account, the abalone samples are assumed to be materials with isotropy and linear elasticity. The Poisson's ratio of all processed samples is set at 0.4 and the density is set at 1.2 g/cm3. Obviously, the abalone samples under different heat treatments have different material properties, which can be distinguished by the elastic modulus measure through the compression experiments. Specifically, the elastic modulus is measured according to the following method.

Firstly, the tested abalone samples are cut into cylinders about 12 mm (diameter) ×10 mm (height) in size. The upper sample surface is the stress surface, which is perpendicular to the muscle fiber. Five duplicates are set for each sample. Secondly, a texture analyzer (FTC, Virginia, USA) fitted with a P/100 probe is used for compression experiments, as shown in the Fig. 3. Each sample undergoes compression experiment at a compression

Fig. 3. TPA texture experimental device.

Table 2. Sensory index criteria of abalone meat

Sensory score	5	4	3	2	1
hardness	Very good	good	Moderate	Bad	Very bad
springiness	Moderate	A little hard	Hard	A little soft	Soft
chewiness	Very good	good	Moderate	Bad	Very bad

level of 60% (relative to sample height), a test speed of 60 mm/min and the triggering stress of 0.1 N [8].

Finally, when the degree of compression is less than 30%, if the stress-strain curve can be used as a straight line fitting based on MATLAB, the elastic modulus of the sample can be easily calculated according to Hooke's law.

The calculation formula is as follows:

$$E=\sigma/\varepsilon=(F/A)/(\triangle L/L) \quad (1)$$

Where

E is the elastic modulus;

A represents the effective area;

F/A stands for the stress;

$\triangle L/L$ indicates the strain;

2.2.3 Reconstruction of the Tooth Surface Model

The dental model of healthy adult men is taken as a sample. A set of reference points on the object surface are applied to assist in measuring the object. Moreover, the 3D data of the incremental reference point and density point clouds are acquired using the ATOS 3D optical scanner, as shown in Fig.4. The point cloud model is then encapsulated into a polygon that is repaired and smoothed. Besides, the 3D solid model of the sample is reconstructed using the scan to the 3D function of Solidworks (Fig. 5).

2.2.4 The Simplified Chewing Movement Model

Chewing movement is a complex phenomenon involving the mandible, masticatory muscles, and temporomandibular joint (TMJ). In this study, the simplified chewing movement models are constructed based on the modern occlusion theory and temporomandibular articulation movement theory, which are further divided into three movements, including cutting movement, compressing movement and grinding movement. The whole process of chewing and crushing food is then simulated [9,10].

Fig. 4. Working diagram of ATOS optical scanner.

Cutting movement is the beginning stage of chewing movement, in which one end of food is fixed and the other one is restricted by the upper incisor. Food will be distorted due to the horizontal and vertical displacement of the lower incisor, as shown in Fig. 6.

Compressing movement can further break the food into smaller food particles through the molars. In this process, food is supported and maintained by the protruding part of the molar. Due to the difference in the shape of upper and lower molars, the deformation will occur when the food bottom is subjected to the vertical extrusion of the lower mo-

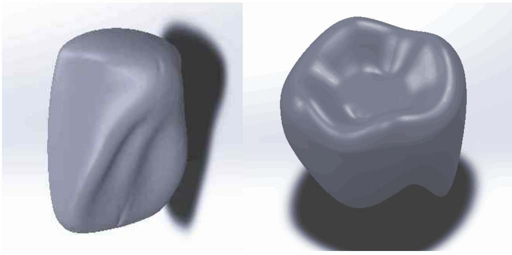


Fig. 5. The reconstruction diagrams of incisor and molar three-dimensional models.

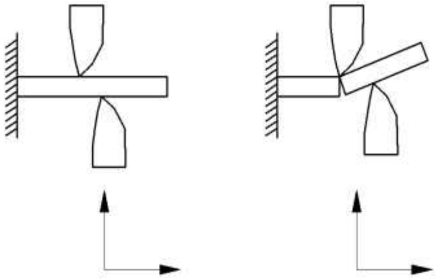


Fig. 6. The simplified diagrams of cutting movement.

lars, which can be ascribed to the difference in the shape between the upper and lower molars, as shown in Fig. 7.

Molars begin to grind food that has been squeezed into small particles. The material will be clamped at the upper and lower teeth and remains at rest. Later, the lower molars begin to move horizontally and vertically, which can thereby crush food, as shown in Fig. 8.

2.2.5 Simulation of Chewing Movement

The chewing movements, including cutting movement, compressing movement, and grinding movement, are simulated and analyzed with the application of ANSYS 15. The simulation process of an incisor in cutting food is shown in Fig. 9. In the cutting movement, the upper incisor remains immobile, while the lower ones are subjected to a displacement of 1.2 mm in both horizontal and vertical directions. Fig. 10 has shown the compressing movement of molars to press food. During this process, the lower molars only have a displacement of 1.2 mm in a vertical direction. The grinding movement is achieved through the upper and lower molars under the comprehensive effects of extrusion, cutting and tearing, resulting in food destruction. Moreover, the food grinding movement process is also simulated, as shown in Fig. 11. Typically, the lower molars have a displacement of 1.2 mm in both horizontal and vertical directions.

30 groups of abalone samples are simulated

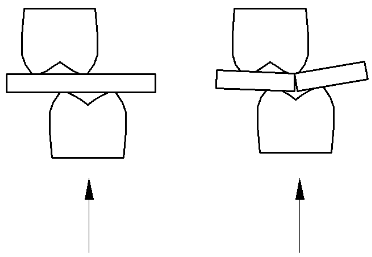


Fig. 7. The simplified diagrams of compressing movement.

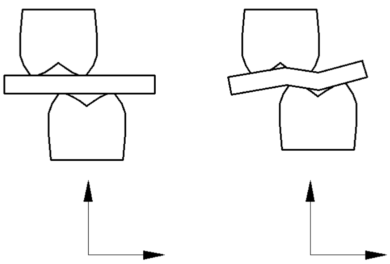


Fig. 8. The simplified diagrams of grinding movement.

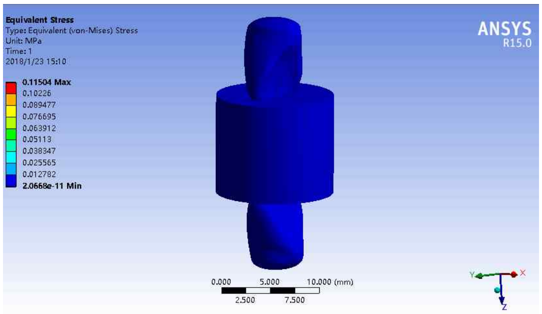


Fig. 9. Simulation of movement process in the cutting mode.

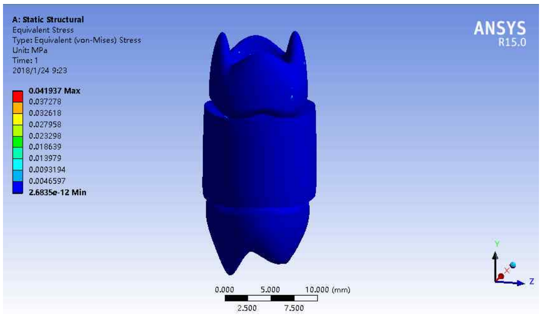


Fig. 10. Simulation of movement process in the compressing mode.

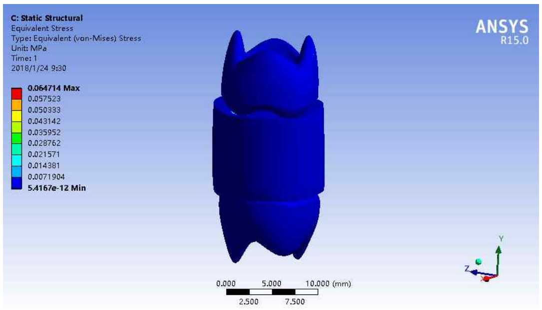


Fig. 11. Simulation of movement process in the grinding mode.

through the three chewing movement models under different heat treatment processes. The stress value of food can be calculated after tooth occlusion with Ansys software.

2.2.6 Neural Network Analysis

The neural network is the abbreviation of an artificial neural network (Artificial neural network, ANN), which is a computer system with artificial intelligence that mimics the biological process of the brain. It has broad application prospects in many academic fields. The neural network is calculated by a large number of artificial neurons connected in parallel in a certain form, and most of them can be classified as an adaptive system that changes the internal structure according to external information. Some scholars had theoretically demonstrated that the three-layer neural network could approximate any function with arbitrary precision, and the neural network with more than three layers could accurately complete the classification of any non-orthogonal set.

So far, more than 40 kinds of neural networks had been used by researchers at high frequencies and could be roughly divided into Hopfield networks, BP networks, and RBF networks. The BP (Back Propagation) neural network is short for error backpropagation neural network [11]. It is a multi-layer feedforward neural network trained according to the error backpropagation algorithm which is simple, can be modeled with fewer data and can be approximated by learning. Nonlinear mapping is also the most extensive and successful neural network in current applications. Xiaodan Wang analyzed the correlation between texture parameters and tenderness of beef. The neural network model was constructed by MATLAB software to achieve a rapid and non-destructive evaluation of meat tenderness grade which was validated. Hui Zhao used the MATLAB toolbox to construct a prediction model of corn quick-freezing time and combined with the genetic algorithm to

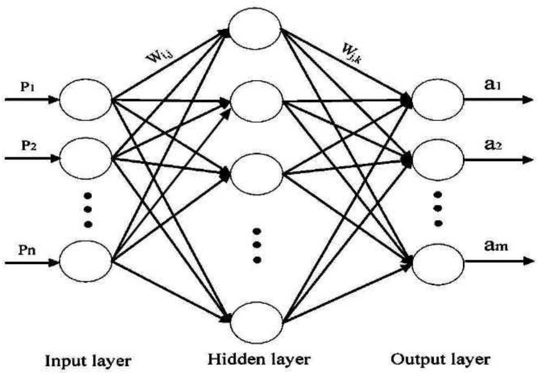


Fig. 12. BP neural network structure.

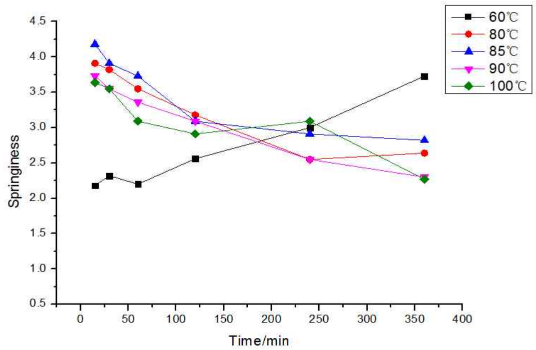
optimize the BP neural network. The accuracy of the model was verified by verification. The BP neural network structure is shown in Fig. 12.

In this study, this network is used to establish the prediction equations of sensory parameters, and the mechanical parameters obtained from the simulation analysis of chewing movement are used as the inputs, whereas the sensory evaluation data serves as the desired outputs. Additionally, the mechanical parameters of maximum von-mises stress and maximum shear stress are selected as the input layer neurons, while the sensory evaluation parameters of hardness, springiness, and chewiness are used as the output layer neurons. To be specific, parameters of the training model are as follows: the allowable error of 1×10^{-6}, the learning rate of around 0.01, the dynamic constant of roughly 0.8, and the maximum number of iterations of approximately 1000 [12].

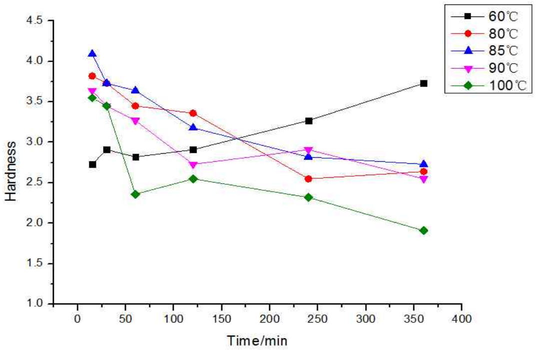
3. RESULTS AND ANALYSIS

3.1 Effects of Different Heating Conditions on Sensory Evaluations

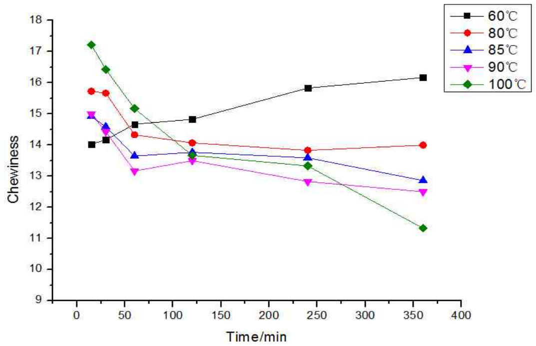
Fig. 13 has displayed the changes in the hardness, springiness, chewiness, and smell of abalone meat under different heat treatments. The results suggest that, during high-temperature heating (≥ 80℃), the hardness, springiness, and chewiness of abalone meat are decreased with the extension of



(a)



(b)



(c)

Fig. 13. Sensory changes in abalone meat during the heating process.

heating time. In addition, it is also found that a higher heating temperature will lead to a more obvious reduction tendency. Furthermore, Fig. 13 demonstrates that the springiness and hardness tend to be abnormal at 60℃ compared with those at the higher heating temperatures. Such abnormal phenomena may be explained by its microstructure [13, 14]. Typically, the network structure becomes a honeycomb after 60 min of heating, and the tighter network structure of honeycomb can increase the hardness, springiness, and chewiness of abalone meat.

3.2 Determination of Elastic Modulus

The proportional coefficient of stress and strain in elastic deformation is referred to as the elastic modulus, which can be used to indicate the difficulty of elastic deformation. In this study, the compression experiments of abalone samples under different heating treatments are carried out using the texture analyzer. Taking sample 1 as an example, the stress-strain curve is shown in Fig. 14. When the compression ratio range is less than 30%, 30%~50% and 50%~60%, the curves are fitted to three linear elastic curves, I, II and III, respectively [15]. This is caused by the change in water loss rate of abalone. Along with the whole compression process, the change of water loss rate can be divided into three stages: the rising stage, the constant speed stage and descending stage [16]. In the rising stage, the water content decreases rapidly from inside to outside. The reason is that the water content of abalone is higher in the early stage, and most of the free water and a small part of the equilibrium water are quickly extruded under compression. In the constant speed stage, the free water content of abalone is less, and the loss of equilibrium water is the main factor, so the water content decreases slowly compared with the rising stage, and the water loss rate is constant [17]. In the descending stage, the water

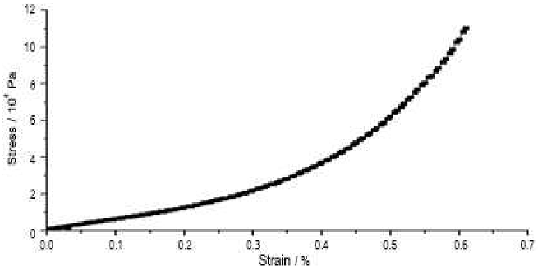


Fig. 14. Stress-Strain curves of the compression.

content of abalone has approached the equilibrium moisture content, the smaller the water gradient, and the smaller the power of water transfer [18], so the water loss rate slowly decreases. In addition, the relation coefficient between the regression equation and the stress-strain curve is over 0.95. According to Hooke's law, the slope of the linear regression equation is the elastic modulus.

The regression equation of sample 1 part I (<30%) :

$$\sigma = 2.73\varepsilon + 0.048 \quad (2)$$

The elastic modulus of sample 1 is calculated to be 2.73×10^4 Pa, while that of the other samples can be obtained by the same method, as shown in Table 3.

3.3 Simulation Analysis of Chewing

The Von-Mises stress and shear stress of the 30 groups of abalone samples are measured in three chewing simulation models, as shown in Table 4-6. Of them, S′ is the vector sum of the vertical and horizontal displacement of moving teeth; while Mises and shear represent the Von-Mises stress and shear stress, respectively.

It can be found from Table 4 and 5 that, the compressing movement will produce greater shear stress and Von-Mises stress when the displacement vector is less than the cutting movement. This can potentially explain for the reason why people tend to use molars to break hard food. Afterward, the grinding movement will produce greater shear stress and Von-Mises stress than those of the compressing movement (Tab.6), indicating that grinding movement may play an important role in breaking elastic food.

3.4 Analysis of the Predictive Sensory Evaluation Model

3.4.1 Correlation Analysis

Correlation between the mechanical characteristics of the chewing simulation system and the sensory evaluation is analyzed using the Pearson correlation. The results have indicated all good correlations, with the correlation coefficients (r) of over 0.71 (Tab.7). As a result, the mechanical characteristics of abalone samples can be used to predict the sensory hardness, springiness, and chewiness.

Only the statistically significant correlation coefficients upon Pearson correlation analysis are presented. *p≤0.05; **p ≤0.01.

3.4.2 Determining the Hidden Layer Nodes

The number of neurons in the hidden layer will greatly affect the accuracy of the prediction model; However, it is quite difficult to determine the num-

Table 3. Elastic Modulus under different heating conditions

S/N	Elastic Modulus			S/N	Elastic Modulus			S/N	Elastic Modulus		
	I	II	III		I	II	III		I	II	III
1	27287	83424	182450	11	47236	100219	318374	21	48569	106549	326834
2	27966	90831	200609	12	25108	84632	235453	22	38293	96770	299242
3	28777	96143	212438	13	33592	94248	263958	23	44986	115906	395806
4	32217	110022	240664	14	40700	98763	296418	24	29745	91284	284951
5	34624	106694	304583	15	56534	163513	376613	25	33019	103169	323894
6	32879	100622	281630	16	46729	107421	307090	26	43796	95654	373286
7	30738	103360	284249	17	41822	102413	270929	27	39278	99638	342031
8	35885	106222	300499	18	42670	99752	301598	28	41045	105333	294413
9	54459	186794	430923	19	36459	95832	293463	29	39669	100366	324091
10	41732	98032	305158	20	36459	91485	285258	30	38064	109374	359986

Table 4. Influence of heating processing on the cutting effect

S/N	T/℃	t/min	S′/mm	Mises/10^4Pa			Shear/10^4Pa		
				I	II	III	I	II	III
1	60	15	2.82	3.00	4.20	5.67	1.73	2.40	3.20
2	60	30	2.82	3.02	4.29	5.91	1.74	2.44	3.32
3	60	60	2.82	3.04	4.41	6.06	1.75	2.51	3.41
4	60	120	2.82	3.44	4.64	6.45	1.97	2.62	3.64
5	60	240	2.82	3.48	4.56	7.40	2.00	2.60	4.16
6	60	360	2.82	3.45	4.47	7.05	1.98	2.55	3.96
7	80	15	2.82	3.09	4.51	7.07	1.78	2.55	3.97
8	80	30	2.82	3.51	4.56	7.33	2.01	2.60	4.11
9	80	60	2.82	3.64	5.72	9.20	2.07	3.25	5.13
10	80	120	2.82	3.60	4.42	7.38	2.06	2.52	4.15
11	80	240	2.82	3.68	4.46	7.59	2.11	2.54	4.26
12	80	360	2.82	2.94	4.22	6.40	1.69	2.40	3.59
13	85	15	2.82	3.46	4.38	6.78	1.99	2.48	3.80
14	85	30	2.82	3.59	4.43	7.27	2.06	2.53	4.09
15	85	60	2.82	3.78	5.38	8.40	2.09	3.04	4.71
16	85	120	2.82	3.68	4.58	7.43	2.11	2.60	4.19
17	85	240	2.82	3.60	4.50	6.91	2.07	2.56	3.87
18	85	360	2.82	3.62	4.45	7.34	2.07	2.54	4.12
19	90	15	2.82	3.52	4.40	7.24	2.02	2.49	4.06
20	90	30	2.82	3.52	4.30	7.11	2.02	2.45	4.00
21	90	60	2.82	3.70	4.56	7.72	2.12	2.59	4.32
22	90	120	2.82	3.55	4.41	7.33	2.03	2.51	4.12
23	90	240	2.82	3.65	4.73	8.70	2.09	2.69	4.87
24	90	360	2.82	3.06	4.30	7.10	1.76	2.45	4.00
25	100	15	2.82	3.45	4.51	7.64	1.98	2.56	4.28
26	100	30	2.82	3.63	4.40	8.38	2.08	2.49	4.68
27	100	60	2.82	3.56	4.45	7.92	2.04	2.54	4.43
28	100	120	2.82	3.59	4.55	7.24	2.06	2.57	4.06
29	100	240	2.82	3.57	4.46	7.66	2.05	2.54	4.30
30	100	360	2.82	3.54	4.61	8.17	2.03	2.60	4.58

bers of hidden neurons. In our study, as can be observed from the results, the number of hidden layer nodes is 17.

3.4.3 Validation of the Predictive Texture Model

The sensory evaluation data of abalone meat are predicted using the BP neural network. The results show little difference between the predicted and measured values, with relatively small average calculation error.

According to the data displayed in Table 8, the maximum error is 27.46%, while the minimum is 2.12%, and the average is 9.12%. These results demonstrate that the established BP neural network has a good prediction effect, which is also associated with the superiority of high prediction

Table 5. Influence of heating processing on the compressing effect

S/N	T/℃	t/min	S′/mm	Mises/10^4Pa			Shear/10^4Pa		
				Ⅰ	Ⅱ	Ⅲ	Ⅰ	Ⅱ	Ⅲ
1	60	15	2	3.48	10.65	23.26	1.84	5.64	12.30
2	60	30	2	3.57	11.60	25.60	1.89	6.12	13.52
3	60	60	2	3.67	12.26	27.12	1.94	6.48	14.34
4	60	120	2	4.11	14.04	30.71	2.17	7.41	16.24
5	60	240	2	4.42	13.60	38.84	2.33	7.20	20.52
6	60	360	2	4.19	12.83	35.95	2.22	6.78	19.00
7	80	15	2	3.92	13.17	36.26	2.07	6.97	19.16
8	80	30	2	4.58	13.55	38.34	2.42	7.18	20.27
9	80	60	2	6.95	23.84	54.98	3.67	12.60	29.60
10	80	120	2	5.32	12.51	38.92	2.81	6.62	20.56
11	80	240	2	6.02	12.78	40.60	3.19	6.75	21.44
12	80	360	2	3.20	10.81	30.01	1.69	5.70	15.87
13	85	15	2	4.28	12.02	33.68	2.27	6.35	17.80
14	85	30	2	5.19	12.61	37.80	2.74	6.66	19.98
15	85	60	2	7.21	20.85	48.02	3.81	11.01	25.36
16	85	120	2	5.96	13.71	39.16	3.15	7.26	20.70
17	85	240	2	5.33	13.06	34.54	2.82	6.90	18.26
18	85	360	2	5.44	12.72	38.47	2.88	6.73	20.32
19	90	15	2	4.65	12.23	37.45	2.46	6.46	19.80
20	90	30	2	4.65	11.67	36.40	2.46	6.16	19.24
21	90	60	2	6.19	13.58	41.70	3.28	7.18	22.01
22	90	120	2	4.88	12.34	38.16	2.58	6.52	20.15
23	90	240	2	5.74	14.79	50.50	3.03	7.83	26.70
24	90	360	2	3.79	11.64	36.36	2.01	6.15	19.20
25	100	15	2	4.21	13.16	41.32	2.23	6.96	21.83
26	100	30	2	5.59	12.22	47.60	2.95	6.45	25.16
27	100	60	2	5.01	12.70	43.62	2.65	6.70	23.05
28	100	120	2	5.24	13.44	37.56	2.77	7.11	19.84
29	100	240	2	5.06	12.81	41.34	2.68	6.78	21.85
30	100	360	2	4.86	13.95	45.93	2.57	7.38	24.26

efficiency. Thus, the mechanical characteristics of the chewing simulation system can be used to predict the human sensory evaluation results using the BP neural network model [19].

4. CONCLUSIONS

In this study, the sensory characteristics of abalone meat are analyzed under different heat treatments. Our findings suggest significant reductions in springiness, hardness and chewiness of abalone meat at a shorter heating time (<60 min), which may reach the appropriate range. Meanwhile, an extended heat treatment (>120 min) will result in a slow downward trend. Moreover, the heating condition at 60℃ is abnormal compared to

Table 6. Influence of heating processing on the grinding effect

S/N	T/℃	t/min	S′/mm	Mises/10^4 Pa			Shear/10^4 Pa		
				Ⅰ	Ⅱ	Ⅲ	Ⅰ	Ⅱ	Ⅲ
1	60	15	2.82	5.37	16.45	35.94	2.79	8.56	18.70
2	60	30	2.82	5.50	17.89	39.50	2.86	9.31	20.54
3	60	60	2.82	5.66	18.92	41.84	2.95	9.84	21.76
4	60	120	2.82	6.34	21.66	47.40	3.30	11.26	24.64
5	60	240	2.82	6.81	21.02	60.00	3.54	10.93	31.21
6	60	360	2.82	6.47	19.80	55.48	3.37	10.31	28.85
7	80	15	2.82	6.05	20.36	55.97	3.15	10.60	29.12
8	80	30	2.82	7.06	20.92	59.17	3.67	10.88	30.78
9	80	60	2.82	10.72	36.80	84.88	5.58	19.14	44.14
10	80	120	2.82	8.21	19.31	60.11	4.27	10.05	31.26
11	80	240	2.82	9.30	19.74	62.71	4.84	10.26	32.61
12	80	360	2.82	4.94	16.66	46.36	2.57	8.67	24.11
13	85	15	2.82	6.61	18.55	51.99	3.44	9.65	27.05
14	85	30	2.82	8.01	19.44	58.37	4.17	10.12	30.35
15	85	60	2.82	11.13	32.21	74.17	5.79	16.75	38.56
16	85	120	2.82	9.20	21.16	60.48	4.78	11.00	31.45
17	85	240	2.82	8.23	20.18	53.35	4.28	10.51	27.75
18	85	360	2.82	8.40	19.64	59.41	4.37	10.21	30.90
19	90	15	2.82	7.18	18.88	57.82	3.73	9.82	30.07
20	90	30	2.82	7.18	18.00	56.15	3.73	9.36	29.20
21	90	60	2.82	9.56	20.99	64.36	4.97	10.92	33.48
22	90	120	2.82	7.54	19.06	58.94	3.92	9.90	30.64
23	90	240	2.82	8.85	22.80	77.95	4.61	11.86	40.54
24	90	360	2.82	5.85	17.96	56.12	3.05	9.35	29.20
25	100	15	2.82	6.50	20.30	63.80	3.38	10.56	33.18
26	100	30	2.82	8.62	18.84	73.52	4.48	9.80	38.24
27	100	60	2.82	7.73	19.62	67.35	4.02	10.21	35.03
28	100	120	2.82	8.08	20.74	57.98	4.20	10.78	30.14
29	100	240	2.82	7.81	19.76	63.84	4.06	10.28	33.20
30	100	360	2.82	7.49	21.54	70.91	3.90	11.21	36.89

Table 7. Correlation matrix

	Cutting Mises	Cutting Shear	compressing Mises	compressing Shear	grinding Mises	grinding Shear
springiness	0.712**	0.710**	0.744**	0.736**	0.872**	0.854**
hardness	0.820**	0.819**	0.755**	0.755**	0.930**	0.931**
chewiness	0.820**	0.819**	0.756**	0.755**	0.930**	0.930**

that at higher temperatures, which may be resulted from changes in chemical forces.

The stress-strain curve of the sample is obtained by a compression test using a texture analyzer, which is fitted using MATLAB software and the elastic modulus of the abalone sample is obtained. Also, reverse engineering technology is used to reconstruct the 3D models of incisors and molars; At the same time, the chewing movement models have been simplified and divided into three modes, including cutting mode, compressing mode and grinding mode. Subsequently, the whole process of chewing and crushing abalone is simulated using the finite element simulation, which allows obtaining the mechanical properties of abalone samples under different heat treatments.

Table 8. Comparison of predictions using the BP neural network model with the actual results

S/N	Sensory index	Sensory results	Predictive results	Error/%
1	Springiness	2.73	2.96	8.26
	Hardness	3.45	3.08	10.67
	chewiness	1.82	2.01	10.26
2	Springiness	2.82	2.90	2.85
	Hardness	3.45	3.36	2.49
	chewiness	2.36	2.71	15.02
3	Springiness	3.18	2.97	6.73
	Hardness	3.55	3.35	5.61
	chewiness	2.18	2.78	27.46
4	Springiness	3.45	3.10	10.14
	Hardness	3.91	3.63	7.29
	chewiness	2.73	3.41	25.00
5	Springiness	3.18	3.08	3.15
	Hardness	4.09	3.82	6.56
	chewiness	3.45	4.03	16.85
6	Springiness	3.27	3.11	4.85
	Hardness	3.73	3.40	8.97
	chewiness	2.45	3.10	26.50
7	Springiness	3.36	3.12	7.27
	Hardness	4.09	3.84	6.00
	chewiness	3.73	4.23	13.33
8	Springiness	3.27	3.05	6.80
	Hardness	3.27	3.37	3.03
	chewiness	2.82	2.95	4.71
9	Springiness	2.73	2.96	8.36
	Hardness	3	3.06	2.12
	chewiness	2.36	2.51	6.61
10	Springiness	3.18	3.05	3.90
	Hardness	3.45	3.53	2.45
	chewiness	3.27	3.61	10.46
Average error/%				9.12

Using Pearson's correlation analysis method, it is found through correlation analysis that the correlation between the elasticity of sensory texture evaluation and the simulation cutting mode exceeds 0.71, which proves that the two have good correlation. Therefore, the chew simulation test results can be used to predict the springiness, hardness, and chewiness of the sensory texture evaluation. Thus, the BP neural network is introduced to predict the sensory evaluation parameters (including sensory hardness, springiness, and chewiness) based on the mechanical properties obtained from chewing simulation analysis. Our findings indicate that the average error of the prediction model can reach 9.12%. To sum up, this method is associated with great advantages and application prospects, which can be attributed to its simplicity, handling convenience, and high accuracy.

REFERENCES

[1] J. Dong, X. Fang, H. Wang, X. Zhang, and X. Tao, "Abalone Muscle Texture Evaluation and Prediction Based on TPA Experiment," *Journal of Food Quality*, Vol. 2, No. 1, pp. 1-9, 2017.

[2] B. Zhu, *Research on the Theory and Technology of Seafood Processing*, Science Press, 16 Donghuangchenggen North Street, Beijing, 2010.

[3] Y. Wang, W.L. Kang, S.G. Xin, and W.Q. Xing, "Analysis of Trace Elements in Abalone and Sea Cucumber," *Spectroscopy and Spectral Analysis*, Vol. 29, No. 2, pp. 511-514, 2009.

[4] Z. Sun, Y. Sun, Y. Li, J. Liu, and J. Li, "Design and Experiment of Bionic Food Texture Analyzer," *Transactions of the Chinese Society for Agricultural Machinery*, Vol. 43, No. 1, pp. 230-234, 2012.

[5] P. António, D. Luis, T.P. Barcelos, S.M. Jorge, and M. Adelio, "An Electronic Tongue for Juice Level Evaluation in Non-alcoholic Beverages," *Procedia Chemistry*, Vol. 1, No. 1, pp. 1023-1026, 2009.

[6] G. Xiao, B. Zhu, X. Dong, X. Chen, and S. Chen, "Effects of Hot Processing Conditions on Partial Processing Properties of Abalone," *Journal of Dalian Institute of Light Industry*, Vol. 31, No. 1, pp. 1-7, 2012.

[7] B. Zhu, X. Dong, L. Sun, G. Xiao, X. Chen, Y. Murata, et. al., "Effect of Thermal Treatment on the Texture and Microstructure of Abalone Muscle (Haliotis Discus)," *Food Science and Biotechnology*, Vol. 20, No. 6, pp. 1467-1473, 2011.

[8] W. Cheng, Y. Zhou, J. Zhang, and Y. Ruan, "Effects of Additives on Elasticity Modulus of Fish Balls Prepared by Broken Rice and Aristichys Nobilis," *China Food Additives*, Vol. 2, No. 6, pp. 205-209, 2012.

[9] L. Chen, Y. Sun, J. Liu, and G. Xie, "Simulation Analysis of Food Materials Damage Effect Based on Chewing Movement," *Modern Food Science and Technology*, Vol. 1, No. 5, pp. 147-152, 2014.

[10] J. Chen, "Food Oral Processing-A Review," *Food Hydrocolloids*, Vol. 23, No. 1, pp. 1-25, 2009.

[11] L. Chen, Y. Sun, J. Liu, and G. Xie, "Simulation Analysis of Food Materials Damage Effect Based on Chewing Movement," *Modern Food Science and Technology*, Vol. 30, No. 1, pp. 147-152, 2014.

[12] Y. Jia, C. Ji, X. Luo, and N. Chen, "Classifying Beef Muscle and Fat Pixels Using Bp-ga Neural Network," *Transactions of the Chinese Society of Agricultural Engineering*, Vol. 11, No. 6, pp. 216-219, 2007.

[13] L. Deng, Y. Li, X. Dong, Y. Wang, Q. Xin, and J. Pan, "Chemical Interactions and Textural Characteristics of Abalone Pleopod Muscle Protein during Heating," *Transactions of the Chinese Society of Agricultural Engineering*, Vol. 30, No. 18, pp. 307-316, 2014.

[14] Y. Zhang, X. Gao, J. Xu, Y. Sun, Y. Chang, and C. Xue, "Comparative Study on Natural Drying and Hot-air Drying of Abalone," *Transactions of the Chinese Society of Agricultural Engineering*, Vol. 24, No. 1, pp. 296-299, 2008.

[15] Y. He, "The Research on Piecewise Linear Fitting of Tool Wear Curver," *Mechanical and Electrical Engineering Technology*, Vol. 44, No. 12, pp. 88-89, 2015.

[16] Z. Gao, *Study on Drying Technology and Product Characteristics of Abalone*, PhD Thesis of Fujian Agriculture and Forestry University, 2011.

[17] S. Huang and L. Fan, "A Kinetics Study on the Combined Drying of the Osmotic Dehydration and Vacuum Frying for the Carrot Chips," *Modern Food Science and Technology*, Vol. 29, No. 2, pp. 223-225, 2013.

[18] F. Jia and Y. Zhou, "Study on Moisture Diffusion Regularity of Brown Rice under Storage Conditions," *Journal of the Chinese Cereals and Oils Association*, Vol. 27, No. 1, pp. 87-90, 2012.

[19] R.Y. Zhan and E.J. Lee, "Human Face Recognition used Improved Back-Propagation (BP) Neural Network," *Journal of Korea Multimedia Society*, Vol. 21, No. 4, pp. 471-477, 2018.

Xiaochen Li

received her B. S. at Dalian Polytechnic University in China (2013-2017). Currently, she is studying in Department of Mechanical Engineering from Dalian Polytechnic University in China for M. S. Her main research areas are computer vision and image processing.

Yuyang Zhao

received his B. S. at Dalian University in China(2013-2017). Currently, he is studying in Department of Mechanical Engineering from Dalian Polytechnic University in China for M. S. His main research area is electromechanical product design and control technology.

Renjie Li

received his B. S. at Jilin Institute of Chemical Technology in China(2011-2015). Currently, he is studying in Department of Mechanical Engineering from Dalian Polytechnic University in China for M. S. His main research area is electromechanical product design and control technology.

Ning Zhang

received his B. S. at Dalian Polytechnic University in China (2008-2012), and received his master degree at Busan Tongmyong University in Korea (2014-2016). Currently, he is studying in Department of Information and Communications Engineering Tongmyong University, Korea for doctoral degree. His main research areas are image processing and pattern recognition.

Xueheng Tao

received his B. S. degrees from Dlian Institute of Light Industry University, China, in 1985, and received his M. S. and Ph. D. from Dalian University of Technology, China, in 1988 and 1997. From March to April 2003, as a visiting scholar at the National Kanazawa University, Japan, engaged in experimental research on new composite materials. From may to June 2006, as a visiting scholar at the European Institute of Technology, France, engaged in computer engineering and professional education research. From February to July, as a senior visiting scholar at the University of Michigan, America, engaged in higher education management and engineering education research.

Eung-Joo Lee

received his B. S., M. S. and Ph. D. in Electronic Engineering form Kyungpook National University, Korea, in 1990, 1992, and Aug. 1996, respectively. Since 1997 he has been with the Department of Information & Communications Engineering, Tongmyong University, Korea, where he is currently a professor. From 2000 to July 2002, he was a president of Digital Net Bank Inc. From 2005 to July 2006, he was a visiting professor in the Department of Computer and Information Engineering, Dalian Polytechnic University, China. His main research interests include biometrics, image processing, and computer vision.